

Design of fines separation system

Improving separation using 2D-simplified testing and coupled CFD-DEM simulation

MSc. Graduation Thesis
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by

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Preface

Nothing in the world is worth having or worth doing unless it means effort, pain, difficulty... I have never in my life envied a human being who led an easy life. I have envied a great many people who led difficult lives and led them well.

Theodore Roosevelt

Do the difficult things while they are easy and do the great things while they are small. A journey of a thousand miles must begin with a single step.

Lao Tzu

*If you want to go fast, go alone
if you want to go far, go together.*

Abstract

The objective of this research is to reduce fines inside a novel comminution machine. Fines are detrimental to the energy efficiency of the comminution process and induce additional wear. An experimental setup was developed and built, the slice rig (SR), to obtain air flow measurements and mass rates which are used to determine the energy efficiency of the fines extraction.

In-chamber geometries were adapted to enhance the separation capabilities of air. Multiple layouts were tested and two cases are extensively discussed,

It is hypothesised that in-chamber geometries could enhance the separation capabilities of air. Multiple layouts were tested, and two cases are extensively discussed, namely the empty chamber case (ECH), and a case including vanes (WCH). To further increase understanding of the fluid-particle behaviour a CFD-DEM model was built.

During the experiments the airflow was measured to be $0.017 \text{ [m}^3/\text{s}]$ with an pressure drop of -47 [Pa] . Separation quality and collection efficiency were improved by the placement of vanes inside the chamber domain. Vanes in the air chamber guide and increase air velocity close to the particle stream. As a result the separation ability of the air flow was improved. PIV was used to measure the average particle velocity. The average bulk velocity field was obtained. The bulk velocity in the particle stream was found to be around 5 to 6 [m/s] in the ECH case, and 4 to 5 [m/s] in the WCH case. The implementation of vanes improved the particle loading from $262 \text{ [g/m}^3\text{]}$ to $472 \text{ [g/m}^3\text{]}$. The grade of particle separation in the 125 and 75 micron mesh size improved with 23% and 114% respectively. $\eta_{d_p \leq 125 \mu\text{m}}$ was improved from 39% to 48%.

These values are used to calculate the energy consumption of the ECH and WCH case. The energy consumption for fines extraction in the slice rig was reduced from 0.11 [kWh/ton] to 0.06 [kWh/ton] up-to the exit of the air chamber. This is a reduction of approximately 50%. By increasing the loading capacity of the air flow, the specific energy consumption was lowered. The increased loading capacity of the airflow, achieved in the air chamber, will improve energy consumption in the whole fines extraction process.

The simulations, performed using open-source CFD-DEM coupled software, were strongly guided by the experiments and relied heavily on the theory introduced in part I. The model is not quantitatively valid, but can be used as an engineering aid. The fines rate in the ECH simulation was differs more than 100% from the fines rate found in experiments. This also induced differences in the PSD of the simulation with respect to the experiments. The CFD-DEM model is a promising path for further developing insights in particle-fluid interaction in the SR and larger test setups.

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Nomenclature

Abbreviations

Abbreviation	Definition
suffix f	fluid
suffix p	Particle
PSD	Particle Size Distribution
GED	Grade Efficiency Curve
CUM Pass	Cumulative passing [%]
Capacity	Machine throughput [tph or kg/s]
SR	Slice Rig
ECH	Empty Chamber Case
WCH	Wall Chamber Case (with vanes)
PIV	Particle Imagery Velocimetry
PTV	Particle Tracing Velocimetry
PSD	Particle Size Distribution
CFD	Computational Fluid Dynamics
DEM	Direct Element Methods
CFD-DEM	coupled simulation method
FOAK	First-of-a-Kind
LV	Low Velocity
COMSOL	enterprise CFD and multi-physics software
FPT	Fluid Particle Tracing module (in COMSOL)
OpenFoam	open-source CFD (Field Operations and Manipulations) software
Liggghts	open-source DEM software
CFDEMproject	open-source coupling software

Symbols

Symbol	Definition	Unit
η	(Overall) Collection Efficiency	[%]
μ	Viscosity	[Pa · s]
ρ	Density	[kg/m ³]
ρ_B	Bulk specific gravity of the feed	[T/m ³]
ν	Poisson's ratio	[-]
A	(Cross-sectional) Area	[m ²]
C_d	Drag coefficient	[-]
D	Diameter of roller	[m]
D	Drag force	[N]
E_η	Specific Energy Efficiency	[kWh/ton]
f_D	Specific drag correction	[-]
$G(d_p)$	Fractional Collection Efficiency	[-]
g	Gravitational constant	[N]
L	Gaps size between rollers	[m]
LC	Load capacity	[g/m ³]
m_p	Mass particle	[kg]
$\dot{m}_F$	Mass rate feed	[kg/s]

Symbol	Definition	Unit
$\dot{m}_P$	Mass rate product	$[kg/s]$
$\dot{m}_f$	Mass rate fines	$[kg/s]$
O	Occupancy	$[\%]$
p	Absolute pressure	$[Pa]$
P_{fan}	Fan power	$[W]$
Q	Mass flow rate	$[kg/s]$
RPM	rotation per minute	$[min^{-1}]$
RR	Reduction Rate	$[-]$
Re	Reynolds number	$[-]$
SP_i	Static pressure Fan	$[Pa]$
U	Velocity field	$[m/s]$
u	Velocity in X-direction	$[m/s]$
$\dot{V}$	Volume flow rate	$[kg/m^3]$
v	Velocity in Y-direction	$[m/s]$
V_p	Volume particle	$[m^3]$
W	Width of roller	$[m]$
$w(d_p)$	Weight fraction of Fractional Collection Efficiency	$[-]$
Y	Youngs modulus	$[GPa]$

Part I

Theoretical background

1

Introduction

This chapter will introduce the social relevance of mineral mining, the differences between mineral mining and mining of fossil fuels, and how this relates to mining operations' energy consumption. Comminution contributes strongly to mining operations' energy consumption. Fines are found to be detrimental to comminution efficiency. It is proposed by the developers that air extraction of fines, in situ, could improve the energy efficiency and capacity of a novel mill design. To test the energy efficiency of fines extraction a test setup is proposed. The hypothesis for more efficient fines extraction will be introduced afterwards.

1.1. Social relevance

Transforming our energy structure from fossil to renewable energy sources is one of the most considerable challenges of the 21st century. In order to reduce carbon dioxide emissions fossil energy sources are replaced with renewable sources such as wind and solar. The intermittent nature of these renewable sources indicates the need for energy storage capacity and dynamic energy consumption of industry on a large scale. The usage of renewable energy can reduce carbon emissions significantly if done efficiently. Given that solar panels and windmills need large amounts of raw materials, and batteries even more than this, it's evident that the mining industry will need to increase the production of (critical) raw materials in the future. Critical raw materials referred to are for example: Co, Ni, Mn for batteries, Nd for windmills and electric motors, and Si, Ag, Cd and Ge for solar panels [1][2]. Improved fines separation could decrease the energy consumption for the production of these critical materials, indicating the significance of this study.

The projected demand for various critical minerals will rise significantly in the coming years. Critical minerals demand such as Cobalt and Nickle, shown in figure 1.1 are projected to increase. The current material need for electric vehicles alone is expected to outrank the current production significantly as shown in figure 1.1. Electric motor production will overtake wind turbines as a major consumer of rare earth materials shortly [1].

It will also become more challenging to mine critical minerals. Global ore grades and quality have decreased over the decades, resulting in the fact that lower ore grades are becoming financially viable [3][4].

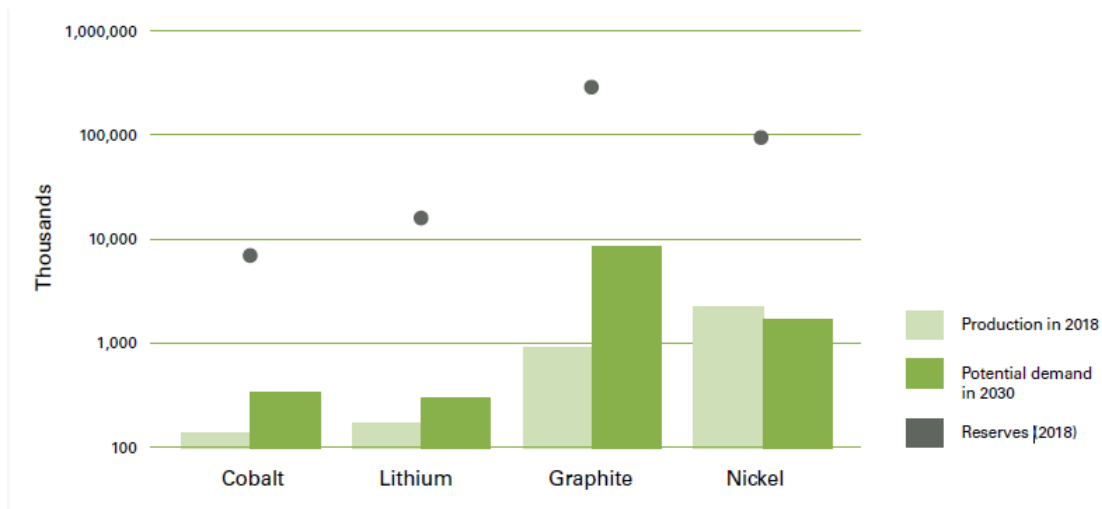


Figure 1.1: Critical mineral demand for electric vehicles in tonnes of materials [2]

Due to increased material demand, the size of mining operations will further increase, leading to an increase in the energy consumption of mining operations. Electrification and more efficient mining methods, such as improved comminution, are desired to keep energy consumption under control. Implementing new techniques could pose a significant challenge as mining operations take over ten years to develop [4].

Hence, mining and its processes should attract a major part of research so that our ever-increasing need for minerals can be satisfied while limiting our impact on the local and global environment.

A large variety of minerals and fuels are currently mined. These mining operations have great similarities. Mining minerals or fuels both negatively impact the environment by CO_2 emissions, both consume large amounts of energy, and both are currently essential for global prosperity. Mining influences *everything* that society possess and use. However, there are also significant differences between mining minerals and fuels.

Fossil fuels like oil, gas, and coal are mined for single-use purposes. Among these, coal is most similar to mineral mining since both involve solid materials. Coal can be mined as a solid, which produces a net positive balance in "available" energy. One uses energy to obtain more energy from a source. However, coal can only be burnt once. This means that mining operations should continue indefinitely for a consistent energy flow. This makes coal a non-recyclable/unsustainable source of energy. Mining minerals can contribute to a sustainable source of energy. Minerals are not an energy source in themselves. Minerals are used to produce products that can extract energy from renewable sources, such as wind, water, and sun. Renewable energy sources create a possibility for a circular energy provision.

From a geopolitical point of view, there are even more arguments for using renewable energy sources versus fossil fuels. These are shown in figure 1.2:

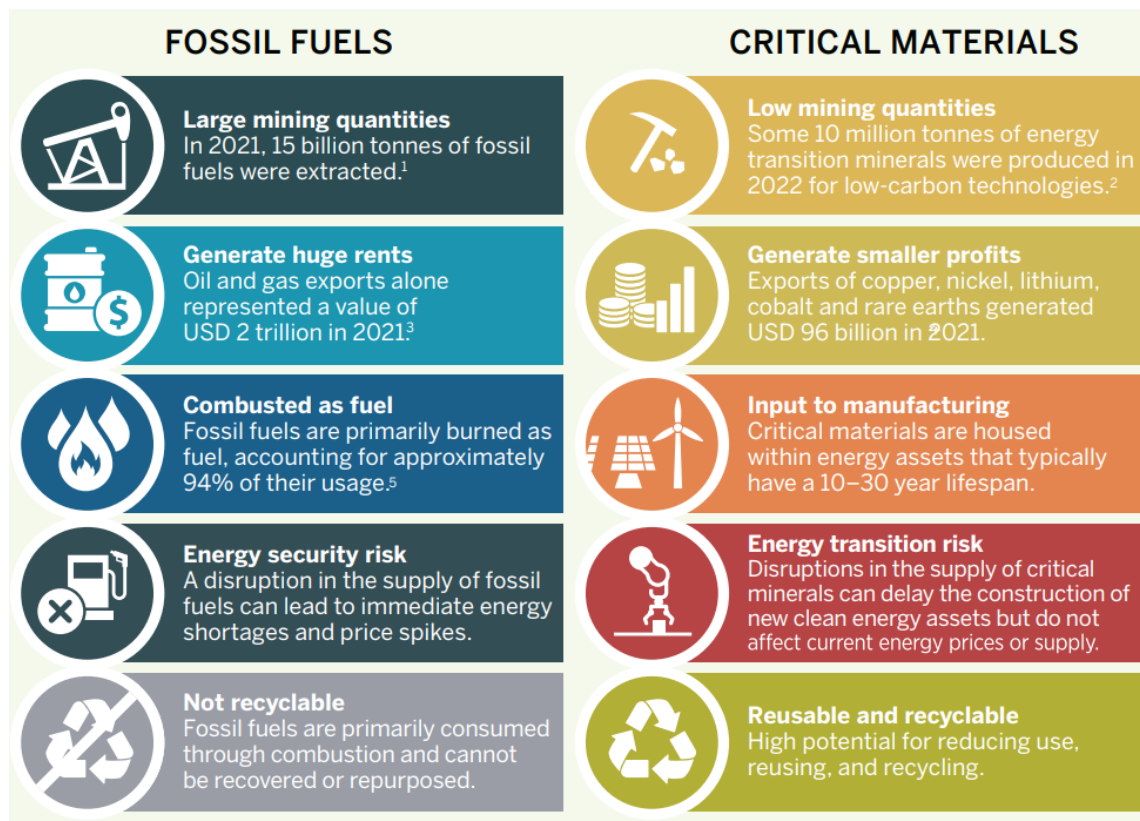


Figure 1.2: Advantages of mining minerals versus fuels [5]

Figure 1.2 shows that the consequences of disruption in the supply chain of critical minerals are different from the consequences of disruption of the supply chain in fuel. A disruption in the mineral supply chain will only delay new energy production facilities as critical minerals are only used to produce energy-generating devices. It will not interrupt already existing plants on which one relies. This gives a significant advantage over combustible fuels and is a geo-political reason to invest in better mining of minerals. Fossil fuels must be replenished at the same rate as they are used. Making energy-poor countries long-term dependent on energy-rich countries.

1.2. Comminution & energy consumption

A lot of energy is needed to perform mining operations. Currently, this energy is mostly used in the form of fossil fuels. Energy consumption of mines predominantly consists of hauling equipment, comminution, and other ore processing steps [2]. Comminution is a process in which rocks are crushed and ground until a desired particle size is reached. Around 36% of a mine's energy consumption is attributed to comminution [2]. The energy consumption of comminution is dependent on the mined ore. To decrease a mining operation's carbon footprint, energy consumption should be reduced, and processes should be electrified to be powered by renewable sources.

Comminution is a highly energy-intensive process [6]. Sources report comminution energy consumption between 29% and 36% of the energy consumption of a mine [2][7]. The comminution process, therefore, can take up between 1.14% (USA) or 1.48% (Australia) of the total energy consumption of the nation [7].

Most of the comminution is currently done by tumbling mills. Large horizontal drums rotate, dropping ore and metal balls on themselves, inducing rock breakage. The sheer size of these operations means that a single mill can take up to 28 MW of power [8]. Running year-round, one mill can consume up to 245 MWh. Some mining operations have multiple mills operating at the same time. These mills are quite inefficient. Based on

the work of Fuerstenau, it is found that for a given set of stipulations, the performance index of the commonly used ball mill when grinding dolomite is found to be 21% compared to 44% for a High-Pressure roll mill [9]. Theoretical lower bounds on the energy investments are calculated for the single particle breakage mode [9]. This suggests that there is a lot of energy efficiency gain to win. A part of the energy efficiency improvement can be obtained by separating fines from the product to prevent over-crushing.

If the comminution process can be made more efficient, the reduction in carbon emissions and energy consumption can be significant [2].

Diesel generators produce energy for comminution in remote areas, making it possible to operate 24/7. However, diesel and transportation costs contribute to the operational costs of the comminution process. In the future, energy could be produced (partially) by renewable sources on location. Solar panels could provide energy for the comminution process. Current tumbling mill processes are unfit for intermittent renewable energy sources as they are not suited to variable energy supply and require a lengthy startup and shutdown process. A new technology is being developed to provide high capacity and flexible operation to use renewable energy sources.

1.3. Comminution & environment

As ore is scarcely deposited; large amounts of material need to be processed to produce the desired amount of product. This will cost more energy and create more waste if done in the traditional manner. Mining and processing ore produces significant quantities of waste materials. Typically one or two magnitudes larger than the amount of material produced [4]. For example, copper mines have concentrations of 0.35% to 0.8%

Waste materials can be stored in slime ponds. Slime storage has a significant environmental impact, as dams and large ponds need to be constructed. Dams can be as large as 2.9 km long and 165 meters high [4]. Smaller slime dams are desired as they destroy less area and reduce the magnitude of the consequences if a dam breaks.

Using dry comminution processes and subsequent proper fines extraction can significantly reduce the amount of wet waste material. Costs for waste material disposal are high in Europe; reducing these costs can increase financial viability [6]. Dry comminution can reduce water consumption in arid regions where water stress is high [6]. Dry stacking has benefits compared to wet tailing; it can optimise land use, reduce groundwater contamination and minimise the risk of dam failure. Dry tailing will form a more stable final storage [6].

1.4. Comminution technology

A new new energy-efficient dry particle comminution milling process is being developed. The comminution machine is based on the theory of Roller grinding [10]. This machine breaks rocks using two counter-rotating rollers. This produces a product stream, predominately of the desired particle size (d_p), resulting in the mill being more energy efficient than the standard tumbling mills [6][9].

Microscopic particles (fines) are created in any fracture event, and the production of smaller fines will increase if exposed to ongoing crushing events. This Over-crushing is undesirable due to wear, increased energy consumption, reduced throughput capacity and it increases costs [6]. Furthermore, fines also interfere with downstream processing, increasing downstream costs [3].

This work studies the extraction of air-suspended fines between two sets of rollers. Fines are defined by all particles with a particle diameter (d_p) of less than $125 \mu m$. The fines will be removed by an extraction airflow, increasing the energy efficiency and capacity of the novel mill.

The airflow direction can be seen in the simplified figure 1.3. The narrowing of the grey sheet between the rollers in figure 1.3 visualises the material reduction.

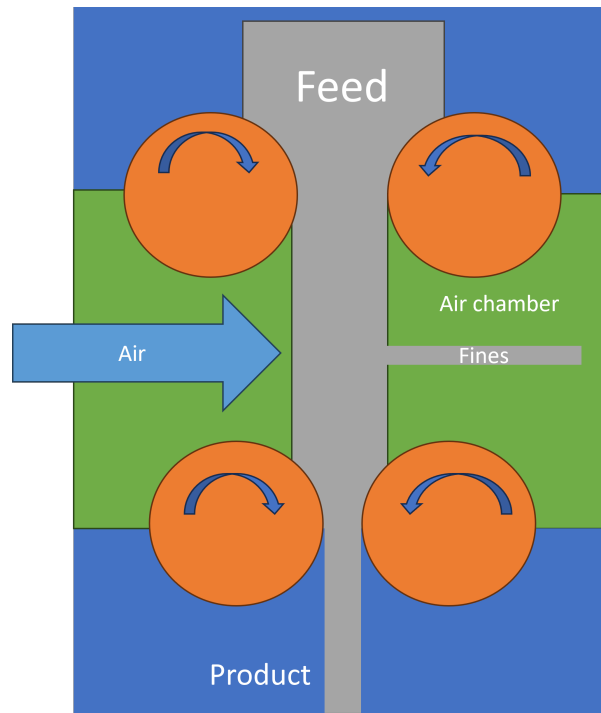


Figure 1.3: Simplified cross-section of 2 roller sets. Feed enters the air chamber (green) through top roller. Air enters the air chamber from the left and separates out fines. Product proceeds to through the bottom set of rollers. The fines exit the air chamber with the air to the right.

The dynamic behaviour of the material stream proves challenging to analyse. The extraction and entrance airflows influenced by the rollers and particle movements are not understood.

This master's thesis aims to improve fines separation from the air chamber. It is hypothesized that extraction of fine particles between spinning rolls can be achieved by sufficient airflow across the falling stream of particles, and this can be improved by varying the geometry of the enclosing chamber. The current airflow within the chamber is insufficient to effectively remove fine particles from the sheet of material. The separation of fines could be enhanced by placing in-chamber geometries to increase air velocity and improve particle guidance.

Improvements that will be under consideration are the position of the fines exit, the volumetric air flow rate and geometries such as vanes in the chamber. Extraction quality, collection efficiency, and energy efficiency are important performance indicators for comparing fines extraction performance.

1.5. Summary

To meet global desire to increase renewable energy use, and decrease dependence on fossil fuels, more critical raw materials should be produced by mines. Mining operations consume a lot of energy, and one of the largest consumers is comminution. Within comminution, fines are created, which cause a significant loss in energy efficiency and capacity of machines. This MSc. thesis will focus on extracting fines from an air chamber with spinning rolls

2

Equipment basics

Section 2.1 introduces the basics of comminution. The importance of size to the cost and energy consumption of the fan are discussed in section 2.2. Thereafter separation efficiency and effectiveness are introduced based on particle classification in section 2.3. Gravitational chambers and cyclones currently used in mining will be discussed and loading capacity is introduced in sections 2.3.1 and 2.5 respectively. Two short remarks on flow velocity in ducting 2.4 and on maintenance 2.6 are given.

2.1. Comminution

Comminution is the process of reducing particle size. Common reasons for size reduction of solids are [11]:

1. to liberate the desired component for subsequent separation
2. to prepare material for chemical reaction by enlarging the surface area
3. to prepare waste for recycling
4. to meet size requirements for the quality of the product

Air classification and cut size play an essential role in evaluating the performance of an air classifier. Energy consumption of air classifiers in fine-grinding classification processes is high [6].

2.1.1. Roll crusher

Roll crushers were once popular for coarse crushing in the minerals industry. The roll crusher, however, lost favour to gyrator and jaw crushers because of their poorer wear characteristics with hard rocks [11]. Renewed dry grinding ambitions and better materials have reignited the interest in energy-efficient roll crushers. Figure 2.1 shows the working of a roll crusher. Coarse feed enters from the top, as the distance between the rolls decreases a coarse particle breaks. The broken particle falls through in between the two rollers as the product.

The theoretical capacity of roll crushers is defined by equation 2.1 [10]:

$$\dot{m}_F = \pi 60 \cdot RPM \cdot D \cdot W \cdot L \cdot \rho_B \quad (2.1)$$

Where equation 2.1 is the result from no-slip boundary condition on the rollers and conservation of incompressible mass flow rate. All mass that enters the rollers need to exit on the other side, however the particle size has changed.

The mass feed rate $\dot{m}_F$ is dependent on the roll diameter D [m], the rotational speed RPM, the width W [m] of the roller, the gap size between the rollers L [m], and the bulk mass ρ_B [T/m³].

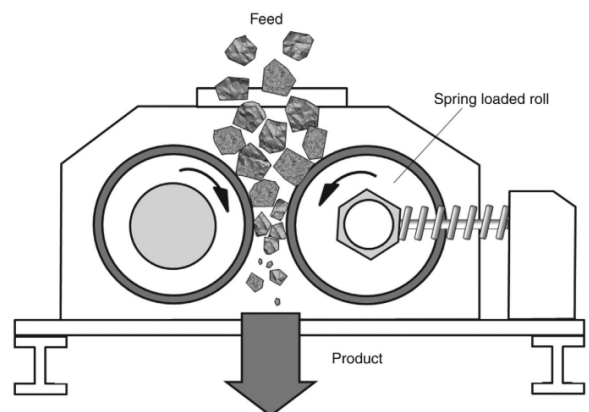


Figure 2.1: Functioning of a roll crusher [10]

The real mass rate however will be strongly influenced by operating conditions. The occupancy is the percentage of volume which is actually in use by particles as the bulk density decreases when falling into the rolls. This strongly determines the capacity of the roll crusher. The actual capacity will vary between 25% and 75% of the theoretical capacity [11]. To determine the actual capacity, the occupancy should be multiplied by the theoretical mass rate. Occupancy can also be referred to as operational density [10].

2.2. Fan

Economies of scale

Within the mining industry, size is of great importance. Mining operations use economics of scale to make expensive processes economically viable, providing complex materials and ores for an acceptable price[4].

The first-of-a-kind (FOAK) size of tumbling mills has steadily increased from 450 kW in 1959 to 28 MW in 2010 [8]. The grade of ore deposits has declined for decades and will decline further [3] [6]. Machines required to handle the tonnage will need to increase in size and capacity [8]. It is, therefore, important that any solution is scalable in a favourable way. An air extraction system's price and operational cost, mainly dependent on fan size. The capital and operational cost of an air extraction system primarily depend on the fan size. This fan size should scale favourably for deployment throughout the comminution industry.

Equation 2.2 is used in (chemical) engineering to predict the cost of fan equipment depending on volumetric flow rate [11][12]. The power of 0.8 in equation 2.2 is called the N-factor and strongly defines whether scaling yields favourable economics. ¹:

$$Cost_{fan} = 4450 + 57\dot{V}^{0.8} \quad (2.2)$$

A more efficient separation process will use less volumetric air flow, $\dot{V}$. Therefore it will require a smaller fan, which reduces capital costs. Correlation 2.2 is valid between a capacity ($\dot{V}$) of 200 - 5000 m^3/hr . The average plant scales with $n = 0.6$ with respect to $n = 0.8$ for a blower [11]. This means that comparable with an average plant, the cost will not scale favourable for a blower used in the air extraction system, therefore an effort should be made to reduce $\dot{V}$.

Fan power

Assuming a certain working range, chamber geometry and inlet/outlet, a fan can be selected. To scale the $\dot{V}$ to the power of the fan P_{fan} , equation 2.3 [13] can be used.

$$\frac{P_{fan_2}}{P_{fan_1}} = \left(\frac{\dot{V}_2}{\dot{V}_1} \right)^3 \quad (2.3)$$

Equation 2.3 shows that increasing $\dot{V}$ will strongly increase P_{fan} and therefore the energy consumption and operating cost of fines separation process. To decrease energy consumption, $\dot{V}$ should be kept to a minimum.

To calculate the absolute energy consumption of an idealized fan equation 2.4 can be used [11]. For this particular equation $\dot{V}$ is given in [m^3/hr] and dp in [cm_{H_2O}].

$$P_{fan} = 2.72 \cdot 10^{-5} \dot{V} dp \quad (2.4)$$

The pressure drop is needed to overcome the pressure drop over the air chamber, following dust separation steps such as cyclones and due to piping systems needed to transport the fines away from the particles. If a high $\dot{V}$ is needed for fines extraction, losses would built up quickly throughout the fines system. Furthermore, an fan is not 100% efficient which would further increase the operational energy consumption with respect to the idealised equation presented in 2.4.

¹Cost correlation based on: U.S. Golf coast - CEPCI 532.9

2.3. Separation efficiency & effectiveness

The mass balance for a separation process is given by equation 2.5 [14]. This equation describes the mass flow between two sets of rollers. Between the two sets of rollers, mass rate is conserved and particle size distribution (PSD) will be constant. It is assumed that there will be no particle abrasion or agglomeration during the fall through the air chamber. Knowing the mass rate and particle size distribution of two of the three incoming streams (feed $\dot{m}_F$, product $\dot{m}_p$, fines $\dot{m}_f$) fully defines the remaining streams. Equation 2.5 defines the mass rates over one chamber [14].

$$\dot{m}_F = \dot{m}_p + \dot{m}_f \quad (2.5)$$

To assure accurate measurements, the fines stream should be one of the measured streams [11]. This poses a challenge in practice as decreasing feed mass significantly reduces the fines sample size, resulting in more significant measurement errors during weighing and sieving. This can offset the proposed increase in accuracy, as described by Perry [11], in calculating the mass balance.

For the separation process, collection efficiency, grade efficiency and energy efficiency will be determined.

The collection efficiency η determines the amount of fines $d_p \leq 125\mu m$ per amount weight fraction $w(d_p)$ available in the sample [11].

$$\eta = \sum G(d_p)w(d_p) * 100 \quad (2.6)$$

Equation 2.6 will focus on the $0 < d_p \leq 125\mu m$ as top size extraction will be considered irrelevant in the current design stage. $G(d_p)$ defines the grade efficiency figure 2.2 visualises the grade efficiency curve of which $G(d_p)$ can be determined.

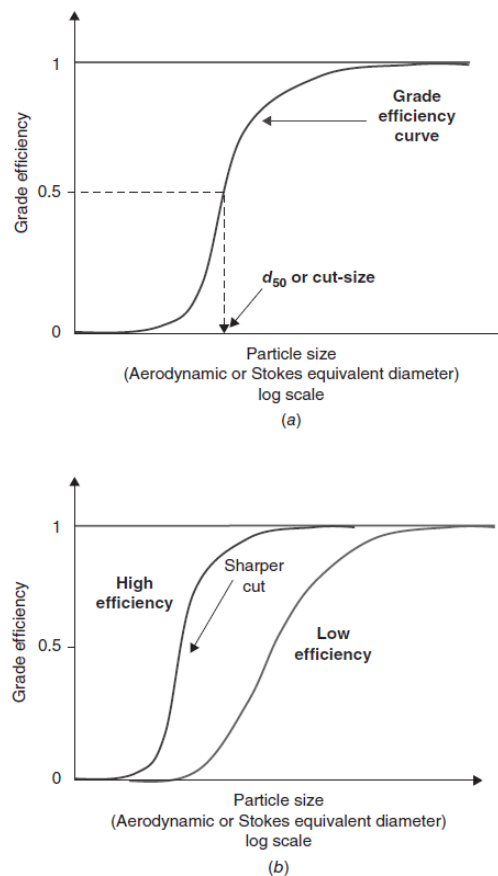


Figure 2.2: a) grade efficiency curve; b) Comparison of different grade efficiency curves [11]

Figure 2.2 visualises a grade efficiency curve (or cumulative passing curve). The Stokes (equivalent) diameter is defined as the diameter of a free-falling sphere in a laminar region. Grade efficiency curves are closely related to cumulative passing curves, which can be produced using size sieving. Sieving relates d_p to mass fractions in a sample. Mass fractions will be used when applying equation 2.6. Figure 2.2 b) also indicates the improvement of separation efficiency when the S-curve becomes steeper.

Separation energy efficiency E_η is a performance indicator that defines the energy spent on generating the air flow energy E to separate the mass of desired fines $m_{d_p \leq 125 \mu m}$. Together with the absolute separated amount, this will define the separation efficiency.

$$E_\eta = \frac{E}{m_{d_p \leq 125 \mu m}} [kWh/ton] \quad (2.7)$$

Using equation 2.7, the energy efficiency of the separation method is quantified. This is a good indication to calculate if energy consumption is reduced for a specific particle size extraction.

2.3.1. Air separation equipment

Gas and particles of different sizes (mass) can be separated in various ways. Common methods in the mining industry are based on gravity, centrifugal forces, and screening (not addressed here).

Gravitational settling chambers, as displayed in figure 2.3a, are used to filter particles using their terminal velocity. These installations can grow very large to allow for a sufficiently low flow velocity. Target plates can direct the airflow downwards, enhancing separation [15].

This method can be used within the air chamber to guide particles in the desired direction. However, particles may have a large velocity due to the acceleration of the rollers.

Alternatively, cyclones use centrifugal force to separate lighter and heavier particles [16]. The working of a cyclone is depicted in figure 2.3b [15]. Equation 2.8 describes the primary force applied in a cyclone on the particles [15]. Velocity has a quadratic influence on the force applied, therefore steep separation can be achieved in a smaller area than in a gravitational settling chamber.

$$F = \frac{mv^2}{r} \quad (2.8)$$

The fact that smaller particles can better follow a strongly curved flow, could be used to separate particles in the air chamber. Equation 2.8 also defines the ability of particles to follow the circular flow velocity induced by the rollers, the behaviour will be strongly dependent on velocity (v), particle mass (m) and curvature radius (r).

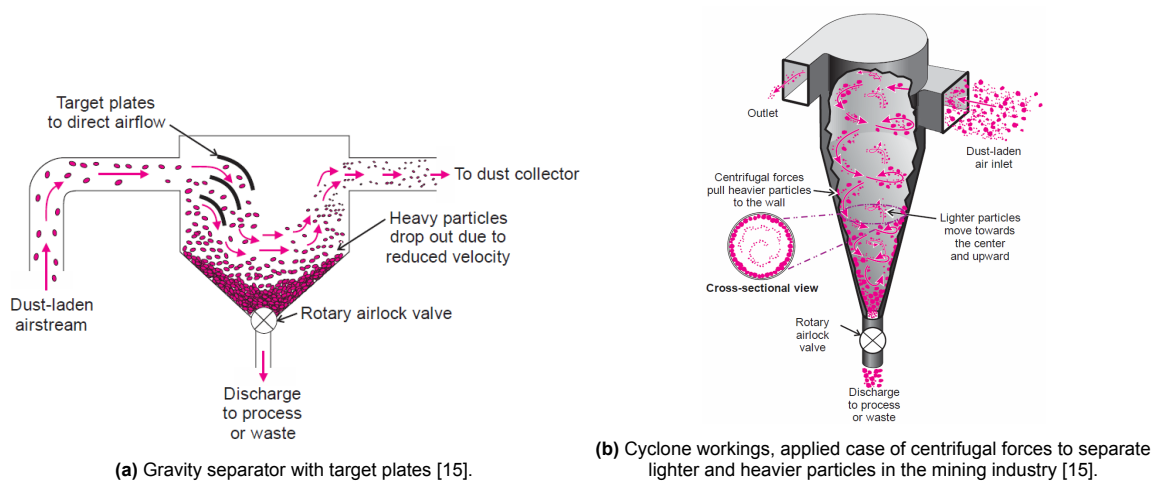


Figure 2.3: Two methods used for air fines separation.

2.4. Flow velocity in ducting

An industrial mill will be connected to piping using nozzles. To optimise the design, it should be taken into account that fines flow easily through this piping to other dust separation processes (for example, cyclones).

Using low-velocity (LV) systems ($< 9 \text{ [m/s]}$) has the benefit of less expensive elbows and mitered bends [15]. However, care should be taken that there is no horizontal ductwork. Horizontal distances should be covered by tilted sections of a minimum of 45° for up-going sections and 30° for down-going sections. As the design of this machine is vertically oriented, height could be advantageous while extracting dust, as it can fall downwards without driving flow.

2.5. Particle loading

The particle loading of the airflow, Loading Capacity (LC) is defined in equation 2.9.

$$\frac{\dot{m}_p}{\dot{V}_f} = LC \quad [g/m^3] \quad (2.9)$$

The definition 2.9 is adapted from formula 2.8 from "dust control handbook" [15]. This formula indicates how much fines are carried by the air. Table 2.2 gives some industry standard loadings, adapted from [15]. A high loading capacity results in maximum separation with minimal air displacement requirements.

Table 2.1: General dust loading values for various applications.

Concentration	Lower limit	Unit
Low	<35	g/m^3
Typical	35-177	g/m^3
High	177-353	g/m^3
Very high	>353	g/m^3

2.6. Maintenance

Reliability and low maintenance are crucial to aspects to take into account when developing a fines extraction solution. A mill should be able to work continuously for multiple days/weeks without stopping for maintenance. Maintenance within the air chamber is complex and requires significant downtime. In the air chamber, the accelerated particles will function like a sanding beam.

Piping and ducting systems will be necessary to convey fines. It is important that the attrition in the flow system is low. It has been estimated that the attrition in solid conveying systems is proportional to the power of α 3-5 depending on velocity (attrition $\propto v_p^\alpha$) [11]. Consequently, doubling the velocity in a conveying system can significantly degrade the piping [11]. This knowledge can also be applied to geometries placed in the air chamber which will be exposed particles.

2.7. Summary

This chapter introduces the basics of a roll crusher device and its feedrate. Mining uses economies of scale, to decrease capital plant cost. For fines extraction it is important that the capital and operation cost scale favorably with the average plant scaling. As blower cost and power consumption scale unfavourable with volumetric flowrate, volumetric flowrate should be minimized. Existing air separation devices and particle sieving methods are introduced as working methods which could be applied during experiments.

3

Flow & Particle physics

A fluid flow can be laminar, or turbulent, dependent on various factors such as density, viscosity, velocity and geometry size. That makes fluid dynamics a challenging, fascinating and interesting area of research and engineering. During this section, the basics of flow and particle interactions are introduced. Starting from dimensionless numbers 3.1. Force interaction between fluids and particles are discussed in 3.2, followed by particle-particle interactions in section 3.3.

3.1. Dimensionless numbers

Dimensionless numbers are one of the strongest assets within fluid dynamics. Dimensionless numbers are relations that can be determined using the Π -Buckingham theorem [17]. In short, this theorem states that a physical problem only depends on certain physical relations that can be made dimensionless by multiplying or dividing certain physical properties of a problem. When these properties are chosen carefully, relations enable the user to scale, analyse, and predict fluid behaviour. The dimensionless numbers shown in table 3.1 were checked on their physical relevance for this model [18][19][20][21]:

Table 3.1: Proposed important dimensionless numbers applicable on fluid and particle fluid interaction

Dimensionless number	Abbreviation	Definition	Description	Physical relevance
Reynolds rotational	Re_ϕ	$\frac{\rho_f \Omega r^2}{\mu}$	$\frac{\text{inertia}}{\text{viscous}}$	Small
Reynolds particle	Re_p	$\frac{\rho_f U d_p}{\mu}$	$\frac{\text{inertia}}{\text{viscous}}$	Large
Drag coefficient	C_d	$\frac{F_d}{\frac{1}{2} \rho V^2 A_x}$	$\frac{\text{drag force}}{\text{dynamic pressure}}$	Large
Friction coefficient	C_f	$\frac{\tau}{\frac{1}{2} \rho V^2}$	$\frac{\text{shear stress}}{\text{dynamic pressure}}$	Undetermined
Stokes number	Stk	$\frac{\tau_p}{\tau_f}$	$\frac{\text{shear stress}}{\text{dynamic pressure}}$	Large

The above-mentioned dimensionless numbers will be discussed shortly and provided with a range expected in the flow domain. Dimensionless numbers also have been used to calculate if the experiments could be performed in water. Shifting to water for a test setup could reduce particle and fluid velocities in the problem. The results of these calculations can be found in appendix C.1. Due to the difference in density between water and air, buoyancy would have significantly affected the measurements. Furthermore, the Stokes number could not have been matched, therefore this path was rejected.

3.1.1. Reynolds rotational

The Reynolds number (Re_ϕ) associated with the flow around a rotating cylinder determines the flow regime around that cylinder. The rollers disturb the airflow and drag particles with them. The approximate limit for laminar flow for rotational Reynolds number is somewhere between 40 to 60 [19].

The calculated Re_ϕ for the rollers varies from $4 \cdot 10^3$ to 10^5 during steady state operation. $Re_\phi \gg 60$, therefore the inertial effects are significantly larger than the viscous terms, and the flow can be considered inviscid outside the boundary layer.

The production capacity is a linear function of roller radius as defined in equation 2.1. This is not the case for the Reynolds rotational number. From the definition of Re_ϕ in table 3.1 it is clear that the effects of roller radius will be non-linear. Increasing the roller size would increase Re_ϕ quadratically. This could pose problems when solutions are scaled to larger plants, as is desirable based on the argument for economics of scale section 2.2.

This would pose challenges if experiments found that this heavily influences the air or particle flow. Ideally, the rollers would not increase in radius because increasing radius brings more cost. However, increasing roller size is necessary because of stiffness and wear limitations.

3.2. Fluid and Particles

Air flow does not have a large influence on particles the size of rocks and pebbles, however when particles become smaller, for example sand or dust, the force balance shifts dramatically. This section introduces the interaction between particles and fluids and explains why air flow influence smaller particles more than larger particles.

A dust particle is a very fine particle. The geometry of cracked particles can vary a lot, particles can be almost cubic, flat flakes, almost spherical, oval, and variations between these simple shapes. Shape strongly influences the drag coefficient and projected cross-sectional area of an particle to the flow. To simplify this problem, only a spherical dust particle will be addressed. This does influence the particle-fluid interaction. In future research this can be compensated for by the Sauter mean diameter [11] or other drag correlations [21]. The basic properties of the spherical dust particle are defined in table 3.3.

Table 3.3: Physical characteristics for a spherical particle

Math sign	Value	Unit
d_p	125	$[\mu m]$
ρ_p	2500	$[kg/m^3]$
V_p	$1.0 \cdot 10^{-12}$	$[m^3]$
m_p	$2.6 \cdot 10^{-9}$	$[kg]$

The focus is on the fluid-particle interactions. The forces that the fluid will apply on the particle. The particle can be in a different flow domain than the overall domain considered. This is the case because the particle has a different specific dimension with respect to the fluid. The various particles can experience different flow domains. To deduce in which flow regime the particle will be Re_p will be approximated.

3.2.1. Reynolds particle

The Reynolds number for a particle, together with the drag C_d coefficient is of great importance for the settling velocity and the systems classification capabilities.

The Reynolds number determines the flow regime experienced by the particle. Re_p number is defined in equation 3.1 [21].

$$Re_p = \frac{\rho_f d_p |\mathbf{u}_f - \mathbf{u}_p|}{\mu_f} \quad (3.1)$$

The particle velocity in equation 3.1 defined as $\mathbf{u}_f - \mathbf{u}_p$, which is the slip velocity $\mathbf{V}_p$ of the particle with respect to the air flow. For the simplest case, a particle falling through stationary air, the slip velocity will be equal to the settling velocity. This velocity is dependent on the drag coefficient C_d , which is, in turn, dependent on the Re_p .

3.2.2. Drag

When a particle starts falling through air, a velocity is induced with respect to the stationary fluid. The velocity with respect to the air will induce a force, called the drag force [17]:

$$D = \frac{1}{2} \rho_f C_d U^2 A \quad (3.2)$$

Where:

A equals the projected surface area [m^2];

C_d is the drag coefficient [-]

The drag force is based on the velocity of the fluid with respect to the object. When both the fluid and object are moving in a particular direction and filling in the cross-sectional area for a spherical particle, the drag force can be rewritten equation 3.3 [22].

$$D = \frac{\pi}{8} \rho_f d_p^2 C_d (\mathbf{V}_p)^2 \quad (3.3)$$

To determine C_d in equation 3.3 the drag coefficient correlation of Schiller-Naumann is introduced in table 3.5. The definition of the terminal velocity U_t will be used to solve for Re_p and C_d numerically. Table 3.5 shows the used drag coefficients for individual particles [23].

Table 3.5: Drag coefficient sphere based on Schiller-Naumann drag correlation

Reynolds domain	Relation
$0.1 < Re_p < 1000$	$C_d = \frac{24}{Re} + \frac{3.6}{Re^{0.313}}$
$Re_p < 1000$	$C_d = 0.44$

The relations defined in table 3.5 are plotted by Reynolds number in figure 3.2.

The comminution process will produce a wide range of particle sizes. To determine the various corresponding Re_p a good estimation is needed for the velocity. The particle velocity is chosen as the particle terminal velocity. Equation 3.4 defines the particle terminal velocity adapted form [21].

$$U_t = \sqrt{\frac{2m_p g}{\rho_f A_p C_d}} \quad (3.4)$$

Using a simple solver to iterate over velocity, drag coefficient and Reynolds number, the terminal velocity can be calculated. This gives an estimate of the velocity a single particle of a given size would travel in free fall.

In figure 3.2 the terminal velocity is plotted over the particle size, indicates when the gravity force and drag are balanced.

Figure 3.2 b) displays the terminal velocity for particle sizes relevant to this study. The Schiller-Naumann correlation gives a significantly different result w.r.t. a Re_p constant drag coefficient. The Schiller-Naumann correlation predicts a stronger non-linear relation dependence on d_p than may be expected based on equation 3.3 solely. This behaviour can be exploited to separate fines from the main product.

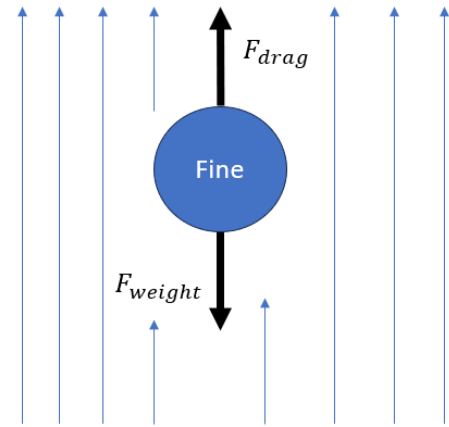


Figure 3.1: weight and drag force are in equilibrium, particle is falling with a constant velocity which appears to the particle as a uniform upward stream

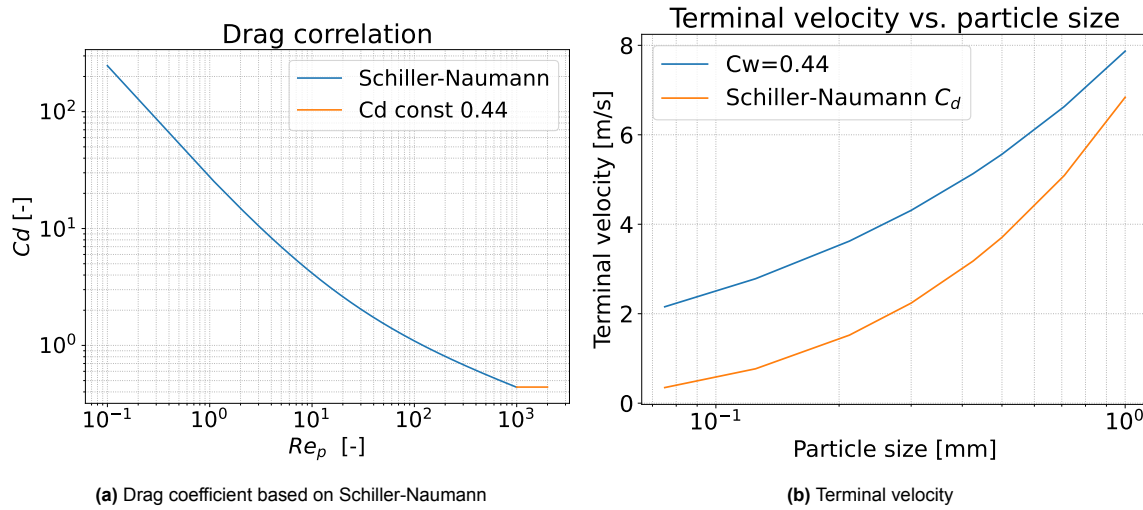


Figure 3.2: Drag based on Schiller-Naumann correlation

It is clear how the particle will behave in a falling stationary flow situation. The apparent flow velocity counteracts gravity, leading to a steady state.

This concludes the steady state behaviour of the particle in an uniform flow field.

3.2.3. Stokes Number

It could be the case that there is a forced, steady, uniform flow field from another direction than opposing gravity. This flow field will change the falling velocity and direction. The drag force is decomposed in 2 directions as shown in figure 3.3. In this state, extra acceleration related phenomena can influence the force on the particle. These forces are the virtual mass and the history forces. The model neglects these forces as their influence is insignificant and are computationally challenging. More information can be found in the appendix C.1.1.

To determine a relative measure for the ability of a particle to follow the airflow, the stokes number (Stk) is calculated. The stokes number is defined in equation 3.5 [21] and is dependent on the characteristic fluid time and particle time τ_f and τ_p respectively.

$$Stk = \frac{\tau_p}{\tau_f} \quad (3.5)$$

The characteristic fluid time τ_f is defined in equation 3.6 and the characteristic particle time τ_p is defined in equation 3.7.

The characteristic fluid time refers to velocity fluctuations along the particle trajectory. The value of τ_f is often inferred from dimensional analysis as a ratio between a length scale and a characteristic velocity to the problem [24]. Considering the flow behaviour of interest, the terminal velocity is used for V_p . The particle diameter d_p is used as length scale [21].

$$\tau_f = \frac{d_p}{V_p} \quad (3.6)$$

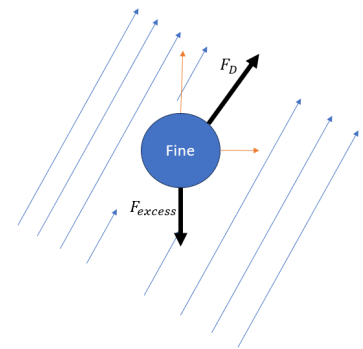


Figure 3.3: In orange decomposed forces on particle with diagonal incoming flow field

The characteristic particle time, defined in equation 3.7 refers to the ability of a particle to respond to fluid flow change.

$$\tau_p = \frac{1}{18} \frac{\rho_p d_p^2}{\rho_f \mu_f f_D} \quad (3.7)$$

Where f_D is defined by the specific drag.

The specific drag, given in equation 3.8, is a correction function for the stokes stopping time for non-stokasian Re_p number [21]. Equation 3.8 is derived from work by Israel et al., which states that if drag is non-stokasian, the stokes number can be compensated using a specific drag function [25].

$$f_D = \frac{C_D Re_p}{24} \quad (3.8)$$

Equation 3.8 is shown to be valid for $Re_p \leq 1024$. For simplicity, the current correlation is also used for higher Re_p as it is a better alternative than the pure stokasian characteristic fluid time.

Using the drag correlation in table 3.5 and the calculated terminal velocities τ_p and τ_f can be calculated. Using τ_p and τ_f the stokes number is calculated for a range of particle sizes. Figure 3.4 shows the relation between the physical particle size and the stokes number. Considering the total particle size distribution $Stk \gg 1$, the particles cannot follow the airflow precisely. However, a smaller particle will respond significantly faster to a change in air velocity than a larger particle.

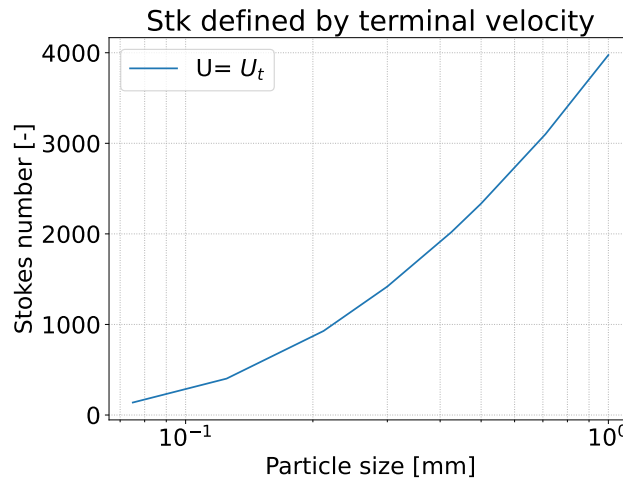


Figure 3.4: Stk number based on terminal velocity

3.2.4. Lift forces

Lift forces are an effect of circulation [17]. Within particle-fluid interaction there are two possible effects which can induce lift on a particle.

One Lift effect can be generated by existing shear in the flow due to the surface resistance of the particle. Because of the shear a circulation is created over the particle. The particle will experience lift which is directed 90 degrees on the incoming flow direction. This force becomes prevalent especially at very low Reynolds numbers. Increasing Reynolds number has shown that this lift force significantly decreases [22]. This effect will be neglected.

Two Particles can also rotate around their axis. This rotation can be initiated due to bouncing or bouncing of the spinning rollers. At very high Reynolds number, this force can provide extra lift to the particle [22]. This force will be neglected as it is not assumed that lift due to high Reynolds numbers will be of importance.

3.2.5. Particle-Fluid force

Combining the forces given in the previous subsections, the force balance presented in equation 3.9 was found. This force balance is based on work by Zhou [26].

$$\mathbf{f}_{pf,i} = D_i + f_{\nabla p,i} + f_{\nabla \cdot \tau,i} + f_{vm,i} + f_{B,i} + f_{L,i} \quad (3.9)$$

Effects that are dependent on the density of the fluid are negligible. The Buoyancy force which would have been included in $f_{\nabla p,i}$, virtual mass $f_{vm,i}$, and the History force $f_{B,i}$ are therefore neglected. Furthermore, the lift forces discussed in subsection 3.2.4 are neglected due to computational concerns and estimated low relevance [21] [26].

This reduces equation 3.9 to equation 3.10:

$$\mathbf{f}_{pf,i} = D_i + f_{\nabla p,i} + f_{\nabla \cdot \tau,i} \quad (3.10)$$

Equation 3.9 is the identified particle-fluid forces that will be present in the air chamber. As $Stk \gg 1$ the particulates will no longer be in equilibrium with the surrounding fluid phase, therefore they contribute significantly to the momentum transfer from the particulate to the fluid [22].

3.3. Particle interaction

Particle-Particle interaction are solid bodies interactions. The significance of these interactions are different between the various areas in the machine. Starting from the rollers, the particles will have an occupancy of 20% at the gap. Thereafter the particle flow quickly widens. The particle occupancy area goes from gap width, 1 mm magnitude to larger width, assume 10 mm. This decreases the occupancy to 2%. The flow in the curtain is estimated to be dense, the flow in the rest of the chamber will be calculated more precisely in subsection 3.3.1.

3.3.1. Interaction Regimes

To determine the interaction between the particles and fluid we determine the expected particle load. Till now, only the behaviour of individual particles inside a fluid has been discussed. The particles will be densely distributed throughout the air chamber, which influences the behaviour of individual particles. The particles will experience the force of the fluid and the force of (colliding with) their neighbours. To determine the impact of the particle density, an estimation will be made. The volume fraction is defined by in equation 3.11 [27].

$$\Phi_p = \#_p \cdot V_p / V \quad (3.11)$$

Where: $\#_p$ = number of particles

V_p = volume of particles

V = volume available

- dilute one-way $\Phi_p \leq 10^{-6}$
- dilute two-way $10^{-6} \leq \Phi_p \leq 10^{-3}$
- dense four-way coupling $10^{-3} \leq \Phi_p$

Equation 3.11 seems sophisticated. However, it does not include the "empty zones" between spherical particles. Therefore this will return the volume used by mass (based on density). It does not matter if it is in 1 block or a million spherical particles.

The volume of particles is calculated and compared to the volume of the chamber.

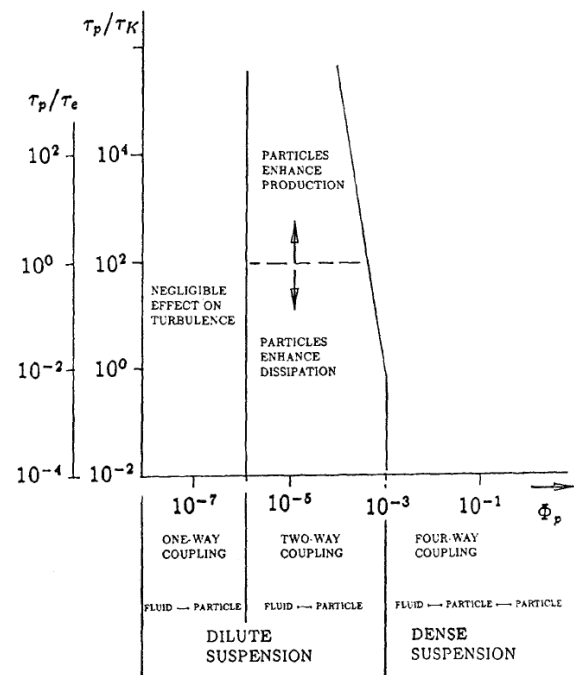


Figure 3.5: Map of regimes of interaction between particles and airflow (turbulence) [27]

$$V_p = \frac{m_{ch}}{\rho_p} = \frac{0.011[kg]}{2500[kg/m^3]} = 4.4E^{-6} \quad [m^3] \quad (3.12)$$

The chamber volume V_{ch} is roughly defined by the box between the roller axis:

$$V_{ch} = H \cdot W \cdot L = 0.33 * 0.05 * 0.18 = 2.97E^{-3} \quad [m^3] \quad (3.13)$$

Using equation 3.11 we find $\Phi_p = V_p/V_{ch} = 1.5E^{-3}$. Including the space the rollers take increases the volume fraction to $\Phi_p = 2.6E^{-3}$. Figure 3.7 shows interaction domains between fluid and particles depending on volume fraction. The y-axis indicates the influence of particles on the dissipation or production of turbulence within the fluid domain. Using $\Phi_p = 2.6E^{-3}$ and reading x-axis in figure 3.5 yields that the chamber will be a dense suspension regime. Four-way coupling should be applied when modelling the interaction between the two roller sets; $Fluid \leftrightarrow Particle \leftrightarrow Particle$. Potentially, the interactions in the system can be simplified when choosing two-way coupling without particle-particle interaction, however, this simplification becomes invalid with increasing feed rate and is therefore undesirable.

3.3.2. Particle interactions

Till now, the fluid particle interactions were discussed. These interactions are based on (simplified) forces that fluids apply to the particles and the particles on the fluid. The roller sets will also influence the velocity and direction of particles. Due to equation 2.1, the particles will also have a certain velocity. In-chamber geometries can be used to guide air and particle streams.

When the particles impact each other, they will transfer momentum.

The equation defining momentum is given in equation 3.14 [28]:

$$p = mv \quad (3.14)$$

When two particles bounce elastically the situation before and after is given by conservation of linear momentum 3.15 [28]:

$$\mathbf{p}_1 + \mathbf{p}_2 = \text{constant} \quad (3.15)$$

Rewriting the momenta for their respective mass and velocity, one can deduce:

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2 \quad (3.16)$$

Where u and v are the velocity vectors before and after the collision, respectively.

The particles will not collide with an infinite hardness. Elasticity plays a role in the collisions. In DEM simulations, non-linear springs, such as Hertzian springs, are used. The Hertzian model will be further introduced in section 9.2.2. The Youngs modules of the material will determine the spring coefficient. The physical Youngs modulus of limestone is found to be within 20 and 80 GPa [29]. This will differ per ore type.

A smaller number ($\approx 5E6$) will be used in computations. This modules will defines the bounce between particles and particle and walls. This will not significantly influence the particle behaviour.

3.3.3. Capillary Bonds

Agglomeration is a known problem in the comminution of all types of processes. Heavy agglomeration can occur when moisture levels increase above 1 percent. One possible reason of agglomeration within dry particle processing is capillary bonds.

If an extremely small water drop would nest between two 100-micron particles, the drop would pull these particles together. This schematically depicted in figure 3.6 [30].

To calculate the capillary force in a simplified way, equation 3.17 is used [30].

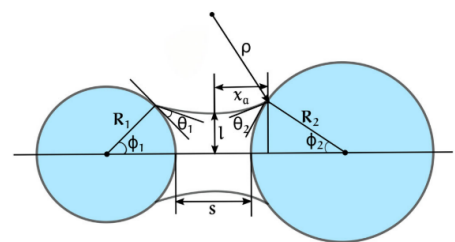


Figure 3.6: Capillary bonds indicative figure [30]

$$F = 2\pi\gamma l \left(1 + \frac{l - R_b}{2R_b}\right) \quad (3.17)$$

Where: γ is the surface tension of the liquid (water) l is half the height of the bond (axis-symmetric assumption) R_b is the radius of the bond ¹.

An estimation determines if this capillary bond would significantly influence small particles. Plugging values from table 3.7 into equation 3.17 we find $F \approx 7.6 * 10^{-6}$ [N].

Table 3.7: Information for simplified calculation of fines agglomeration.

Math Sign	Magnitude	Unit
γ	0.0728	[N/m]
l	30	[μm]
R_b	400	[μm]

To improve air separation, it is important to minimize the negative impact of moisture. Air separation can be used to evaporate the moisture between particles and disperse the small particles. This will reduce the possibility of particles agglomerating together. Perry suggests that simple dry dispersion, such as a fall shaft with impact plates, could be enough to separate particles $d_p > 300\mu m$. Higher forces have to be applied to separate smaller particles [11]. These forces are depicted in figure 3.7. Agglomeration could be reduced using the fluid dynamics in the chamber. Figure 3.7 c) displays a method using (air) velocity gradients.

3.4. Summary

Chapter 3 introduced the various forces that are expected to be present in the air chamber. The Re_p number is introduced which will be used to determine the drag coefficient based on Schiller-Naumann drag coefficient. To calculate for a known force balance, the terminal velocities of different particle sizes is calculated. Based on the Stokes number, calculated for the range of inserted particles it is clear that a small particle (fines) will be able to follow the airflow in the chamber significantly better than a larger particle. Furthermore, the volume density is calculated to predict the particle fluid interaction regime and found to be just in the dense suspension domain. Particle interactions for particles and structures are introduced. A side track on capillary bonds is introduced to make the reader aware of the potential of using air to extract agglomerated fines.

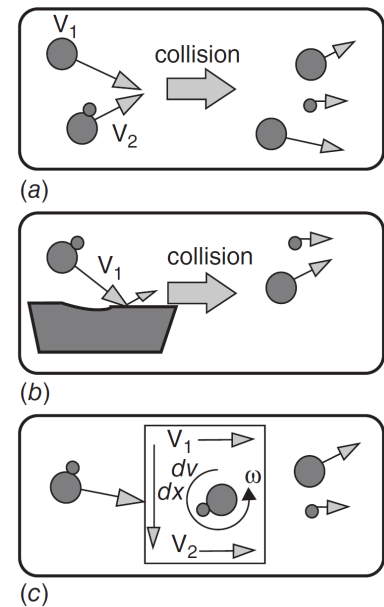


Figure 3.7: a) by particle-particle collision
b) by particle-wall interaction
c) by strong velocity gradients

¹ ρ from figure 3.6 equals R_b in formula 3.17

4

Preparatory research

Due to the complex nature of the flow in the air chamber finding an optimal solution is complex. Simplifications can be used to disentangle different observed behaviours in the industrial setup. The industrial partner hoped to gain new insights by modelling the air behaviour in the novel mill, further discussed in section 1.4. As this did not provide sufficient insights into the workings of the machine, a test setup was built. Earlier a test setup was built, the air rig, specifically for airflow measurements, roughly based on the layout of the novel mill. Work performed on the air rig is discussed further in section 4.2. Together with experiments performed on the industrial scale pilot plant, discussed in 4.3, this formed the basis of new insights and theories that laid the foundation for the development of the slice rig, introduced in part II of this research.

4.1. CFD

Earlier work on air behaviour in the novel mill was conducted using the CFD package of COMSOL. The main focus was understanding the airflow through the machine. COMSOL was used for the first CFD simulations and learning the software package. Previous work was conducted in a 2D and 3D CFD setup. The 2D work assumed no (significant) flow around the axial directions of the rollers. After solely simulating the flow with CFD, the Fluid Particle Tracing (FPT) was introduced. The FPT module could not correctly model particle behaviour such as sliding and rolling. Furthermore, it could also not predict particle-particle physics such as soft sphere collisions. There would therefore be no energy losses to slow down particles moving and bouncing through the chamber. It was attempted to implement simplified particle physics with guidance of the COMSOL support team, however this led to the software automatically removing particles, which was an undesirable result and could not be changed. After research conducted on the Air rig, the 2D assumption was deemed to be non-negligible for the Air rig. 3D feed irregularities, even on small scale, will also significantly change the air influence through the falling feed. It was therefore concluded that following the path of sole CFD simulations including the FPT package was not a viable path forward.

4.2. Air Rig

Air indicated by the blue arrow in figure 4.1 is sucked into the air chamber (green) from the left side of the chamber. The feed (grey) is introduced from the top and travels through the top rollers. The air will transport small particles, fines (narrow grey), out of the feed. The feed proceeds through the bottom rollers -without fines- as the product. The air rig was supposed to be a sound basis for developing a model and predicting air separation performance. However, due to design choices, unwanted and complex behaviour remained in the test setup. Introductory tests performed are discussed in 4.2 to explain the challenges of the air rig.

The air rig gave a good indication of the challenges with the setup explained in figure 4.1. Controlling air and particle flow and fines extraction in a more extensive test setup was challenging. 3D air behaviour and leakages were examined in the air rig. Losses and 3D behaviour were found to be of the same magnitude as cross-sectional flow -as proposed in figure 4.1- induced by the air extraction system. The first measurements taken on the air rig were simple "telltale" measurements. A wool wire was used to indicate air velocity in the chamber. There was almost no significant airflow throughout the chamber. The wool wire barely moved, only

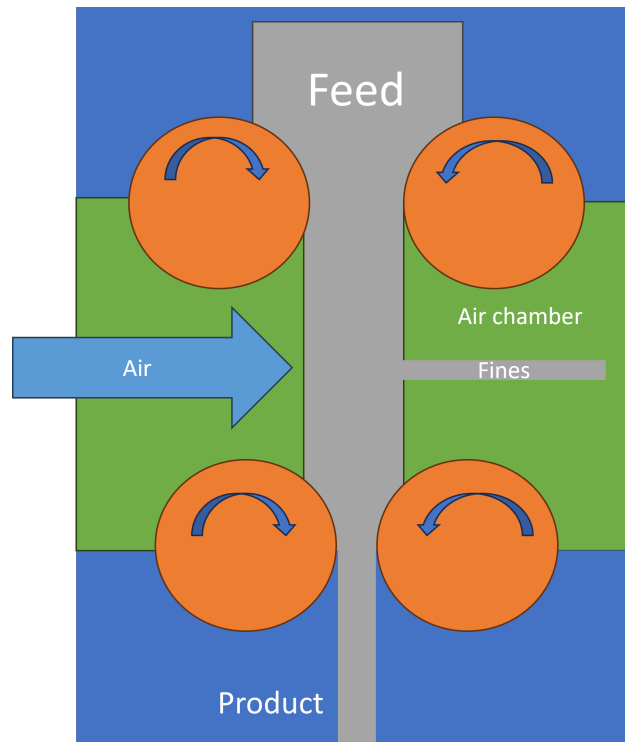


Figure 4.1: Basic idea for fines extraction using air between 2 sets of rollers.

until the nozzle entrance was approached closer than 1cm. This was later verified using a hot wire velocity meter. The developers suspected that the boundary layer effects of the rollers imposed an issue in the flow of the chamber. The telltale experiment eased concerns on the boundary effect. The telltale, even with rollers spinning on high RPM, indicated no significant airflow coming from the rollers. Therefore Re_{Ω} was deemed to be of low significance. Attempts were made to perform reliable and repeatable flow velocity measurements on the air rig, chamber, and vacuum circuit. To decrease flow losses, the machine was made more airtight, and pressure-inducing couplings on the air entry side were removed. This reduced the volumetric flow rate losses. However, there were still significant 3D flow behaviour and losses. The 3D air behaviour and losses complicated chamber flow analysis and proper volumetric flow measurements. Therefore, it was extremely difficult to obtain useful results. No measurements or quantification of the results are presented in this report, as the quality of the measurements and validity of the system provide little value to the study. The importance of these preparatory tests should be emphasized, as they clearly highlighted the challenges and limitations of the air rig. The use of the air rig and its inconsistent results led directly to the design of a new test setup, the slice rig (SR), which tries to address these problems. The slice rig will be further introduced in section 6 as it forms the foundation of the research discussed in part II.

4.3. Novel Mill

The novel mill is an industrial-size test plant. This large scale makes it extremely difficult to perform tests with varying layouts. These tests focused on obtaining statistically differentiable results and repeatability, which turned out to be challenging. On the mill, volumetric flow rate and pressure drops were measured. Weight scales under the cyclones measured the collected particle masses extracted during a test. To enhance the fines extraction, adjustments on flow velocity and symmetric versus asymmetric layouts were tested. Due to varying moisture in the feed samples, it was difficult to keep constant experimental conditions. As earlier discussed in subsection 3.3.3, moisture negatively impacts the performance of a roller crusher and could obstruct air extraction system. This industrial test work was very enlightening and strongly inspired the tests and insights presented in part II of this research. However, the inconsistency in conditions and scatter in the few datasets collected render it of little value in the study of airflow in the system.

Part II

Research

5

Research questions

Part I introduced the importance of comminution to society, the basic introduction of a roller crusher and thereafter the theoretical interaction between, fluids and particles. Furthermore previous conducted experimental methods are introduced to give the reader a background of the preparatory work that has been conducted before moving to the current research.

Part II will apply the introduced theory from chapter 2 and 3 and insights gained from preparatory CFD work and experiments discussed in chapter 4 to develop a new test procedure. Chapter 6 will introduced the new test setup further. This chapter will also introduce the aim of a new model, based on CFD-DEM coupled simulations. Chapter 7 and 8 will introduce the performed experiments and obtained results of the experiments. Chapter 9 will introduce the setup of the CFD-DEM model and the latest results.

Lessons learned from the preparatory research are used to develop a simplified experimental setup which can be modelled within CFD-DEM software to further enhance the knowledge about the various interactions inside the air chamber. The descriptive hypothesis introduced in section 1.4, is defined as:

It is hypothesized that extraction of fine particles between spinning rolls can be achieved by sufficient airflow across the falling stream of particles, and this can be improved by varying the geometry of the enclosing chamber.

Based on preliminary testing, it was deduced that the current airflow within the air chamber is insufficient to remove fines effectively from the falling material sheet, and that the separation of fines could be enhanced by placing in-chamber geometries to increase air velocity and improve particle guidance.

Improvement under consideration are the position of the fines exit, the volumetric air flow rate and geometries such as vanes in the chamber. Grade efficiency, loading capacity, and energy efficiency are essential performance indicators for comparing fines extraction performance.

This leads to the following research questions:

1. *Experimental setup* How can a simplified experimental setup be developed to better understand the fluid particle dynamics in the air chamber?
2. *In-chamber geometries* What types of geometries improve fines extraction in the air chamber?
3. *Decrease energy consumption* Is there a decrease in energy consumption by using an in-chamber geometry?

Research Methodology

To answer the research questions posed in chapter 5 a new research methodology was proposed. The current available test setups are very useful to mimic real life operations. However, to have more control over the test conditions and be able to obtain new insights further simplifications are needed.

The main objectives of the new test setup were to significantly reduce air losses and 3D flow behaviour. It is needed to be transparent to visualize the particle behaviour in the air chamber. Furthermore ease of adjusting side walls, air entrance and in-chamber geometries are of utmost importance.

6.1. Slice Rig

The slice rig (SR), shown in figure 6.1, was built to perform an idealized test of air extraction behaviour between the rollers. It's design was strongly guided by the insights obtained during preparatory tests on the air rig.

Figure 6.1 displays a picture of the slice rig. Feed enters from the orange funnel and passes through the top set of rollers. The particles exit the top set of rollers and enter the air chamber. This chamber has a horizontal airflow (from left to right). By sucking air from left to right through the chamber between the rollers, fines are extracted. The product leaves the chamber through the bottom rollers and is collected. The walls are engineered to be clamped and airtight between the transparent plates. This clamping construction also enables ease of change for different walls and in-chamber geometries.

The slice rig is significantly different from the air rig. The SR was designed to perform like a 2D air tunnel. Reducing 3-D behaviour by minimizing air losses around the axial direction simplifies the behaviour observed in the air rig. The SR therefore is an idealized depth-wise cross-section of the air rig. Various testing methods are used to obtain information of the airflow with particles. The slice rig was used to visualize the flow of air and particles in the air chamber. Distinguishing the (unsteady) behaviour in the chamber is difficult with the naked eye, therefore slow-motion images are taken. The volumetric air flow rate and particles mass balance over the air chamber was measured. This is an easy way to establish the amount of product and fines extracted. Product and fines streams of interesting experiments were sieved to determine the grade efficiency of the separation. The slow-motion images were used to perform Particle Image Velocimetry (PIV) measurements. By filming the particles in the chamber, velocities in the chamber could be quantified, which are used to verify simulation results of the particle velocities.

By using the quantitative and qualitative methods described above, the hypothesis and research questions can be answered.

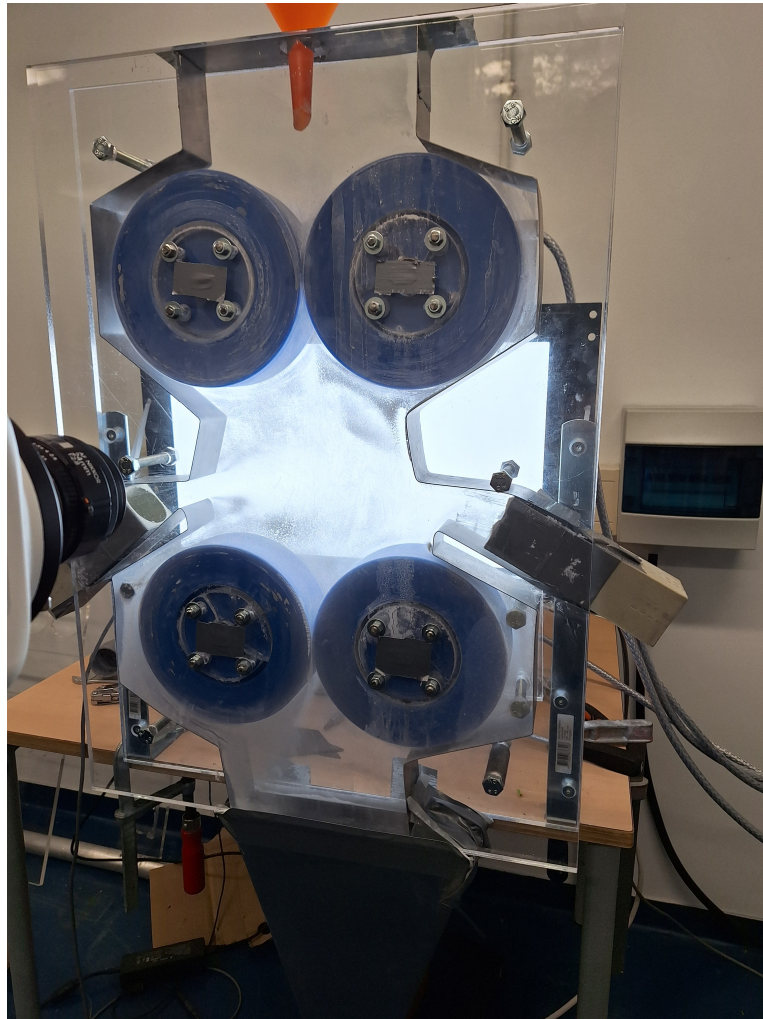


Figure 6.1: Slice rig (SR) setup, feed is introduced by the top rollers using the orange funnel. Air is sucked out from left to right (vacuum pipe missing in picture). Picture is taken after an experiment, as can be seen by the light gray areas under the rollers. These areas are deposited particles, as the airflow is relatively stagnant in these areas particles tend to stick to the perspex plates. Left in image the lens of the high speed camera.

6.2. CFD-DEM

Intertwined with the experiments and insights obtained from the SR experiments, a CFD-DEM coupled model is developed using opensource software CFDEM project. A coupled model between Openfoam, and Liggghts. The main objective of this model is to see if the behaviour in the air chamber can be modelled and if predictions can be done on the separation quality in the air chamber. Future purpose would be to take the insights gained from the experiments and CFD-DEM modelling to be able to more easily predict the air separation performance of larger setups, with varying feedrate, air flow rate and different layouts. It is believed that having a good model which relates the particle and fluid dynamics physics could mean reduced testing time and costs on larger scales setup.

7

Experimental setup

The slice rig setup is introduced in chapter 6 as a simplified 2D test setup. The experimental setup and testing procedures are further introduced in this chapter. The chapter is structured to follow the data acquisition used during the experiments. The first data obtained during an experiment are the slow-motion images for visualisation. Thereafter the mass samples are collected and weighed. The mass samples collected are sieved for interesting experiments.

7.1. Slice rig

Figure 7.1 shows the position where the feed enters the top rollers; the fines were extracted from the side (indicated by the fines arrow) by a vacuum cleaner. The product, with reduced fines is forced out by the second roller set. As shown in figure 7.1, the product and fines were weighed, and certain samples are sieved. The camera was placed in the axial direction of the rollers. This gives a good perspective through the Perspex front and back plate on the behaviour within the air chamber. Air velocity was measured at the air entrance of the air chamber, opposite of the fines exit in figure 7.1. The pressure drop was measured just before the fines exit.

The experimental setup consists of the following parts:

- Mass rate funnel (39 g/s)
- In-chamber geometries
- Vacuum cleaner
- Photron NOVA S9 camera
- Led panel opposite side to the camera
- Scales (accuracy 0.1 g)
- Reitz sieves 1, 0.71 0.5 0.425 0.300 0.212 0.125 0.75 [mm]
- Anometer
- Pressure sensor

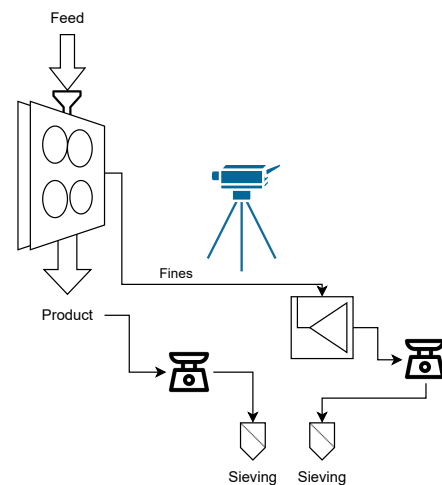


Figure 7.1: Simplified drawing experimental setup

7.2. Visualisation

First, the particle movement was visualized using the slow-motion camera. This is the fastest way to obtain data from the experiment. Initially, experiments were mainly focused on adjusting the nozzle entrance. The

inlet and outlet dimensions and placement were assumed to influence extraction performance significantly. Based on the first visualisation, large stagnant regions were identified. The stagnant regions in an early experimental stage are shown in figure A.2 a), based on this result the air entrance on the left was enlarged. Figure 7.2 a) shows the initial wall setup, sub-figure b) shows the setup with the enlarged air entrance. The final exit nozzle was kept the same (connection to the vacuum pipe). This reduced the stagnant areas and led to better (visual) results.

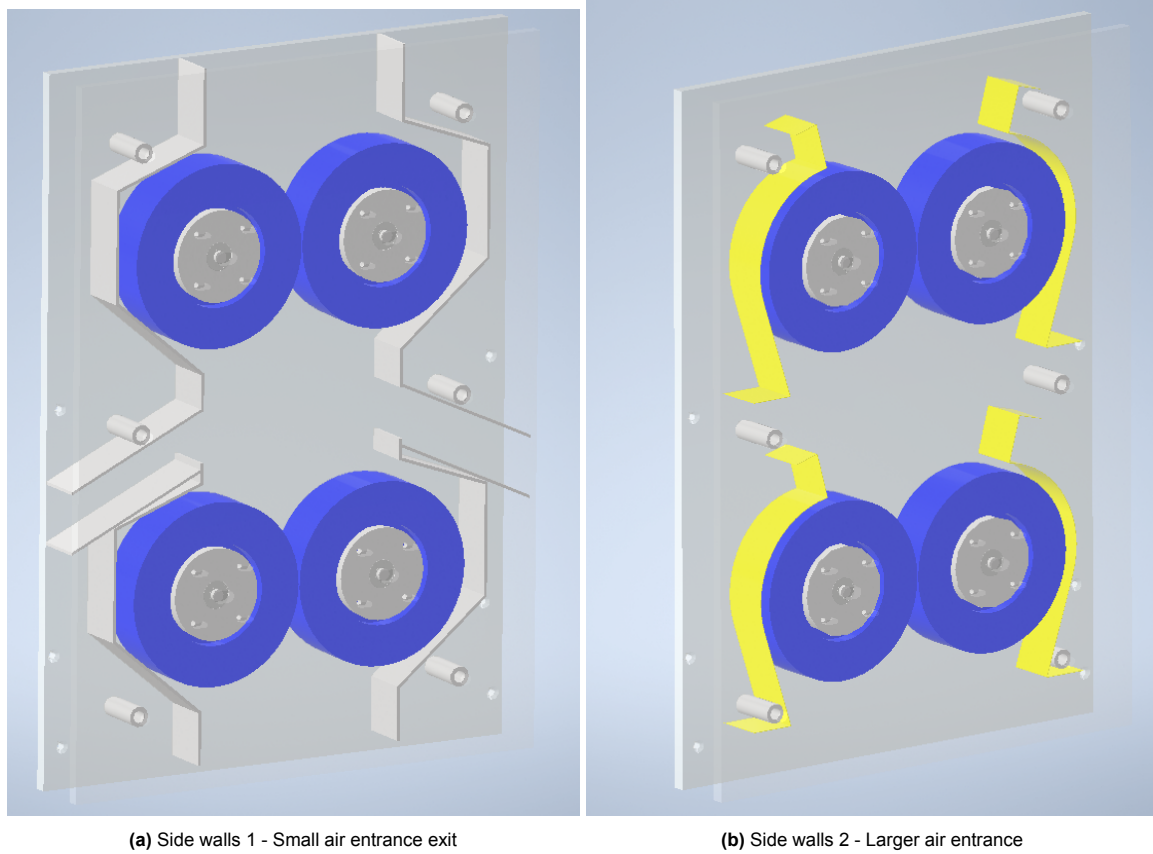


Figure 7.2: First iteration based on visualisation results. Larger air entrance reduced the stagnant areas in the air chamber

To further enhance the extraction, various other setups were tested. These setups can be found in A.2. Two setups of particular interest are discussed further in this report. The two chamber layouts are displayed in figure 7.3. Figure 7.3 a) shows the Empty Chamber (ECH) case. This is the simplest case without other flow-enhancing measures. Figure 7.3 b) shows the WCH case. The WCH case uses inserted vanes. These vanes help to guide particles and airflow to increase separation efficiency.

During testing, the chamber was filled with particles and filmed. This can be seen in figure 7.4. It was proposed by the developers to maximise the roller velocities to increase the rollers' influence on the particles and air chamber behaviour. The motors of the top rollers were set to 1260 RPM and the bottom rollers to 1800 RPM. Frame rates during filming were set to 5000 FPS. A visual comparison of slower experiments roller velocity experiments showed very similar behaviour within the chamber. No quantitative data is available for experiments with lower rotational speeds.

The base case is an empty chamber. This empty chamber lets the air flow freely from left to right and force the fine particles out of the dense sheet of material. The material is depicted in figure 7.4.

The heavier particles can be distinguished from the fines. The size distributions between fines cannot be differentiated. Fines are smaller than $<125\mu m$ and, therefore, not differentiable because they are only visible due to diffraction. Diffraction allows the fines still to be seen and tracked by PIV. However, information on the diameter of individual particles is lost. The video measurement is used to determine the velocity of the particles [24].

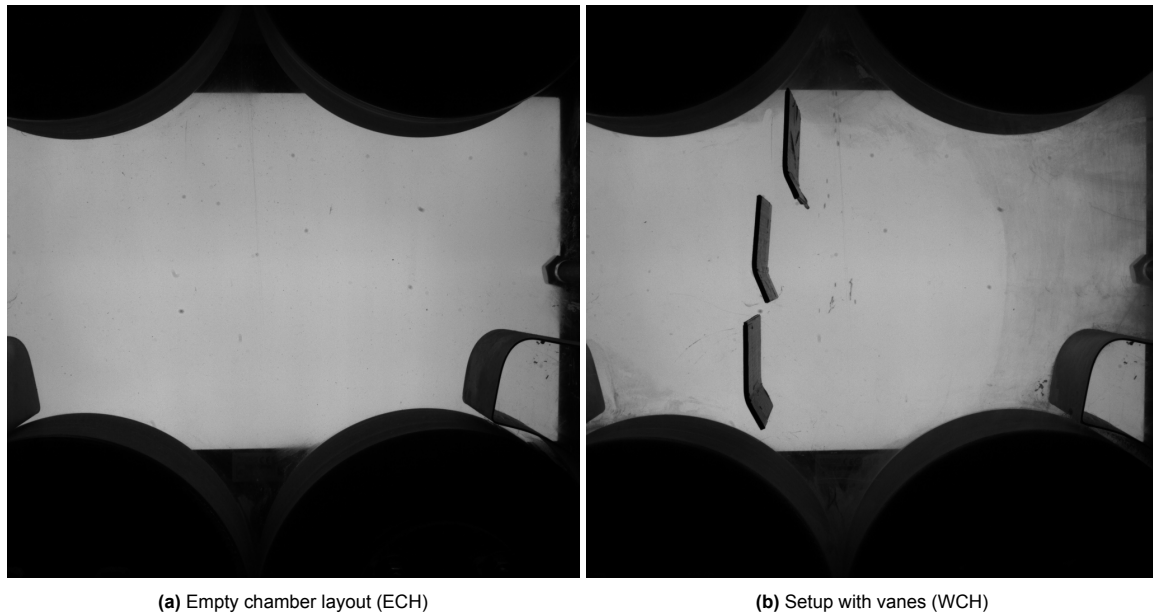


Figure 7.3: Slice rig chamber layouts - top and bottom rollers can be partially distinguished.

7.3. Mass and size distribution

After the experiment is concluded, the size distribution can be determined. This is done by measuring the product's total mass and comparing the sieving results of the product and fines with the original baseline PSD.

Samples must be representative and homogenised. Sampling particles poses many problems, and sample reduction should be performed to get multiple representative and homogenised samples. Sufficient quantity of mass needs to be collected to for an experiment run, this results in excessive mass for standard screening analysis, thus a representative sub-sample needs to be extracted for size analysis of the collected product and fines. Splitting the baseline samples and product/fines was done using a sample splitter. By checking the error in the baseline, it is confirmed that this is a sufficient, precise method of splitting.

A variety of setups were tested and sieve results were documented. To maintain coherence in this report, only the ECH and WCH cases are discussed extensively. Other slice rig layouts can be found in the appendix A.2. The sieve results of other variants can be found in A.1.

7.4. Particle tracking

This research focused on the interaction between particles and flow; a particular type of measurement can be applied—particle tracing using software. There are two main strategies. Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) [24].

The desired method would be to do PTV, which yields the individual paths of particles. However, due to high particle loading, this was found to be impossible [24].

Using PIV, the software followed packages of particles and calculated velocity based on these packages. The PIV measurement could not be to measure the air flow directly. This is due to the high Stokes numbers as calculated in 3.2.3; the particles do not represent the flow velocity well as there is an excessive lag time for the particles to adapt to the velocity fluid.

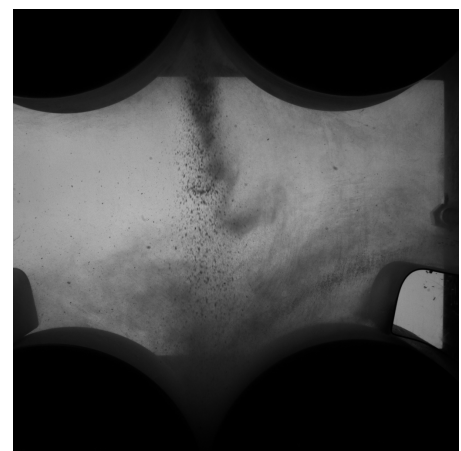


Figure 7.4: Empty chamber during operation filled with particles

Experimental results

Experiments on the Slice Rig were conducted to measure the performance of the air extraction in the chamber. The experimental results will help to answer the research questions. In 8.1 the optimising of chamber geometries is reviewed using visualisation 8.1.1 and a better understanding of particle velocity 8.1.2. Combining the results of air rate measurements subsection 8.2.1, the fines rate subsection 8.2.2 and the grade efficiency subsection 8.2.3 the energy efficiency can be calculated for both the ECH and WCH case.

8.1. In-chamber geometry

8.1.1. Visualisation

The simplification of the test setup significantly improved the visibility in the air chamber. Using the slow-motion camera to visualise the behaviour of the particles in the chamber significantly improved the understanding of the flow behaviour. The two layouts introduced in figure 7.3, ECH and WCH, are showed in figure 8.1 during operation. By observing the movement of the fines with respect to the roller and heavy particles design improvements have been realised.

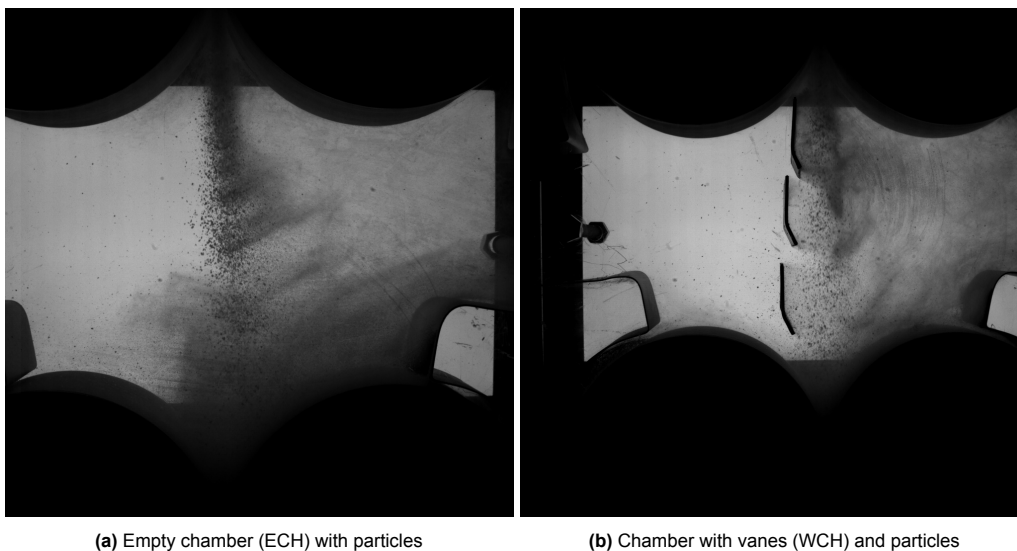


Figure 8.1: Comparison of ECH and WCH chambers using high speed images. Individual large particles can be distinguished from the darker clouds consisting mostly of fines. Rollers are spinning, narrow gap between the rollers is out of image.

Shown in figure 8.1, the chambers during operating subfigure a) ECH, subfigure b) WCH. The airflow direction is from left to right, and the particles are drawn into the extraction tube, further to the right out of image. The inlet volumetric flowrate of ECH is identical to the WCH case. The effect of the vanes on guiding the particle stream can be seen in subfigure 8.1 b) due to the fact that there are barely fines on the left of the vanes.

Furthermore, by inserting the vanes, the airflow gets restricted, and the air velocity is increased close to the particle stream, in between the vertical gaps of the vanes. The increased velocity enables the airflow to penetrate the particle stream more effectively. This is deduced from the fact that coming from the first vane, there is a cloud to the right, and significantly more light is already passing through the particle stream than at the same height in the ECH case. The heavier particles cannot follow the quick changes in the air velocity as larger particles have a significantly higher Stk number. The stokes number for particles is calculated in subsection 3.2.3. In the WCH case, the left side of the chamber is almost entirely free of fines, whereas in the ECH case, the fines are also deposited on the left side of the chamber.

The fines in the WCH start separating out higher in the chamber **1**, which gives the particles more time to separate. This can be seen higher in the chamber; broader clouds of fines are forming to the right of the top vane. Going down with the particle stream, more light comes through the product stream before it enters the next set of rollers **2**. This indicates that more fines are separated from the product stream. The fines in the ECH case are dragged with the main particle stream to the next set of rollers. When the particles meet the roller set, the air dragged with the particles is reversed upwards, taking (part of) the smaller particles back up **3**. This is referred to as backlash, it is clear that WCH experiences almost no backlash. On the top of the bottom rollers, there also seems to be less backlash in the WCH case than in the ECH case. This indicates that more particles are separated

In figure 8.2 and 8.3, slow-motion stills are displayed from experiments. The frames are arbitrarily chosen 60 frames apart to visualise video images. The ECH case seems much more chaotic than the WCH case. The vanes are improving the flow of air to the right.

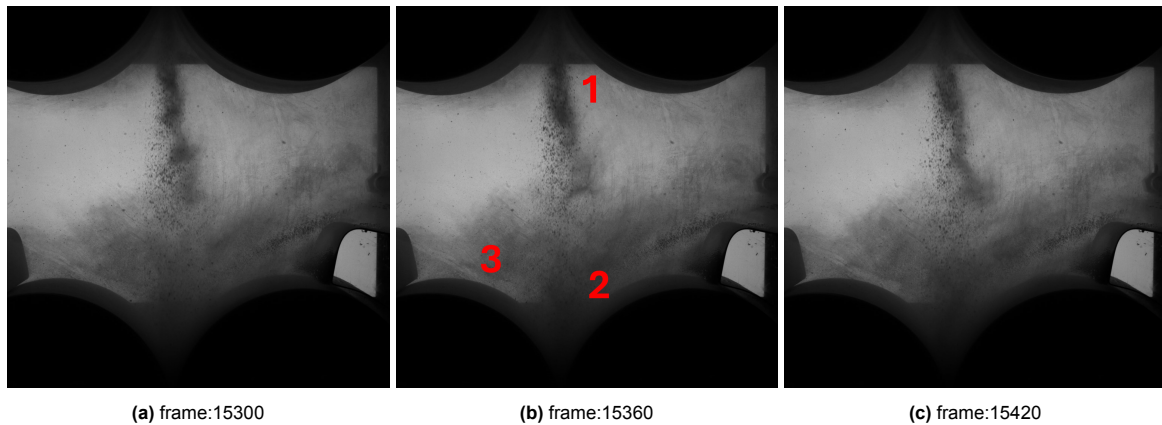


Figure 8.2: Slow motion image of the ECH, fines form a cloud underneath the incoming air entrance, when moving from left to right the cloud is pulled upwards towards the exit nozzle

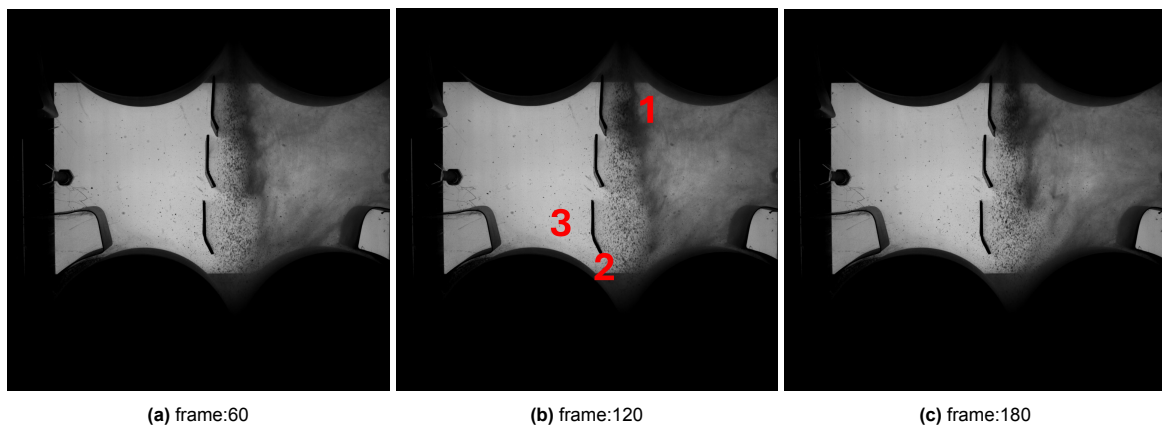


Figure 8.3: Slow motion image of WCH - shows significantly less fines clouds on the left of the particle stream w.r.t. the particle stream. More light is coming through the particle stream on the top of the bottom rollers indicating less fines present going to the product compared to the WCH

8.1.2. Averaged Particle Velocity

A PIV analysis is conducted on the particles to determine the average particle velocities within the chamber.

The main goal was to assess the particle speed and direction depending on the in-chamber geometry. This was done by analysing groups of particles using PIV software. The velocity visualisations with velocity standard deviation are shown in figure 8.4 and 8.5 for the ECH and WCH cases, respectively. In both cases the chamber shows unsteady behaviour, so the time average of the particles was taken. The dense arrows in the centre of figures 8.4 and 8.5 are the velocity representation of the particle stream. The green arrows to the right depict the fines velocity. The average particle stream velocity of ECH is around 5 to 6 $[m/s]$. The fines in the ECH, to the right of the particle stream, travel at around 2 $[m/s]$.

In figure 8.4 (ECH) close to the edge of the particle stream, it is observed that the velocity standard deviation becomes larger. This is most likely because the amount of heavier (faster) and lighter (slower) particles alternate here and increase the velocity standard deviation. The alternation is due to the number of particles inside an interrogation window. In the middle of the particle stream, the PIV software will have enough large particles to resolve the velocity of the more abundant particles constantly.

To the right of the particle stream, the interrogation window will mostly resolve on smaller particles; however, due to stray of particles, larger particles will also move through the interrogation window. The larger particles will move faster than the smaller particles, inducing small velocity fluctuations in the measurement.

On the left side of the particle stream in the ECH and WCH, figure 8.4 and 8.5, the velocity deviation is higher than expected compared to the right side of the domain. This is likely because of the low number of particles. This decreases the quality of PIV resolution and increases the measured deviation. In the ECH figure the backlash upwards described in section 8.1.1 is also found on the left side of the particle stream.

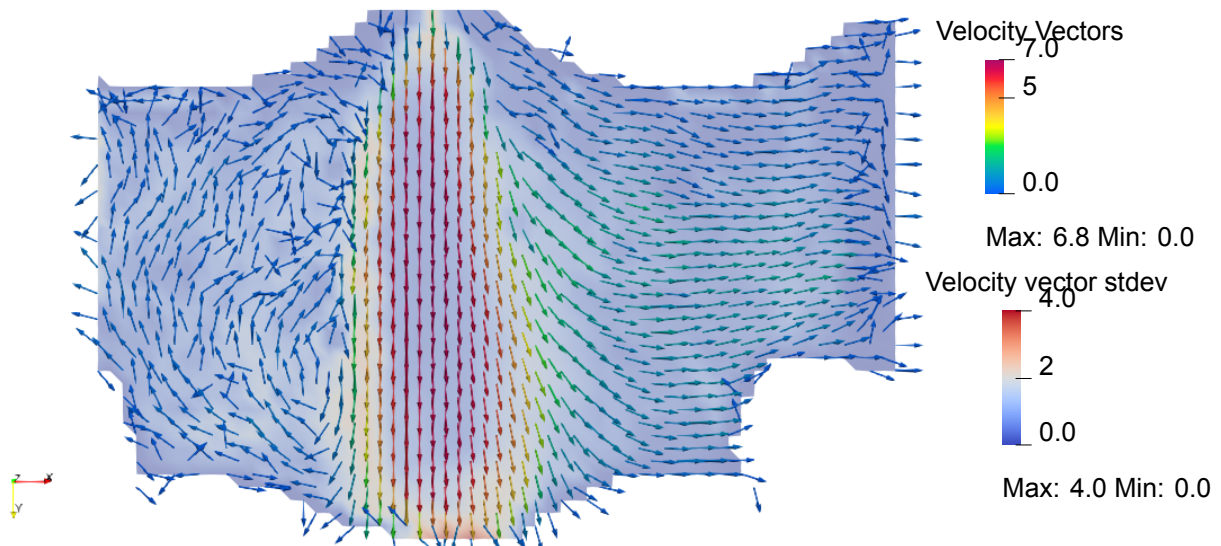


Figure 8.4: PIV results of empty chamber (ECH) (Particle velocity)

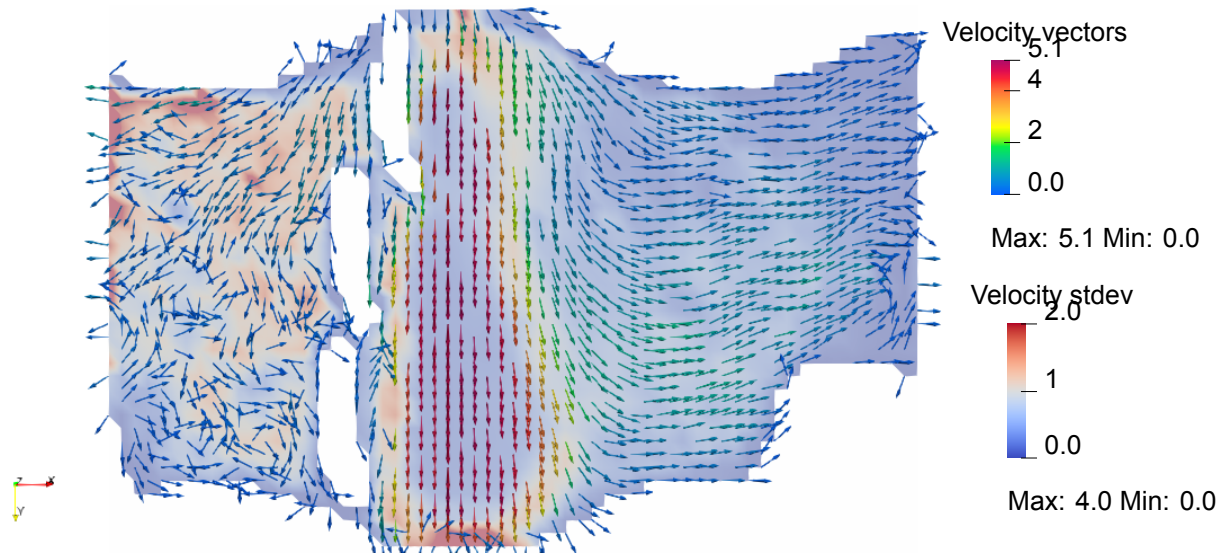


Figure 8.5: PIV results WCH (Particle velocity), white inserts in the domain are the vanes which are "masked" in PIV software.

Figure 8.5 shows the PIV results of the WCH. The white areas in the domain are the inserted vanes. The vanes are excluded from the calculation domain in the PIV software. Based on the length of the velocity arrows, the WCH seems to have a more asymmetric gradient to the right.¹ The vanes and the improved airflow don't allow the fines to waver into the air direction therefore creating a velocity gradient to the right. The vanes have also slowed the particle velocity down compared to the ECH case. The particle velocity in the WCH is around 4 to 5 $[m/s]$. The reduction of vertical velocity will give the smaller particles more time to get separated out. The flow velocity in between the walls has not been fully analysed.

The change in flow cannot properly explain the improved separation found in subsection 8.2.3. The vanes have improved the airflow but mainly prevented the fines from spreading out into the direction of the air. This can be seen in figure 8.5 because the velocity deviation steeply increases on the left of the vanes. This is mainly due to the lack of particles, therefore reducing the ability of the PIV algorithm to predict the (particle) velocities correctly.

The PIV results of ECH and WCH differ significantly in the velocity. As can be seen on the max velocity values in figure 8.4 and 8.5. As the average particle velocity is almost 1 $[m/s]$ slower. This gives the air more time to extract fines. Furthermore, it reduces the inertia the fines and other particles will have, making it easier to divert the direction of the particle.

¹Figure 8.5 might seem more structured than the results in figure 8.4. This is only due to the figure's visualisation settings.

8.2. Energy efficiency

Combining the results of air rate measurements subsection 8.2.1, the fines rate subsection 8.2.2 and the grade efficiency subsection 8.2.3 the energy efficiency can be calculated for both the ECH and WCH case.

8.2.1. Air rate

Before the experiment, the airflow rate and pressure drop were measured. The pressure drop over the chamber was measured to be 47 [Pa]. The volumetric flow rate was found to be 0.017 [m³/s]. First tests were conducted with almost double the airflow, this however was not deemed useful to test as this was far of the (equivalent) volumetric flowrates measured in the Air rig and industrial test plant. No changes were made to the volumetric flow rate or pressure drop between the ECH and WCH cases. The placement of guide vanes did not significantly change the pressure drop or volumetric flow rate. Initially a (significant) drop was expected by introducing the vanes as the airflow encounters more resistance. For further calculations, the pressure drop and volumetric flow rate are kept constant.

Rewriting the power equation for a fan given in formula 2.4 equation 8.1 is found.

$$P_f = dp \cdot \dot{V} \quad [W] \quad (8.1)$$

This would yield for the results found on the slice rig an idealised power consumption of $\approx 1[w]$ which is a low number.

8.2.2. Fines Rate

Table 8.2 presents the results of the fines rate of the ECH and WCH case. Based on the air volumetric flow rate given in subsection 8.2.1, the loading capacity can be calculated. The WCH experiment significantly improves performance over the ECH as the fines rate was increased from 5 to 8 [g/s]. This is an increase of +60%. As the air rate is constant and the fines rate is increased, the loading capacity increases proportionally.

Table 8.1: Performance indicators of the ECH and WCH chambers. Error based on SEM.

Test	ECH (error)	WCH (error)
$\dot{m}_f$	$5 \pm 0.2 [g/s]$	$8 \pm 0.3 [g/s]$
LC	$262 \pm 10 [g/m^3]$	$472 \pm 15 [g/m^3]$

8.2.3. Grade efficiency

By measuring and sieving the feed mass, product mass, and fines mass, the collection efficiency can be calculated. First, the sieving results are shown in figure 8.6. The cumulative passing curve indicates if more or less mass of a certain particle size was present in a sieve size. The main interest is in the lowest three sieve sizes. The higher sieving stages yield no significant difference between the ECH and WCH products. The three lower sieve sizes are presented in figure 8.6 b). The feed only contains around 3% mass of 75 μm and around 11% 125 μm particles. Figure 8.6 b) shows that the WCH extracted more fines in the lower two mesh sizes. The 212 μm WCH measurement point supports the trend of improved fines extraction but is within the error bar of the ECH case.

As the presented mass fractions differences in subfigure 8.6 b) are very small, the percentual changes are calculated. Table 8.4 shows the relative separation quality with respect to the feed. The percentage decrease compared to the feed is very similar between the ECH and WCH for larger particles. Only for smaller particle sizes starting from the 212 μm WCH outperforms the ECH in separation efficiency.

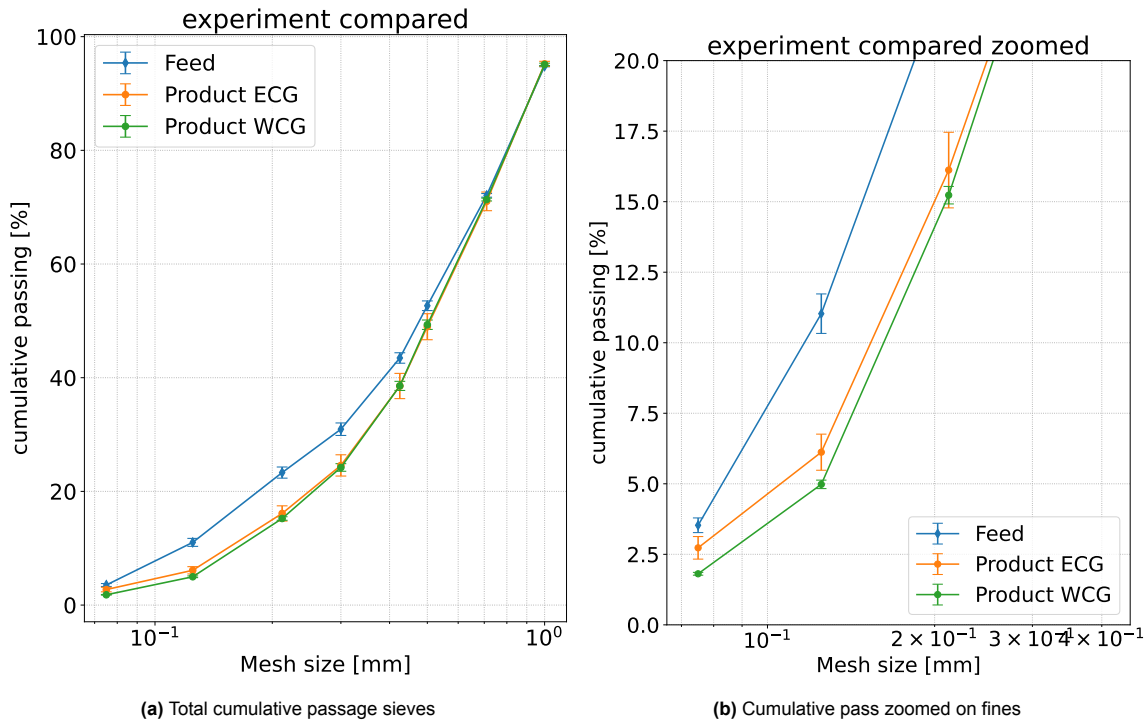


Figure 8.6: Sieved results of consistent baseline

Table 8.3: Fines present in the sieved product -percentage decrease compared to feed.

Mesh size [μm]	% ECH	WCH
1000	0%	0%
710	-1%	-1%
500	-7%	-6%
425	-11%	-11%
300	-21%	-22%
212	-31%	-35%
125	-45%	-55%
75	-23%	-49%

The data of table 8.4 is visualised in a bar chart shown in figure 8.7. The black numbers in figure 8.7 indicate the percentage change between the ECH and WCH case. The percentual change is calculated based on the cumulative passing curves.

Combining the fines rate information from section 8.2.2 and the separation quality information from 8.4 the specific collection efficiency can be calculated. The collection efficiency (η) of particles $d_p \leq 125 \mu m$ was increased from 39% to 48%.

The inserted vanes induce better separation results. The large particles are relatively unbothered by vanes. However, the smaller fractions are significantly better separated. This is up to a 100% improvement compared to the ECH for the $75 \mu m$ fraction, indicated by a smaller fraction in the coarse product stream out of the air chamber classification zone. As small fines are of a major concern, this is a desirable result.

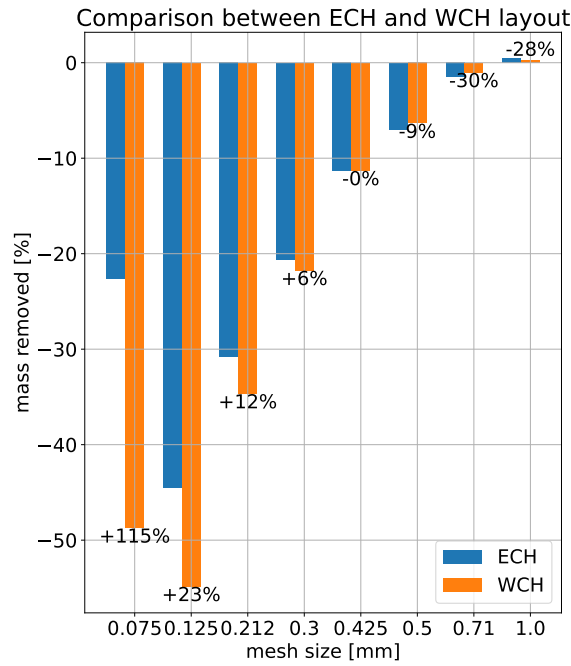


Figure 8.7: Percentual to baseline and relative improvement using vanes

8.2.4. Energy consumption

Combining the air results from subsection 8.2.1, the fines rate information from table 8.2 and collection efficiency given in subsection 8.2.3 the energy efficiency can be calculated using equation 8.2. The energy efficiency will be expressed in KWh/ton and the results of the ECH and WCH can be found in table 8.6.

The energy efficiency is calculated from the power and fines rate using the specific collection efficiency. Equation 8.2 defines the energy consumption of fines extraction and is based on the descriptive equation 2.7.

$$E_{\eta} = \frac{1}{3.6} \frac{P_f}{\dot{m}_f \eta} \quad [kWh/ton] \quad (8.2)$$

Table 8.5: Idealised energy consumption based on the specific collection efficiency and fines rate for the exit of the chamber

	ECH	WCH
Energy consumption	0.11 $[kWh/ton]$	0.06 $[kWh/ton]$

The energy consumption using vanes dropped from 0.11 to 0.06 $[kWh/ton]$, this is an decrease almost 50% energy consumption. Though it is measured in simplified system, it is a promising result for further scaling to industrial scale.

The results presented in table 8.6 are valid upto the exit of the air chamber. This is, however, not the end of the fines transport on an industrial scale system, it is just the beginning. Fines will be transported throughout ducting and cyclones out of the system, knowing the $\dot{m}_f$ and $\dot{V}$, together with a pressure drop over the total system will define the actual energy consumption of the fines extraction. Reducing the $\dot{V}$ or increasing $\dot{m}_f$ reduces the energy consumption of the fines extraction.

8.2.5. Discussion and Recommendation Experiments

In-chamber visualisation

The visualisation was an extremely useful method to observe the behaviour of particles. This immediately clarified the inner workings of the chamber. It has proven to be a very useful tool for making fast results and adjustments. The fps settings (5000 fps) as discussed in section 7.2 could have been lowered, as 5000 fps yielded a large stream of data without much additional information. The experiments' visualizations give a good insight into the particle movements, especially the slow-motion images, which also captures the bounce behaviour and individual particles. The bouncing from the rollers explains the particles flying out of the air inlet as particles are shot out from the opposite roller and our found to be. To add more insights about the fluid behaviour, smoke could be introduced to follow the airflow through the particle stream. This could enhance the understanding of the particle fluid interaction.

Average particle velocity

It is currently difficult to compare the velocities with the simulation results as the PIV software averages out individual particles and, therefore, only provides the average bulk velocity. To increase the comparability of the PIV measurement method, an experiment on multiple single particle size samples could be performed. For example take a sample only consisting of $d_p = 212 \mu m$ particles. Then running the test and performing the PIV on this homogenised particle set this could give an accurate velocity field of a single particle size, which could later be compared with a single particle size simulation of the CFD-DEM software. A picture of such an experiment is included in the appendix section A.2. Future research could take the existing videos, preview displayed in figure A.4 a) b) and c) $d_p = 75 \mu m$, $d_p = 180 \mu m$ and $d_p = 212 \mu m$ respectively. These figures show the varying behaviour of different particle sizes.

Energy efficiency

The error on the total mass balance for ECH and WCH as discussed in section 8.2 is between 4.6% and 2.3%. The lost mass can be accounted for in two ways: heavy particles sometimes fly out from the air entrance, however in practice that rarely occurs. Furthermore, the heavy particles influence the total mass balance but not significantly within the particle size domain of interest. Investigation of the vacuum cleaner showed that not all fines can be extracted from the smaller cyclones. This influences the (total) mass recovery. It is recommended that in the future, a different cyclone is used to recover more mass from the cyclone.

The sieving results provide the most critical information. For future experiments, longer runs can give narrower error margins. This can be shown by comparing the error margins of the ECH vs. WCH found in figure 8.6. One of the ECH experiments was initially wrongly performed, so it was repeated using another (homogenised) sample with less material. However that second sample only had around 50% of the other samples mass. The total masses of the experiments can be found in the appendix A.2. The shorter ECH experiment deviated slightly from the larger mass run, increasing the standard error on the mean for the ECH case. Smaller error margins for longer experiment runs can be explained by longer steady-state operations and less influence due to start/stop behaviour.

Airflow measurements should be improved and performed more reliability. Air flow measurements are taken with a 2.6 second, time average using a relatively large anemometer. Steps could be undertaken to more accurately measure the air velocity, maybe even during operation of the SR. Measuring air velocity accurately would probably need a significantly smaller measurement interval than 2.6 seconds.

CFD-DEM Model SR

This chapter discusses the challenges and used (sub)models for the CFD-DEM simulation. The CFD-DEM model was built to be comparable to the SR experiments. To understand the CFD-DEM model for this application, the theoretical background of a CFD-DEM model will be discussed in section 9.1. The implemented physics and boundary conditions are introduced in section 9.2. The challenges of modelling high number of small particles are discussed in section 9.3. Meshing will be shortly discussed in section 9.4. The results follow in section 10, and the recommendations for the model in section 10.3.

9.1. CFD-DEM theory

Chapter 3 introduced interactions between particles and fluid. These known interactions can be used to develop a model which can be solved by a computer. The method often referred to for these types of computations is called CFD-DEM coupled simulations. CFD stands for Computational Fluid Dynamics which is used to solve the continuum physics of the air in the air chamber. The CFD part of the simulation will use an Eulerian (mesh based) method to solve the Navier-Stokes momentum and mass equations. DEM stands for Direct Element Method and will be used to simulate particle physics. DEM is a Lagrangian based method which is based on tracking the velocity and position of particles. CFD-DEM couples the Computational Fluid Dynamics (CFD) to the discrete element method (DEM) to the domain. The software package used for this is CFDEMproject LPP. Within CFDEMproject there are various coupled solvers available. Two distinguished classes can be differentiated, the resolved and unresolved approach. In short, the (Fully) resolved solvers will solve for a mesh which volume size is significantly smaller than the particle size, therefore solving the fluid flow between and including the moving particles. This is too computationally intensive and unnecessary for the current task at hand.

The unresolved solver used in this research uses a completely different method. In contradiction to the resolved approach, this solver does not need mesh sizes significantly smaller than the particles. The unresolved method is based on the mass balances of a mesh cell. As earlier introduced, the CFD method is Eulerian based, therefore using a mesh, to calculate the mass and momentum balances for numerous volume cells. Adding the mass and momentum of the particles from the DEM computations gives a new mass balance.

The unresolved method uses a volume fraction of the CFD cell to calculate the mass and momentum equation over the volume of the CFD cell.

Equation 9.1 defines the mass conservation principle in differential form over a volume-cell. ρ_f defines the density of the fluid and α_f defines the fluid volume fraction of the cell [22] [31]. α_f is therefore strongly dependent on the volume taken by the solid particles. The second term of equation 9.1 defines the divergence of the mass flux.

$$\frac{\partial \alpha_f \rho_f}{\partial t} + \nabla \cdot (\alpha_f \rho_f \mathbf{u}_f) = 0 \quad (9.1)$$

Equation 9.2 defines the momentum balance over a cell-volume [22] [31]. The first term on the left side of equation 9.2 defines the force due to the acceleration of fluid, the second term defines the divergence of the momentum. The first term on the right side in equation 9.2 defines the pressure forces, the second term controls the momentum coupling between particles. The third term defines the internal stress due to the viscous forces. The last two terms in equation 9.2 are body forces, the first defines the body force on the volume cell, the last term defines an body force that can be arbitrarily defined. $\mathbf{f}$ can be used to model electrostatic forces for example, but will be not be used in these simulations.

$$\frac{\partial(\alpha_f \rho_f \mathbf{u}_l)}{\partial t} + \nabla \cdot (\alpha_f \rho_f \mathbf{u}_f \mathbf{u}_f) = -\alpha_f \nabla p - K_{sl}(\mathbf{u}_f - \mathbf{u}_p) + \nabla \cdot (\alpha_f \tau) + \alpha_l \rho_l \mathbf{g} + \mathbf{f} \quad (9.2)$$

Equation 9.3 defines the implicit momentum coupling source term used in equation 9.2 [31]. By solving the velocity of a particle with respect to the fluid velocity in the volume cell the drag force can be calculated and coupled to the momentum calculation of the volume cell. If the particle would move faster than the fluid, the fluid in the cell would be accelerated. If the particle moves slower than the surrounding fluid, the fluid would be slowed down. The inverse is applicable from a particles point of view.

$$K_{sl} = \frac{\alpha_l \cdot \sum_i \mathbf{F}_D}{V_{cell} \cdot |\mathbf{u}_l - \mathbf{u}_p|} \quad (9.3)$$

Using the drag equations given in table 3.5 and will be further discussed in section 9.2.1.

9.2. Implemented physics

The subsection 9.2.1 discuss the used drag model needed to compute the implicit coupling coefficient given in equation 9.3 and the forces on the partilces. The contact model will be discussed in 9.2.2.

9.2.1. Drag model

The Schiller-Naumann (SN) drag correlation, which applies to individual particles, was used to determine the drag force needed for K_{sl} as defined in equation 9.3.

Various drag models are available within CFD-DEM simulations. Two different models are tested: Schiller-Naumann model as earlier discussed, and the Beetstra drag model. The Beetstra drag model is designed for systems in which the packing fraction $0.1 < \Phi_p < 0.65$ and the Re_p ranges from 10-10.000 [32]. A trade-off is be made between accurately modelling the complete chamber dynamics and separation from the particle sheet. Considering the complete air chamber, the volume fraction is relatively low. This would make the SN model an appropriate drag model, as the combined particle interaction will be negligible. However, the material sheet of particles has a high volume fraction. Here, the influence of a falling group of particles could be more significant. The Beetstra drag model could be more valid as Φ_p increases. Φ_p increases when the feed rate increases, this will happen in industrial application and was therefore tested. The results presented are calculated with Schiller-Naumann as low particle volume fractions are modelled.

9.2.2. Contact model

The collisions between particles will be modelled as soft-spheres. It is therefore required that the particulate collisions are of finite duration's [22]. For dense flows this model is considered to be far more efficient than the hard-sphere model and it can be applied to any configuration including static and dynamic situations [22]. The collisions will be modelled using the Hertz contact model which is an non-linear contact model. The Hertzian model is described by Di Renzo et al, [33]. The Force equation is implemented like:

$$\mathbf{F} = (k_n \delta n_{ij} - \gamma_n v n_{ij}) + k_t \delta t_{ij} - \gamma_t v t_{ij} \quad (9.4)$$

$k_n = \frac{4}{3} Y^* \sqrt{R^* \delta_n}$ defines the elastic normal constant. The $\gamma_n = -2 \sqrt{\frac{5}{6}} \beta \geq 0$ viscoelastic damping constant for normal contact. $k_t = 8 G^* \sqrt{R^* \delta_n}$ defines the tangential spring constant. $\gamma_t = -2 \sqrt{\frac{5}{6}} \beta \sqrt{S_t m^*} \geq 0$ is the tangential viscoelastic damping [31]. The square root in the multiplication terms of the matrices lead to a non-linear response in spring stiffness and energy dissipation. This therefore is inelastic modelling as earlier explained in subsection 3.3.2

The time step is depending on the contact time, which can be calculated using the equation 9.5. All values in equation 9.5 using the asterisk suffix are referred to as effective values [31].

$$t_c = 2.87 \left(\frac{m_*^2}{r_* Y_*^2 V_c} \right)^{1/5} \quad (9.5)$$

The effective mass is defined as $m_* = \frac{m_{p1} \cdot m_{p2}}{m_{p1} + m_{p2}}$, the effective radius as $r_* = \frac{r_{p1} \cdot r_{p2}}{r_{p1} + r_{p2}}$ and the effective Youngs modulus is given in equation 9.6.

$$Y_* = \frac{1}{\frac{(1-nu_1^2)}{Y_{*1}} + \frac{(1-nu_2^2)}{Y_{*2}}} \quad (9.6)$$

The t_c time defines the period of collision. The DEM time step should be set around a factor 5 10 smaller than the smallest calculated t_c time step. Adjusting the (numerical) Young's modules increases the t_c , which can be used to reduce computational times if the convergence criteria allow it.

9.2.3. Boundary conditions

Boundary conditions (BC) are needed to solve the equations over the air chamber. Within the model there are different boundary conditions applied. The CFD solver receives the following boundary conditions:

Rollers indicated red in figure 9.1 the fluid boundary condition for the rollers is an imposed velocity field. The surface of the roller has a fixed fluid boundary velocity.

Walls indicated yellow in figure 9.1 the front and back of the fluid domain has a slip wall boundary condition. This represents closely the front and back perspex plates of the real slice rig.

Inlet indicated turquoise in figure 9.1 the inlet conditions receives a zero gradient conditions for pressure and a volumetric flow condition corresponding to the volumetric flow rate of the SR experiments of $0.017 [m/s^3]$.

Outlet The outlet pressure BC was set to $-50 [Pa]$. Furthermore, the outgoing velocity was set to correspond with the incoming volumetric flow rate, therefore ensuring proper outflow conditions and reducing divergence when large amounts of particles crossed the domain.

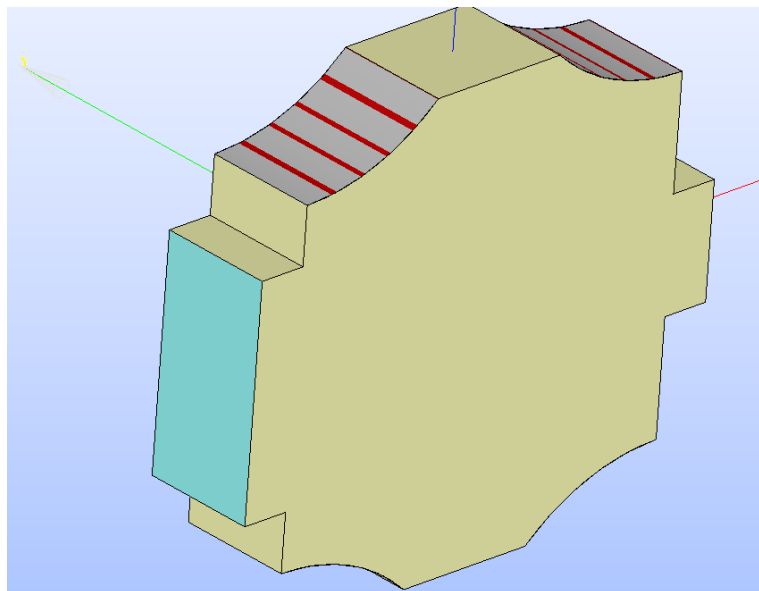


Figure 9.1: Fluid domain of ECH case. Boundary conditions indicated by various colours.

The DEM solver also needs boundary conditions, the rollers receive a type 1 boundary conditions, which defines that the tangential forces will also be included. This is applicable as the rollers need to have a good frictional and tangential force accuracy as this is the main source of dispersion for heavier particles. All other walls receive a type 2 conditions, which uses a simplification for the tangential part of bounce modelling.

9.3. Number of particles

The CFD-DEM simulation is heavily dependent on the number of particles.

The insertion of particles was the same as in the SR experiments. The feedrate $\dot{m}_f$ was set to 39 [g/s]. The number of particles in the chamber can be calculated using the size distribution weight fraction and mass of each particle size. The size distribution is based on the measured size distribution of the experiments described in section 8. It is introduced here to explain the challenges of simulating the DEM behaviour.

The number of particles can be calculated using the PSD of the experimental results discussed in 8.

Table 9.1: Size distribution based on experimental data. As the bottom product is not present ($d_p \leq 0.075$) the input mass will be normalized to 100%

Size [μm]	% Mass retained	V_p	Number particles/100g	Number %
1000	5.2	5.2E-10	4.5E+02	0.0%
710	22.7	1.9E-10	5.5E+03	0.2%
500	19.4	6.5E-11	1.4E+04	0.6%
425	9.2	4.0E-11	1.0E+04	0.5%
300	12.5	1.4E-11	4.0E+04	1.8%
212	7.6	5.0E-12	7.0E+04	3.1%
125	12.3	1.0E-12	5.5E+05	24.5%
75	7.5	2.2E-13	1.5E+06	69.3%

Using the capacity equation 2.1, and the dimensions of the SR we calculate the feed rate of the mass through one set of rollers. We find $\dot{m}_F = 0.039[kg/s]$. Applying the same theory to the chamber, we can calculate the mass inside the air chamber:

$$m = WLH\rho_b * O \quad (9.7)$$

Where: W is the width of the roller [m], L is the gap between the rollers [m], H is the height between the rollers [m], ρ_b SG of bulk T/m^3 O is the occupancy at the roller [%].

Using equation 9.7 yields an estimated mass of around 11 grams in the SR chamber during steady operation. Using the PSD from table 9.2, we find that the chamber will have around $2.2E^6$ particles. This can be computationally challenging. The computation time is heavily dependent on the number of particle-particle interactions and particle-wall interactions.

The problem could be simplified by neglecting the largest contributors to particle number, the 125- and 75-micron particles. As seen in column 5 of table 9.2 the smallest particles contribute significantly more to the number of particles than it's mass fraction. The number of particles is calculated using equation 9.8. The equation shows that with decreasing particle size (d_p), there is a cubic increase in the number of particles. As all information about these particles needs to be tracked, they heavily influence the DEM computation time. Furthermore, smaller particles need shorter DEM time steps to resolve the bounce properly; more on this in subsection 9.2.2.

$$\#particles = \frac{m_{size}}{\frac{4}{3}\pi(\frac{d_p}{2})^3 * \rho_p} \quad (9.8)$$

However as these particles are the main interest of this study and behave significantly different from the larger particles these cannot be excluded. It is expected that reducing the mass-flow rate could be a solution to simplify the simulation, however this would significantly change the mass rates in the chamber. The simulation time of 0.039 kg/s in the WCH case is longer than 10 hours on six cores.

9.4. Meshing

The CFD part of the simulation is mesh-dependent. The computational mesh must have at least four times the volume of the largest particle. For the ECH case a relatively coars mesh can be used. Extra attention could be given to the rollers and their boundary layer. It was chosen to cut off the narrowing part of the rollers in the ECH case to keep the flow domain simple.

As more experience was obtained during the simulations, the WCH case was modelled with more detail. The simulation presents the challenge of many particles in the vertical (particle stream) direction while air moves in the horizontal direction.

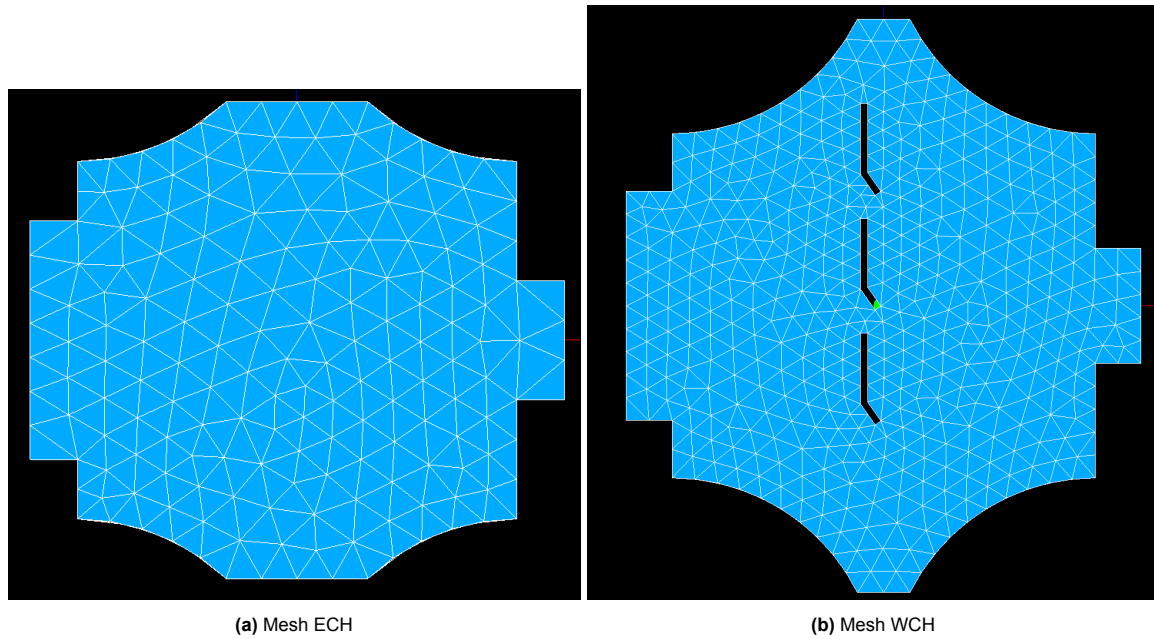


Figure 9.2: Meshes for the ECH and WCH simulations

Different meshes were tried. Initially, a rougher mesh seemed more stable; however, a finer mesh in later simulations yielded better predictions of unstable behaviour (seen during experiments) than the coarser mesh. The WCH mesh posed a real challenge, as obtaining stability in the simulation was very difficult. The results shown for WCH were obtained with an (eventually) unstable solver. The simulation would diverge on the CFD solver, as the particles seemed to overflow the solver, after which the outgoing air velocity reversed direction. This quickly violated the CFD incompressibility criteria causing the solver to diverge.

10

CFD-DEM Results

The CFD-DEM simulations are compared to the SR experiments. The simulation was designed to simplify the SR. One issue while simulating was the bottom mass fraction of the sieved product.

This bottom product mass was around 3.5% of fines with a diameter of less than $75\ \mu\text{m}$. To solve this, particles with a diameter of $50\ \mu\text{m}$ could be included in the simulation, however, this would increase the computational time significantly. Therefore, the total mass was corrected after processing the simulation result to compensate for the missing bottom sieve product. Implementing the sub $75\ \mu\text{m}$ particles posed floating point warnings, as the volume of a single particle fell below the floating point accuracy but less than factor ≈ 10 . This warning was therefore ignored as floating point inaccuracy was not expected to pose a problem.

10.1. ECH simulation

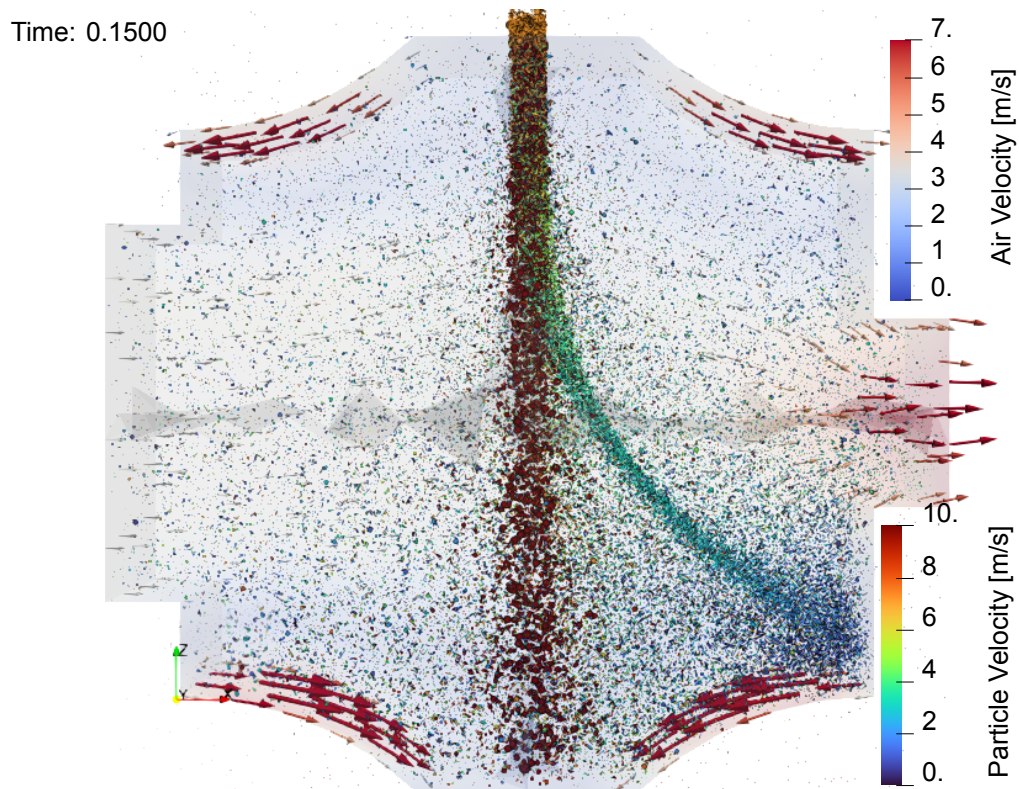
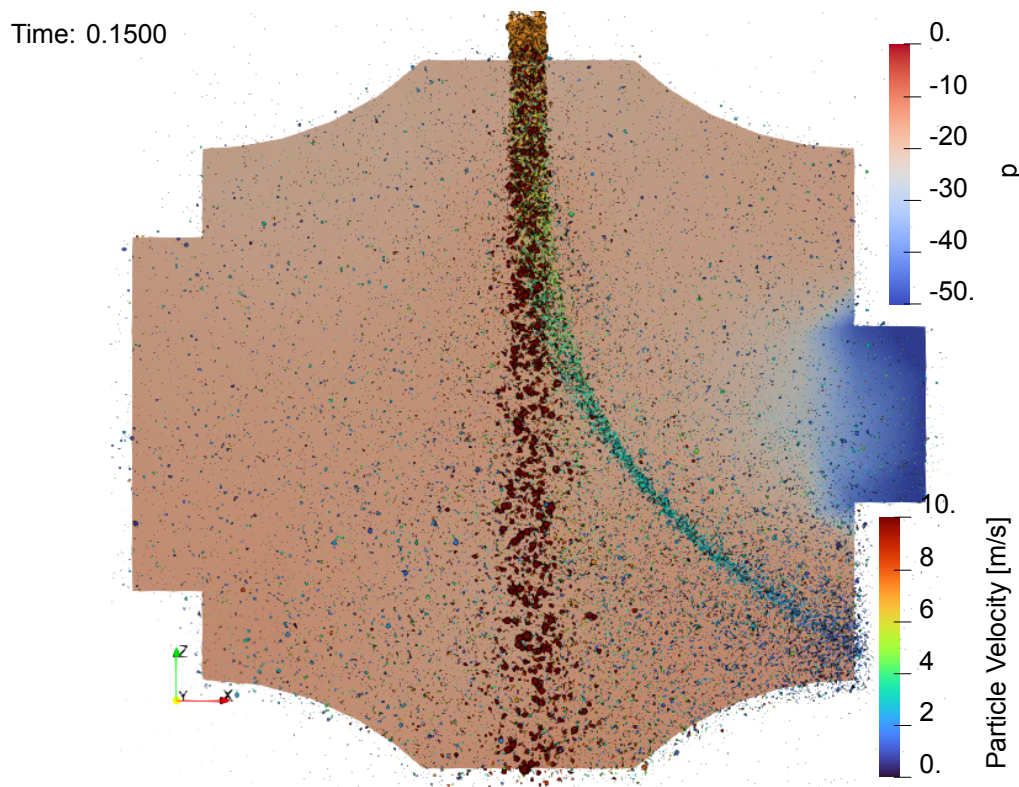
The empty chamber (ECH) was simulated as proposed in the figure 7.3. The wall shapes are simplified. The same airflow, mass feed rate and roller velocity are used as in the experiments. Figure 10.1 gives the particle distribution throughout the chamber. The particles are enlarged by a factor of three for visualisation purposes.

10.1.1. Visualisation

At first sight, the particle velocity seems to be too high with respect to the values found using the PIV method in section 8.4. As discussed in section 8.4, this could be a result of the PIV measurement following average particle velocity. The averaging will reduce the influence of the "fast-flowing" heavy particles the most. Fewer large particles are in the stream, reducing the impact on the averaged particle velocity. The simulated velocity is closer to the upper confidence interval of the PIV measurement. The ECH simulation paints an almost steady-state behaviour of the small particles getting blown to the right (turquoise stream bending out of the main particle stream). This is not the case in reality, where the particle separation behaviour appears much more unstable.

The Schiller-Naumann drag model appears to give better (visual) results than the Beetstra drag model. This is explained by the packing fraction in the particle stream, which drops under the $\phi < 0.1$, making the Beetstra drag model invalid. However it is useful to have compared the results from the Beetstra drag model as, for increased mass rate, the particle fraction in volume mesh cells will increase. Increasing mass rate is desirable from the developers point of view, and could change the interaction regimes of particles.

In figure 10.1, a pressure slice in the middle plane of the ECH simulation is plotted. This yields the outcome that the pressure over SR air chamber is relatively constant. In the exit nozzle, the pressure reduces towards the $-50\ \text{[Pa]}$ set as outlet pressure.

**Figure 10.1:** Empty Chamber Simulation**Figure 10.2:** Empty Chamber Simulation air pressure field

10.1.2. Mass collection and PSD

The data of the mass rate measurements through the fines and product outlet yielded that the fines outlet did not get the right amount of mass. The experiments showed a fines rate of 5 [g/s] while the simulation predicted around 1 [g/s]. This was the initial indication that the simulation results strongly deviated from the experimental findings. The comparison is further discussed in section 10.4

Figure 10.3 presents data from the collection measurement from the simulation. At the exit of the product and fines domain, like in the experiments, measurements are performed to obtain the mass balance. For the PSD each particle was counted. To get the mass, the following approach was used: The number of particles of a specific diameter were counted and then multiplied by the mass per particle. This gave the mass of a certain sieve fraction. Using this method the cumulative passing graph could be plotted. As explained in 9.3 the feed data is taken from the NB experiments feed.

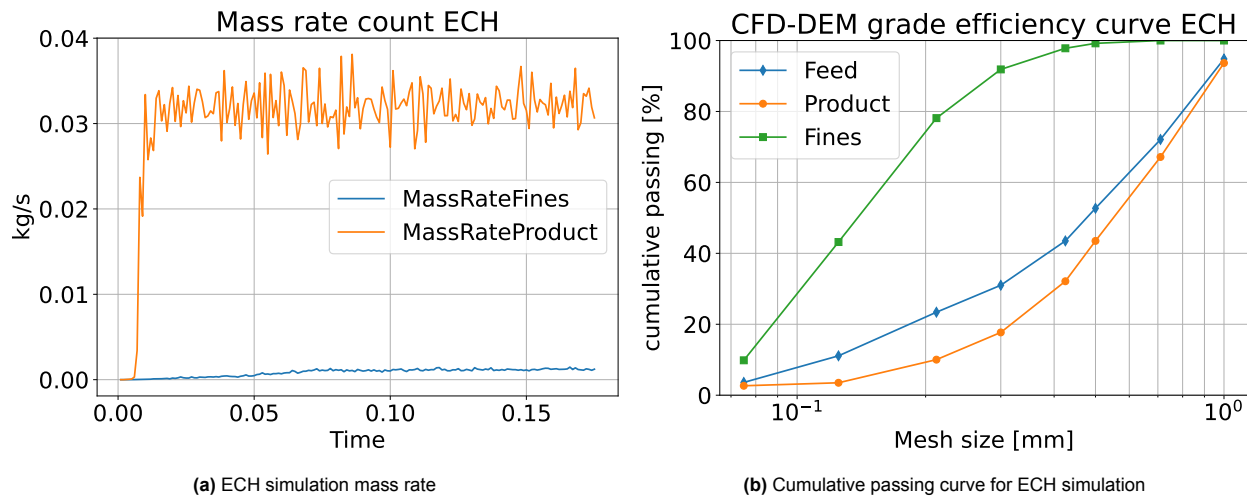


Figure 10.3: ECH simulation results

10.1.3. ECH simulation & experiment

This subsection will compare the ECH "sieving" results with the sieving of the experiment. Convergence was a significant problem during (longer) simulations. The simulation has been executed with 75-micron particles and the experiments' feed-rate and volumetric flow rate. In the post-processing, the total mass fractions were corrected for the absence of the <75 micron. This was done by increasing the summed mass measured in the simulation with the fraction of the mass that was not simulated. The total mass in the simulation was multiplied by one plus the amount of the bottom product of the sieving. This corrects the simulation lines to the same lowest cumulative passing and makes the lines comparable for the domain 75 - 1000 μm . Figure 10.4 presents the sieving results of the ECH simulation versus the experiments.

The results of the experiments and simulation don't coincide, as shown by the different size distribution for the fines and product graphs in figure 10.4. An explanation can be found by the duration of the experiments vs. simulated time. The simulation simulates around 0.17 seconds of experimental time w.r.t. 8 seconds of ECH experiment duration. At the beginning, the chamber is empty. While filling the chamber, the simulation is 'unsteady' as seen in figure 10.3 a); therefore, particles fill the chamber without anything coming out. Because the portion of 'filling' is relatively long with the short real-time simulation, mass is excluded, which is still present in the chamber. Therefore, the error is smaller in the larger particle sizes because large particles fall straight through and don't accumulate in the chamber. The smaller particles are further dispersed in the chamber are therefore not measured in one of the two exit planes.

The fines extraction results in table 10.2 show the comparison between the SR and the ECH simulation. Considering the fines mass rate, a correction should be made. The fines rate of the experimental data also includes sub 75 μm mass, which is earlier corrected for in the cumulative passing curve by increasing the total mass. The smaller particles that are not modelled, but are included in the experiment, represent a missing fines rate of around 1.6 [g/s] which is a significant portion of the difference between the simulated and experimental fines rate.

When adding the mass rates of the fine and product together, it is clear that it does not add up to 39 [g/s], this reinforces the suspicion that the fines rate and extraction efficiency is not well predicted because the mass flow rate is not steady state. The error between the simulated and experimental fines rate is more than 100%.

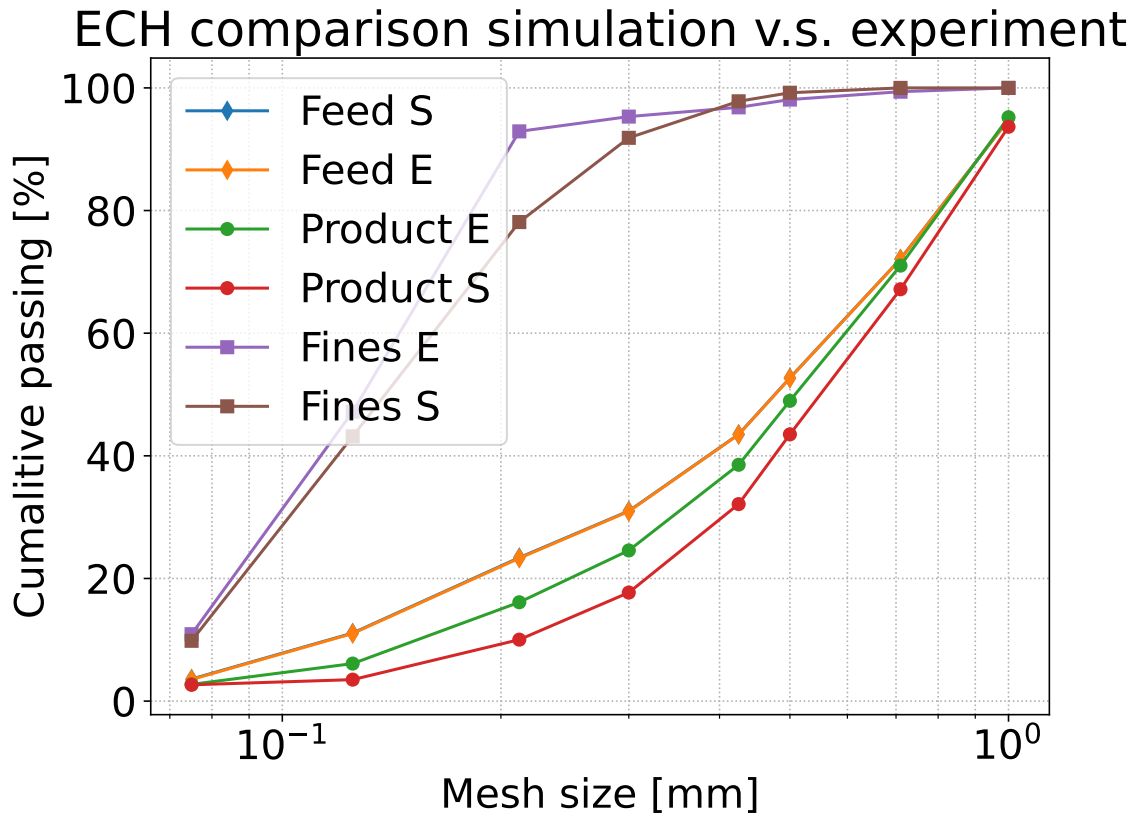


Figure 10.4: Comparison ECH Simulation (S) and Experiments (E)
Feed S is plotted, however directly under Feed E, This shows that experimental and simulation input is identical.

Table 10.1: Comparison of the measured fines and product rate for the simulation and experiment.

test	ECH (SIM)	ECH (EXP) (error)
$\dot{m}_f$	1 [g/s]	5 ± 0.2 [g/s]
$\dot{m}_P$	32 [g/s]	34 ± 0.2 [g/s]

10.2. WCH simulation

In the WCH simulation, the vanes are placed almost directly in the particle stream. The excluded black zones figure 9.2 b) indicated the walls in the mesh. These zones can also be seen in white, in figure 10.5. The visualisation in figure 10.5 shows that the particles are mainly kept to the right of the walls. This closely resembles the experiments and shows a large difference with the ECH simulation. This can be attributed to the vanes inside the chamber.

The WCH simulations posed severe simulation instabilities issues. Simplifications had to be made to create a working model, and to keep computational times under control. No longer runs than 0.1 second were conducted for the WCH case. The WCH simulations are presented, but they do not represent quantitatively valid results.

The simulation calculates that the particles are ejected towards the right exit. This does not happen to such severity in the SR experiments. There could be several reasons for the bouncing; these are discussed in subsection 10.2.1.

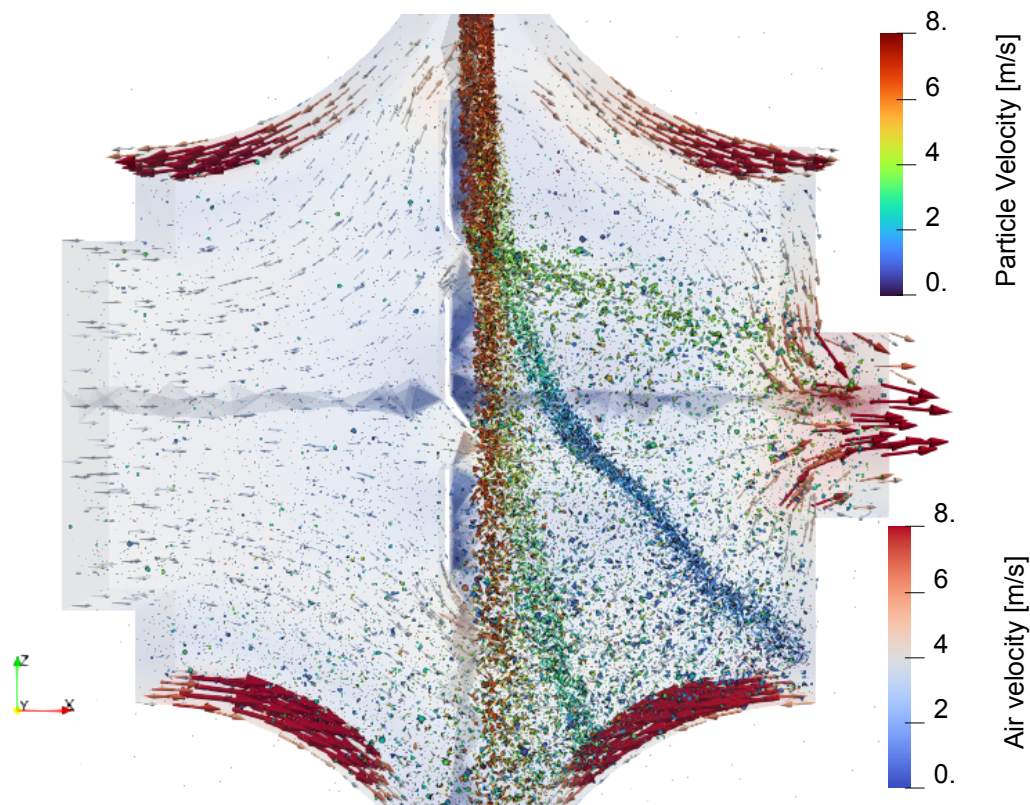


Figure 10.5: WCH simulation results visual

10.2.1. Mass collection and PSD

When reviewing the "sieving" results of the WCH simulation, it is clear that the simulation overestimates the presence of the heavier particles in the fines stream. The experimental results plotted in figure 8.6 show significantly fewer heavy particles in the fines sieving.

In reality, the large particles are not ejected that far out to the right. This simulation error could arise for various reasons: bounce is overestimated, vanes are wrongly placed or air carrying capacity in the horizontal direction is overestimated, among others.

If the bounce is overestimated, too much initial velocity is converted into the horizontal direction. If the walls are wrongly placed, it could be that the real-life experiments also perform worse if the walls are too far in the particle stream. During the experiments, the walls seemed slightly more to the particle stream's left side compared to the simulation. In the experiment, the vanes influence the heavier particles less than in the simulation. This could be a sign that the vanes, as found in the experiments, only have a positive impact

when placed correctly. If the air carrying capacity is overestimated by the simulations, heavier particles could be dragged out. This does not seem the case as this behaviour does not show during the ECH simulations.

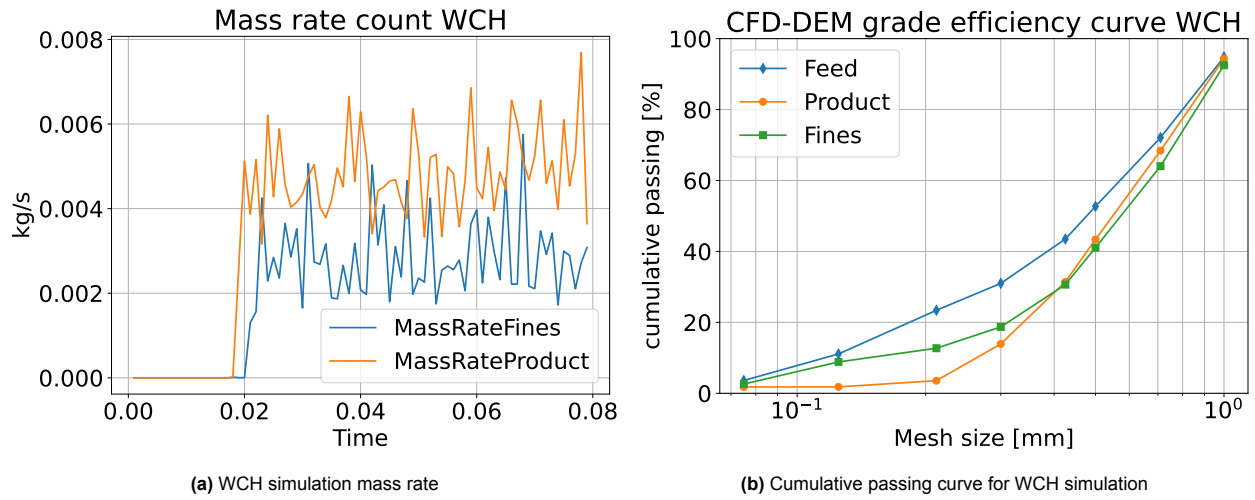


Figure 10.6: WCH results

Table 10.4 shows the percentage of collected fines mass based on the inserted mass. The fines rate of the simulation is too low compared to the experimental results. This is also the case on the product exit. As 5 [g/s] is extracted, it is clear that steady state has not yet been reached. Due to the low fines mass rate, the load capacity is also significantly lower than the experimental values.

Table 10.3: Mass collection specifications product based.

Test	WCH (SIM)	WCH (EXP) (error)
fines collected	37%	21% $\pm$ 0.7% _{pt}
$\dot{m}_f$	2 [g/s]	8 $\pm$ 0.3 [g/s]
$\dot{m}_P$	5 [g/s]	34 $\pm$ 0.2 [g/s]
LC	127 [g/m ³]	472 $\pm$ 15 [g/m ³]

10.3. Recommendations

Due to legacy reasons CFD-DEM simulations were not promptly used for this work. Therefore wasting valuable time. CFD simulations on their own cannot predict the behaviour within the chamber, as the particles, and particle-roller interaction will also influence the airflow in the chamber.

A longer "steady-state" operation could improve the simulation's results; however, this would also considerably increase the simulation time. The simulation execution time was six hours on four cores. Improvements in simulation time could be made when running on a dedicated system High Performance Cluster such as Delft Blue. Earlier work in COMSOL was run on the HPC Delft Blue; significant computation time improvements could be obtained in those simulations. Due to time constraints, this was impossible for the CFD-DEM coupled simulations.

The modelled area is a simplified geometry. To ease the constraints on the CFD solver the narrowing towards the roller gap was widened (see ECH mesh), therefore excluding a part of the rollers. This narrow part on the bottom rollers could cause the lack of coarse particles in the fines stream as found in the experimental results. The heavier particles now leave the domain directly through the bottom plane, as the air force does not have strength to move the particles towards the rollers where they could be bounced off, as happens in the experiments.

Furthermore, the particle extraction quality is one of the most important factors to consider. Considering the simulated fines rate presented in table 10.2 it is clear that there is a large difference between the experimental fines mass rate and the simulated fines mass rate.

A start was made to perform a mesh independence study (MIS) for the CFD part of the model. Due time constraints this is not be completed on time. In the appendix B the used meshes for the MIS can be found, together with preliminary results on the performance of the different meshes. The preliminary results show an large difference between the Coarse and Fine mesh. After modelling the MMF mesh, it was found that the model wasn't heavily mesh dependent, but random induced behaviour of the particles depending on the DEM timestep was found to contribute largely to the end result. Future simulations could opt for a stiffer coupling better predicting the force balance for newly injected particles. The MMC case

Future work can proceed with the coupled CFD-DEM based simulations as these include the most important physics. In the future Beetstra drag model could turn out to give better results when the particle feedrate is increased, as it is desirable to operate with a higher particle feed than currently tested. Potential optimisation of computational time could be achieved when the smaller particles (sub $100\mu m$) are modelled as an injection of an immiscible fluid using Two-Fluid Model (TFM) modelling. Combining the CFD-DEM and TFM models to get the influence of larger particles but improving computation time because the sub 125-micron particles are simplified as a continuum. This reduces the information the model can yield, as it will no longer be possible to measure the PSD of the continuum (as it is now a continuum) and no individual particles. A comparative method could be developed for this.

11

Conclusion

Experimental setup This report has established a possible path for research & development to improve industrial-scale fines extraction. It is established that simulating and testing the separation efficiency on the industrial mill is challenging. To simplify the behaviour in the industrial mill and subsequent air rig, a subsection of an air chamber was built. The Slice Rig (SR) chamber represents an air chamber with two roller sets. The slice rig was designed for flow and particle visualisation, and mass measurements over the air chamber. The open structure of the air rig significantly increased the understanding of the particle and flow behaviour in the slice rig. These practical tests on the SR have proved indispensable knowledge on the validity of various simulations. Furthermore, the SR tests give more insight into behaviour qualitatively observed in the novel mill.

In-chamber geometries

Air flow properties as volumetric flow rate and pressure drop were measured before the experiment. During the experiments the airflow was measured to be $0.017 [m^3/s]$ with an pressure drop of $-47 [Pa]$. Separation quality and collection efficiency were improved by the placement of vanes inside the chamber domain. Vanes in the air chamber guide and increase air velocity close to the particle stream. As a result the separation ability of the air flow was improved. PIV was used to measure the average particle velocity. The implementation of vanes improved the particle loading from $262 [g/m^3]$ to $472 [g/m^3]$. The grade of particle separation in the 125 and 75 micron mesh size improved with 23% and 114% respectively. $\eta_{d_p < 125 \mu m}$ was improved from 39% to 48%.

Energy consumption

These values are used to calculate the energy consumption of the ECH and WCH case. The energy consumption for fines extraction in the slice rig was reduced from $0.11 [kWh/ton]$ to $0.06 [kWh/ton]$ upto the exit of the air chamber. This is a reduction of approximately 50%. By increasing the loading capacity of the air flow, the specific energy consumption was lowered. The increased loading capacity of the airflow, achieved in the air chamber, will improve energy consumption in the whole fines extraction process.

Simulation Modelling the SR experiments with open-source CFD-DEM was initiated. The simulations could give a partial prediction of the particle behaviour within the chamber. The visual qualitative comparison was positive; the CFD-DEM visualisation overlapped relatively well with the visualised slice rig experiments. Quantitative comparison was obtained by comparing the mass balances of the simulations with the experiments. Comparing the fines rate between experiment and simulation yielded large differences, these can be found in table 10.4 and 10.2. The fines rate prediction is more than 100% off and, therefore, not valid. The velocities predicted by the CFD-DEM software are on the high side of what may be expected based on the PIV measurements (plus 20%). This could be explained by the averaging effect of the PIV algorithm.

11.1. Future research

The slice rig has proven to be a very useful test setup to visualize and quickly test various setups. It would be advisable that a thorough comparison between larger test setup such as an (air tight) Air rig would be done to verify the simplifications in the SR are valid. With large mass rates, the Beetstra drag model could give more reliable results in the CFD-DEM model with higher feed rates.

Future research could also focus on:

1. Validate the experimental results of the slice rig to the air rig. Incorporate 3D behaviour and more losses to review the impact versus idealised air rig performance.
2. Improve time dependent air flow measurements to increase differentiability between various setups.
3. Experiments including precise moisture measurements and varying moisture percentages to investigate influence of moisture and agglomeration on the separation performance and energy consumption.
4. Further adjust and try to optimise airflow and particle stream by including more vanes/positioning.
5. Simulated particle velocities could be averaged to obtain better comparable results with respect to the experimental PIV results.
6. Validation and verification of particle velocity of the simulation for single particle species.
7. Validation and verification of higher feed rates to approach desired operating conditions and review the influence of higher particle loading to investigate the validity of the Schiller-Naumann drag model and/or Beetstra drag model.

Focus should be on matching equivalent volumetric flow and feed rate which could be used to verify the fines rate, loading capacity and collection efficiency between various experimental setups and the simulations.

The simulations could yield very useful results in the future when simulated time can be increased passed the unsteady start up phase. If the CFD-DEM model could predict the behaviour of the SR, less experiments are needed and iterations and more varying particle distributions can be tested automatically. This could be extremely useful when scaling from the SR to industrial size.

Acknowledgement

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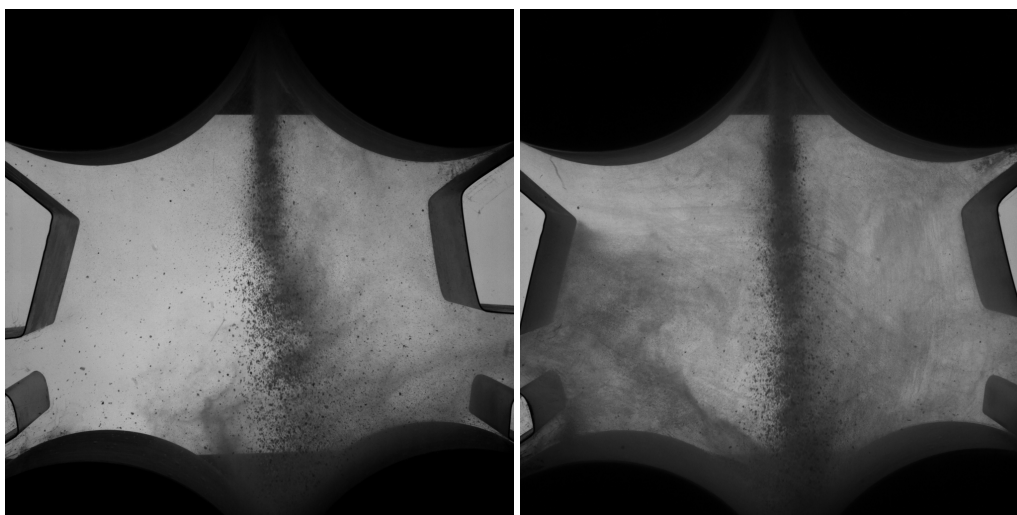
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A

Additional experimental results

Table A.1: ECH versus WCH performance

	ECH-1	ECH-2	WCH-1	WCH-2	Units
feed	435.9	237.0	410.3	415.9	g
product	383.2	210.5	321.5	331.5	g
finest	32.7	21.0	74.6	73.6	g
missing	20	5.5	14.2	10.8	g
error missing mass	4.6	2.3	3.5	2.6	%
time	11	6	11	11	s
finest rate	5	4	8	8	g/s
load capacity	272	252	487	457	g/m ³



(a) side walls layout 1

(b) side walls layout 1 symmetric extraction

Figure A.1: Various tested layouts

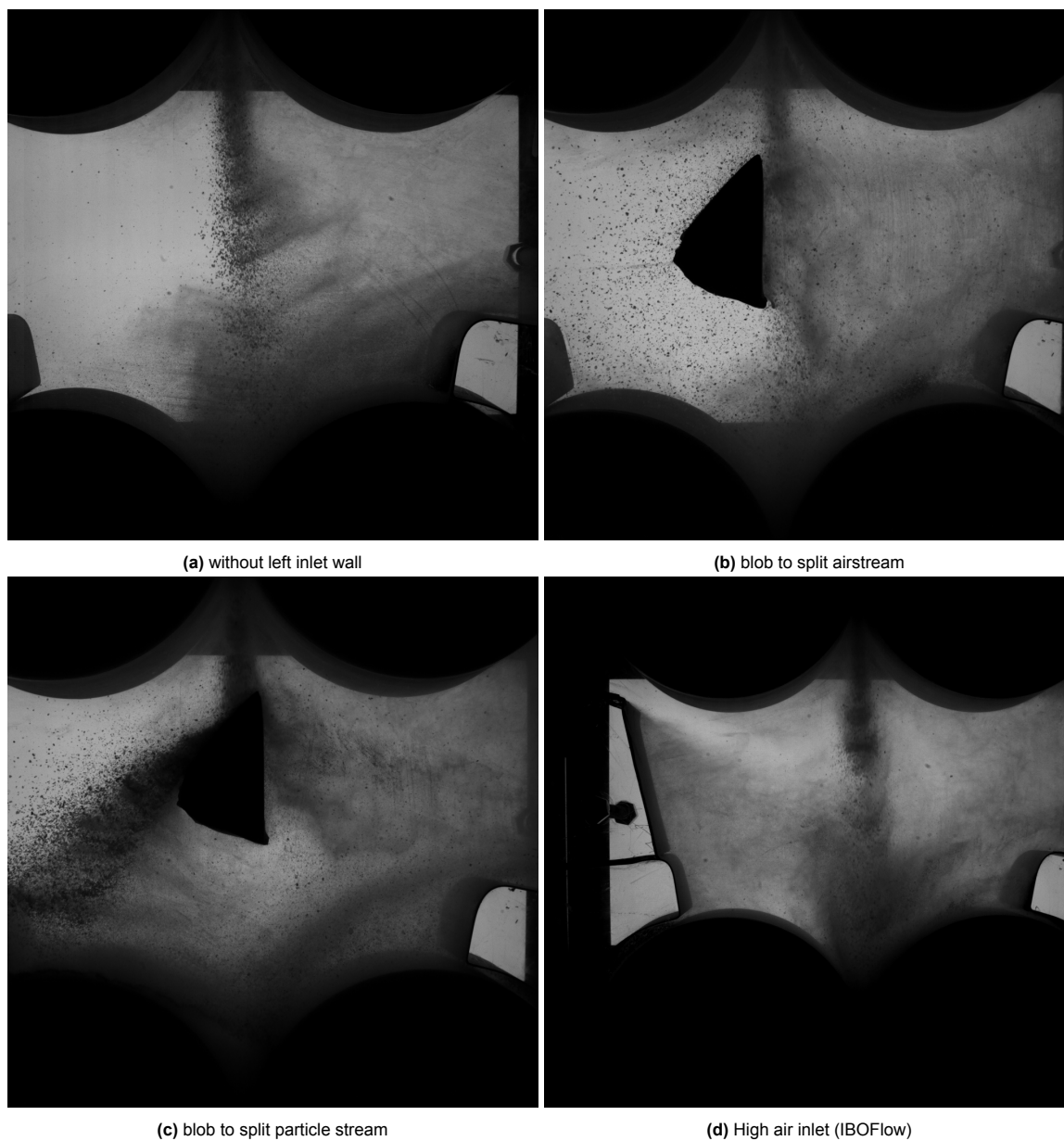


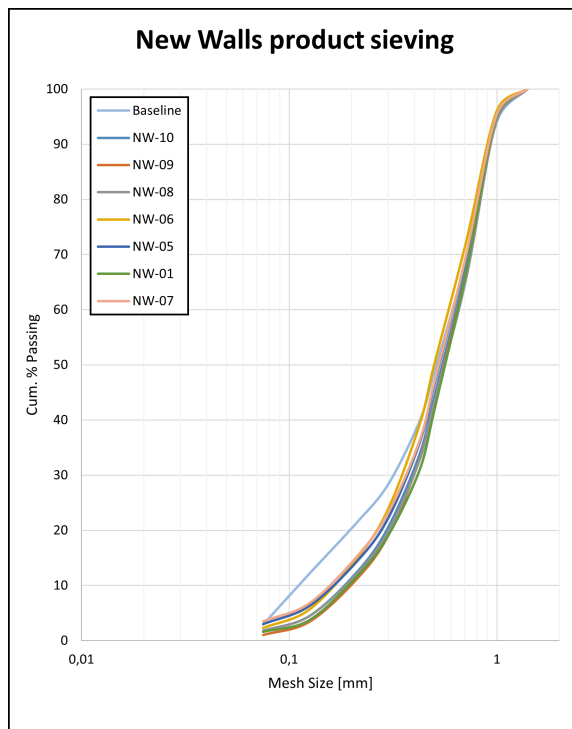
Figure A.2: Various tested layouts

A.1. Sieving result earlier experiments

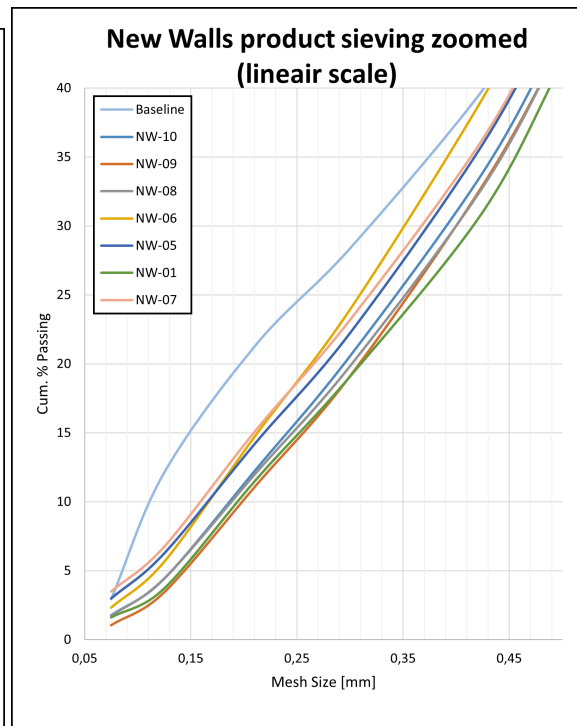
The following data is given for various cases, however the samples were not equally split, therefore these test were only used to guide which experiments should be repeated with high accuracy. Description is given by sieving results in table A.3.

NW-10	subversion of WCH case with vertical wall, not shown
NW-09	subversion of WCH case with roller covering wall, not shown
NW-08	WCH
NW-06	WCH with higher open inlet
NW-05	blob splitting particle stream A.2 c)
NW-01	ECH case
NW-07	high inlet shown in figure A.2 d)

Table A.3: description on sieving results ASYM figures A.3a and A.3b



(a) Various sieved cases of ASYM test series



(b) Various sieved cases zoomed of ASYM test series. Please note the Linear X-axis

A.2. Single particle size experiments

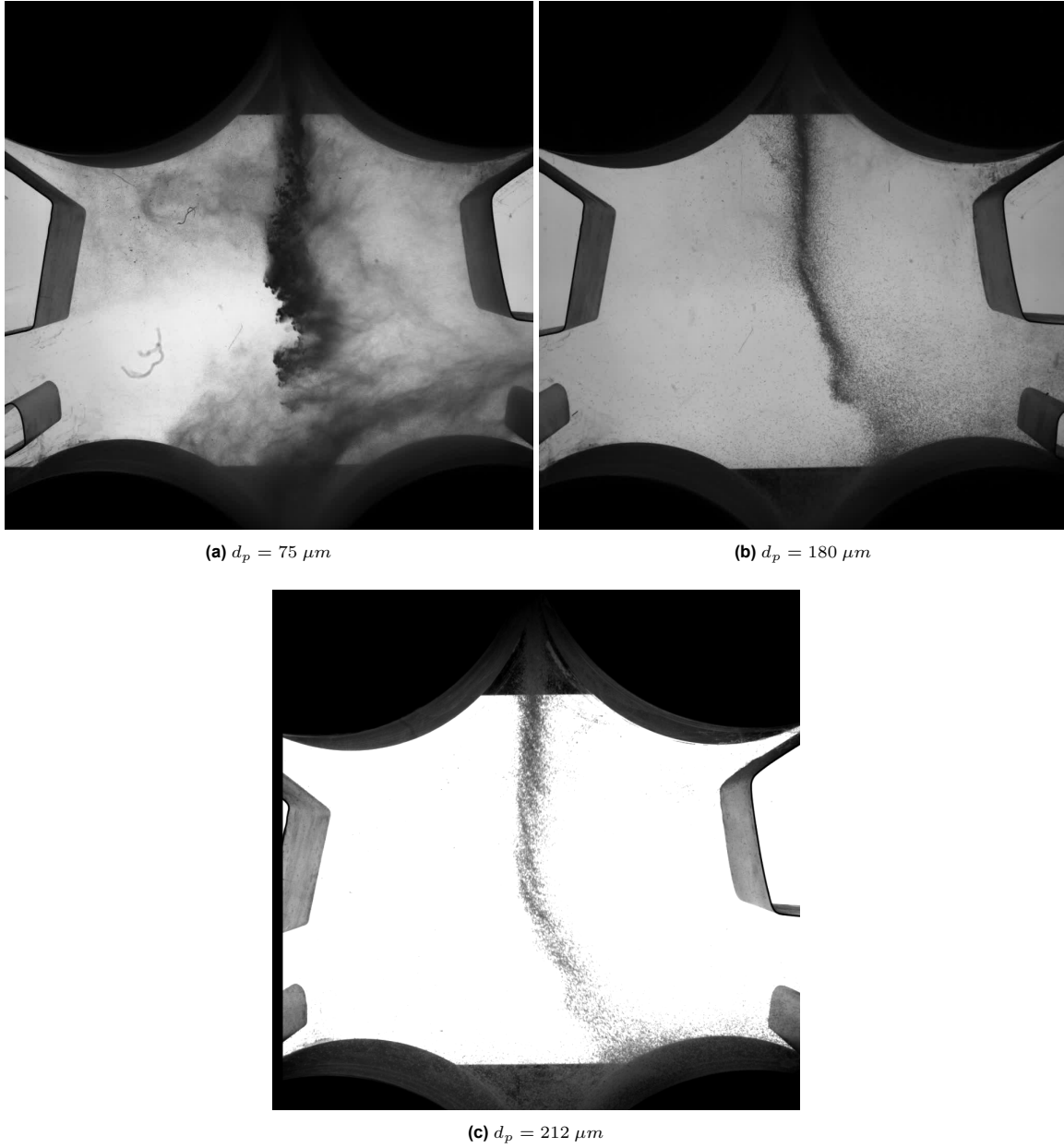


Figure A.4: Single diameter particle experiments

B

Mesh independence study

A start was made to perform Mesh Independence Study. The following meshes and corresponding results have been obtained.

B.1. Validation

A validation is performed for 4 different kind of meshes. From coarse to finer: Coarse (CM), Moderate (MM), Moderate Coarse (MMC), Moderate Fine (MMF) and Fine mesh (FM).

	CM	MM	MMC	MMF	FM
Number of cells [k]	2	7	20	54	268
dT DEM	5e-6	5e-6	multiple	2e-6	2e-6
dT CFD	2.5e-4	2.5e-4	multiple	1e-4	1e-4
coupling interval	50	50	multiple	50	50

Table B.1: Mesh independence study information ECH

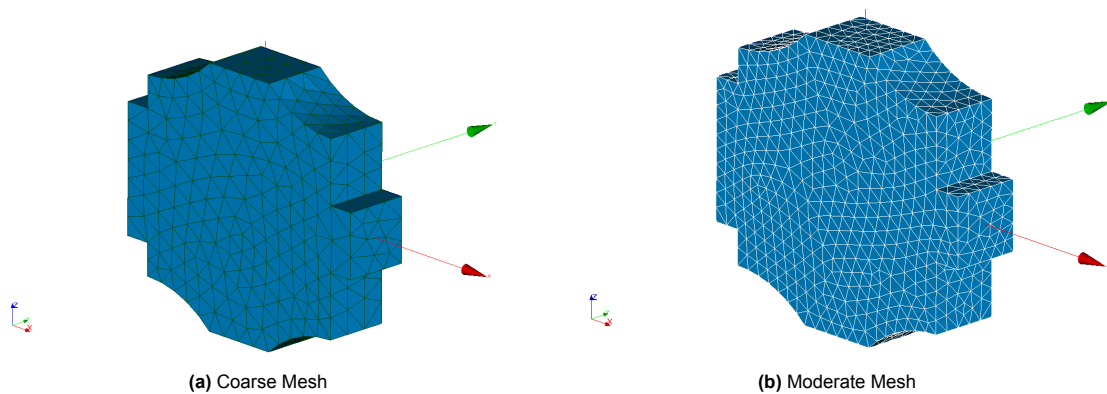


Figure B.1: screenshots of Mesh dependent study

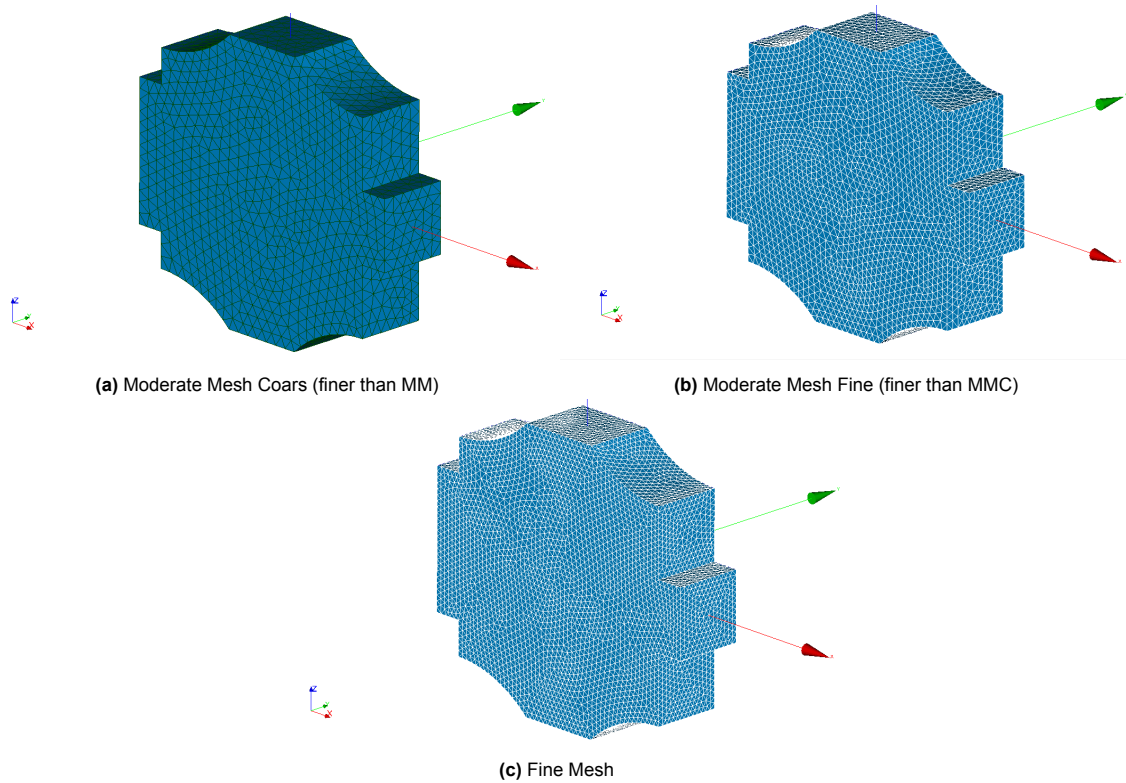


Figure B.2: screenshots of Mesh dependent study

B.2. Convergence

All simulations discussed earlier converged. For some simulations the Courant number became stable, others seemed to keep an increasing Courant number (with finer mesh sizes) this is due to the build up of particles into the chamber.

The residuals for the CM are given below. Figures B.3 presents the velocity residuals in the different axis for the flow field. Figure B.4 displays the Courant number, which presents the stability of the CFD-DEM interaction. Figure B.5 shows the pressure field solver. The pressure residual has been approximated by the orange line, the blue line shows the convergence of the pressure field, the solver iterated for the final residual 10^{-6} . Similar convergence and behaviour was also found for the other meshes.

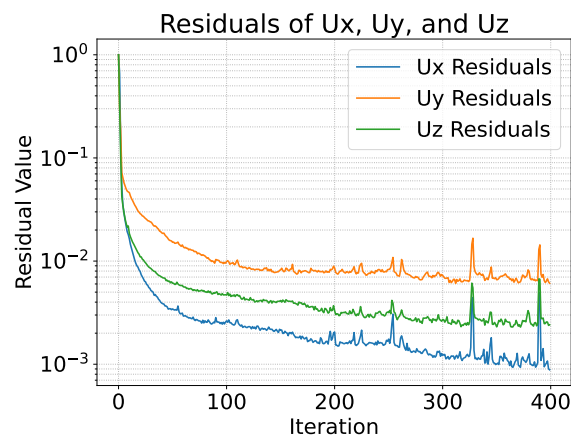
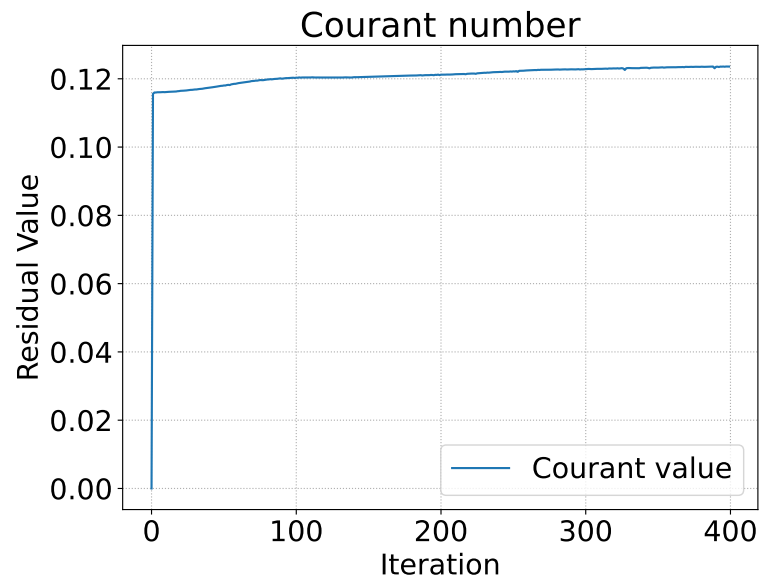
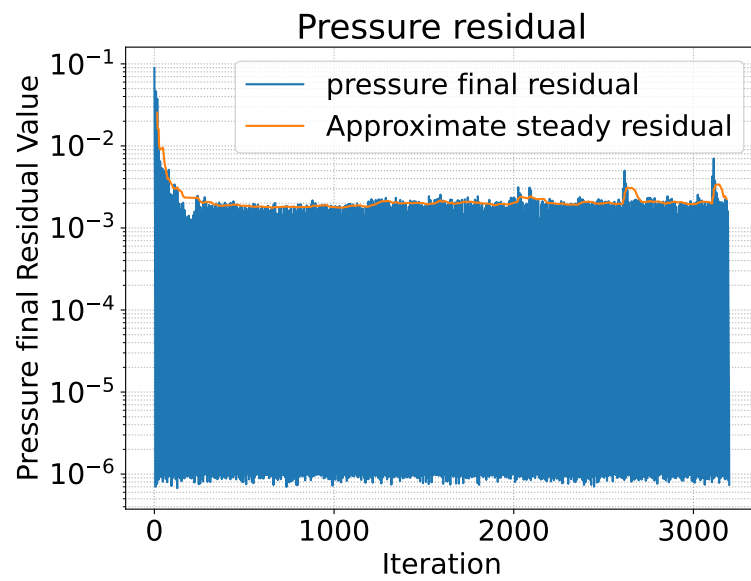


Figure B.3: Velocity residuals CM

The courant number is shown in B.4

**Figure B.4:** Courant number CM

Pressure residuals are shown in figure B.5

**Figure B.5:** Pressure residuals CM

B.3. Preliminary results

Based on the preliminary result a mesh dependence for the solution is found. It was later found that this is also influenced (strongly) by time step. Therefore the MMC mesh was run with various time step settings. Stiffer coupling (lower coupling interval) was seemed to show earlier separation (higher in the chamber).

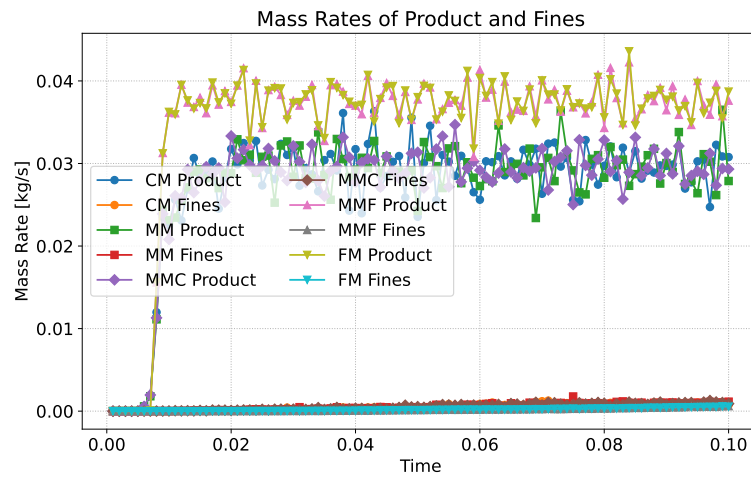


Figure B.6: Mass rate dependent on various meshes for fines (f) and product (p).

Mass collection displayed in figure B.7

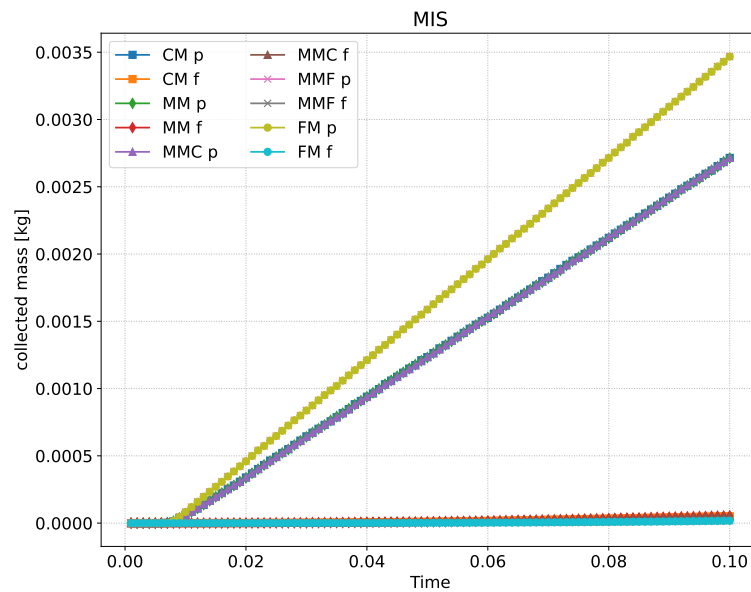


Figure B.7: Collected mass dependent on various meshes for fines (f) and product (p).

PSD mesh dependence study in figure B.8

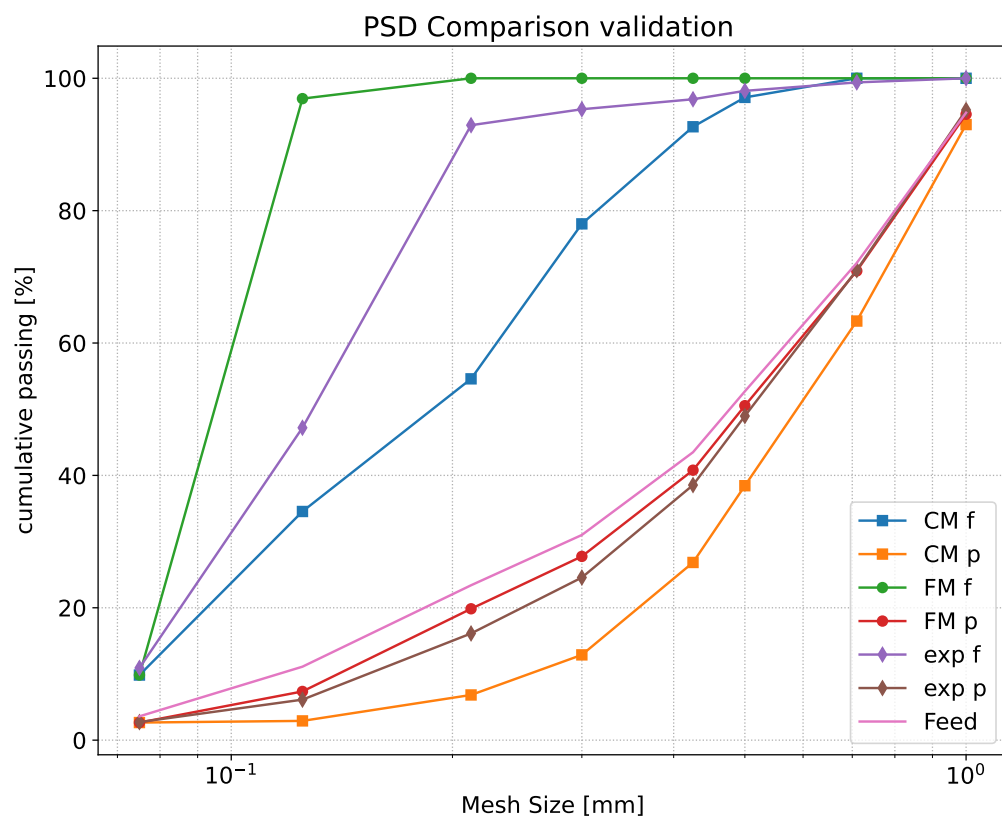
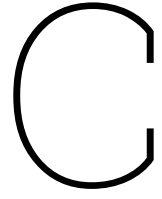


Figure B.8: Sieve results of CM and FM validated against the experimental sieving results. NOTE: Mesh size presented on the X-axis is the particle mesh size, corresponding to the experiments.



Extra Calculation

C.1. Buoyancy force

In a stationary situation, two forces will be dominant. These are the buoyancy force and the gravity force.

$$F_{buoyancy} = \rho_f V_p g \approx 10^{-11} [N] \quad (C.1)$$

$$F_{gravity} = m_p g \approx 10^{-8} [N] \quad (C.2)$$

These two formula's define the effective weight of a particle:

$$F_e = \frac{4}{3} \pi a^3 g (\rho_p - \rho_f) \quad (C.3)$$

As the density of air is smaller than the density of the particle ($\rho_r \ll \rho_f$), the buoyancy force in air is negligible in comparison with the gravity force.

C.1.1. Unsteady forces

In a stationary fluid, the particle will start falling towards earth. Considering a denser fluid, for example water, this buoyancy force will be a factor 1000 larger. This increase the ratio between weight and the buoyancy from $\approx 0,05\%$ to $\approx 37,04\%$. This will therefor significantly change the stationary and dynamic behaviour of the particle in water and makes testing in a water set-up impossible. This result is important if we would like to scale the experiments to a smaller test setup with water. The buoyancy force on the particle will be neglected when air is used as the working fluid.

The force effectively changes:

$$F = ma \quad (C.4)$$

To

$$F = (m + m_{vm})a \quad (C.5)$$

The added mass of a sphere is given by equation C.6 [17]

$$m_{vm} = \frac{2}{3} \pi \rho_f r^3 \quad (C.6)$$

Equation C.6 heavily depends on the displaced volume and the acceleration. However as the density of the surrounding fluid is very small the virtual mass will be negligible with respect to the normal inertia of the particle.