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Scrubbing Theory, and Concept Evaluation and Flow Simulation of One-inlet Cyclone for Clean Marine AS

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Mechanics and Process Technology

Foreword

This is a Master's thesis written for the Department of Mathematical Science and Technology at the University of Life Sciences (NMBU), and is done in collaboration with Clean Marine, a scrubber vendor for the shipping industry. I have been working for Clean Marine as a design engineer, which led to the opportunity to write my dissertation for them.

Scrubbing systems for the shipping sector is a growing business due to recent regulation changes, and is therefore, in my personal opinion, an interesting subject for a Master's thesis.

A great thanks is due to my advisor, Associate Professor Odd-Ivar Lekang. Odd-Ivar has shown a genuine interest for my thesis and has been very helpful with advises along the way. His expertise in aquaculture has been especially helpful, and I want to thank him for all his help regarding this work.

Clean Marine's CEO Nils Høy-Petersen and CTO Ivar Johan Ervik gave me the opportunity to write for them, which I'm grateful. I hope they will keep on the good work for Clean Marine, and that the company will continue to grow the next years to come.

Svein Ole Strømmen, M.Sc., has worked with scrubbing systems for many years and has great insight in this regard. Thank you, Svein, for helping me understand the chemical aspect of scrubbing.

Acona's Senior Advisor, Marit Kleven, PhD, has been helping me with issues regarding computational fluid dynamics, and have consistently been answering my many questions by e-mail. She gives valuable, thought-out answers, and she presents a great knowledge of the complexity that is CFD. Thank you for your help.

I hope this dissertation will prove useful for Clean Marine, and any other interested parties.

Oslo, May 15th, 2017

Olav Andreas Kaasa Hammer

Abstract

The purpose of this study is to investigate the effects which can occur if Clean Marine changes their cyclone design to have one inlet instead of two. The reason for this is that Clean Marine consider changing their scrubber layout due to concerns regarding its size and footprint. Different cyclone concepts have been evaluated, and one was chosen for further investigation. CFD (Computational Fluid Dynamics) has been used to assist in analyzing the new cyclone suggestion, and comparing it with the current two-inlet cyclone design.

Scrubbing theory and techniques with regards to cleaning of SO_2 and exhaust particles is accounted for in this thesis. Understanding the processes of scrubbing is necessary to be able to evaluate the cyclone concepts and the CFD analysis. Scrubbers installed on ships are under regulation of emissions of sulphur dioxide, but emissions of particulates are also reduced when scrubbing the exhaust.

The different cyclone concept ideas was presented by Clean Marine. The concepts has been visualized and described, and been weighed against each other using an objective decision matrix, before choosing one for further analysis.

The cyclone named *Regular one-inlet cyclone* was chosen for CFD analysis. Clean Marine wanted to see if there would be any notable changes when using different width and height ratio on the inlets on the chosen concept. Three different inlets was therefore used for the CFD analysis. The turbulence model used for analysis was the Reynolds Stress Model, and the results shows that there is no indication of difference between those three inlets. The results does, however, show a difference between the one-inlet cyclone and the two-inlet cyclone. The one-inlet cyclone has somewhat lower vertical velocities and a lower pressure drop. It is concluded that this does not affect the performance of the cyclone.

For further research it is suggested that Clean Marine does 2D flow simulation on the upper part of the cyclone house with the accelerator, which is an internal part of the cyclone provided by a sub-supplier. The accelerator was not included in the CFD analysis in this thesis.

Sammendrag

Formålet med denne studien er å undersøke effektene som kan oppstå hvis Clean Marine velger å endre sitt syklondesign til å ha ett innløp istedenfor to. Bakgrunnen for dette er at Clean Marine vurderer å endre scrubber-designet deres med et ønske om å utnytte tilgjengelig plass på skipet mer effektivt. Ulike syklonkonsepter har blitt evaluert, hvorav én ble valgt for videre analyse med hjelp av CFD (Computational Fluid Dynamics). Simuleringsresulatene har blitt sammenlignet med en syklon med to innløp.

Scrubbingteori og -teknikker, med hensyn til rensing av SO_2 og partikler, er redegjort for i oppgaven—dette er for å kunne evaluere de ulike syklonkonseptene og CFD-resultatene. Det er SO_2-utslipp som blir regulert på skip, men våt-scrubbere reduserer også utslipp av eksospartikler.

Endring av syklondesignet er en del av en helhetlig endring Clean Marine ønsker å gjøre til scrubberen deres. Disse endringene er beskrevet i oppgaven. De ulike syklonkonsept-idéene ble presentert av Clean Marine. Konseptene er visualisert, beskrevet, og veiet opp mot hverandre med bruk av Pughs seleksjonsmatrise.

Syklonen med navnet *Regular One-inlet Cyclone* ble valgt for videre analyse med CFD. Clean Marine ønsket å se om bruk av innløp med forskjellige høyde- og breddeforhold av valgt konsept har en påvirkning på funksjonen til syklonen. Det ble derfor gjort tre forskjellige versjoner av syklonen for CFD-analysen. Valgt turbulensmodell ble RSM (Reynolds Stress Model), resultatene viser ingen indikasjon til forskjell mellom de tre ulike innløpene. Resulatene viser imdlertid forskjeller mellom syklon med ett inløp og syklon med to innløp. Syklonen med ett innløp har noe lavere vertikale hastigheter og har lavere trykkfall. Det konkluderes med at dette ikke påvirker funksjonen til syklonen.

For videre arbeid foreslås det at Clean Marine utfører en 2D-simulering på syklonhuset med "akseleratoren", som er en intern del i syklonen som fabrikkeres av en underleverandør. Akseleratoren er ikke inkludert i den utførte CFD-analysen.

List of Abbreviations and Symbols

Abbreviation	**Description**
AAB	Ambient Air Pollution
CFD	Compututional Fluid Dynamics
CM	Clean Marine
DES	Detached Eddy Simulation
ECA	Emission Control Area (sea ares with regulated emissions)
EGCS	Exhaust Gas Cleaning System
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LES	Large Eddy Simulation
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NMBU	Norges miljø- og biovitenskapelige universitet (Norwegian University of Life Sciences)
NTU	Nephlometric turbidity units
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
R&D	Research and Development
RANS	Reynolds-averaged Navier-Stokes
RNG	Re-Normalization Group
RSM	Reynolds Stress Model
SST	Shear-Stress Transport
WHO	World Health Organization
H^+	Hydrogen ion
H_2O	Water
H_2SO_4	Sulfuric acid

HSO_3^-	Bisulfite ion
Na^+	Sodium ion
NaOH	Sodium hydroxide
NOx	Nitrogen oxides
O_2	Oxygen
OH^-	Hydroxide
SO_2	Sulphur dioxide
SO_3^{2-}	Sulfite ion

Symbols	**Description**	**Unit**
A	Area	m^2
D_h	Hydraulic diameter	m
H	Henry's constant	atm/(mol fraction)
h	Height	m
l	Characteristic length	m
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
ν	Kinematic viscosity	m^2/s
P	Pressure	Pa
P_β	Partial pressure of gas	atm
ρ	Density	kg/m^3
Q	Volumetric flow rate	m^3/s
R	Ideal gas constant	$Pa \cdot kg^{-1} \cdot K^{-1}$
Re	Reynolds number	-
T	Temperature	K
V	Volume	m^3
v	Velocity	m/s
w	Width	m
X_β	Concentration of gas in water	mol gas/(mol gas + mol water)

List of Terms

Adsorption	Process of holding molecules as thin film on the surface of a material, like particles on the surface of water.
Affinity	The degree to which a substance combines with another substance.
Alkaline	Adjective to describe a basic solution.
Carbon fixation	Process of conversion from carbon dioxide to organic compounds (eg. photosynthesis).
Caustic soda	Term used for sodium hydroxide.
Damper	A valve that stops or regulates air flow.
Dry-docking	The process of bringing a ship to dry land by pumping or draining water from a flooded basin.
Eddy	An eddy is the swirling of a fluid.
Flue gas	Gas that exits to the atmosphere via a flue (e.g. pipe, channel). Often refered to as combustion exhaust gas.
Funnel	Metal chimney on a ship.
Handymax bulk carrier	A ship transporting unpackaged cargo that can carry between 40 000 and 50 000 tons of cargo.
Hygroscopic	Tending to absorb moisture from air.
Involute inlet	An inlet that is spirally curved.
Isosurface	A 3-dimensional surface that represents points of constant value.
Packed bed scrubbing	Scrubbing technique that uses packing material to improve contact between the gas and liquid.
Panamax tanker	A tanker that is size limited to be capable of travelling through the lock chambers of Panama Canal.
pH	Potential of hydrogen, a numerical scale to specify acidity or basicity.
Residual	The "error" in a result. A lower residual value means a more accurate solution.
Retrofit	Adding new equipment to existing/old systems.
Salinity	Measure of dissolved salt in water.

Scrubber	A device or equipment that is used to clean unwanted pollution from exhaust emissions.
Scrubbing	The process of cleaning exhaust.
Sea trial	The testing phase of a newly built ship.
Sludge	A muddy mass. Usually a precipitation of solids from a water treatment process.
Spray nozzle scrubber	Scrubbing technique that uses spray nozzles to clean the exhaust.
Surface tension	The elastic tendency of a fluid surface that cause adhesive forces which can create attraction between a liquid and a solid.
Tetrahedral cells	Cells with four faces, also known as "triangular pyramid".
Vortex finder	The inlet of the axial inner pipe of a cyclone.
Washwater	Discharge water from the scrubber with extracted pollutants.

Contents

Chapter 1

Introduction

This master's thesis is written in cooperation with Clean Marine, a scrubber supplier for the shipping industry. Clean Marine was founded in 2006, and in 2009, a test scrubber was built on a panamax tanker named *Baru*. In 2011, a full-scale scrubber was installed on a handymax bulk carrier, *Balder*, that became certified in 2013 [1].

Clean Marine's current scrubber design is an all-in-one unit, which makes it difficult to install in small funnels. They are therefore considering modularizing the system, creating individual components that can be installed independently of each other on the ship according to the layout of the funnel, this scrubber system is hereby referred to as *The Flex System*. With this change, design and process challenges emerges, which is the basis of this thesis. The details of the scope of the thesis is described in section 1.4.

1.1 Background

This sub-chapter will go into detail of the emissions from the shipping industry and the effect it has on human health and surroundings, which is the reasoning behind the usage of scrubbers.

1.1.1 Health and Environmental Impact due to Air Pollution

According to a WHO report, there are about 2.9 million deaths worldwide attributed to ambient air pollution (AAP), where South-East Asia and low- and middle-income countries in the Western Pacific is the most exposed regions—accounting for about 1.9 million deaths [2].

Ambient air pollution is a generic term for mixtures of air pollutants. The fine particulate matter, which is sum of solids and liquids in air that are smaller than 2.5 µm, are the most hazardous to human health. Most fine particulate matter ($PM_{2.5}$) are produced through fuel combustion, which is dominated by the energy and transportation sector [3].

Acid rain, which main anthropological sources are from NO_x and SO_2 emissions, can be a serious environmental issue, as it can damage soil, forest trees, crop plants, human health and more. Some of the ecological and health issues it can cause, are: [4]

- Nutrient deficiency in soil, which will decrease the growth of plants and trees.
- CO_2 fixation reduction in crop plants.
- Human health issues: breathing difficulty; eye and skin irritation; consumption of heavy metals that are liberated from soil due to acidification, that can cause various health problems.

- Acidic streams and lakes, causing increased mortality in fish and amphibians (eg. toads, frogs).
- Damage to buildings materials with large amounts of carbonate and tall buildings made of concrete.

Figure 1-1 illustrates how the sulphur dioxides emissions from the energy and shipping sector affects the environment. The sulphur dioxides reacts with water and forms sulfuric acid (H_2SO_4):[5]

$$SO_2(g) \xrightarrow{O_2} SO_3(g) \xrightarrow{H_2O} H_2SO_4 \tag{1.1}$$

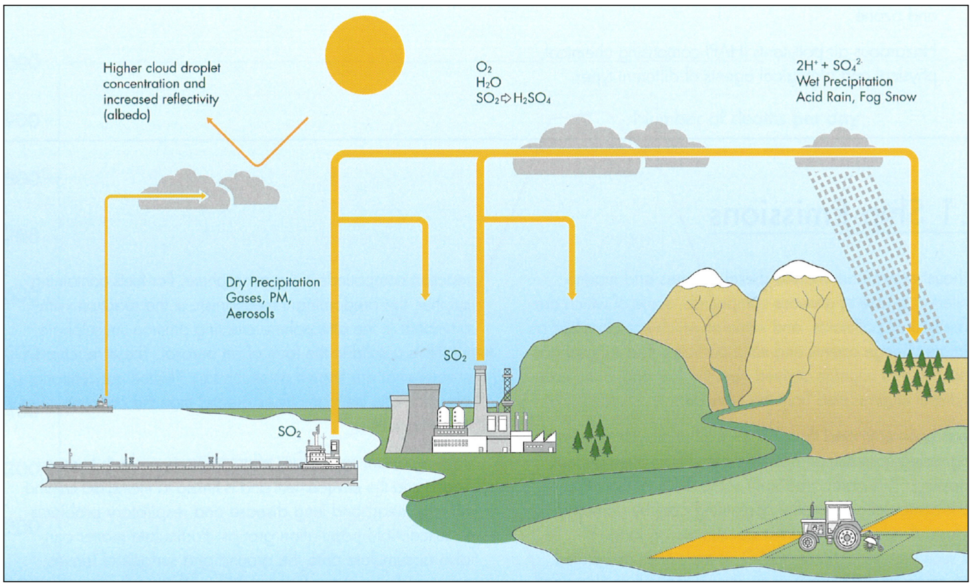

Figure 1-1. Illustration of sulphur dioxide emissions and how it effects the environment.[6]

The sulphur emissions travels with the wind and will eventually be converted to acids in the form of rain, snow, fog or sleet, which can cause the pre-mentioned ecological and health issues.

1.1.2 Exhaust Emissions in the Shipping Industry

Global emissions from shipping are indicated to be 2-3% CO_2, 10-15% NO_x and 4-9% SO_2 of the total anthropological emissions, and in certain coastal areas, the contribution of acidification can be in the range 10-50%[7,8]. The main focus is to reduce the sulphur emissions, as reduction of acid rain is the main priority to the International Maritime Organization (IMO), though scrubbing the exhaust will lead to some reduction of NO_x, CO_2 and particle emissions as well.

IMO, the International Maritime Organization, has currently an emission cap of sulphur in ECA-regions of 0.1%. They also announced in the fall of 2016, that from 2020, there will be a global sulphur emission cap of 0.5%[9].

The reason for the high sulphur emission from ships is the widely use of HFO (Heavy Fuel Oil), which maximum content of sulphur is 3.5%[10], and according to IMO, the average sulphur content of residual fuels (HFO) used in shipping is 2.45%[11]. For comparison, the current sulphur content used in diesel cars in the EU, does not exceed 0.001% (according to standard EN 590).

1.2 Use of Scrubber Technology

For ship owners to comply with IMOs regulations, they can either change to fuel with low contents of sulphur or they can install a scrubber and continue to burn HFO while cleaning the sulphur from the exhaust. Low sulphur fuel is more expensive and scrubber vendors claim that, in the long run, ship owners will benefit from purchasing a scrubber and that the payback time is about 1-3 years[12]. There are also concerns that in 2020 there will be a shortage of low sulphur fuel (MDO/MGO), but there is not a consensus to this statement[13].

Installing a scrubber system requires dry-docking of the ship, which is an extra expense and downtime of the usage of the ship, resulting in further loss of income. Scrubber systems also requires a large amount of physical space in the funnels and installations can often be a challenge, especially on retrofits.

1.3 Waste Treatment of Washwater

What is done with the washwater that is produced by scrubbing the exhaust? It is dumped in the ocean. Although this sounds like a shady business, the environmental impact is minor if it is done according to set restrictions. IMO requests monitoring of[14]:

- pH
- PAH
- turbidity
- temperature

The minimum pH value at the discharge pipe, as required from IMO, is set to 6.5, the pH value in the washwater can be much lower due to acidification from the SO_2, meaning that it has to be diluted with water and/or neutralized with solvents with high basicity, like sodium hydroxide, before it's discharged overboard. If the pH value of the washwater is kept above 6.5, it will not, according to IMO, have an impact on human health or aquatic life[15].

PAH, polycyclic aromatic hydrocarbons, are products of incomplete combustion, PAH is toxic and can have "sub-lethal effects on some aquatic organisms"[15]. The PAHs must therefore be filtered out before disposal of the washwater. The monitoring of PAH is only for phenanthrene, whereas the other 15 US EPA PAHs is not accounted for. It is disputed if the monitoring of phenanthrene alone is sufficient, although IMO claims that phenanthrene is the most prevalent PAH, in a degree that monitoring of other PAHs is not necessary[15,16].

Turbidity, which is the cloudiness of a fluid, is measured by how the light is scattered when it hits the water, the more the light is scattered the more suspended particulates are in it[17]. The meaning of turbidity measurements in an exhaust gas cleaning system is to indicate the amount of particulate matter in the washwater, however, there is not a direct correlation between turbidity and the amount of exhaust particles, meaning that the measurements of particulate matter is figuratively clouded[15]. Maximum continuous turbidity in the washwater is set to 25 NTU according to IMO guidelines[14].

1.3.1 Natural Cycle of Sulphur

The main reservoir for sulphur is in the ocean. The ocean contains about 10^{15} tonnes of sulphur, the amount is really not fathomable, but to understand it better: if you put all the sulphur from the ocean, and distribute it on the surface of all oceans, it would be 1.7 m thick(!). Now if you put all the sulphur from all exploitable fossil fuel resources on top of all the oceans, the surface would be as thick as a piece of paper. It is safe to say that the sulphur content that is discarded in the ocean from a scrubber unit is not harmful to the ecology[18]. This does not mean that the washwater is not harmful. As explained in chapter 1.3, there are harmful contents in the washwater, like PAH, that need to be monitored to ensure safe discarding of washwater.

1.4 Scope of Thesis

One of the changes that the Flex System causes is that the cyclone Clean Marine uses in their scrubber will have one gas inlet instead of two[1]. The objective for this thesis is to evaluate different one-inlet cyclone concepts and to select one for further investigation. The chosen concept will undergo an analysis with the help of computational fluid dynamics to see if the design will have any effect on pressure drop and cleaning efficiency with regard to removal of sulphur dioxide and particles compared with Clean Marine's current cyclone design.

It is important to be familiar with the scrubbing theory and scrubbing technology to be able to analyze and judge the cyclone concept and its CFD results. Therefore, literature study with regards to scrubbing of sulphur dioxide and particles will be an important part of this thesis.

The objective of this thesis can thus be categorized into three parts:

1. Literature study with regards to scrubbing theory.
2. Concept evaluation and selection of one-inlet cyclone.
3. Analysis of chosen cyclone with the use of CFD.

1.4.1 Limitations

A mathematical approach and validation of the flow simulation will not take place in this thesis.

[1] Read about Clean Marine's current scrubber in chapter 2.3 and the Flex System in chapter 3.2.

Chapter 2

Scrubbing

Scrubbing is the process of removing gases and/or particles from exhaust streams. Scrubbing exhaust on power plants has been done in many years, with the intent to remove sulphur dioxide from the gas. The process is usually referred to as FGD, which stands for flue-gas desulfurization [18].

Scrubbing on ships on the other hand, is quite new—in 2012, sulphur content was limited to 0.1% in ECA, which is the Baltic Sea, North Sea, North America, and United States Caribbean Sea area. In 2020, a global sulphur content cap will be set for 0.5%, according to IMO [14,9].

Although the scrubbing systems on ships are technically a FGD system, it is referred to as an exhaust gas cleaning system (EGCS).

There are different ways of scrubbing the exhaust from ship engines. There are wet scrubbers, that can use either fresh water or sea water (or both) to extract pollutants, and there are dry scrubbers, that use adsorption to remove gases—in this thesis the focus will be on wet scrubbing. Wet scrubbing is the method that Clean Marine use and that is virtually the only used scrubbing method in the ship transportation industry [6].

A wet EGCS will in most cases have the three following basic components:

- A scrubbing vessel that mixes exhaust and water with either fresh water or seawater (or both).
- A treatment plant that monitors and, if needed, remove pollutants from the washwater.
- A sludge handling facility that stores sludge that must be disposed ashore.

Figure 2-1 demonstrates the process of scrubbing the exhaust, though bear in mind that this is a simplified overview of a complicated process. Exhaust pipes from the ships engines are connected to the scrubber(s), as the exhaust flow through the unit, seawater is sprayed on the gas which then absorbs the SO_2 and adsorbs particulate matter. Clean exhaust leaves the scrubber and the washwater, if needed, is filtered and then dumped overboard.

Most EGCSs suppliers offers open loop and closed loop systems, and hybrid systems, which is a combination of the two. An open loop system continuously pumps seawater from the ocean to use in their scrubber system, and the washwater is dumped overboard. In a closed loop system, the washwater is filtered and reused in the scrubber, rather than dumping it overboard. Use of closed loop mode can be useful in harbours where washwater discharge is restricted [6].

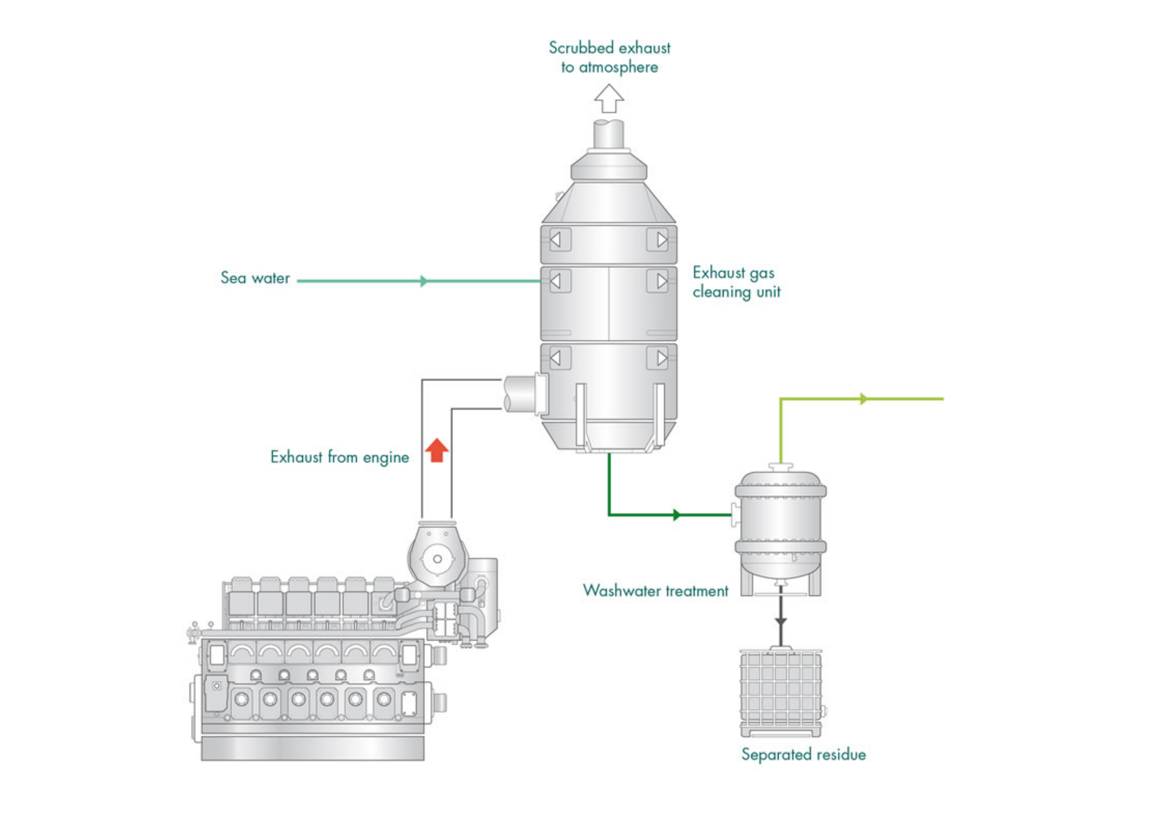

Figure 2-1. Simplified overview of a typical exhaust gas cleaning system[6].

This chapter will go into detail of the process of scrubbing with seawater, and the theory behind scrubbing of gas and particles.

2.1 Gas Absorption

The method behind scrubbing of sulphur dioxide, in a wet scrubber, is to have the gas dissolve in water—the process is called *gas absorption*, not to be confused with adsorption. The amount of SO_2 that dissolves in water depends on its solubility. SO_2 is highly soluble, but the solubility will vary according to factors like temperature, pressure and salinity. The gas will dissolve in water until the water is saturated[19,20,21].

While solids will dissolve more easily in water solutions at higher temperatures, like sugar in a cup of tea, gases dissolves better at lower temperatures. The reason is that the kinetic energy increases with increased temperatures—and with increased kinetic energy, the molecules are more likely to move out of the solution. A similar effect is a shaken coke bottle, when you shake it, you increase the kinetic energy and the carbon dioxide escapes from the solution[21].

As one can see in figure 2-2, the solubility of sulphur dioxide differs drastically with change of temperature. As an example, with a partial pressure of 1 kPa at a temperature of 323 K (50°C), the solubility of SO_2 is approximately 0.7 g/kg water. At a temperature of 273 K (0°C), the solubility is about 5 g/kg water. The temperature of the flue gas on a ship depends on the source, and will have a temperature of minimum 200°C, but can be as high as 400°C. The solubility of the SO_2 will therefore increase when it cools due to heat exchange between the warm exhaust and the cool seawater.

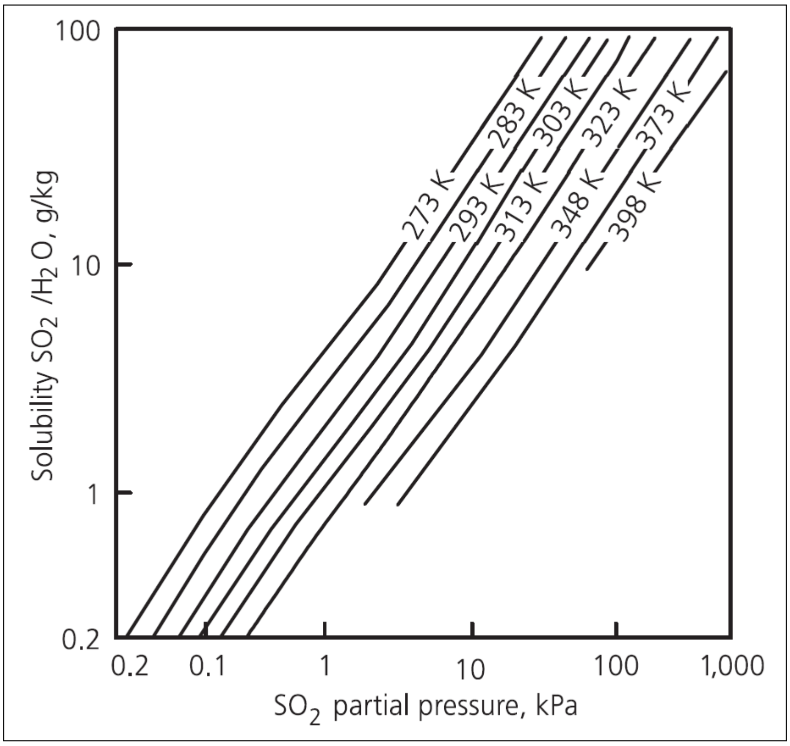

Figure 2-2. Solubility of sulphur dioxide in water with regards to partial pressure and temperature[20].

The efficiency of a wet scrubber, with regards to gas absorption, boils down to maximizing contact time and surface area between the gas and water[22].

Calculating the theoretical amount of SO_2 that can be absorbed, can be done by using Henry's law, which tells us the amount of gas that can be dissolved in water[19].

$$P_\beta = HX_\beta \tag{2.1}$$

where:

P_β = partial pressure of gas (atm)
H = Henry's constant (atm/mol fraction)
X_β = concentration of gas in water (mol gas/(mol gas + mol water))

Henry's law states that partial pressure of any gas is proportional to the amount of gas that is dissolved.

2.1.1 Gas Absorption Equipment

Gas absorption equipment can be categorized into three classifications[23]:

1. Packed columns
2. Plate columns
3. Miscellaneous

Packed columns are the most commonly used gas absorption equipment. In a packed bed column, the exhaust flows upwards through a column filled with packings, water is sprayed on the top of the packed bed downwards against the exhaust. The packings cause a maze-like flow for the gas which results in a high contact area between the gas and liquid. As the sulphur dioxide content decreases as the exhaust rises through the column, the available water will be increasingly more fresh. This is very much wanted as the partial pressure of SO_2 will be quite low at this stage, which means that the solubility will be lower, thus, high gas absorption property of the water is needed to collect the remaining SO_2 [23].

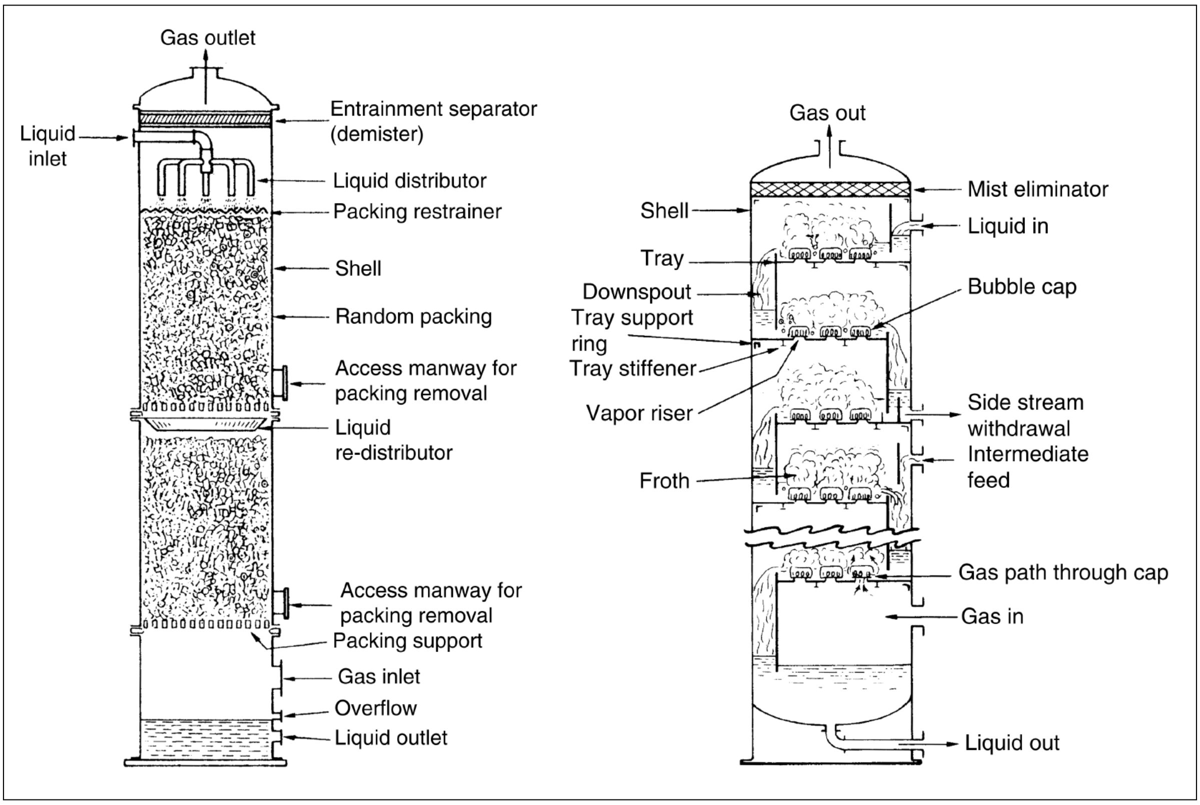

Figure 2-3. Packed bed column scrubber (left) and plate column srubber (right) [23].

In a plate column scrubber, water enters at the top and flows along a tray and down a downspout (or downcomer) to the next tray, and so on. The gas flows upwards through holes in the trays and bubbles through the water to form froth. The gas will disengage from the froth, and flow to the next tray, and so on, until it reaches the gas outlet [23].

Plate column scrubbers are more effective with regards to collecting of particles, compared with packed beds scrubber. Particles larger than 1 µm can be collected effectively [24].

Some pros and cons for the packed bed and plate column scrubbers [23,23]:

- Lower pressure drop in a packed bed scrubber.
- Plate column scrubbers has usually a lower total weight.
- Plate column scrubbers are more effective with regards to collecting of particles. Particles larger than 1 µm can be collected effectively.
- Packed beds are usually preferred for liquids with high foaming tendencies.

2.2 Cleaning of Particles

Particle cleaning is usually done by either gas-solid separation, with the use of a cyclone separator, or wet scrubbing, where the particles are adsorbed by water droplets. In this section, both methods are described, as well as the particle formation in the exhaust gas.

2.2.1 Particle Sizes and Properties

To understand theory of particle scrubbing, one should know the formation process of particles and how they are developed. In the table 2.1, from the Environmental Protection Agency, particles are described according to their size.

Table 2.1. Comparison of fine and coarse particles[25].

	Fine(<2.5 μm)		**Coarse(2.5-10 μm)**
	Ultrafine (<0.1 μm)	**Accumulation (0.1-2.5 μm)**	
Formation processes	Combustion, high-temperature processes and atmospheric reactions		Break-up of large solids/droplets
Formation	Nucleation Condensation Coagulation	Condensation Coagulation Reaction of gases in or on particles Evaporation of fog and cloud droplets in which gases have dissolved and reacted	Mechanical disruption (crushing, grinding, abrasion of surfaces) Evaporation of sprays Suspension of dusts Reactions of gases in or on particles
Composition	Sulfate Elemental carbon Metal compounds Organic compounds with very low saturation vapour pressure at ambient temperature	Sulfate, nitrate, ammonium and hydrogen ions Elemental carbon Large variety of organic compounds Metals: compounds of lead, cadmium, vanadium, nickel copper, zinc, manganese, iron, etc. Particle-bound water	Suspended soil or street dust Fly ash from uncontrolled combustion of coal, oil and wood Nitrates/chlorides from nitric acid/ hydrochloric acid Oxides of crustal elements (silicon, aluminium, titanium, iron) Calcium carbonate, sodium chloride, sea salt Pollen, moulds, fungal spores Plant and animal fragments Tyre, brake pad and road wear debris
Solubility	Probably less soluble than accumulation mode	Often soluble, hygroscopic and deliquescent	Largely insoluble and nonhygroscopic
Sources	Combustion Atmospheric transformation of sulfur dioxide and some organic compounds High-temperature processes	Combustion of coal, oil, gasoline, diesel fuel, wood Atmospheric transformation products of nitrogen oxides, sulfur dioxide and organic carbon, including biogenic organic species such as terpenes High-temperature processes, smelters, steel mills, etc.	Resuspension of industrial dust and soil tracked onto roads and streets Suspension from disturbed soil (e.g. farming, mining, unpaved roads) Construction and demolition Uncontrolled coal and oil combustion Ocean spray Biological sources
Atmospheric half-life	Minutes to hours	Days to weeks	Minutes to hours
Removal processes	Grows into accumulation mode Diffuses to raindrops	Forms cloud droplets and is deposited in rain Dry deposition	Dry deposition by fallout Scavenging by falling rain drops
Travel distance	<1 to 10s of km	100 to 1000s of km	<1 to 10s of km

Table 2.1 gives a clear overview of how particles form and what their given properties are with regards to particle size within the range of <0.1 μm to 10 μm. The table indicates that

particles formed due to combustion, is mostly sized from 2.5 μm and smaller, and will have a travel distance ranging from less than 1 km to as much as 1000s of km. Ultrafine particles are less soluble and less hygroscopic than accumulation mode particles, making them harder to scrub, but fortunately, they have shorter travel distance and atmospheric half-life, meaning that they are less likely to hit the mainland and populated areas from the ocean.

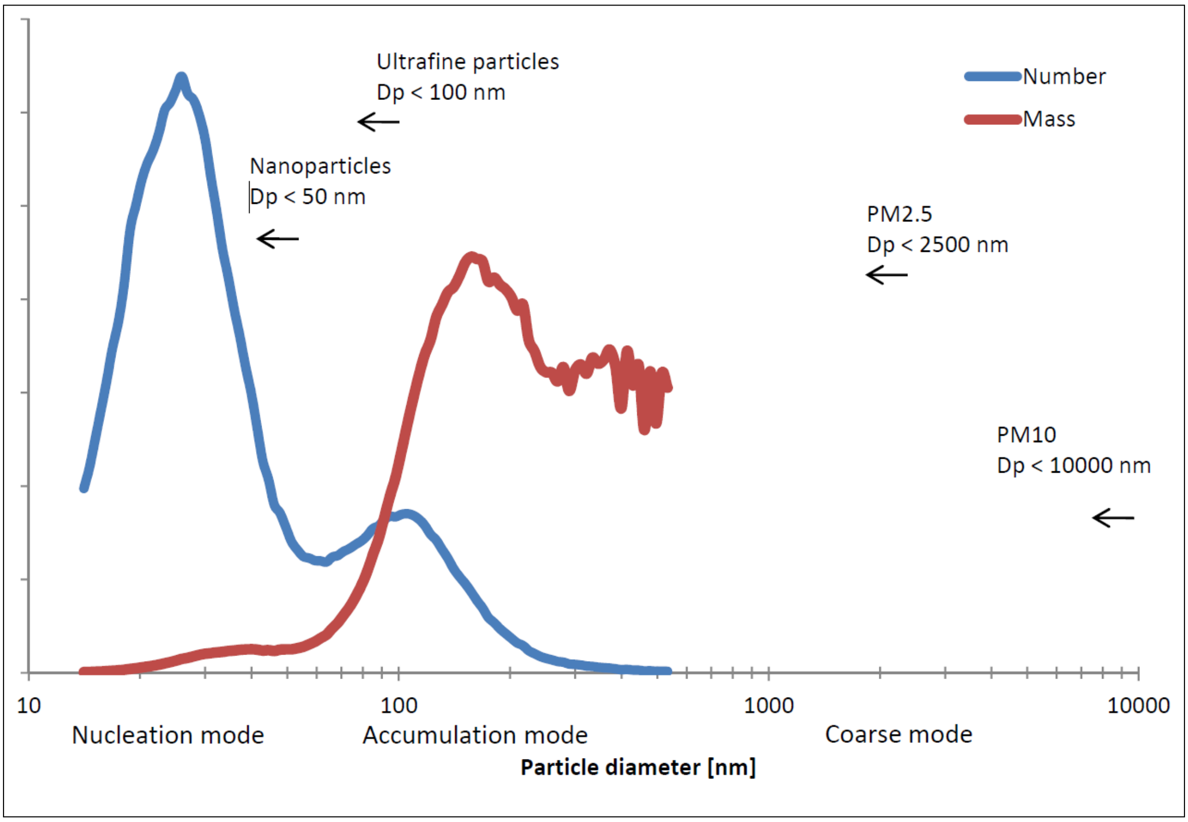

Figure 2-4. Distribution of particles in a typical diesel engine. Figure is collected from a report written by Marintek for Clean Marine in regards to scrubber testing. The curve's cut-off seems to be at about 150 nm (particle size), the reports does not state if the measuring device measured larger particles or not.

Figure 2-4 demonstrates that the number of particles increases significantly according to the decrease of particle size and mass, and vice versa. A scrubber can therefore have a relatively high cleaning efficiency of particles with regards to mass, while the ultrafine and nano particles remains partially uncleaned. Ultrafine and fine particles are categorized to be the greatest health concern and can cause acute and chronic health effects with symptoms like irritation to eyes, nose, throat and lungs, and lightheadedness. Studies also shows particle emissions can cause increased rate of lung cancer[26].

The formation of particles can be described in three steps:

1. **Nucleation** is the first step of the formation, and it begins with crystallization from a solution, liquid, or vapor. A small number of ions, molecules or atoms, get arranged in the form of a solid, making it possible for additional particles to attach[27].
2. **Surface growth** is the attachment of gases to the surface of particles and will increase the mass of the soot[28].
3. **Agglomeration** is the process of forming particle clusters, also known as aggregates, by

particles sticking to each other. This reduces the amount of soot particles, but the mass remains the same[28,29].

The formation of particle can be explained in further steps and details, though the three steps mentioned are the most significant.

Particle size distribution also depends on the engine load. A study conducted at the Indian Institute of Technology Kanpur, tested a single cylinder diesel engine on different loads. The results showed that the number of particles peaked at approximately 25, 50 and 75 nm, with an engine load of 0, 3 and 5 kW, respectively[30].

2.2.2 Particle Scrubbing

Particle scrubbing can be separated into two main mechanisms—gas-solid separation and wet particle scrubbing. For gas-solid separation, the most common method used is cyclonic separation, see chapter 2.2.4 for information regarding this method.

With regard to wet particle scrubbing, what determines the cleaning efficiency is the following:[22]:

- water surface area
- liquid and gas ratio
- particle size
- particulate affinity for water

The main objective for a good wet particle scrubber is to develop small water droplets and to maximize contact between the gas and water. The particles contacts the liquid droplets in three main capture mechanisms, see figure 2-6 for illustration:

1. **Impaction.** This is the primary capture mechanism. When the gas approaches the water droplet, it will flow along a streamline around the water droplet. If the particles has a high enough inertia, it will maintain the trajectory towards the droplet and make contact, rather than to flow around with the gas stream[31].
2. **Diffusion.** The process by which molecules get mixed due to random motion as a result of collisions with gas molecules, this is called the Brownian motion. The particles will be captured by water droplets by diffusion in the waste gas. This occurs mostly for fine and ultrafine particles[31].
3. **Interception.** The particles can gain contact with water droplets by interception. If a particle passes a water droplet closely, it can be captured due to surface tension, the liquid molecules attracts the particle(s). Particles with sizes between approximately 0.1 and 1.0 µm are the ones that are subjected to interception[31].

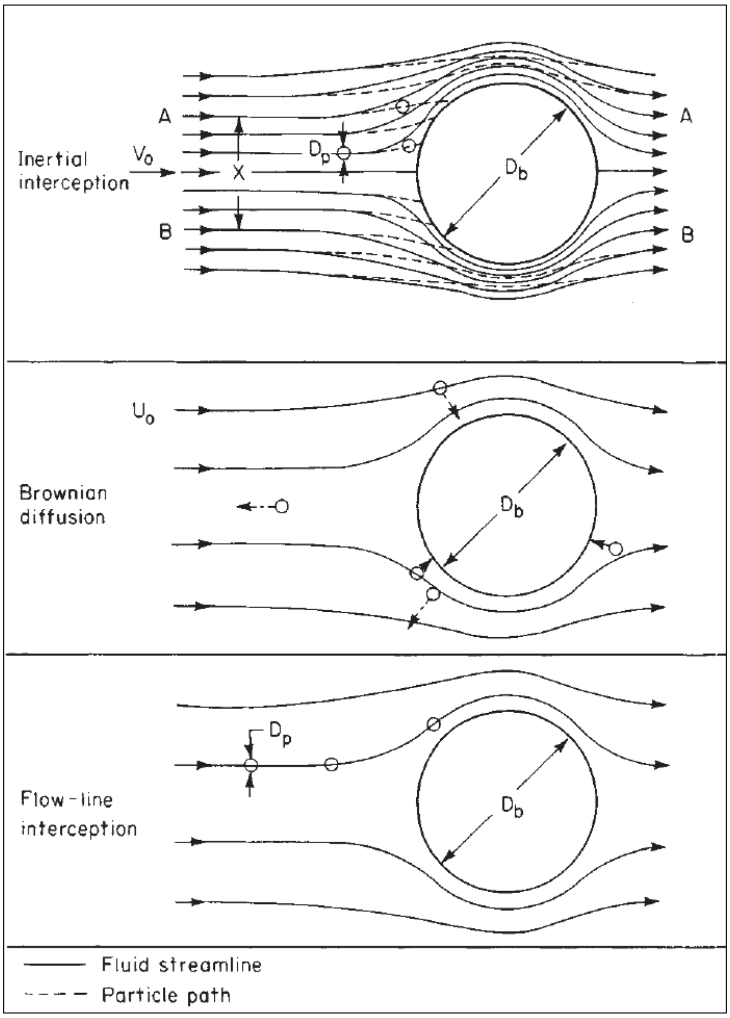

Figure 2-5. Illustration of the main capture mechanisms: Impaction (inertial interception), diffusion, and interception [29].

2.2.3 Wet Particle Scrubbers

Common wet particle scrubbers are: spray towers, wet cyclones, and venturi scrubbers. A spray tower is the most simple version of a wet particle scrubber, it is a simple chamber, usually cylindrical shaped that the gas flows through, water sprays are directed into the chamber to ensure contact between the water droplets and gas. Spray towers can be used for removal of large particles and highly soluble gases. Spray towers has low pressure drop, about 250-500 Pa [22].

A wet cyclone has the gas moving in a cyclonic motion, with the gas inlet(s) positioned tangential to the scrubber wall. Spray nozzles are mounted inside the scrubber and sprays water on the exhaust gas. The reasoning for use of cyclonic spray tower instead of regular spray tower is the increase of cleaning efficiency with regards to particles. Cyclonic spray scrubbers has a cleaning efficiency of 95% for particles larger than 5 μm, and 60% to 70% for submicron particles [31]. In comparison, a regular spray tower has 90% efficiency for particles larger than 5 μm and 50% efficiency for submicron particles. The higher cleaning efficiency is due to higher relative velocity between the gas and the water droplets [31].

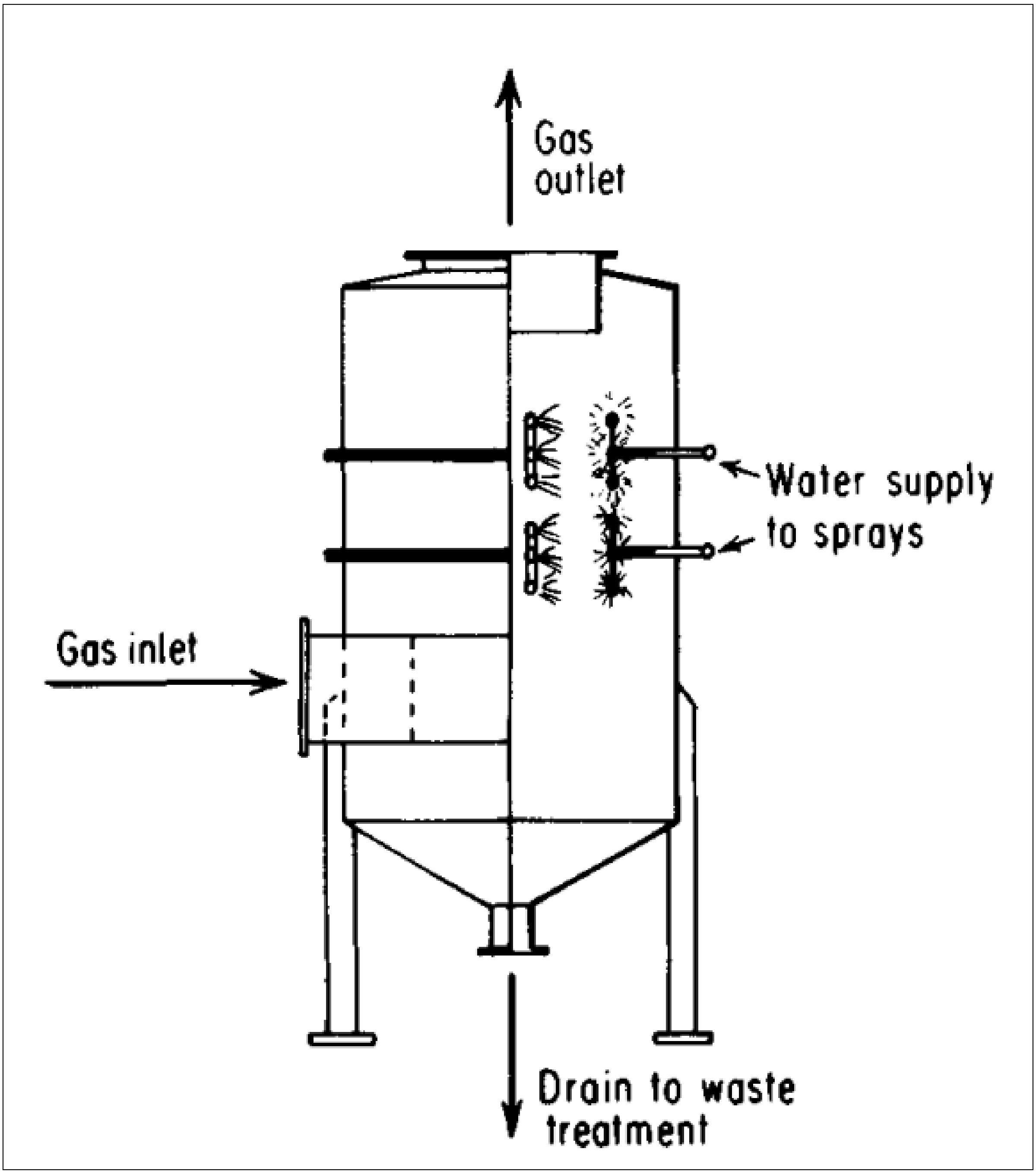

Figure 2-6. Wet cyclone scrubber.[22].

The product and maintenance cost for a typical cyclonic scrubber is higher than a spray tower due to the complexity, it also has a higher pressure drop. The pressure drop in a wet cyclone varies between 1500 Pa and 2000 Pa[22].

Phase 1 of the Clean Marine scrubber resembles a wet cyclone as the exhaust gas moves in a cyclonic motion. More about Clean Marine's scrubber in chapter 2.3.

Venturi scrubbers resembles wet cyclones, the main difference is the inlet. At the inlet of the scrubber, gas and water is forced through a throat section. The gas will accelerate to very high velocities, ranging from 60 to 120 m/s which will cause atomization of the water droplets and good particle collection. Venturi scrubbers are suitable for removal of fine particles, between 0.05 and 5 μm, but at the cost of a high pressure drop, ranging from 500-25 000 Pa[22].

2.2.4 Cyclone Separator

A cyclone separator is a device that separates particles from the gas with centrifugal force. Typically, the gas and solid mixture, enters the cyclone tangentially, and the vortex that is formed will develop a centrifugal force that will push particles to the wall. The air in the cyclone will flow downwards in a spiral, and as it reaches the lower part of the cyclone it will begin to spiral upwards in a smaller vortex into the vortex finder. A cyclone is a much more efficient separator than a gravity settling chamber, because a cyclone can increase the force on the particles by many times the force of gravity[32].

Cyclone separators has very high cleaning efficiency with regards to particles larger than 5-10 μm, which is about 98-99%, finer particles has considerably lower cleaning efficiency[33].

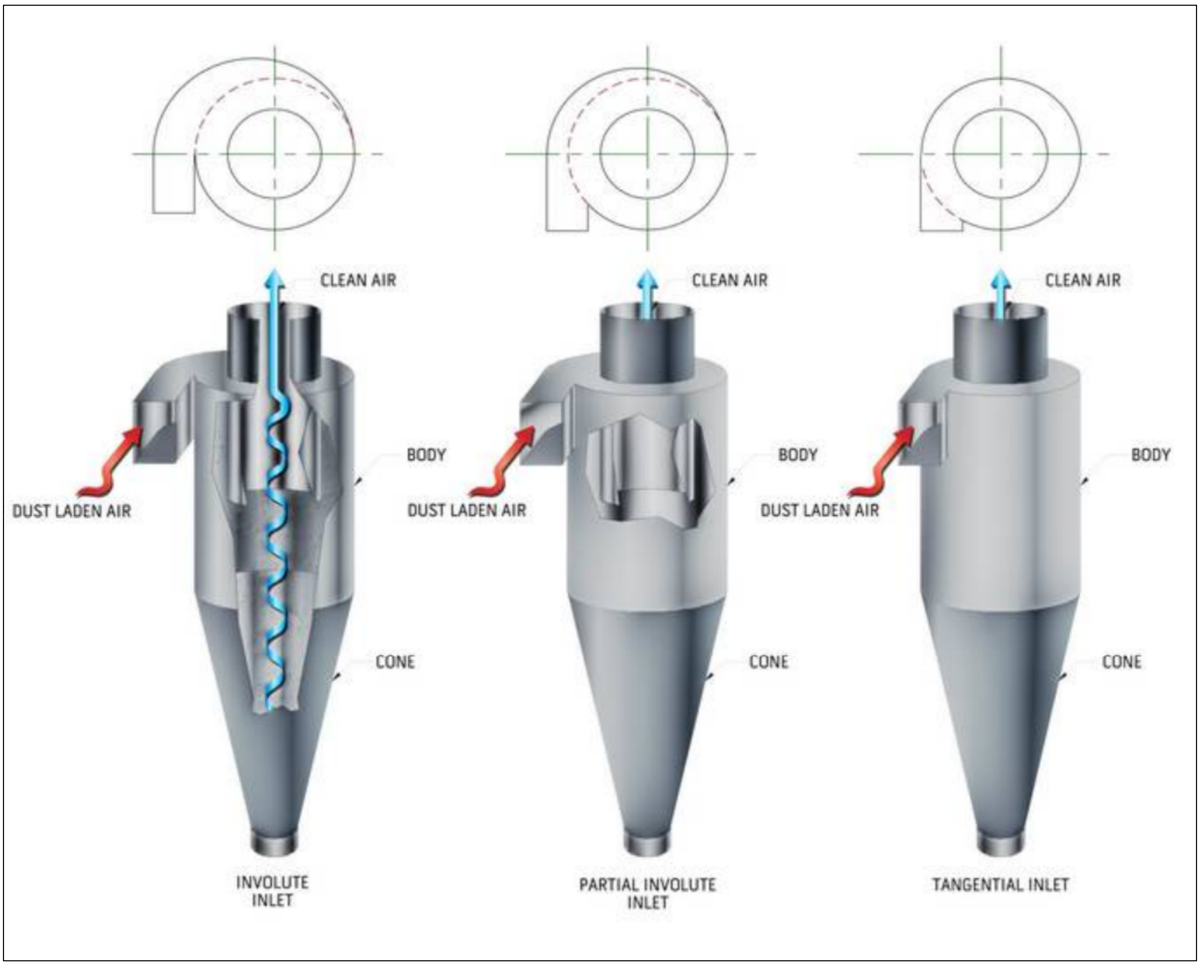

Figure 2-7. Cyclone separators with different kinds of inlets[33].

The purpose of the cyclone used in Clean Marine's scrubber is threefold: increase cleaning efficiency of particles; increase the efficiency of SO_2 absorption in the seawater; and to separate the water droplets from the exhaust. A considerably large amount of water is introduced in the cyclone, which will boost the cleaning efficiency of particles and absorb SO_2 furthermore.

Read more about Clean Marine's cyclone design in chapter 3.3.

2.3 The Clean Marine Scrubber

The Clean Marine scrubber is a spray scrubber that uses sea water and caustic soda. It has exhaust fans to reduce backpressure and a cyclone which separates the gas in water and boosts the cleaning efficiency due to injected seawater. The scrubbing process can be categorized into two phases. Phase 1, pre-injection, is the first stage, where seawater and caustic soda is sprayed on the gas, this phase is similar to a cyclonic spray tower, except that the spray nozzles are arranged co-current instead of counter-current. After phase 1, the gas enters the exhaust fans and into phase 2, the cyclone, where more seawater is introduced to boost the cleaning efficiency. The washwater is centrifuged and separated from the gas, see block diagram in figure 2-8.

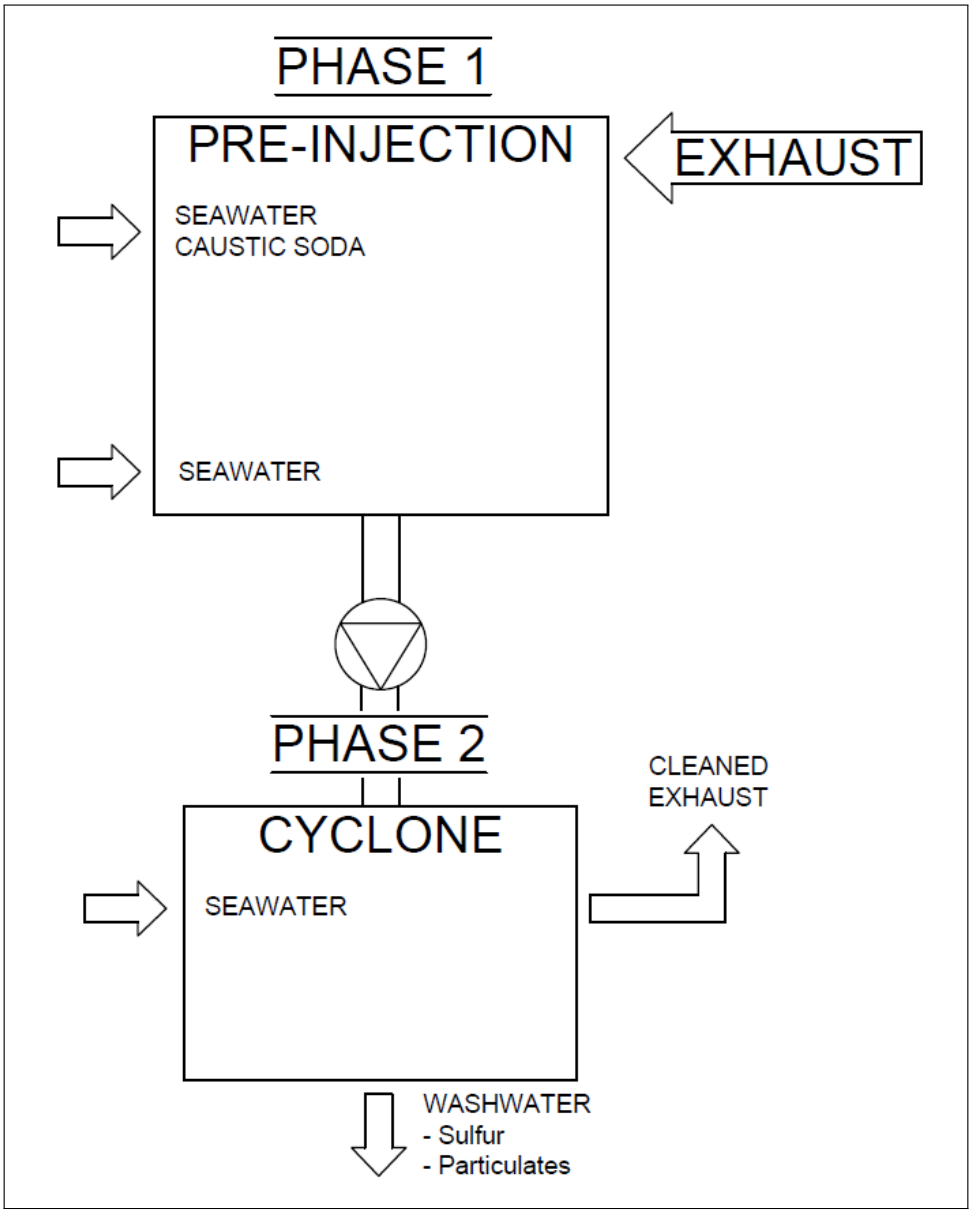

Figure 2-8. Block diagram of the scrubbing process of Clean Marine's scrubbing system.

In figure 2-9, the design of Clean Marine's scrubber can be seen.

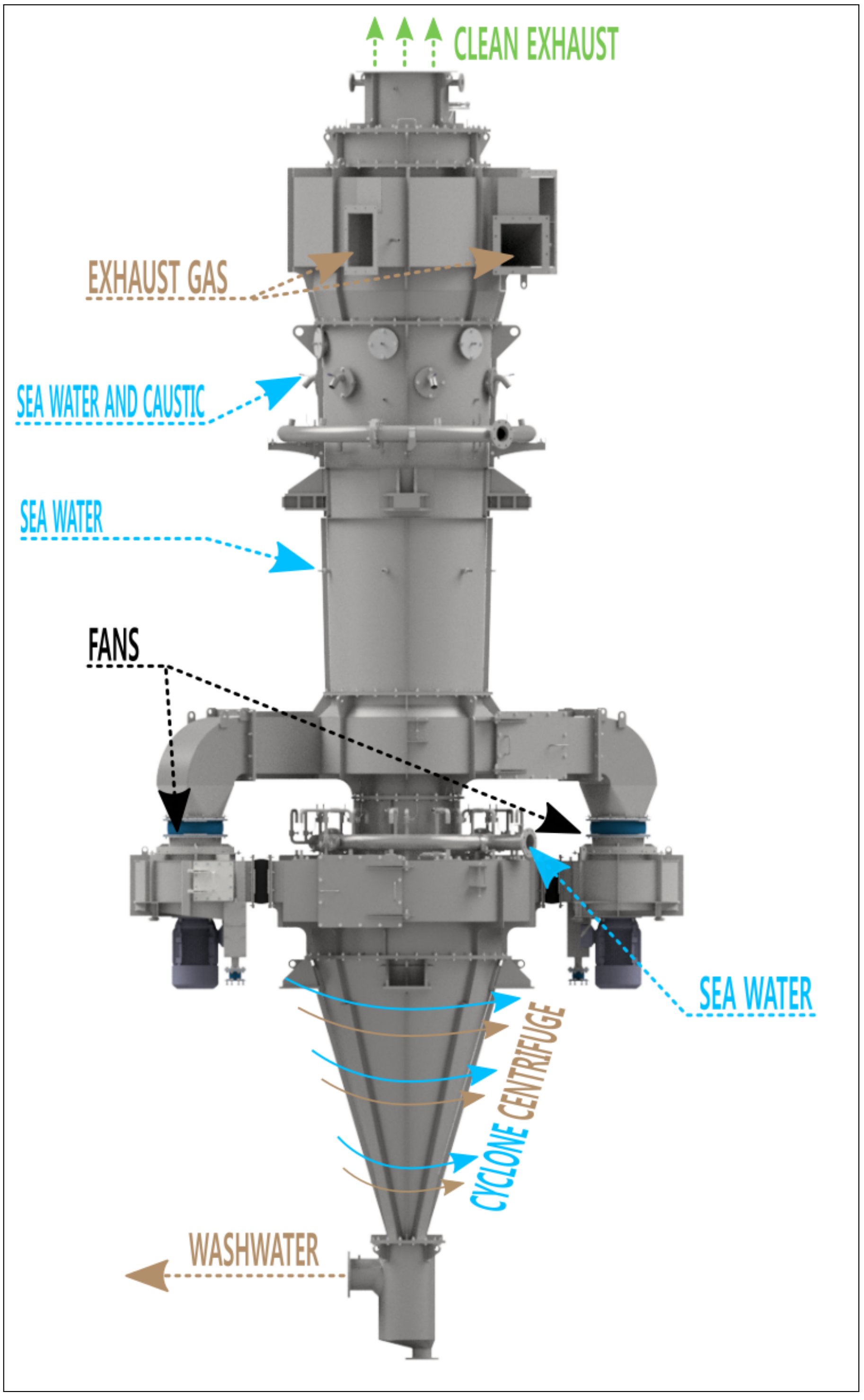

Figure 2-9. Model view of the Clean Marine scrubber with interface annotations.

The exhaust gas is collected at the top of the scrubber, with inlets positioned tangential to the scrubber wall. If there are more exhaust sources than inlets can fit on the scrubber, the exhaust will be collected with manifolds. The exhaust is cleaned in phase 1 and 2 as described, the clean exhaust leaves the scrubber through a co-axial pipe that runs from the inside of the cyclone and to the top of the scrubber. The washwater is discarded at the bottom.

The design and simulation focus will be on phase 2, the cyclone. Read about this in chapter 3 and 4.

2.4 Chemical Process of Seawater Scrubbing

The chemical process that occurs when scrubbing sulphur dioxide with seawater is as follows. The sulphur dioxide is mixed with seawater, and the SO_2 is absorbed in the water.

$$SO_{2(g)} \rightleftharpoons SO_{2(aq)} \tag{2.2}$$

Absorption of SO_2 in seawater causes the SO_2 in the flue gas to dissolve into bisulfate and sulfite. As the amount of positively charged hydrogen ions increases, the pH of the washwater decreases, see reaction 2.3 and 2.4[34,35].

$$SO_2 + H_2O \rightleftharpoons HSO_3{}^- + H^+ \tag{2.3}$$

$$HSO_3{}^- \rightleftharpoons SO_3{}^{2-} + H^+ \tag{2.4}$$

The bisulfate and sulfite will oxidize to sulfate and thus consume the O_2 available in the seawater[15]:

$$SO_3{}^{2-} + \frac{1}{2} O_2 \longrightarrow SO_4{}^{2-} \tag{2.5}$$

With increased concentration of hydrogen ions, reaction 2.3 and 2.4 will reach equilibrium. With reaction 2.3 and 2.4 at equilibrium, the sulphur dioxide will stop absorbing into the solution. Sulfite, $SO_3{}^{2-}$, will oxidize to sulfate, $SO_4{}^{2-}$ (see reaction 2.5), and find its equilibrium, depending on the O_2 level in the seawater.

Seawater is naturally alkaline, with about 4wt% salts. The salts will consume hydrogen ions, which increases the pH and pushes reaction 2.3 and 2.4 to the right. The partial pressure of $SO_{2(aq)}$ will decrease, allowing the solution to absorb more SO_2[18]. As the amount of sulphur dioxide in the exhaust decreases, the partial pressure of the SO_2 decreases, meaning that the sulphur dioxide gets less and less soluble. Higher cleaning efficiency gets therefore increasingly difficult.

The low pH is, as mentioned, damaging to sea life and ecology, the washwater must therefore have a pH value of at least 6.5, according to IMO regulations[14]. There are two ways to increase the pH value of the washwater: one can dilute the washwater with more seawater or use a strong base like sodium hydroxide.

2.4.1 Sodium Hydroxide

The gas absorption can be enhanced by changing the chemistry of the solution to make it react with the pollutant. Sodium hydroxide (NaOH) is the most common used base in marine exhaust gas cleaning systems. When the water absorbs the strong base, it will release hydroxide ions.

$$NaOH \longrightarrow Na^+ + OH^- \tag{2.6}$$

The hydrxoide ions will join the available hydrogen ions and form water.

$$H^+ + OH^- \longrightarrow H_2O \tag{2.7}$$

When NaOH is added to water it will immediately react according to reaction 2.6, producing OH^- ions. Free OH^- ions will react with H^+ ions in the neutralising reaction 2.7. With reduced hydrogen ions, the pH rises, and reaction 2.3 and 2.4 is pushed to the right.

Sodium hydroxide is often used in closed loop systems since the washwater is recycled and is therefore less soluble than clean seawater, but is also used to ensure high enough pH of the washwater and to generally boost the cleaning efficiency.

Unfortunately, use of sodium hydroxide can cause precipitation of calcium and magnesium from the seawater, which can be a big problem for the scrubbing functionality as it can cause problems like malfunction of exhaust fans, clogging of spray nozzles, or be a hindrance of the flow of the exhaust gas. The seawater is in a delicate equilibrium, which means that a slight change in alkalinity (i.e. increase of pH), can cause precipitation of seawater carbonates and salts[36].

Figure 2-10. A container with 1000 mL seawater that was mixed with 10 mL 50% NaOH solution. The white solids are precipitation of magnesium and calcium. This home experiment was executed by Ivar Ervik.

Figure 2-10 illustrates that significant amounts of precipitation of magnesium and calcium can occur with small amounts of added caustic soda. The magnesium and calcium does not do any harm to materials, but a thick layer on a fan impeller can cause motor failure and/or damage to the surroundings.

2.5 Measuring of SO_2

To comply with IMO regulations, the sulphur dioxide must be measured on the outlet of the scrubber and be below set restrictions. If the ship is in ECA, the SO_2 amount in the exhaust must be equivalent or lower than what it would've been with uncleaned exhaust with 0.1% sulphur content in the fuel, and from the year 2020, if the ship is outside ECA, the SO_2 in the exhaust must be equal or lower than the amount from fuel with 0.5% sulphur content. IMO has a specific method of measuring the emissions, which is called *The SO_2/CO2 Ratio Method*. The amount of sulphur dioxide and carbon dioxide is measured at the outlet, the ratio is calculated and compared with a set value by IMO (see table 2.2)[14].

The SO_2 and CO_2 is virtually only derived from the sulphur and carbon content in the fuel, unlike NOx formations. This means that the SO_2/CO_2 ratio will stay the same at different engine loads, different engine designs and so on. The carbon and sulphur mass ratio in residual and distillate differs slightly—the difference is so small that IMO states there is no need to make a distinction between the two, see figure 2-11 for comparison[14,6].

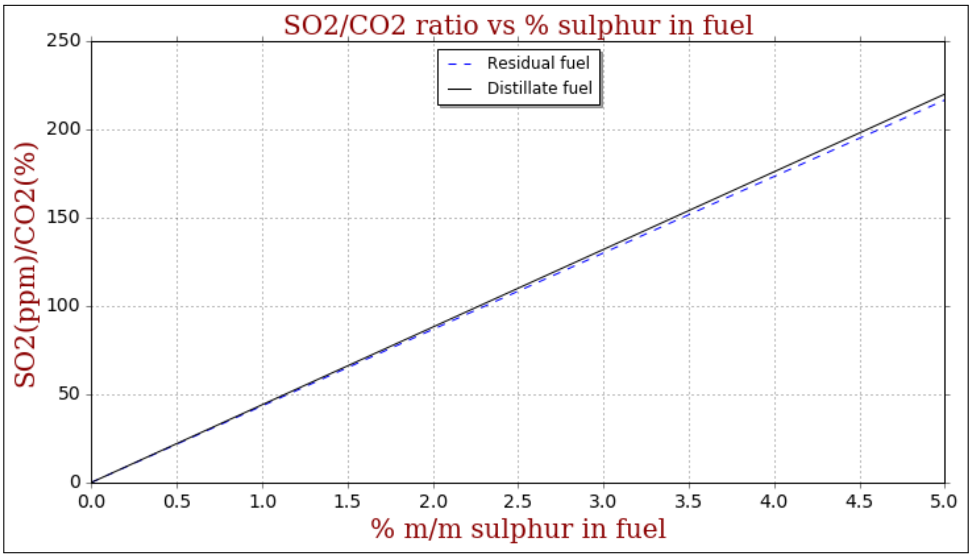

Figure 2-11. SO_2/CO_2 ratio comparison between residual and distillate fuel[14].

Table 2.2. SO_2/CO_2 ratio limits according IMO regulations[6].

Fuel oil sulphur content (% m/m)	Ratio emission SO_2(ppm)/CO_2(%)
0.1	4.3
0.5	21.7
1.0	43.3
1.5	65.0
3.5	151.7
4.5	195.0

In ECA, the emissions is regulated to be maximum the equivalent of a fuel sulphur content of 0.1%, this means that the SO_2/CO_2 ratio must be less than 4.3 to comply with IMO regulations, independently of the sulphur content before cleaning. It is suspected that IMO has chosen this method of measuring SO_2 to make it more difficult for the scrubber vendors and users to cheat on their measurements, as mixing the cleaned exhaust with air, before measurements, would result in a higher SO_2/CO_2 ratio due to the low amount of carbon dioxide in the atmosphere, which would indicate a low cleaning efficiency.

Chapter 3

Concept and Product Design

In this chapter, the concept of the proposed exhaust gas cleaning system, *The Flex System*, will be explained. The different concepts and designs of the one-inlet cyclones will be thoroughly described, as well as the potential issues and solutions.

3.1 Introduction

As mentioned in the introduction chapter, Clean Marine is looking for a solution to make their scrubber more adaptive and easier to fit inside a ship's funnel. Instead of one fixed scrubber, they want to make the main elements in the scrubber into individual components and connect them with piping. In this way, the components can be placed independently of one another, which is potentially a more effective use of the free space in the funnel.

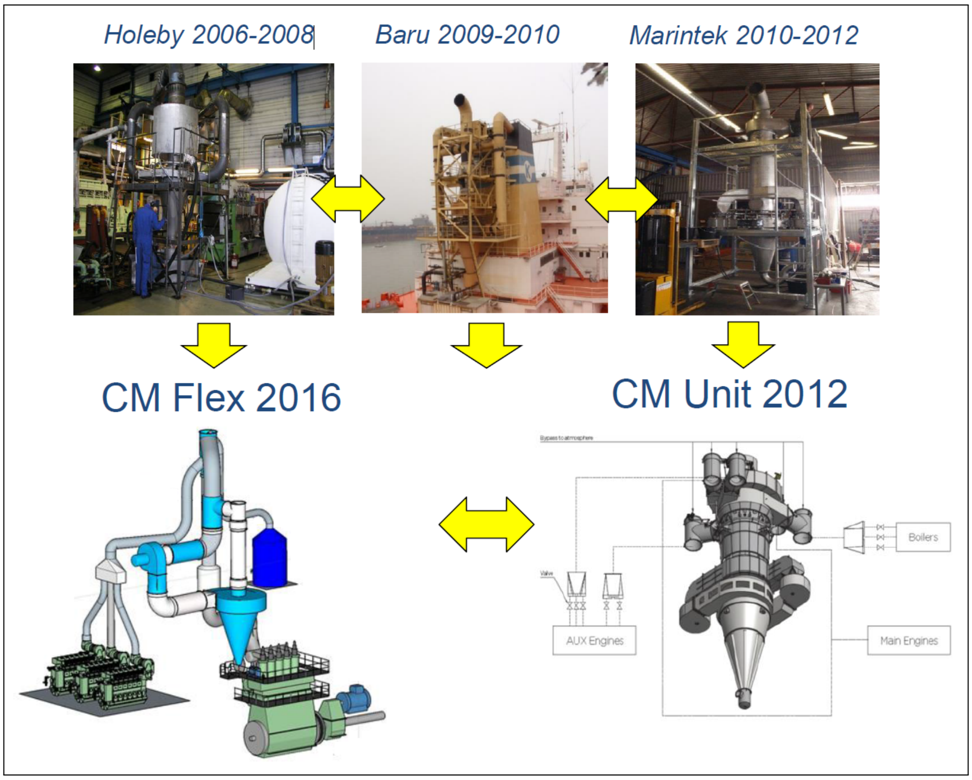

Figure 3-1. Product development history of Clean Marine's scrubber.

In figure 3-1, the development of the scrubber can be seen, starting from 2006, a small scrubber was tested in a laboratory in Denmark, which had a capacity of a 1 MW engine. In 2009, extensive tests were done on board a 10 MW vessel. After another test unit at Marintek in Trondheim, Norway, Clean Marine had in 2012 an all-in-one unit scrubber design ready for commercial use.

They now visualize a scrubber system that combines the different scrubber designs into a funcitonal adaptive EGCS.

3.2 The Flex System

Clean Marine's proposed idea for a flexible scrubbing system is visualised in figure 3-2. The scrubber is split into the following independent components:

- collecor box
- pre-injection
- exhaust fan
- cyclone

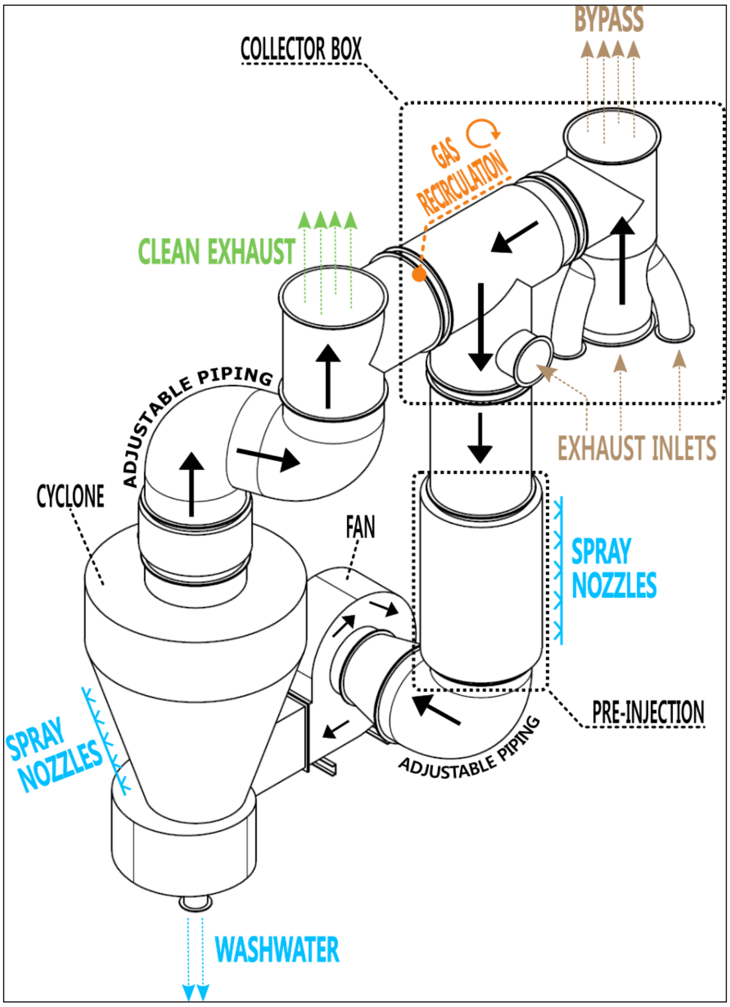

Figure 3-2. Overview of Clean Marine's proposed flex system. The cyclone used in this visualization is one of the proposed concepts, not necessarily the one used for flow analysis.

The collector box (see top right in figure 3-2) is the meeting point for the exhaust from all sources—main engines, auxiliary engines and boilers. On the inlets of the collector box there will be installed dampers so that the exhaust has the possibility to bypass the scrubber system, one damper might be used for several exhaust sources, depending on the layout of the engines. The gas recirculation valve will be a part of the collector box component, which makes it possible to recirculate the exhaust and keep a high flow rate into the inlet of the fan when the engines runs on low load.

The pre-injection component is the first scrubbing process in the system. The component is essentially a pipe with spray nozzles. With a high SO_2 content in the exhaust, the partial pressure of the sulphur dioxide is high, and a big amount will be cleaned in this part of the scrubber. In the current scrubber, Clean Marine estimates that the pre-injection cleans about 90% of the sulphur dioxide, even though the pre-injection only uses 4% of the total water mass, the remaining 96% water is used in the cyclone, where another 90% of the sulphur dioxide is cleaned from the remaining 10%.

After the pre-injection, the exhaust enters the exhaust fan, which is there to reduce back pressure to the engines and boilers, and to function as booster into the cyclone. Depending on the cleaning efficiency of the pre-injection and cyclone phase, there might be necessary to have another cleaning step after the exhaust fan. The piping from the pre-injection phase can be installed freely as indicated in figure 3-2.

In the cyclone, a large amount of water will be injected to get a sufficient cleaning efficiency, the water and gas will separate, the washwater is discarded at the bottom, and the cleaned gas flows upwards. On top of the cyclone gas discharge, there is a droplet catcher that will collect remaining water condensation and drain it to the water discharge. The piping after the cyclone can be installed freely to fit the layout of the funnel.

When the engines runs on low load, a valve will open accordingly (see orange writing in figure 3-2), and the gas will recirculate the system.

3.3 Current Cyclone Design

The current cyclone design is with two exhaust inlets, as can be seen in figure 2-9. There are spray nozzles at both inlets of the cyclone and further in along the wall of the cyclone house. The outer walls of the cyclone house is arced towards the accelerator to increase the centrifuge effect into the cyclone. The exhaust is forced through the accelerator and into the cyclone house—imagine a large cylinder with narrow slots that are angled to keep the rotational momentum. The accelerator is described more thoroughly in chapter 3.3.1. The exhaust will accelerate through the cylinder, increasing the turbulence, which in turn supposedly decreases water droplet size and thus increases the scrubbing efficiency of SO_2 and particles[1]. There are more spray nozzles on the inside of the accelerator (see figure 3-4 and 3-6), which is the last cleaning step before the gas leaves the cyclone. The washwater is centrifuged and discarded at the bottom, the exhaust leaves through the inner pipe.

[1] Lower water droplet sizes causes bigger contact area between the gas and water, thus increasing the gas absorption. Lower droplet sizes also increases the cleaning of particles, as explained in chapter 2.2

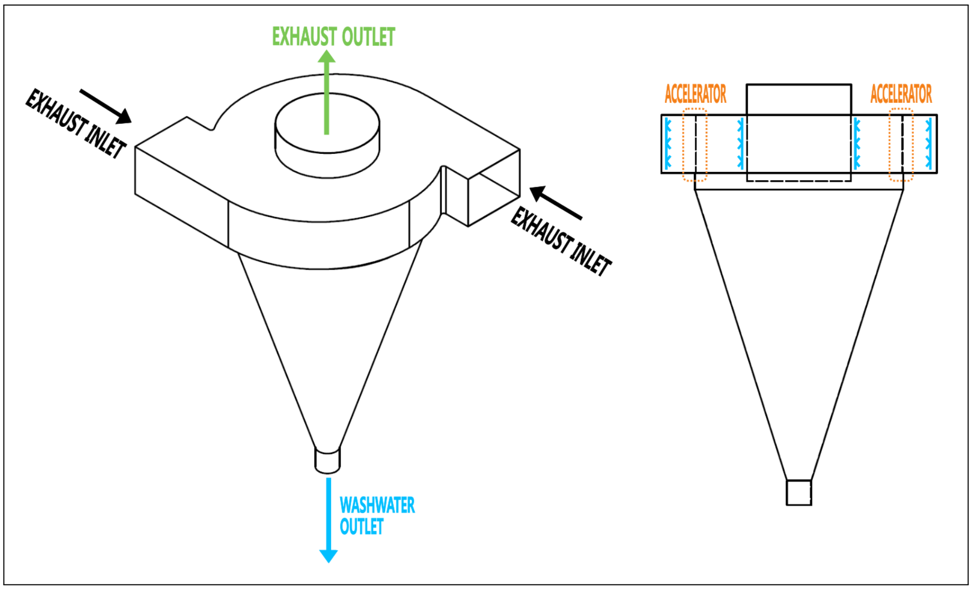

Figure 3-3. Isometric view of the two-inlet cyclone with indication of current spray nozzle arrangements (blue).

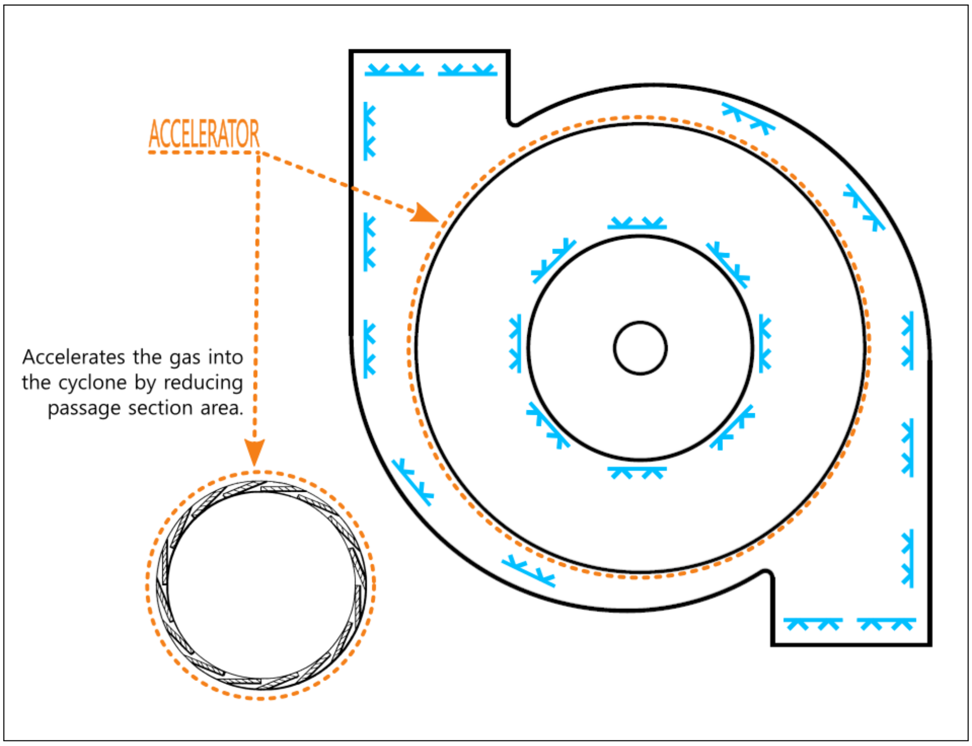

Figure 3-4. Top section view of two inlet cyclone house with indication of current spray nozzle arrangements (blue).

The spray nozzle arrangements has changed over the course of different installments. Usually, the nozzle arrangements have been a mix of counter-current and co-current spray nozzles. The spray nozzles at the inside of the accelerator has been installed at the bottom of the vortex finder because this is a point in the cyclone where there is expected to be high turbulence, which in turn may cause higher scrubber efficiency, at least for particles.

3.3.1 Cyclone Accelerator

The cyclone accelerator, also called *Nozzle Ring*, is a mechanical component in the cyclone, which is there to increase tangential velocities into the cyclone. The process is simple, it is many vertical plates aligned tangentially to the cyclone with small openings. It produces basically the same effect as squeezing a garden hose. The theory behind its use is that due to the high velocities generated through the accelerator, the cyclone diameter can increase in size without the exhaust gas dropping downwards and exiting the cyclone early, which would cause lower cleaning efficiency and gas-liquid separation. The downside of the use of the accelerator is the additional pressure drop it causes.

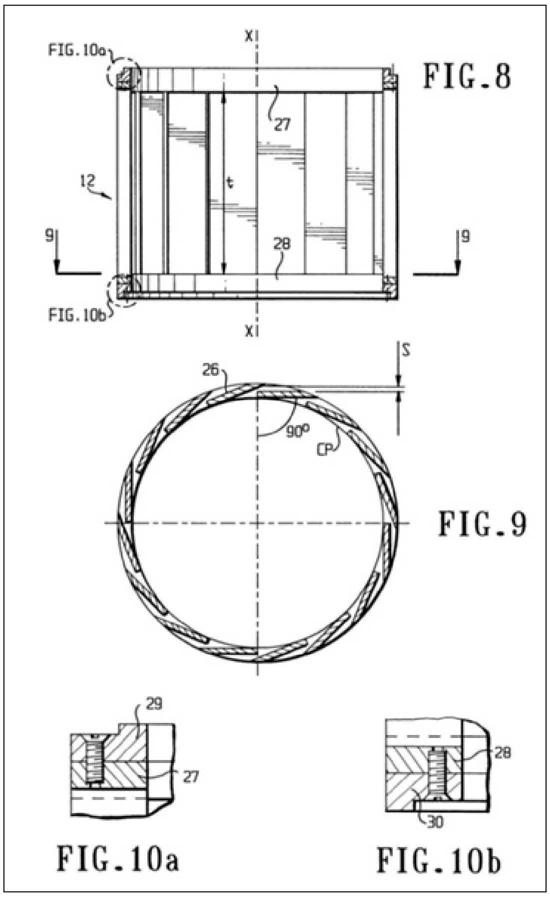

Figure 3-5. Patent drawing of cyclone accelerator, patented by Vortex Ecological Technologies with patent number US 6270544 B1.

FIG. 9 in figure 3-5 is a top view of the accelerator that demonstrates the alignment of the plates. All plates are aligned tangentially to the cylinder with a cross section that decreases as the gas flows through, thus increases the rotational momentum of the gas.

The cyclone accelerator will be incorporated in the suggested design.

3.4 One-inlet Cyclone Concepts

In this sub-chapter, different cyclone concepts are visualized and reviewed. One cyclone concept will be selected to be simulated in ANSYS Fluent. The concept selection is done systematically according to Pugh's selection matrix.

Dimensioning for the new cyclone design will be done according to current dimensions from the two-inlet cyclone, given by Clean Marine, new elements will be calculated according to wanted exhaust velocity, which depends on the concept.

3.4.1 Concept 1: Co-axial Cyclone

This concept is based on having a co-axial cyclone and moving the inlet at the bottom which will reduce the footprint considerably. With an outer cyclone shell, the exhaust will have a higher residence time, which can potentially increase cleaning efficiency compared to the current cyclone design. The outer shell is also thought to distribute the gas evenly into the accelerator. Spray nozzles could be installed at the inlet, in the outside cyclone shell, and on the inside of the accelerator.

The design requires a larger amount of steel and is therefore more expensive to produce, it is expected that the pressure drop will increase and that rotational momentum of the gas will decrease before entering the cyclone. There must also be some sort of drainage of the washwater in the outer cyclone.

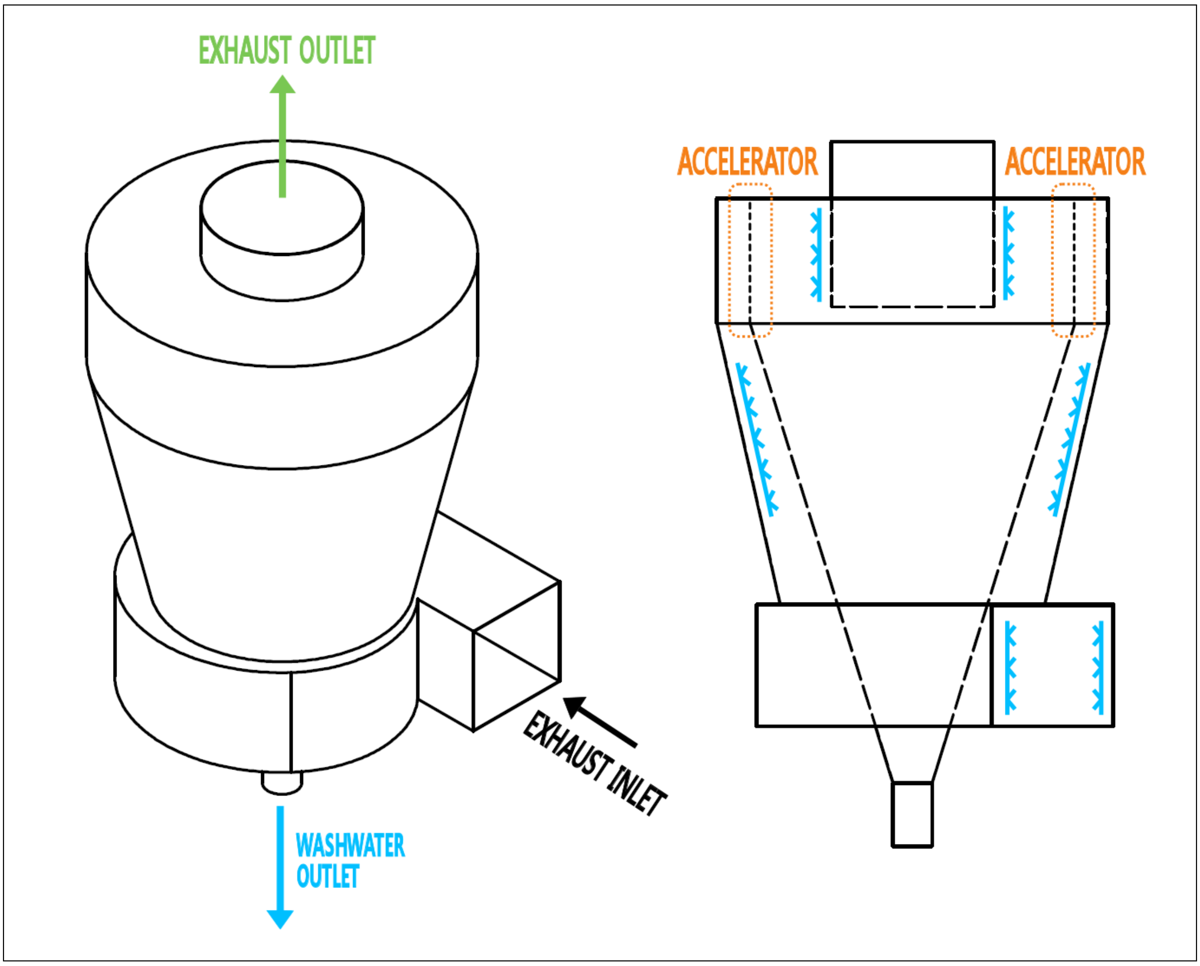

Figure 3-6. Illustration of concept 1: Co-axial cyclone.

3.4.2 Concept 2: Regular Cyclone House

This concept is the same as the current design, only with one inlet instead of two. It is easy to manufacture and cheaper than most other cyclone concepts in this thesis. Spray nozzles are proposed to be installed along the wall of the cyclone house and on the inside of the cyclone, which is the same arrangements as it is on the two-inlet cyclone. The footprint of this concept is quite big, but a flow simulation of this concept can test a more narrow and higher inlet to reduce the width of the cyclone, this will mean that the accelerator must increase in height as well.

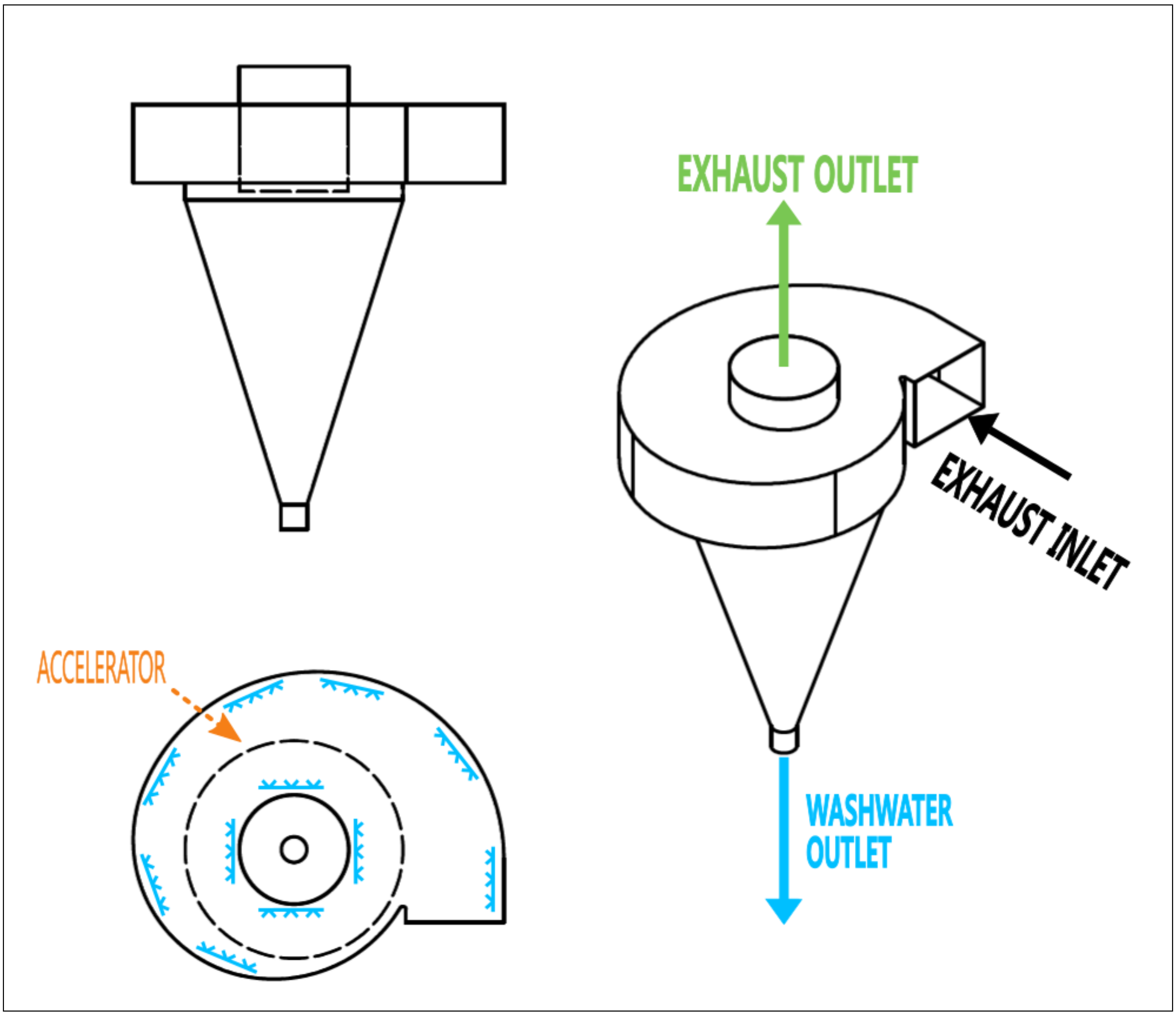

Figure 3-7. Illustration of concept 2: Regular cyclone house.

3.4.3 Concept 3: Regular Cyclone House with Guide Plate

This concept is the same as concept 2, except with a guide plate in the cyclone house. The guide plate is thought to distribute the gas better into the accelerator, though spray nozzle arrangements in this design will be more difficult and expensive to fabricate and standardize.

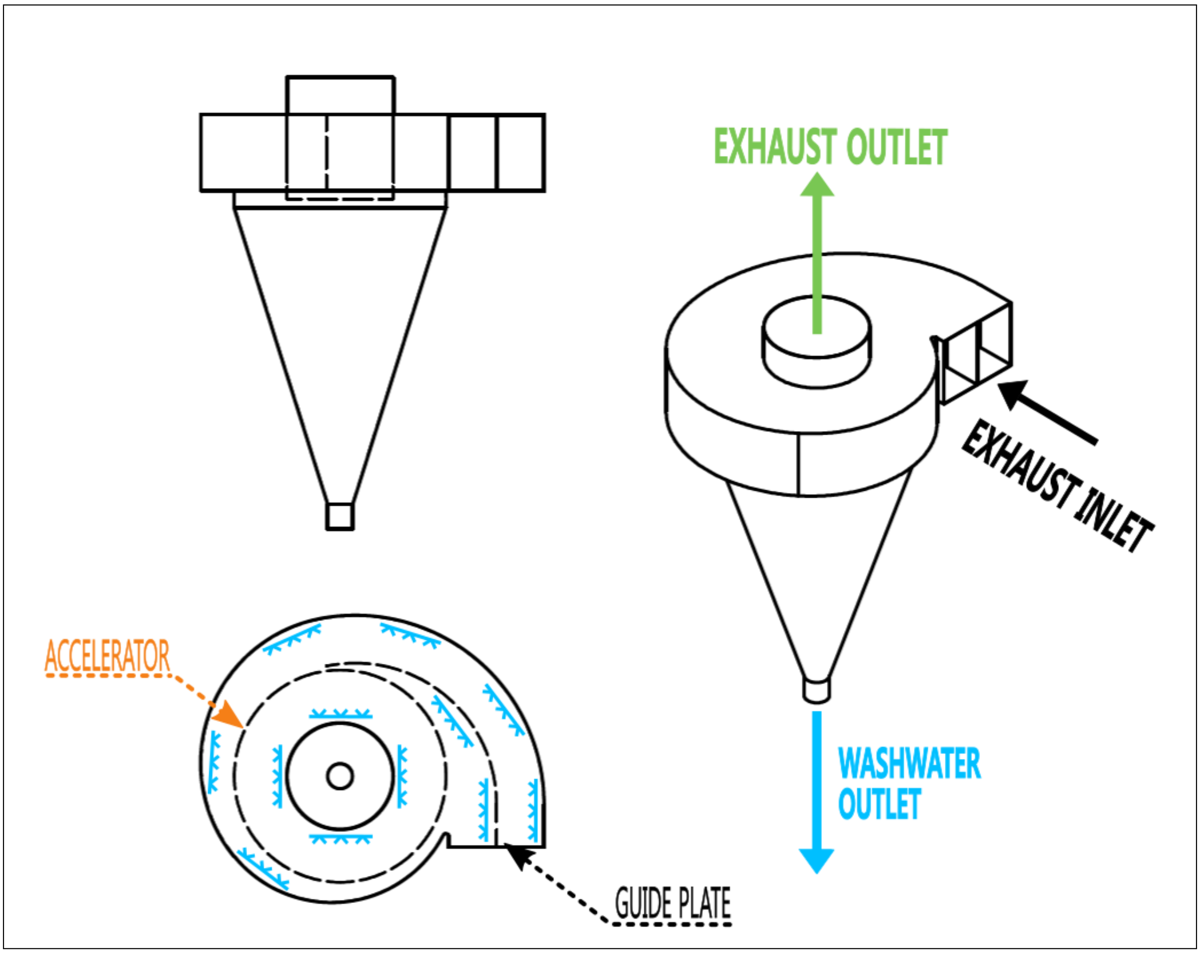

Figure 3-8. Illustration of concept 3: Regular cyclone with guide plate.

3.4.4 Concept 4: Circular Cyclone House

This concept is different from the other concepts because it has a circular cyclone house, instead of spiral formed one. This will make room for a better and cheaper spray nozzle arrangement, though the velocity into the accelerator will be lower. This might cause a lower velocity into the cyclone and may affect the vortex formation.

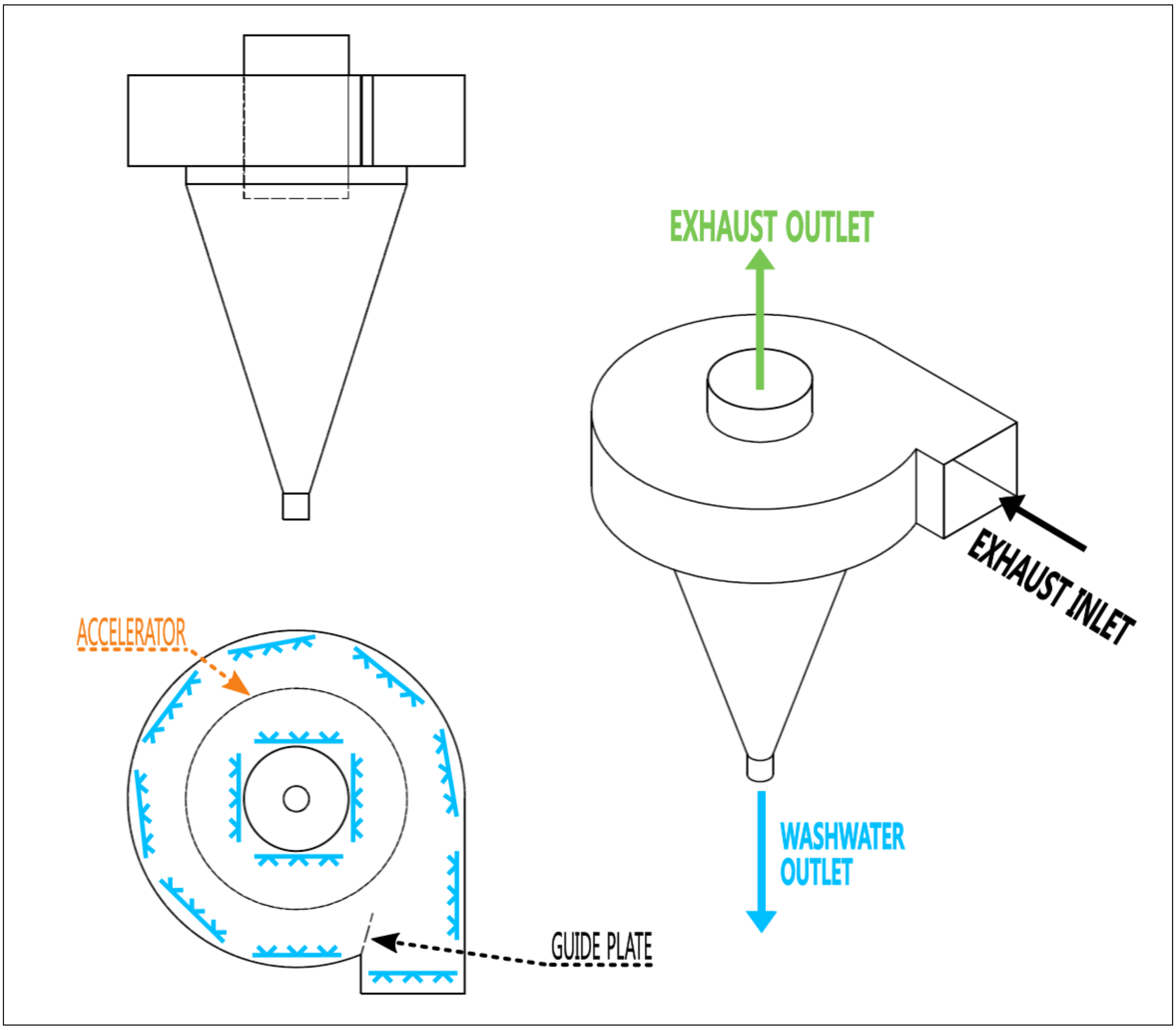

Figure 3-9. Illustration of concept 4: Circular cyclone house.

3.4.5 Concept 5: Slim channel

This concept is similar to concept 3, except the accelerator in this concept remains unchanged. There will be a welded skirt above the accelerator in this case instead of increasing the height. This opens the possibility to make the cyclone house more narrow, leaving a smaller footprint.

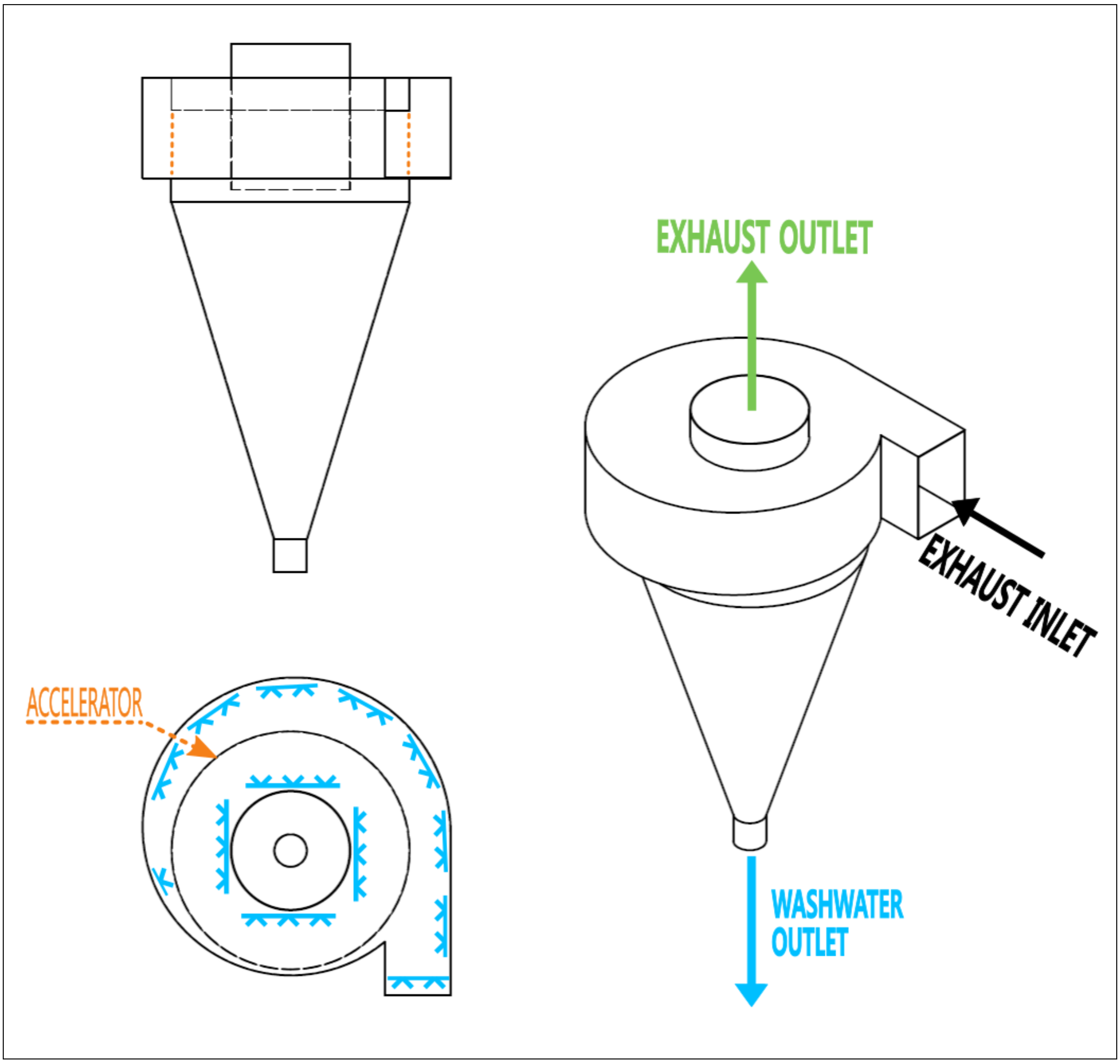

Figure 3-10. Illustration of concept 5: Cyclone house with upper channel.

3.5 Concept Selection

To make an objective concept selection, a decision-matrix method is used. Different criteria that is considered to be valuable is included in the matrix and are weighted in order of importance. Clean Marine's opinions are valued and thus included as a criterion in the matrix. See table 3.1 for the chosen criteria and their respective weights.

Table 3.1. Concept criteria with description and weights, 1 is set to *insignificant* and 5 is set to *very significant*. See chapter 3.4 for the different concepts in question.

Criteria	Description	Weight
Clean Marine's suggestion	Clean Marine's opinions of the different concepts is taken into consideration when choosing concept for simulation.	5
Size and footprint	The size and footprint of the concept is very important, as reduction in size is the basis for this thesis to begin with.	5
Cleaning efficiency potential	The concept will be considered with regard to exhaust gas cleaning potential. Residence time of the exhaust gas and surface area contact between the gas and liquid are considered as potential of scrubbing efficiency.	4
Feasibility	It is important that the concept is practically doable and easy to fabricate, produce, and standardize.	4
Weight and cost	The cost of the design is important to consider, but it is not viewed as significant as criteria like cleaning efficiency, footprint and functionality.	3
Flow expectations	The expectations of the flow distribution and pressure drop is important to consider.	4

Each concept is valued according to each criterion and are given either a $+$, $-$ or $=$ sign, which respectively is 1, -1, and 0 points. For scoring with weights, the score given is the respective weight in points as positive or negative for $+$ and $-$ respectively, $=$ sign still gives 0 points.

Table 3.2. Pugh's selection matrix for the five different concepts, scoring with and without weights.

Criteria	Weight	Concept				
		1	2	3	4	5
Clean Marine's suggestion	5	=	+	−	−	+
Size and footprint	5	+	=	=	=	=
Cleaning efficiency potential	4	+	=	=	=	=
Feasibility	4	−	+	+	+	+
Weight and cost	3	−	+	+	+	=
Flow expectations	4	−	=	=	−	=
Score		−1	**3**	**1**	0	**2**
Score with weights		−2	**12**	**2**	−2	**9**

Concept 2, 3 and 5 gets the highest score from the decision-matrix with and without weights. The reason is that they score better on expected flow distribution and pressure drop, simplicity and feasibility, and suggestion by Clean Marine. It is chosen to do flow simulation on concept 2, regular cyclone house, due to its simplistic design and that it is considered to be the concept that is most likely to be realized.

3.6 Design and Dimensions for Chosen Concept

The dimensions for the cyclone will be according to the current two-inlet cyclone, for a 140k system (i.e. a system capable of scrubbing 140 000 kg exhaust per hour), which Clean Marine often uses for R&D purposes because it's somewhere in between the largest and smallest system they produce.

The given dimensions for the cyclone can be seen in figure 3-11:

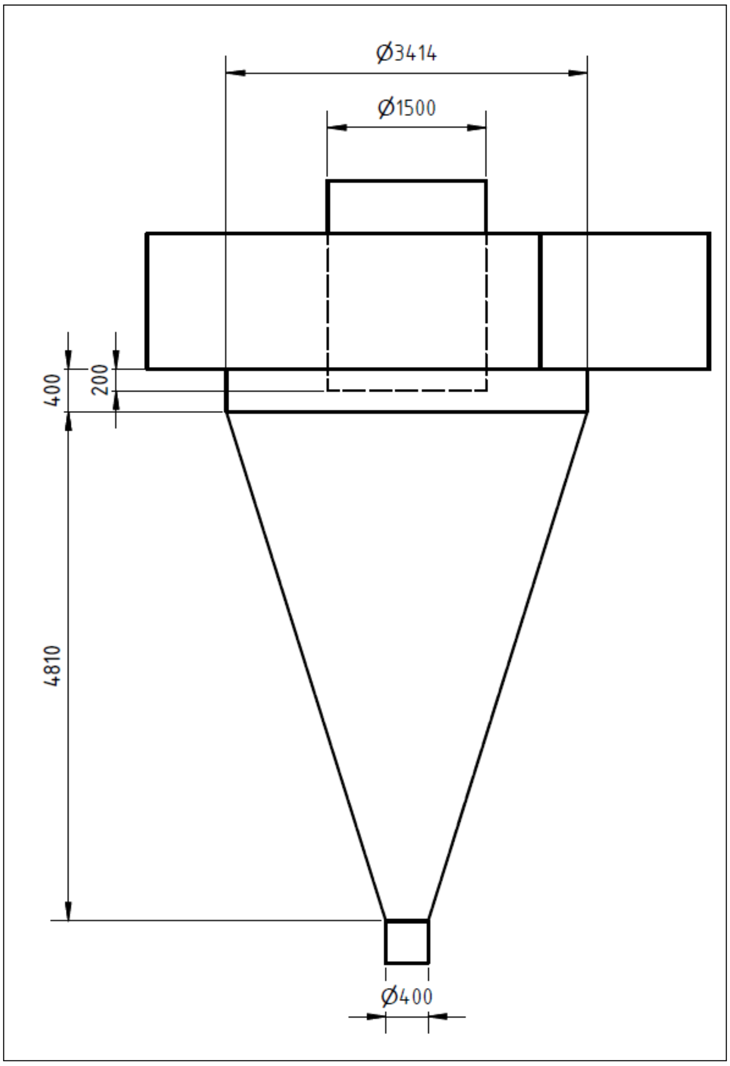

Figure 3-11. Dimensions for the one-inlet cyclone, provided by Clean Marine.

For calculating the inlet area for the cyclone house, the ideal gas law (equation 3.1) is used to calculate the density of the exhaust since it is a compressible fluid. The gas temperature into the cyclone is unknown, it is cooled in the pre-injection phase, and since the gas is mixed with water it is difficult to measure the temperature of the gas accurately. Clean Marine estimates that the gas temperature is about 100°C, this will therefore be used as design temperature when calculating the inlet area.

$$PV = mRT \tag{3.1}$$

where:

P = pressure (Pa)
V = volume (m^3)
m = mass (kg)
R = gass constant ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
T = temperature (K)

The gas constant for air is 287.058 $J{\cdot}kg^{-1}{\cdot}K^{-1}$, and the pressure in the scrubber is assumed to be 1 atm, which is 101 325 Pa. This gives:

$$\begin{aligned} &PV = mRT \\ \Rightarrow &\frac{m}{V} = \rho = \frac{P}{RT}, \text{ where } \rho \text{ is density} \\ &\rho = \frac{101325Pa}{287.058J \cdot kg^{-1} \cdot K^{-1} \cdot (100 + 273.15)K} \\ &\rho = 0.946kg/m^3 \end{aligned} \tag{3.2}$$

The density of the gas at 1 atm and 100°C is 0.946 kg/m^3.

At maximum load, the exhaust flow rate is 140 000 kg/h, which is 38.89 kg/s. The volumetric flow rate is:

$$\begin{aligned} Q &= \frac{\dot{m}}{\rho} \\ Q &= \frac{38.89kg/s}{0.946kg/m^3} \\ Q &= 41.11m^3/s \end{aligned} \tag{3.3}$$

Clean Marine have good results with systems running with a speed of 20 m/s at the inlet of the cyclone house—increasing the velocity might cause a pressure that the exhaust fan can't handle, and decreasing it would increase the size of the cyclone. Using the same velocity will also make comparison towards the current design easier. With a velocity of 20 m/s, the inlet area of the cyclone house is:

$$\begin{aligned} &Q = A \cdot v \\ \Rightarrow &A = \frac{Q}{v} = \frac{41.11m^3/s}{20m/s} \\ &A = 2.0555m^2 = 2055500mm^2 \end{aligned} \tag{3.4}$$

For deciding the different cyclone house inlet sizes, it has been decided that the largest width should correspond to the current width and height ratio of the two-inlet cyclone. The most narrow version should increase the height of the cyclone house with at least 50% compared with the two-inlet cyclone. The results is the values listed in table 3.3. The most narrow version, which is 1200 mm wide, has an increase of height of about 70%[1] according to the two-inlet cyclone.

[1] The inlets on the two-inlet cyclone house on a 140k system has a height of approximately 1000 mm.

Calculating the height of the cyclone house is done according to this equation:

$$h = \frac{A}{w} = \frac{2055500mm^2}{w}, \text{ where h is height and w is width} \tag{3.5}$$

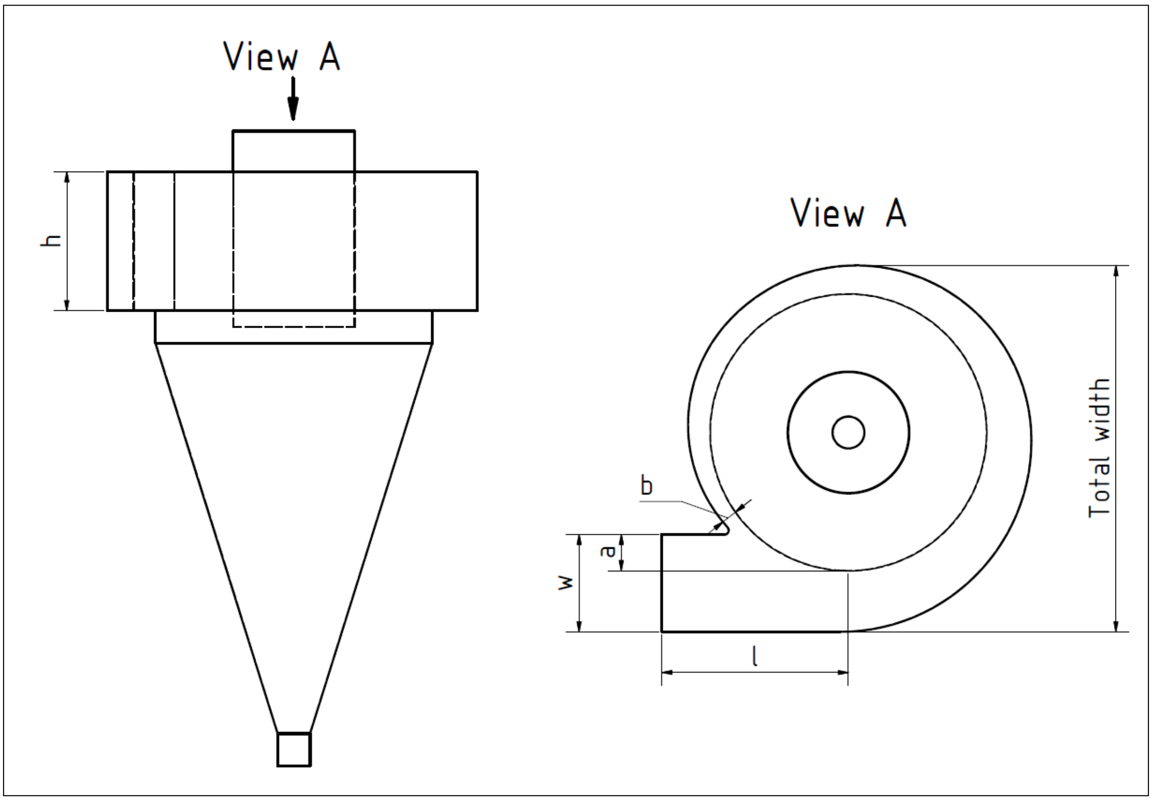

Figure 3-12. Dimension variables for the one-inlet cyclone house, see table 3.3 for values.

Table 3.3. Dimension variables for the cyclone house. See figure 3-12 for reference.

Inlet width, w [mm]	Height, h [mm]	Total width [mm]	a [mm]	b [mm]	l [mm]
1600	1285	5310	450	350	2300
1400	1468	4951	450	200	2300
1200	1713	4510	450	180	2300

With regard to general separation cyclones, there is no apparent drawback of using a high and narrow inlet, in fact, this is the way most cyclones are designed. A narrow inlet will force the gas closer to the wall of the cyclone, which in turn, causes higher centrifugal force on the particles, and therefore higher cleaning efficiency. An inlet width of 1200 mm, reduces the total width of the cyclone with 800 mm compared to a inlet width of 1600 mm.

Clean Marine's number one priority is cleaning efficiency of SO_2, because that is what IMO regulates. Therefore, they aim for an even gas distribution into the accelerator because this would enhance the contact area between the gas and water. A more narrow inlet causes a smaller horizontal space around the accelerator, which might cause an uneven distribution of the gas into the cyclone.

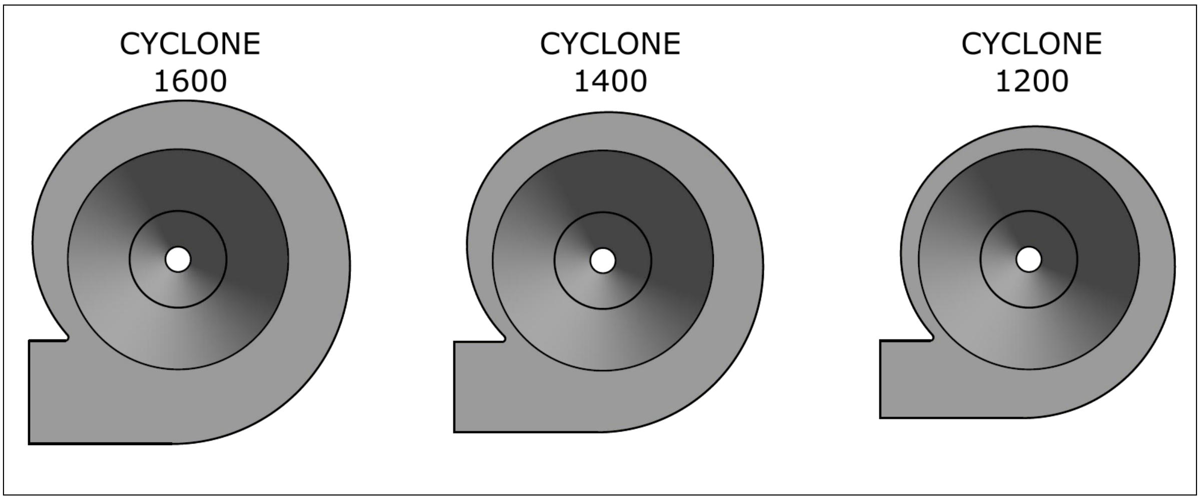

Figure 3-13. Top view comparison of the different cyclone houses.

Figure 3-13 demonstrates how the swirl around the cyclone changes with a more narrow inlet.

3.7 Dimensions for Two-Inlet Cyclone

Simulation of the two-inlet cyclone will be done to be able to make comparisons. In figure 3-14 dimensions that differ from the one-inlet cyclone are accounted for.

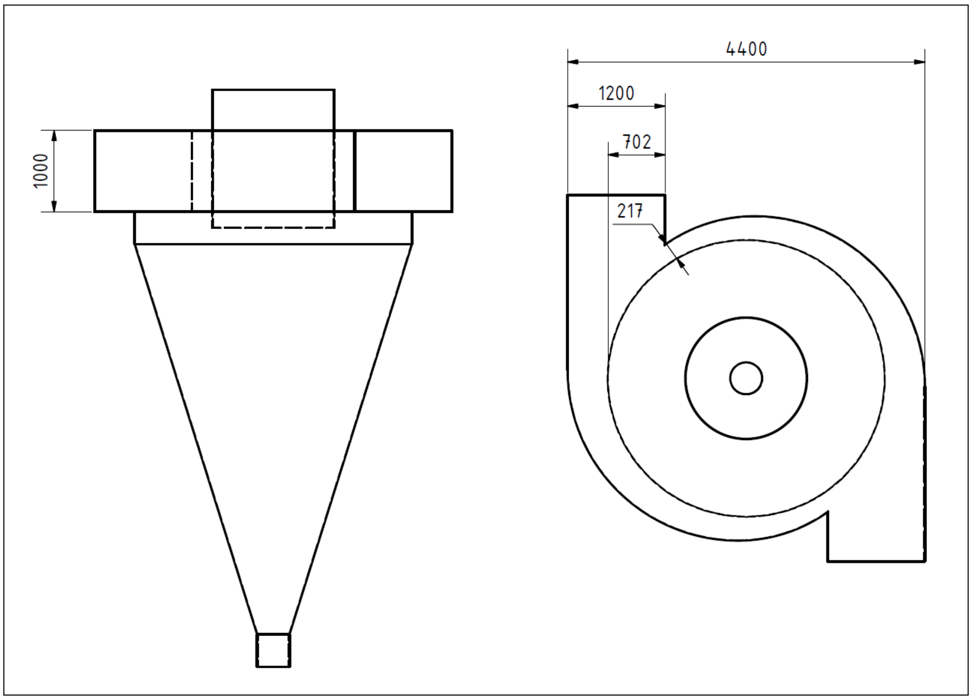

Figure 3-14. Dimensions for cyclone house on Clean Marine's current two-inlet design.

The total width of the two-inlet cyclone is 4 400 mm, the one-inlet cyclone is 4 510 mm for the most narrow version (cyclone 1200). The 1200 cyclone is 110 mm wider and 700 mm higher. Although the one-inlet cyclone is larger than the current design, a lot of space will be spared due to the fact that it has only one inlet.

Chapter 4

CFD Analysis

In this chapter, the analysis method, meshing and simplifications of the physical model, and boundary conditions are described.

For executing the CFD analysis, ANSYS Fluent R17.2 (student version) is used. The student version has a limit of 512 000 nodes/cells.

4.1 Objective

The following are the objectives for the CFD simulation on the chosen cyclone concept:

- Look at the different inlets to see if the width and height ratio has any notable effect on the flow field.
- Estimate total pressure loss in the cyclone.
- To see if the cyclone are able to run on 75%, 50% and 25% capacity while maintaining a vortex.
- Compare the two-inlet cyclone with the proposed one-inlet cyclone.

4.2 Turbulence Model

Turbulent flow is when there is a change of pressure and velocity that causes chaotic behaviour of the fluid, which are identified by swirling patterns, opposed to laminar flow, which is when the fluid has a stable pressure and velocity and flows in parallel layers. Common examples on turbulence is chimney smoke, wake of a ship, or boiling water[37,38].

Reynold's number is a dimensionless number that indicates the state of the flow, where a high Reynold's number means a tendency to turbulent flow and a low number means a tendency to laminar flow. Reynold's number is expressed as follows[37]:

$$Re = \frac{vl}{\nu} \tag{4.1}$$

where:

Re = Reynold's number
v = the fluid's mean velocity (m/s)
l = characteristic length (m)
ν = the fluid's kinematic viscosity (m^2/s)

The critical Reynold's number that distinguishes a laminar and turbulent flow depends on the problem, for example, for internal flow in a low friction circular pipe, the critical Reynold's number is ∼2300, meaning that a the fluid is laminar with a Reynold's number lower than 2300, and turbulent if it is higher[37].

A turbulent model that accurately predicts the flow behaviour while being time-efficient, most be chosen for the simulation. The following are categorization of turbulent models that can be used in ANSYS Fluent and that are evaluated as potential simulation models for the cyclone—the models are listed in order of computational cost[39]:

- One-equation models
  - Spalart-Allmaras
- Two-equation models
  - Standard k-ε
  - RNG k-ε
  - Realizable k-ε
  - Standard k-ω
  - SST k-ω
- Reynolds Stress Model (RSM)
- Detached Eddy Simulation (DES)
- Large Eddy Simulation (LES)

With the exception of the DES and LES models, all models are based on Reynolds-averaged Navier-Stokes (RANS) equations, which are primarily used to describe turbulent flows.

In turbulent flow, velocity components and other variables will randomly fluctuate over time due to a chaotic behavior of the fluid. Instead of mathematically calculating all perturbations (i.e. small changes in the system), which is much more difficult, the equations are time-averaged. Time-averaging will cause some of the fluctuations to be averaged out, which simplifies the calculation[40].

The k-ε model is the most used and validated turbulence model, and can simulate a range of different problems. It does, however, not perform sufficiently with regards to far wakes and mixing layers, and it will have problems with simulating swirling and rotational flows[38].

Large Eddy Simulation is based on the idea to reduce computational cost (compared to direct numerical solution) by separating between large and small length scales—filtering out small scales that are computationally expensive. LES can have a high accuracy, but it demands a high computational cost[38].

The Reynolds Stress Model, also called the second-order closure model, is the most complex of the classical turbulence models. It requires more computational cost than the two-equation models, as it has seven extra partial differential equations compared to the zero-equation models. Reynolds Stress Model is also tougher to converge. RSM is suitable for complex 3D flows and flows with strong swirl/rotation, like cyclones[39,41].

The turbulence model chosen for simulation is the Reynolds Stress Model, which will be solved in a transient state using a pressure-based solver.

4.3 Geometry and Simplifications

The models is created in Autodesk Inventor 2017. It was designed with the dimensions given in figure 3-11 and 3-12. The model was exported to STEP-format which is a supported format in ANSYS Fluent.

It was concluded, in a discussion with NMBU adviser, Odd Ivar Lekang, that the accelerator in the cyclone was to be excluded from the simulation. As the accelerator is patented and owned by Vortex Ecological Technologies, the specific dimensions are not shared with Clean Marine, and if the accelerator were to be dimensioned independently, it would demand a much higher cell count, possibly more than the student version of ANSYS allows. Simulation included with the accelerator would also lead to more inaccurate results and longer simulation time. The accelerator is a core element in Clean Marine's cyclone design, still, a simulation of a "clean" cyclone can still give an indication on its performance.

All spray nozzles and other mechanical components (e.g. hatches, flanges) are also excluded from the CFD model.

4.3.1 Meshing

Meshing the models was done with ANSYS free meshing routine using tetrahedral cells. The following are settings used for all models:

- size function: curvature
- relevance center: fine
- relevance: 20
- smoothing: medium
- max defeature size: 0.005 m
- max tet size: 0.15 m
- max face size: 0.13 m

The size function is set to curvature, which is default for CFD simulations. The size function determines which refinement mechanisms that are activated for the meshing procedure. The curvature function enables minimum element size, max tet size, max face size, growth rate, and curvature normal angle. Adjusted sizes is accounted for in the bullet list above[39].

Relevance center is set to fine, which indicates a fine mesh, and relevance is set to 20, which can be any number between -100 (high speed) and +100 (high accuracy)—this leads to more accurate results, but also longer simulation time[39].

Defeaturing identifies and removes small geometries to prevent poor meshing. It simplifies the model and removes unnecessary details. The maximum defeature size was increased to 0.005 m[42].

Smoothing of a mesh is an attempt to improve the mesh quality by moving nodes with respect to nearby nodes[39]. The smoothing setting is set to medium, which means a "medium" number of smoothing iterations.

Table 4.1. Meshing statistics for the four cyclones used in simulation. Skewness value of >0–0.25 is deemed excellent, 0.25–0.5 good, 0.5–0.75 fair, 0.75–0.9 poor, and 0.9–<1 bad[39].

Cyclone version	Nodes	Elements	Skewness		
			avg.	max.	min.
1200	67 393	354 216	0.23	0.91	~ 0
1400	66 223	348 277	0.23	0.91	~ 0
1600	67 115	352 572	0.23	0.91	~ 0
Two-inlet cyclone	60 543	316 314	0.23	0.84	~ 0

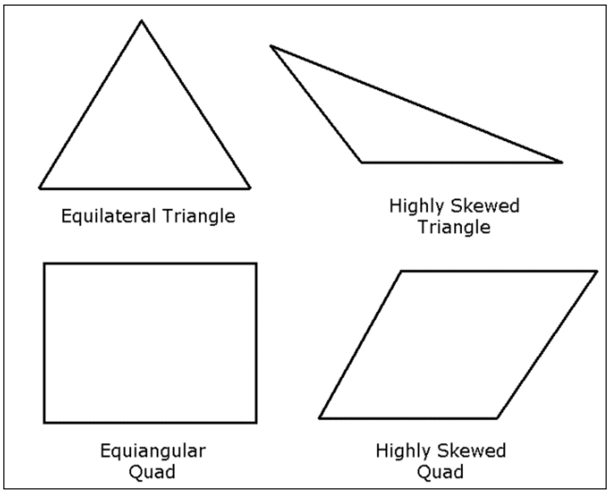

Figure 4-1. Illustration of ideal (left) and skewed (right) cells.

The skewness gives a statistic of the overall quality of the mesh. Highly skewed cells are considered unacceptable because the equations that is solved assumes that the cells are relatively equilateral/equiangular. A skewness value of 0 indicates a perfect cell, while a skewness value of 1 indicates a degenerate cell[39].

Figure 4-2 shows the mesh of cyclone 1200 and locations of refined mesh. To begin with, this locations was meshed with "refined mesh" feature, though this created a fine mesh on the chosen locations, it created an abrupt change to coarser mesh, which is unwanted. Using edge sizing was more successful and created a more even smoothing from fine to coarser mesh.

Meshing procedyre and settings are equal for all cyclones, including the two-inlet cyclone.

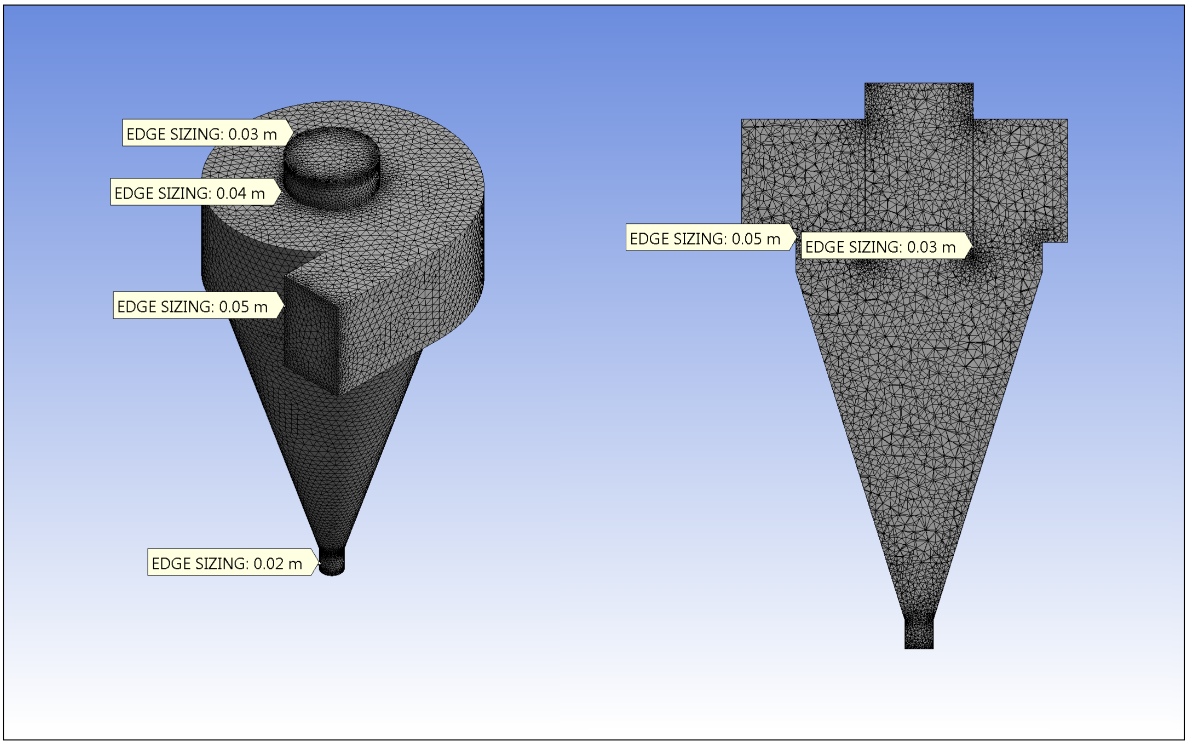

Figure 4-2. Meshing of the 1200 cyclone with isometric view (left) and half-section view (right) with indication of edge sizing locations and sizes.

4.4 Boundary and Initial Conditions

The exhaust is modeled using air properties given in ANSYS Fluent with the change of density as calculated in equation 3.2, which is 0.946 kg/m^3. The fluid is modeled as incompressible and with a constant temperature, but in reality the air density will vary due to cooling and pressure variations. Operation conditions are set as default, with pressure at 101 325 Pa, and gravity is activated and set as -9.81 m/s^2 at the y-axis. The viscosity of the air is set to 1.7894·10^{-5} kg/(s·m).

The velocity inlet condition are used on the inlet(s) with the respective velocity as input. Pressure outlet is used as boundary condition for the exhaust outlet and the static pressure is set to 0 Pa, all other surfaces are set as "wall".

ANSYS Fluent requires specification of transported turbulence quantities. Turbulence intensity and hydraulic diameter is used for the velocity inlet(s) and pressure outlet. For a circular pipe, the hydraulic diameter is equal to the diameter of the pipe, which for the outlet is 1.50 m. For rectangular cross-sections, the hydraulic diameter is calculated using equation 4.2.

$$D_h = \frac{2 \cdot wh}{w + h} \tag{4.2}$$

where:

D_h = hydraulic diameter (m)
w = width of rectangle (m)
h = height of rectangle (m)

Table 4.2. Hydraulic diameter for the inlet with regards to the different cyclones, calculated using equation 4.2.

Cyclone version	Width, a [m]	Height, b [m]	Hydraulic diameter, D_h [m]
1600	1.60	1.29	1.43
1400	1.40	1.47	1.43
1200	1.20	1.71	1.41
Two-inlet	1.20	1.00	1.09

Table 4.2 lists the calculated hydraulic diameters for the different cyclone inlets that is used in the boundary conditions.

Walls are modeled using the standard wall functions.

4.5 Convergence

Simulating complex 3D flows that deals with unstable phenomenon like turbulence can cause convergence issues. The most fundamental measure of the solution's convergence is the residuals. The residuals gives a direct empirical value of the accuracy of the simulation. Low residual values means a better approximation, but this is difficult to achieve with a complex model like a cyclone.

Simulations was tested by varying the time step to see if it had a notable impact on the result. After a flow time of 1.5 seconds, the flow field seem to be stable, and it was therefore chosen to test the simulation with different time step values on the first 1.5 seconds of the simulation. Three test simulations was done with time step 0.1, 0.01, and 0.001, after 1.5 seconds of flow time, the time step was set to 0.1 and the simulation was run until it reached a total flow time of 10 seconds.

The difference between the simulation that had a time step of 0.1 and the one with a time step of 0.001, had a pressure difference, with regards to total pressure in the cell zones, less than 1%. It was therefore chosen to run all simulations with a time step of 0.1 seconds, which is convenient, as it reduces the computational time considerably. All simulations was run on the following solution settings:

- iterations per time step: 40
- time step: 0.1
- total flow time: 10 seconds[1]

4.6 Discrete Phase Model

The discrete phase model, or DPM for short, makes it possible to simulate two-phase flows. DPM uses the Euler-Lagrange approach which is solved by tracking a large number of spherical particles trough the calculated flow field. It is often used for particle-laden flows, water sprays, and combustion. An assumption for the discrete phase model is that it must have a low volume fraction compared to the continuous phase. The volumetric flow rate fraction of the DPM should not exceed 10-12%[39].

[1] The flow time was slightly increased for simulations with lower inlet velocity.

The amount of water that flows through the cyclone is[1]:

- 20 m^3/h which is introduced before the cyclone (3.5%)
- 300 m^3/h which is introduced in the cyclone house (53.6%)
- 240 m^3/h which is introduced on the inside of the cyclone (42.9%)

The total amount of water is 560 m^3/h which is less than 1% of the maximum volumetric gas flow rate. The majority of the water droplets has a size range from 200 µm to 400 µm.

Originally, it was planned to use DPM to account for the water that exists in the exhaust flow to get a closer approximation. Unfortunately, test simulations gave unreliable results when using sizes above ~50 µm, the injected particles will get "stuck" and not get trapped in the water outlet nor escape through the exhaust outlet. As for simulating the gas-liquid separation process, there is no need to simulate to see the effect, particle sizes larger than about 10 µm will give a 100% separation. Water that escapes through the exhaust outlet is most likely due to evaporation and water droplet break-up that causes smaller droplet sizes.

The flow simulation was done as a one-phase simulation, accounting only for the exhaust.

[1] Data given by Clean Marine.

Chapter 5

CFD Results

This chapter accounts for the flow simulation results. At Clean Marine's wish, the flow simulation results focuses on varied capacity on cyclone 1200, and comparing cyclone 1200, 1400, and 1600. Simulation results of the two-inlet cyclone is inclcuded in this chapter for comparisons.

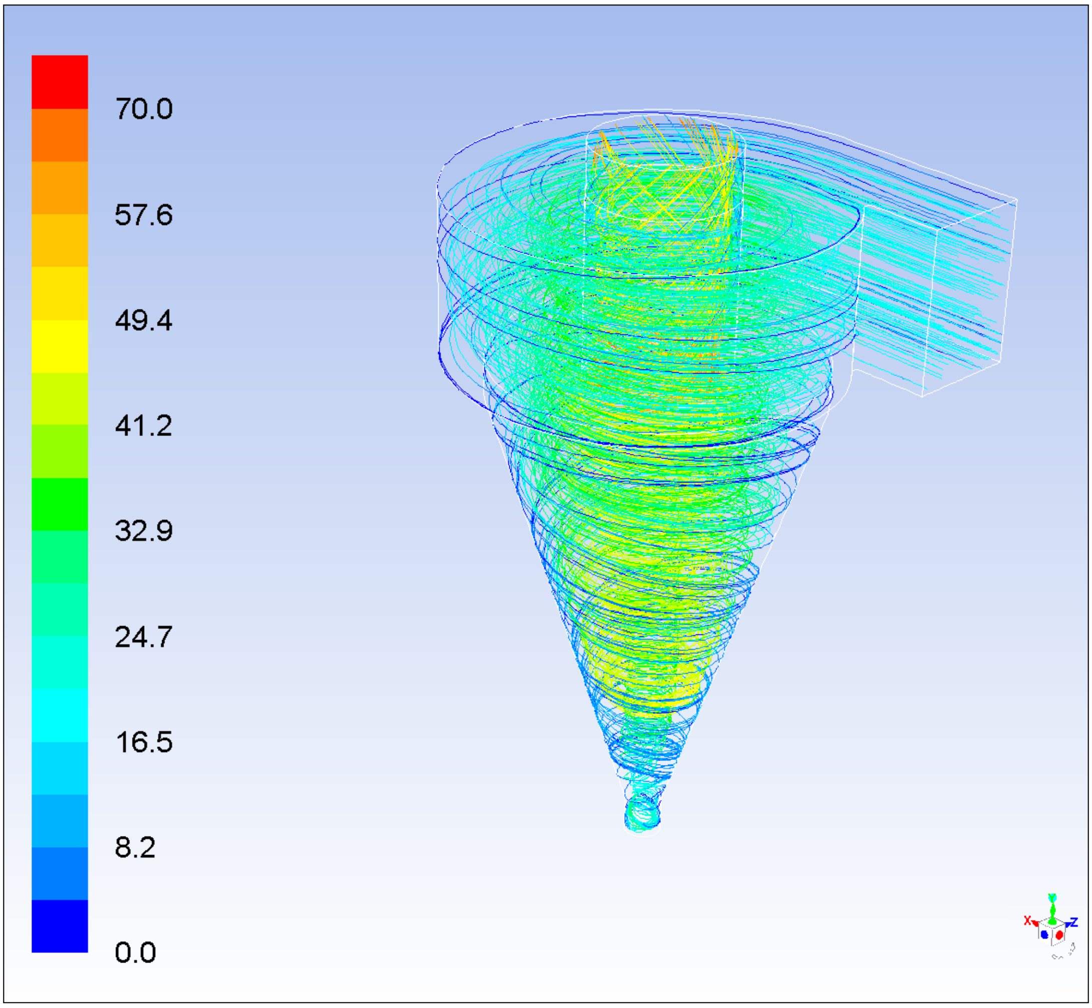

Figure 5-1. Streamlines on cyclone 1200 with inlet velocity of 20 m/s. Colors shows the velocity of the streamlines in m/s.

The streamlines shown in figure 5-1 shows a flow pattern that is expected in a cyclone—a swirling motion of the fluid which develops an inner vortex.

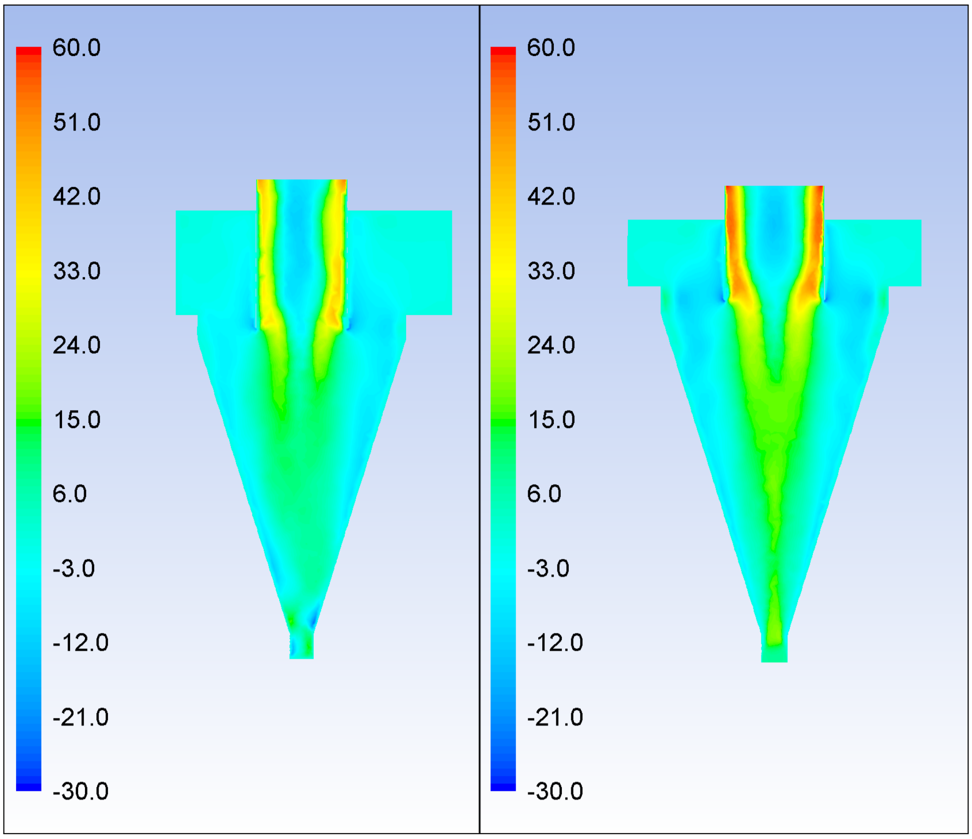

Figure 5-2. Vertical velocity in m/s for one-inlet cyclone 1200 (left) and two-inlet cyclone (right), with an inlet velocity of 20 m/s.

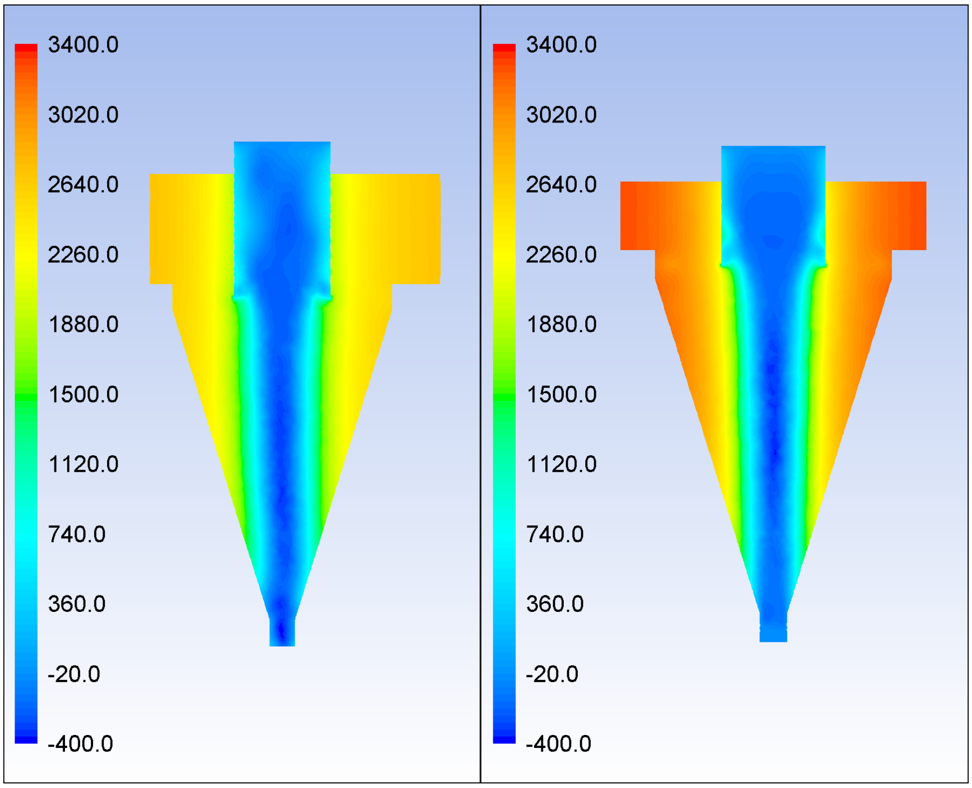

Figure 5-3. Static pressure in Pascal for one-inlet cyclone 1200 (left) and two-inlet cyclone (right), with an inlet velocity of 20 m/s.

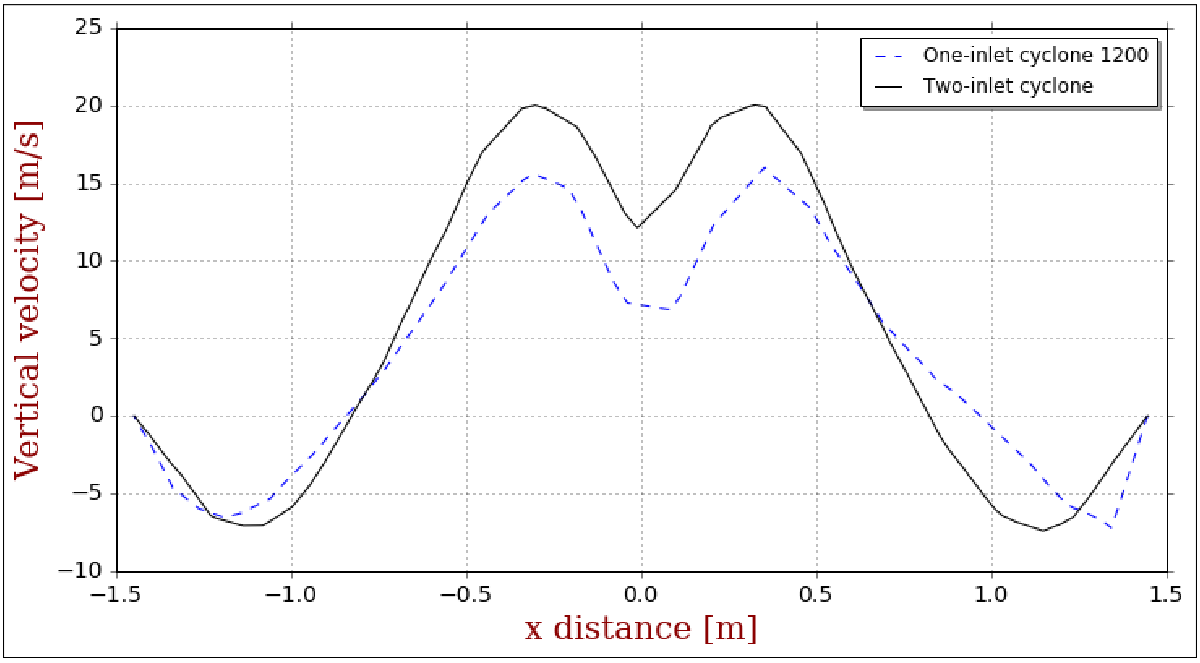

Figure 5-4. Vertical velocity for the two-inlet cyclone and the one-inlet cyclone 1200 with an inlet velocity of 20 m/s. This plot section has been taken 4.4 m above the water outlet, along the x axis, in both cases.

Figure 5-4 shows the difference in vertical velocity between the one-inlet cyclone 1200 and the two-inlet cyclone. The maximum velocity is approximately ±0.4 meters from the center axis. The maximum vertical velocity for the two-inlet cyclone (in this section) is 20 m/s, and the one-inlet cyclone has a vertical velocity of 15 m/s. There is a velocity difference between the two of approximately 5 m/s.

5.1 Varied Capacity and Vortex Identification

Clean Marine worries that when the engines run on a lower load, and the velocity into the cyclones decreases, the vortex will not form and the exhaust exits the cyclone early. This leads to lower contact area between the water and exhaust, which decreases the cleaning efficiency.

For identifying the vortex in the cyclone, the vortex core region feature in CFD post have been used. This tool makes it easy for the user to identify vortex regions. There are different sets of equations that detect vortices which can be used, and all of them are case-dependent—it is up to the analyst to determine which method suits the simulation most. Chosen method is "Swirling strength", which represents the strength of the swirling motion around local centers[39].

Table 5.1. Static inlet pressure on the two-inlet cyclone and one-inlet cyclone 1200 on different inlet velocities.

Inlet velocity [m/s]	One-inlet cyclone 1200 [Pa]	Two-inlet cyclone [Pa]
5	169.5	200.4
10	718.9	815.3
15	1624.6	1865.6
20	2962.7	3338.1

All static inlet pressures (table 5.1 and 5.2) are gathered using the area-weighted surface integral on the cyclone inlets in ANSYS Fluent. The static inlet pressure represents the pressure drop in the cyclone as the static pressure at the outlet is set to 0 Pa.

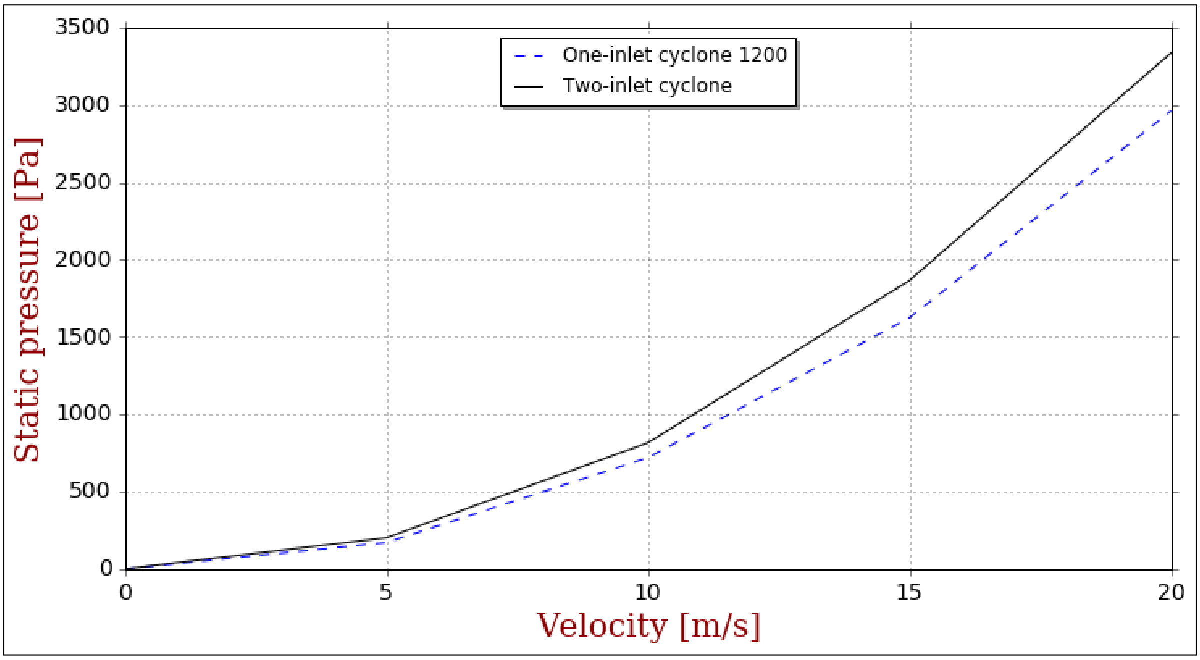

Figure 5-5. Inlet static pressure for one-inlet cyclone 1200 and the two-inlet cyclone on different inlet velocities. Data used from table 5.1.

As illustrated in figure 5-5, the two-inlet cyclone has a higher inlet static pressure than the one-inlet cyclone 1200 on all simulated inlet velocities.

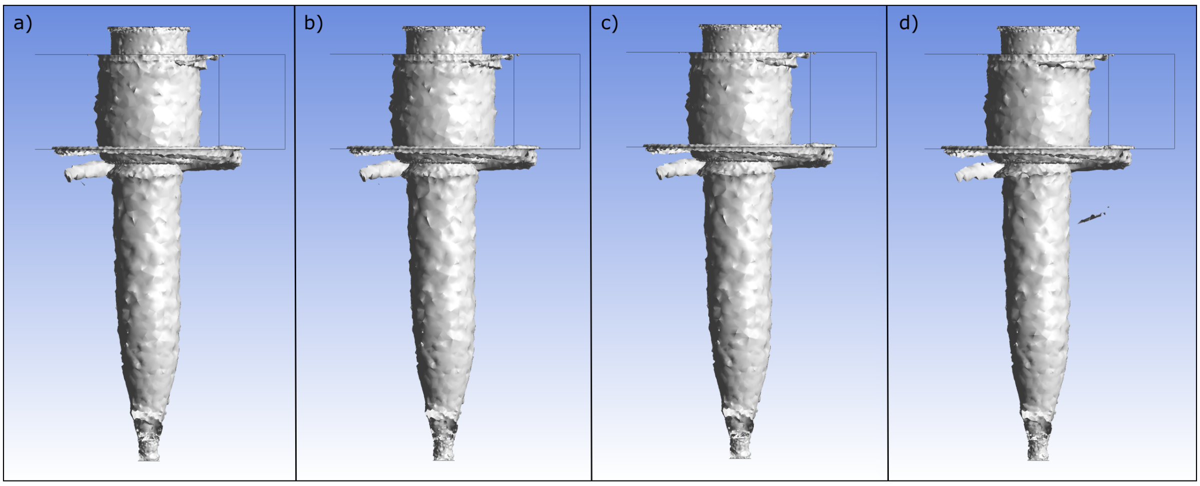

Figure 5-6. Results of vortex core region on cyclone 1200 with different inlet velocities: a) 20 m/s, b) 15 m/s, c) 10 m/s, and d) 5 m/s. The swirling strength of the vortices are: a) 15.01 Hz, b) 11.44 Hz, c) 7.64 Hz, and d) 3.74 Hz.

The vortices is kept almost identical on all four inlet velocities, with varying strength, which is measured in Hertz. This would indicate that the cyclone can run on 25% of maximum capacity while maintaining a vortex. However, this might not be the case in actuality. The reason why is discussed in chapter 6.3.

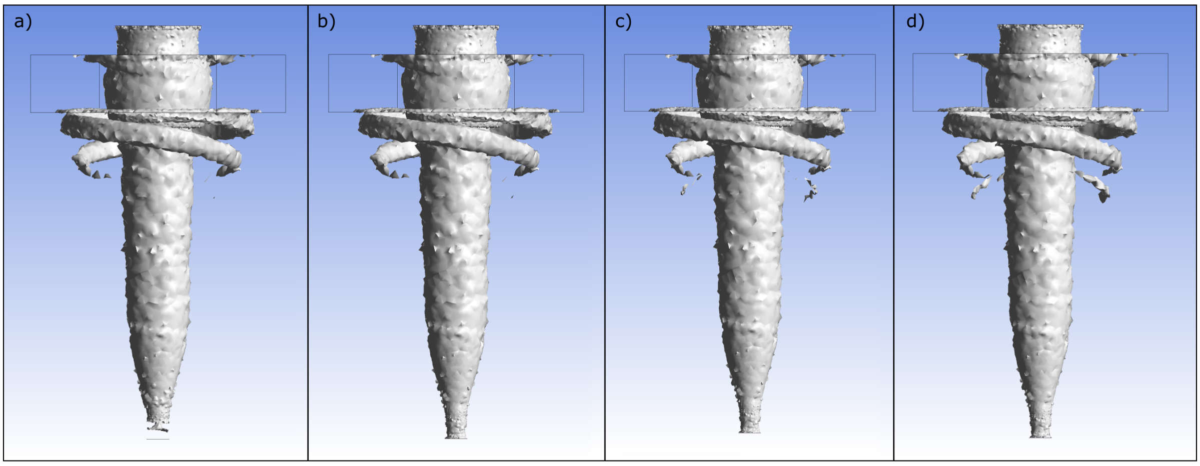

Figure 5-7. Results of vortex core region on two-inlet cyclone with different inlet velocities: a) 20 m/s, b) 15 m/s, c) 10 m/s, and d) 5 m/s. The swirling strength of the vortices are: a) 10.65 Hz, b) 7.99 Hz, c) 5.27 Hz, and d) 2.62 Hz.

As one would expect, there is no apparent difference in the vortices in the two-inlet cyclone compared to the one-inlet cyclone. The swirling strength values presented in the caption in figure 5-7 do differ from the ones for cyclone 1200, but this does not mean that the vortices are weaker in the two-inlet cyclone. The vortices shown is chosen by an arbitrary number in CFD post (0.01 in this case), and the swirling strength are readable values. This arbitrary number can be increased to give the same swirling strength values as cyclone 1200, while maintaining the vortices almost identical.

5.2 Varied Inlets

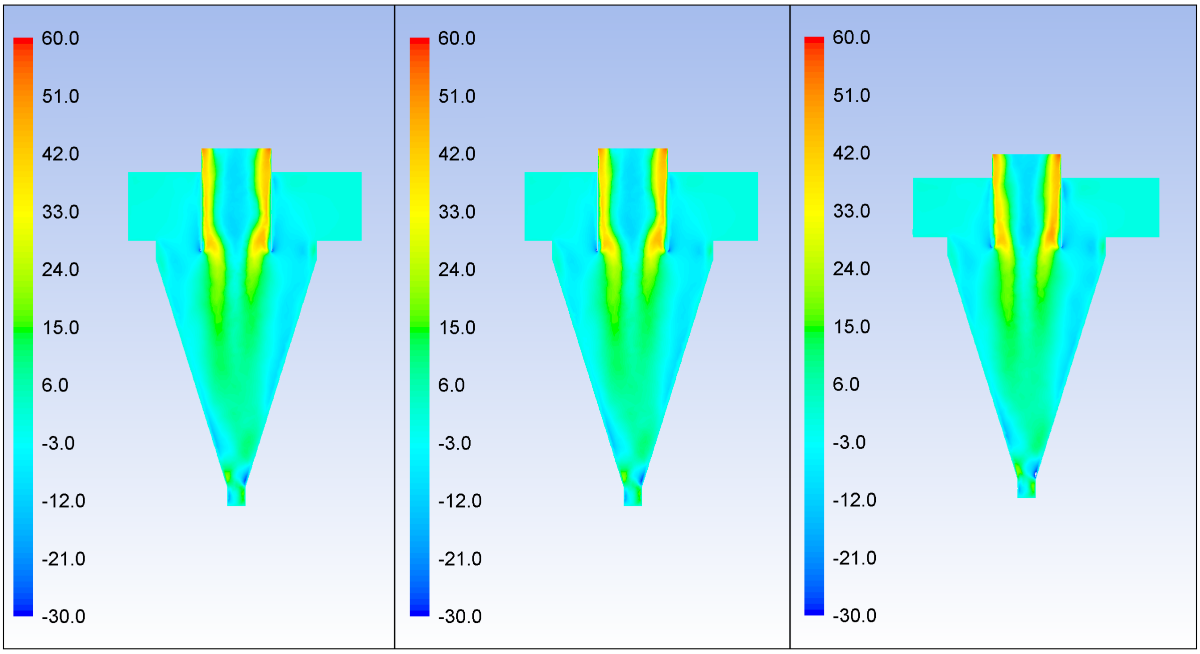

Figure 5-8. Vertical velocity for the three different one-inlet cyclones with an inlet velocity of 20 m/s: cyclone 1200 (left) cyclone 1400 (center), and cyclone 1600 (right).

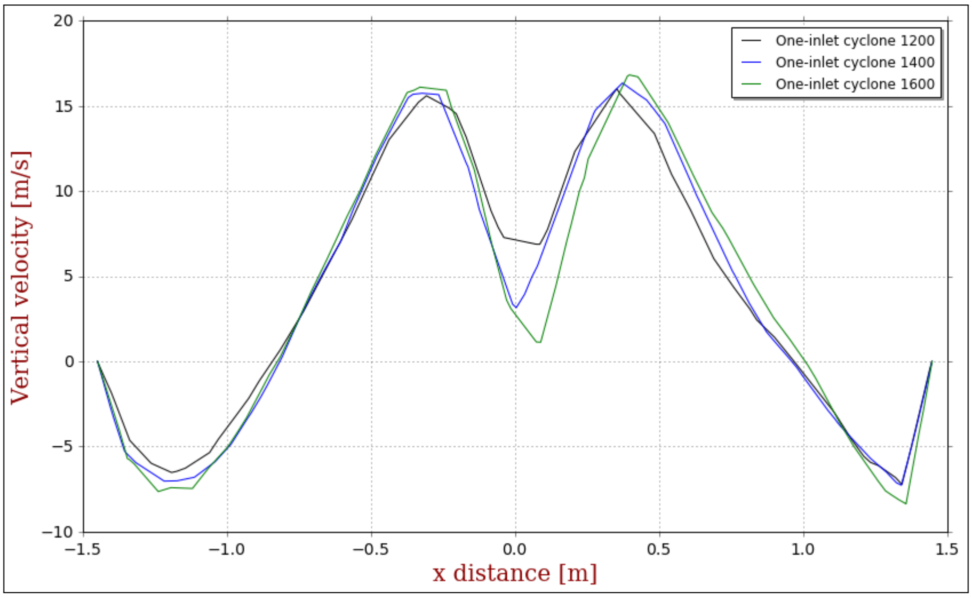

Figure 5-9. Vertical velocity plot for the three different one-inlet cyclones with an inlet velocity of 20 m/s. Plot section is taken 4.4 meters above the water outlet along the x axis (see figure 5-1 for axis reference).

The vertical velocity across the three different one-inlet cyclones is seemingly consistent. Only very small changes occur, which is considered negligible.

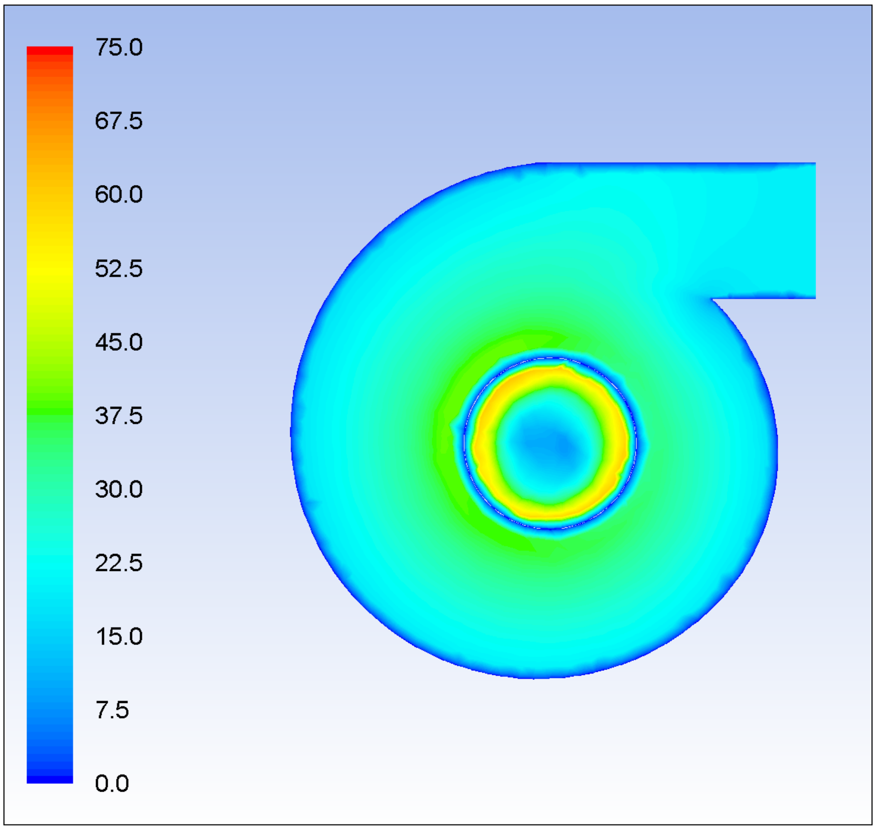

Figure 5-10. Velocity contour of cyclone 1200 with an inlet velocity of 20 m/s.

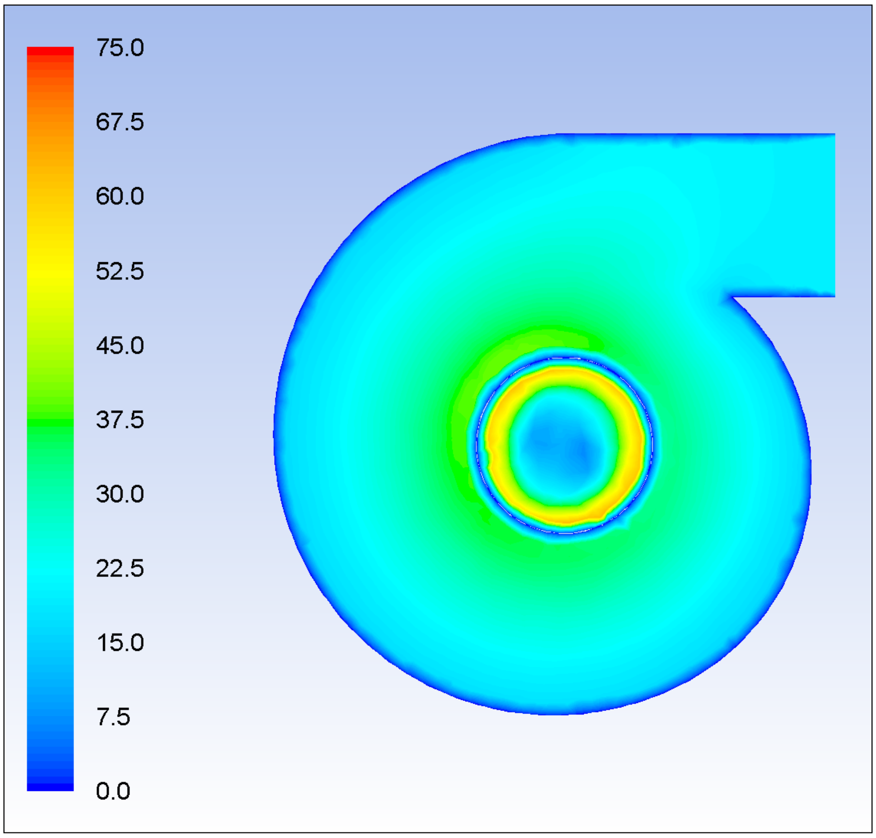

Figure 5-11. Velocity contour of cyclone 1400 with an inlet velocity of 20 m/s.

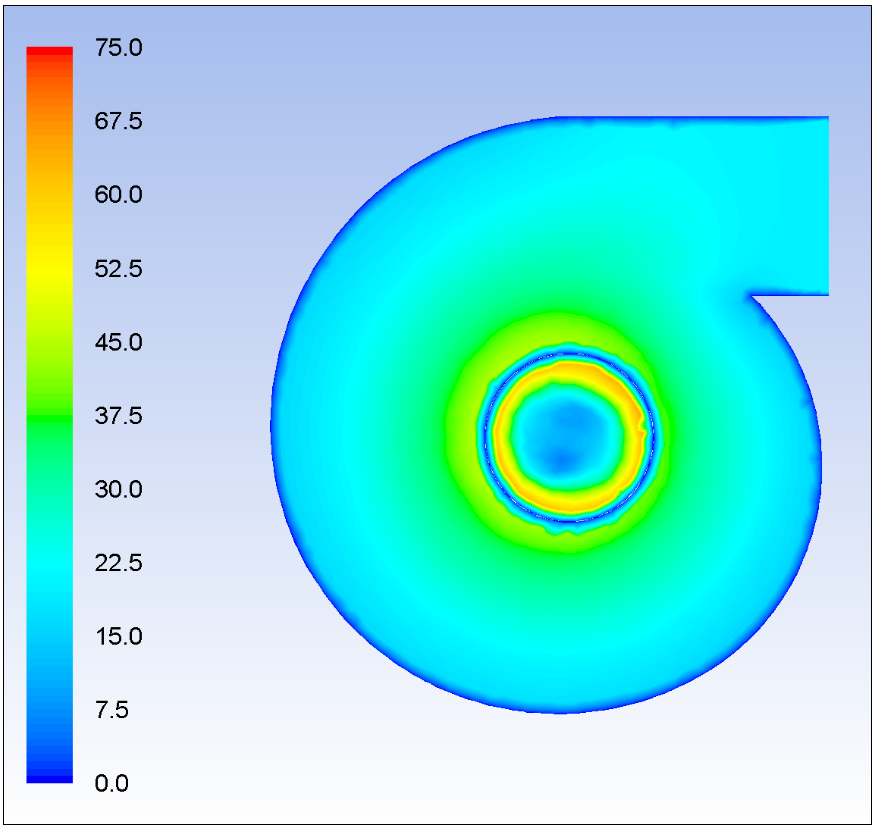

Figure 5-12. Velocity contour of cyclone 1600 with an inlet velocity of 20 m/s.

The velocity contour plots shown in figure 5-10, 5-11 and 5-12, are plotted at the vertical center of the inlets. The differences between cyclone 1200, 1400, and 1600 are insignificant. There are some barely noticeable higher velocities around the vortex finder—cyclone 1600 is slightly more yellow at this area, which indicates a higher velocity.

Table 5.2. Static inlet pressure on one-inlet cyclones with inlet velocity of 20 m/s.

Cyclone version	Inlet static pressure [Pa]
Cyclone 1200	2962.7
Cyclone 1400	2889.7
Cyclone 1600	3084.6

The static inlet pressure on the three different one-inlet cyclones differs with 100-200 Pa.

5.3 Comparison with Measured Data

Clean Marine has measured the pressure drop on an installed 140k[1] system. The two pressure sensors is installed on each inlet of the two-inlet cyclone and the pressure drop has been logged on different occasions. In table 5.3, four pressure measurements is accounted for on different engine loads.

Table 5.3. Pressure measurements on the cyclone inlets on a 140k system. P_1 and P_2 is measurements on the respective inlets, P_{avg} is the average of the measured pressure. The mass flow rate is the exhaust amount into the scrubber, not necessarily into the cyclone. This data is collected from a sea trial report (see appendix C).

Measurement No.	Mass flow rate [kg/h]	Perc. of max flow rate	P_1 [Pa]	P_2 [Pa]	P_{avg} [Pa]
#1	44 125	31.5%	752	800	776
#2	68 105	48.6%	1 053	1 120	1 087
#3	93 966	67.1%	1 624	1 736	1 680
#4	94 729	67.7%	1 655	1 738	1 697

The mass flow rate is provided by the ship crew, and is most likely calculated from measured fuel consumption on the respective engines and boilers. Unfortunately, the gas recirculation valve, which recirculates the gas from the inner pipe and through the system, causes a higher flow rate into the cyclone than what the provided flow rate data indicates. This misconstrues the data as we cannot know the actual flow rate through the cyclone. Data with regards to the regulation of the gas recirculation valve is not included in the log, and if it did, there would be no way of knowing the amount of gas that it recirculates, unless it was to be completely shut.

The only certainty the data in table 5.3 provides is the minimum flow rate into the cyclone. It does, however, provide an *indication* of pressure drop. For instance, measurement No. 4 reports that the pressure drop is ~1 700 Pa when the flow rate is 94 729 kg/h. The actual flow rate is most likely higher, and is probably around 80-90% of the maximum capacity of the

[1] A 140k system is a scrubber that is capable of scrubbing maximum 140 000 kg exhaust per hour.

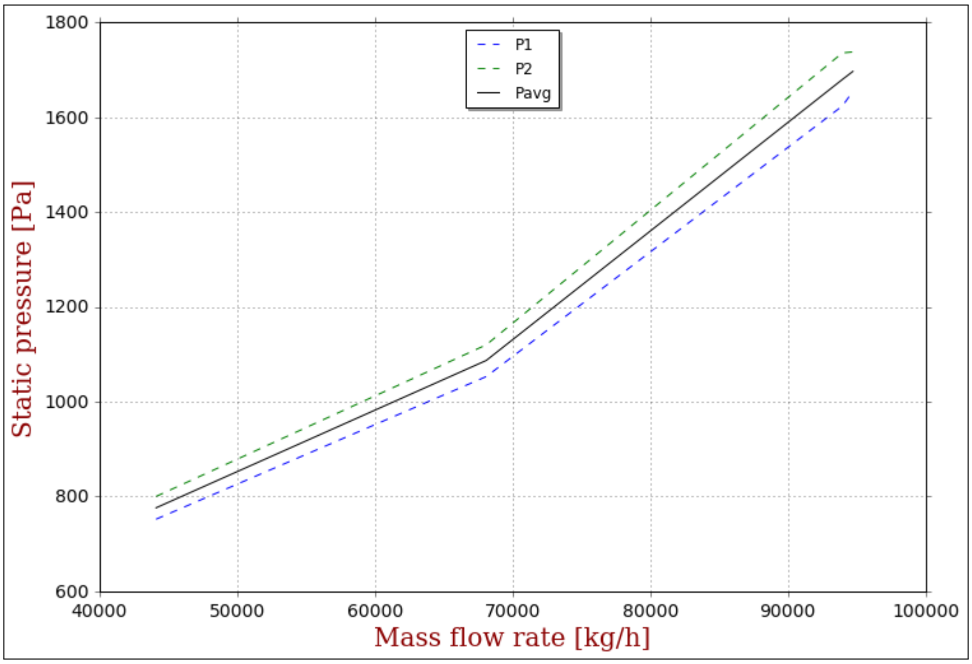

Figure 5-13. Plotted measured pressure values on the two-inlet cyclone from a 140k system. Data is from table 5.3.

scrubber. Therefore, it is assumed that the pressure drop is about 1 700 Pa when the mass flow rate is somewhere in between 112 000-126 000 kg/h.

5.4 Verification

Verifying the results can only be done by comparing the simulation results with key values from experiments. Measured pressure values on the two-inlet cyclone, which is accounted for in chapter 5.3, is the only data which can be used to compare with the CFD analysis.

The accelerator has not been included in the simulation. This means that the measured static inlet pressure, from the installed 140k system, should be higher than the simulated ones (given the same inlet velocity), as it is expected a pressure loss across the accelerator. There's a big uncertainty with regards to the pressure drop according to the actual inlet velocity due to the unknown mass flow rate in the cyclone. The simulated static inlet pressure in the two-inlet cyclone is 3338.1 Pa with an inlet velocity of 20 m/s. Measured data shows an inlet static pressure of ∼1 700 Pa, whereas the inlet velocity can technically be anything from 14 m/s (no gas recirculation) and up to about 20 m/s. Clean Marine claims there is a considerable amount of gas that recirculates the system, which would indicate that the static inlet pressure results from the CFD analysis is too high.

Chapter 6

Discussion

This purpose of this chapter is to interpret the results of the flow simulation and to discuss this research as a whole.

6.1 Objective and Theory

To be able to evaluate the different design concepts and the results of the flow simulation, the theory of this report has been regarding scrubbing theory and scrubbing techniques.

The focus on this thesis has been on phase 2 of the scrubber, the cyclone. It does not resemble any textbook gas absorption equipment. This makes it difficult to connect the theory with the research. Although cyclone separators is a well-known and used concept, it has generally only been used for separating particles from exhaust/air. Some research has been conducted regarding injection of water droplets into the cyclone to enhance the cleaning efficiency of particulates[1], but not with regards to gas absorption.

The cyclone is used to separate the water from the exhaust as well. In most wet scrubbers, water-liquid separation is done with the use of a demister, which is a simple mechanical device that eliminates mist with wired mesh.

This thesis is split into concept development and evaluation, and CFD analysis of chosen concept. This creates some issues with regards to CFD preparation, as the preparation for the CFD, to some extent, cannot begin until concept is chosen. This resulted in less time for the CFD analysis, which could have been used to learn and execute mapped meshing. Which could have led to a higher quality of the mesh.

In retrospect, the objective of the thesis should probably have been more specific. The focus could for instance have been solely on concept and product development or on flow simulation to ensure higher quality of either subject. If it were to be the latter, a concept must in that case have been chosen on beforehand.

6.2 Cyclone Model and Design

The cyclone is designed by Clean Marine, but the critical dimensions, like height and diameter of the cyclone, is provided by their sub-supplier, Vortex Ecological Technologies. How they

[1] An example of research regarding use of water injection in a cyclone separator, is a paper from the Shiraz University in Iran which is titled "Effects of droplet injection on particle separation efficiency of cyclone separators" [43].

dimension the cyclone is unknown. As mentioned earlier, the accelerator used in the cyclone is patented and designed by the same sub-supplier, and the dimensions are not shared with Clean Marine.

The cyclone doesn't resemble any standard cyclone designs, like the Stairmand or Swift cyclone. Cyclone separators are dimensioned according to theoretical cut-off diameter, which defines as the particle diameter which corresponds to a specific cleaning efficiency—usually a cleaning efficiency of 50% [44]. Clean Marine's cyclone doesn't really classify as a cyclone separator, because the main goal is to absorb SO_2. Thus, the question of how the cyclone is dimensioned remains unanswered.

6.3 The CFD Analysis and Results

In a cyclone it is expected that the flow is completely turbulent, but low inlet velocities may cause a flow closer to a laminar flow. This affects the choice of turbulence model.

RSM was used for all simulations, but with an inlet velocity of 5 m/s the Reynold's number for the flow is considerably lower than what it is with an inlet velocity of 20 m/s. Another turbulence model for this case might be a more sensible choice, like the Realizable k-epsilon model or one of the k-omega models. Those turbulence models assumes isotropic turbulent viscosity, which is not really valid for flows with strong swirls, but when the inlet velocity is low enough, this assumption might report a closer approximation than what the Reynolds Stress Model does.

To estimate the minimum velocity that will cause a vortex to develop in the cyclone is difficult. The Reynolds Stress Model promotes swirling motion, so it might show rotational motion in the fluid and create a vortex when it is not the case in actuality. The expectation of how the fluid will behave is important in choosing the correct turbulence model, which is a bit backwards in this case, because this is the information that is wanted from the simulation results.

Meshing the cyclones was done with tetrahedral elements. Tetrahedral elements provided much greater mesh quality when using automated meshing in ANSYS Fluent than the hexahedral elements did. The hexahedral elements produced much larger amount of highly skewed and coarse cells.

Meshing the models with mapped meshing with software like ANSYS ICEM CFD with hexahedral mesh could potentially give a higher quality of the meshed model, and might be the more correct cell type to use in that case. Modeling hexahedral cells do however demand higher meshing skill and is more time consuming.

The results shows that an inlet velocity as low as 5 m/s will develop a full inner vortex. This result is deemed somewhat unreliable, as there is an uncertainty regarding if the chosen turbulence model is a good enough approximation.

The static inlet pressure seems to be higher than measured values. Why this is, is uncertain, but one can speculate that the simulation simulates higher number of swirls than what the actual cyclone would. The higher number of swirls (i.e. the amount of times the fluid rotates the vertical axis), the higher the pressure drop would be due to friction between the fluid layers and the friction between the fluid and the cyclone wall. This may also cause higher fluid velocities, which in return causes higher pressure drop.

Chapter 7

Conclusion

The cleaning efficiency of gases in a wet scrubber is determined by the amount of water injected in relation with the amount of gas, the contact area between the gas and liquid, and the residence time of the gas in the scrubber. The amount of gas dissolved in the water is also dependent on the gas and water temperature, alkalinity in the water, and the partial pressure of the gas.

The cleaning efficiency of particles in a wet scrubber is also determined by the amount of water and the contact area between the gas and liquid, but relative velocities between the water droplets and the exhaust particles do also play a big role in the cleaning efficiency.

The CFD results show no notable difference between the three different one-inlet cyclones. It is therefore concluded that there will be no difference in cleaning efficiency in regard to those cyclones. There is, however, a small difference in pressure drop, but this is deemed to be insignificant, and would probably not be noteworthy in actuality.

The results show a difference in between the two-inlet cyclone and the one-inlet cyclone. The two-inlet cyclone has a higher inlet static pressure, and demonstrates a higher vertical velocity of the fluid, the reason for this is unclear. The vortex core regions results show that the inner vortex is almost indistinguishable between the two. Though, the two-inlet cyclone has a larger formation of vortices in areas besides the inner vortex, especially in the transition from the cyclone house to the cyclone (see figure 5-7). This, and the higher vertical velocities, might be the reason for the larger static pressure in the two-inlet cyclone.

Even though the simulation show some difference between the one-inlet and two-inlet cyclone, it is concluded that differences is not significant for the functionality of the cyclone.

The one-inlet cyclone house will probably have a lower cleaning efficiency than the two-inlet cyclone house, because in the latter there is more space to inject water, the contact area between the gas and liquid will likely be higher in this area. This, however, has nothing to do with the functionality of the cyclone.

It should also be brought to attention that the results from the simulation should only be used as an indication for further research, and not be used as definite answers for important design changes and decisions.

7.1 Further Research

For further research, it is suggested that Clean Marine does 2D simulations on the accelerator and the cyclone house to get a better picture on how the fluid gets distributed on the three different one-inlet cyclones.

Clean Marine should also consider executing pressure measurements on their installed systems with the gas recirculation valve shut. This could for example be incorporated in the procedure on sea trials. This data would give Clean Marine more accurate information on the pressure drop in the cyclone with regards to inlet velocity, which can be useful for further research and development of their scrubber.

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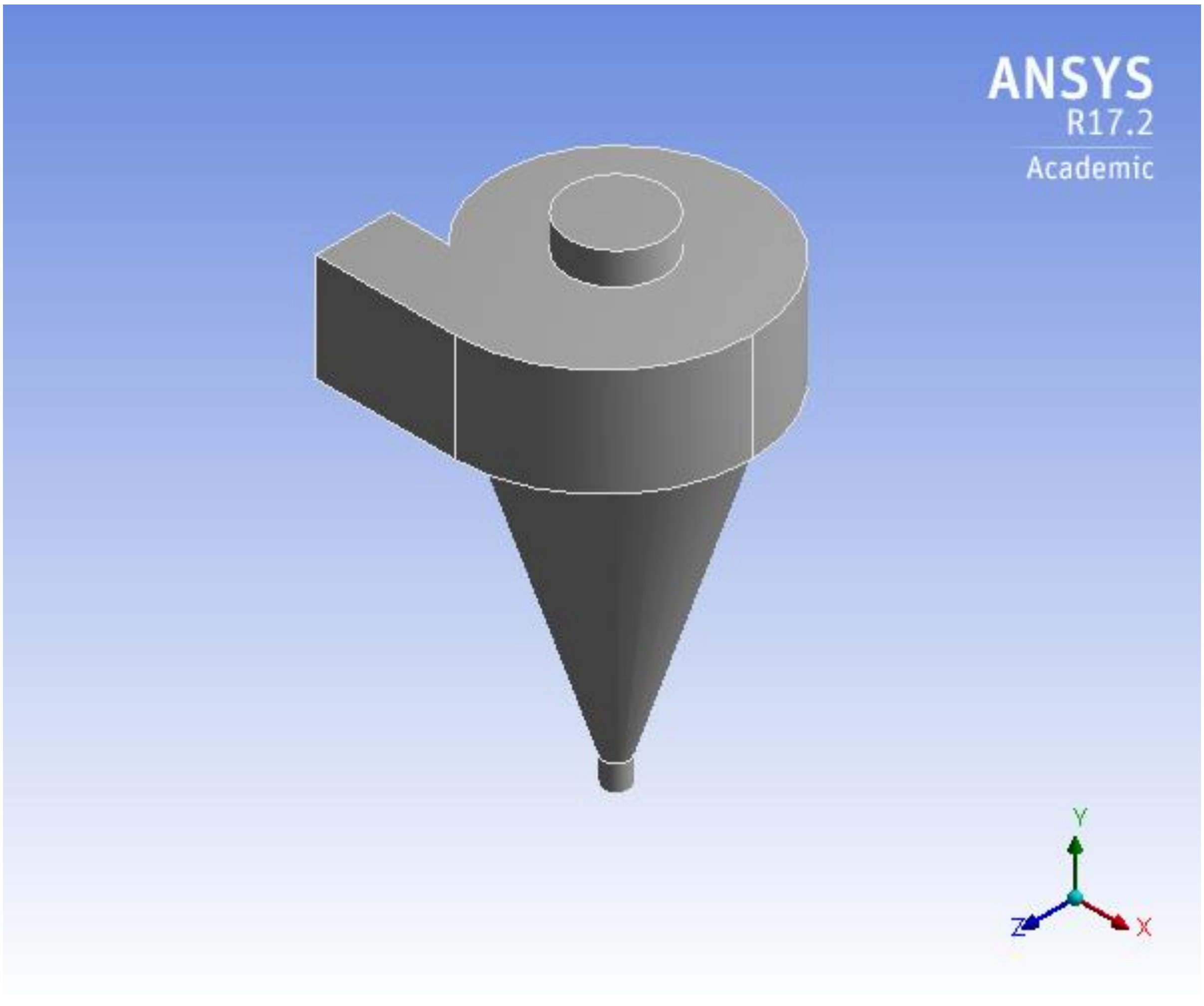
Appendices

Appendix A

Mesh Report for One-Inlet Cyclone 1200

Project

First Saved	Tuesday, April 18, 2017
Last Saved	Saturday, April 22, 2017
Product Version	17.2 Release
Save Project Before Solution	No
Save Project After Solution	No



Contents

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (J3)

Geometry

TABLE 2
Model (J3) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	D:\Masteroppgave - Ansys og Inventor\Konstruksjonsfiler\Proposed cyclone design\regular one inlet\regular one inlet - 1200mm mesh test.stp
Type	Step
Length Unit	Meters
Bounding Box	
Length X	4,553 m
Length Y	7,823 m
Length Z	4,506 m
Properties	
Volume	48,569 m³
Scale Factor Value	1,
Statistics	
Bodies	1
Active Bodies	1
Nodes	71546
Elements	377256
Mesh Metric	Skewness
Min	9,2908969788752E-06
Max	0,903628622873123
Average	0,231152599333135
Standard Deviation	0,126096132338894
Basic Geometry Options	

Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	No
Parameters	Independent
Parameter Key	ANS;DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\mf18\AppData\Local\Temp
Analysis Type	3-D
Mixed Import Resolution	None
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	No

TABLE 3
Model (J3) > Geometry > Parts

Object Name	*regular one inlet - 1200mm mesh test*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Coordinate System	Default Coordinate System
Behavior	None
Reference Frame	Lagrangian
Material	
Fluid/Solid	Defined By Geometry (Solid)
Bounding Box	
Length X	4,553 m
Length Y	7,823 m
Length Z	4,506 m
Properties	
Volume	48,569 m^3
Centroid X	-1,0061e-002 m
Centroid Y	5,1175 m
Centroid Z	0,17748 m
Statistics	
Nodes	71546

Elements	377256
Mesh Metric	Skewness
Min	9,2908969788752E-06
Max	0,903628622873123
Average	0,231152599333135
Standard Deviation	0,126096132338894

Coordinate Systems

TABLE 4
Model (J3) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0,
Origin	
Origin X	0, m
Origin Y	0, m
Origin Z	0, m
Directional Vectors	
X Axis Data	[1, 0, 0,]
Y Axis Data	[0, 1, 0,]
Z Axis Data	[0, 0, 1,]

Mesh

TABLE 5
Model (J3) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	20
Export Format	Standard
Shape Checking	CFD
Target Skewness	Program Controlled
Element Midside Nodes	Dropped
Sizing	
Size Function	Curvature
Relevance Center	Fine
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Fine
Curvature Normal Angle	Default (15,840 °)
Min Size	Default (1,3517e-003 m)
Max Face Size	0,130 m
Max Tet Size	0,150 m

Growth Rate	Default (1,1880)
Automatic Mesh Based Defeaturing	On
Defeature Size	5,e-003 m
Minimum Edge Length	0,902540 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre
View Advanced Options	No
Assembly Meshing	
Method	None
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	
Number of Retries	0
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Triangle Surface Mesher	Program Controlled
Topology Checking	No
Pinch Tolerance	Default (1,2166e-003 m)
Generate Pinch on Refresh	No
Statistics	
Nodes	71546
Elements	377256
Mesh Metric	Skewness
Min	9,2909e-006
Max	0,90363
Average	0,23115
Standard Deviation	0,1261

TABLE 6
Model (J3) > Mesh > Mesh Controls

Object Name	*Edge Sizing*	*Edge Sizing 2*	*Edge Sizing 3*	*Edge Sizing 4*	*Edge Sizing 5*	*Edge Sizing 6*	*Edge Sizing 7*
State	Fully Defined						
Scope							
Scoping Method	Geometry Selection						
Geometry	4 Edges	1 Edge	2 Edges	1 Edge			
Definition							
Suppressed	No						
Type	Element Size						
Element Size	5,e-002 m	3,e-002 m	2,e-002 m	4,e-002 m	3,e-002 m	5,e-002 m	3,e-002 m
Advanced							
Size Function	Uniform						
Behavior	Soft						
Growth Rate	Default (1,1880)						
Bias Type	No Bias						

Named Selections

TABLE 7
Model (J3) > Named Selections > Named Selections

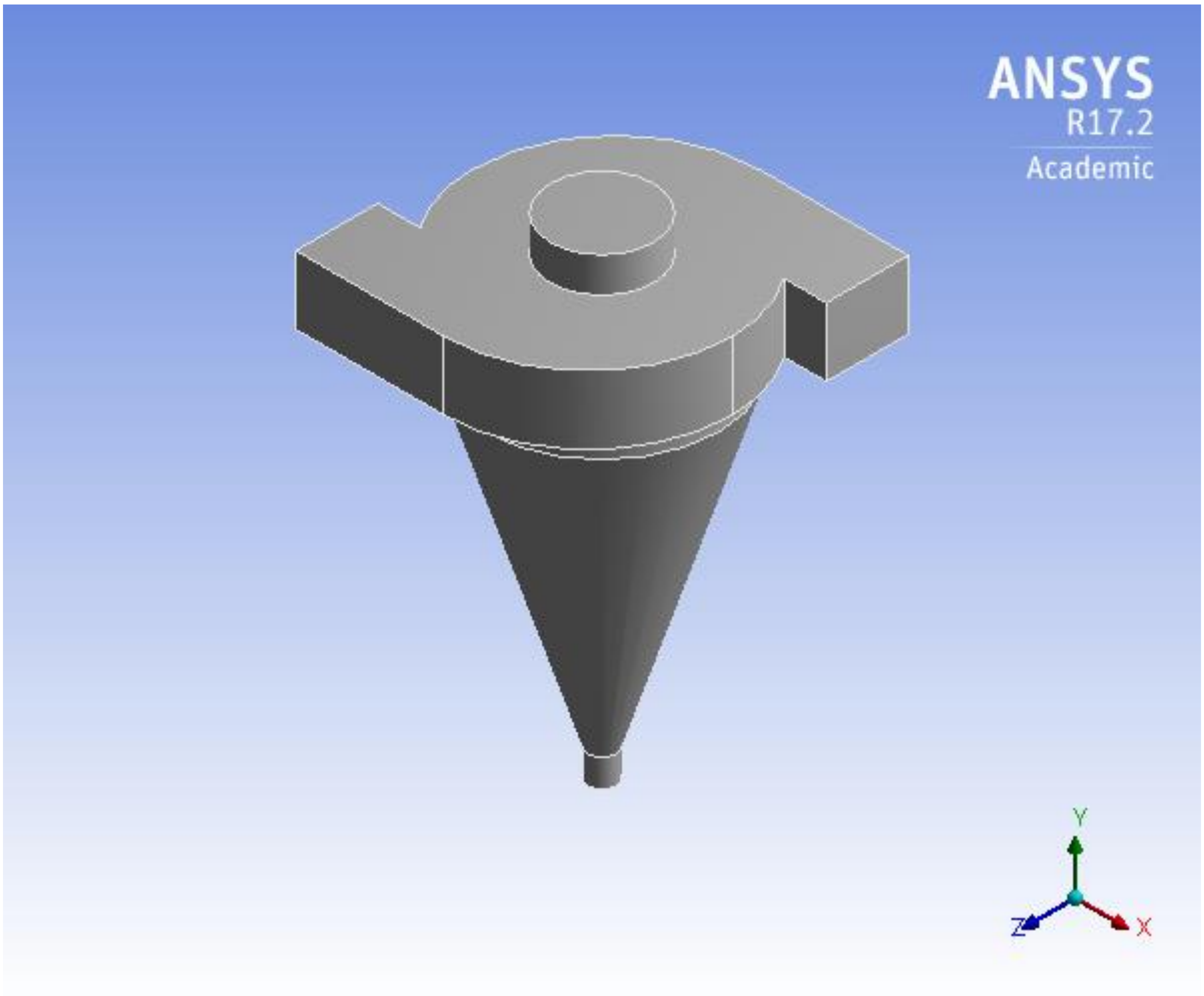
Object Name	*high_flow*	*inlet*	*low_flow*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Face		
Definition			
Send to Solver	Yes		
Visible	Yes		
Program Controlled Inflation	Exclude		
Statistics			
Type	Manual		
Total Selection	1 Face		
Surface Area	1,7284 m²	2,0324 m²	0,11931 m²
Suppressed	0		
Used by Mesh Worksheet	No		

Appendix B

Mesh Report for Two-inlet Cyclone

Project

Author	Olav Andreas Kaasa Hammer
Subject	Two inlet cyclone
First Saved	Friday, February 10, 2017
Last Saved	Wednesday, April 26, 2017
Product Version	17.2 Release
Save Project Before Solution	No
Save Project After Solution	No



Contents

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (A3)

Geometry

TABLE 2
Model (A3) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	D:\Masteroppgave - Ansys og Inventor\Konstruksjonsfiler\Current cyclone skeleton\two-inlet skeleton - 154k new.stp
Type	Step
Length Unit	Meters
Bounding Box	
Length X	4,512 m
Length Y	7,11 m
Length Z	4,39 m
Properties	
Volume	36,876 m³
Scale Factor Value	1,
Statistics	
Bodies	1
Active Bodies	1
Nodes	60543
Elements	316314
Mesh Metric	Skewness
Min	1,55601468601052E-05
Max	0,835855390060997
Average	0,228731904584839
Standard Deviation	0,122137885607399
Basic Geometry Options	

Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	No
Parameters	Independent
Parameter Key	ANS;DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\mf18\AppData\Local\Temp
Analysis Type	3-D
Mixed Import Resolution	None
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	No

TABLE 3
Model (A3) > Geometry > Parts

Object Name	*two-inlet skeleton*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Coordinate System	Default Coordinate System
Behavior	None
Reference Frame	Lagrangian
Material	
Fluid/Solid	Defined By Geometry (Solid)
Bounding Box	
Length X	4,512 m
Length Y	7,11 m
Length Z	4,39 m
Properties	
Volume	36,876 m³
Centroid X	3,4552e-004 m
Centroid Y	5,0487 m
Centroid Z	4,0177e-004 m
Statistics	
Nodes	60543
Elements	316314

Mesh Metric	Skewness
Min	1,55601468601052E-05
Max	0,835855390060997
Average	0,228731904584839
Standard Deviation	0,122137885607399

Coordinate Systems

TABLE 4
Model (A3) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0,
Origin	
Origin X	0, m
Origin Y	0, m
Origin Z	0, m
Directional Vectors	
X Axis Data	[1, 0, 0,]
Y Axis Data	[0, 1, 0,]
Z Axis Data	[0, 0, 1,]

Mesh

TABLE 5
Model (A3) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	20
Export Format	Standard
Shape Checking	CFD
Target Skewness	Program Controlled
Element Midside Nodes	Dropped
Sizing	
Size Function	Curvature
Relevance Center	Fine
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Fine
Curvature Normal Angle	Default (15,840 °)
Min Size	1,e-003 m
Max Face Size	0,130 m
Max Tet Size	0,150 m
Growth Rate	Default (1,1880)

Automatic Mesh Based Defeaturing	On
Defeature Size	5,e-003 m
Minimum Edge Length	0,616520 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre
View Advanced Options	No
Assembly Meshing	
Method	None
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	
Number of Retries	0
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Triangle Surface Mesher	Program Controlled
Topology Checking	No
Pinch Tolerance	Default (9,e-004 m)
Generate Pinch on Refresh	No
Statistics	
Nodes	60543
Elements	316314
Mesh Metric	Skewness
Min	1,556e-005
Max	0,83586
Average	0,22873
Standard Deviation	0,12214

TABLE 6
Model (A3) > Mesh > Mesh Controls

Object Name	*Edge Sizing*	*Edge Sizing 2*	*Edge Sizing 3*	*Edge Sizing 4*	*Edge Sizing 5*	*Edge Sizing 6*	*Edge Sizing 7*
State	Fully Defined						
Scope							
Scoping Method	Geometry Selection						
Geometry	8 Edges	1 Edge	2 Edges	1 Edge			
Definition							
Suppressed	No						
Type	Element Size						
Element Size	5,e-002 m	3,e-002 m	2,e-002 m	3,e-002 m	Default (0,13 m)	5,e-002 m	4,e-002 m
Advanced							
Size Function	Uniform						
Behavior	Soft						
Growth Rate	Default (1,1880)						
Bias Type	No Bias						

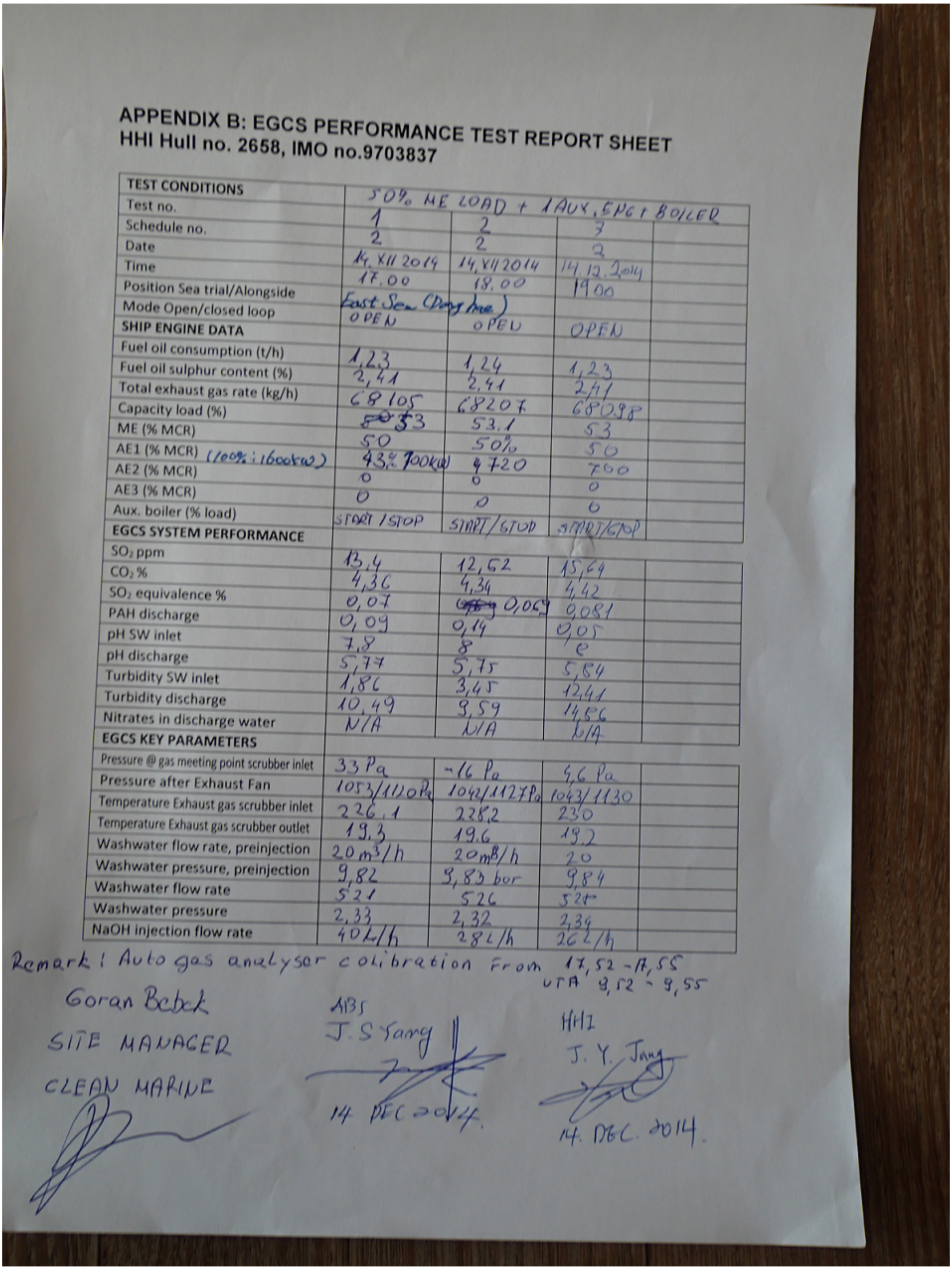
Named Selections

TABLE 7
Model (A3) > Named Selections > Named Selections

Object Name	*inlet*	*high_flow_outlet*	*low_flow_outlet*	*inlet2*
State	Fully Defined			
Scope				
Scoping Method	Geometry Selection			
Geometry	1 Face			
Definition				
Send to Solver	Yes			
Visible	Yes			
Program Controlled Inflation	Exclude			
Statistics				
Type	Manual			
Total Selection	1 Face			
Surface Area	1,1781 m²	1,7238 m²	0,1181 m²	1,1781 m²
Suppressed	0			
Used by Mesh Worksheet	No			

Appendix C

Sea Trial Report



APPENDIX B: EGCS PERFORMANCE TEST REPORT SHEET
HHI Hull no. 2658, IMO no.9703837

TEST CONDITIONS	50% ME LOAD + 1 AUX, ENG + BOILER			
Test no.	1	2	3	
Schedule no.	2	2	2	
Date	14. XII 2014	14, XII 2014	14.12.2014	
Time	17.00	18.00	1900	
Position Sea trial/Alongside	East Sea (Dong hae)			
Mode Open/closed loop	OPEN	OPEN	OPEN	
SHIP ENGINE DATA				
Fuel oil consumption (t/h)	1,23	1,24	1,23	
Fuel oil sulphur content (%)	2,41	2,41	2,41	
Total exhaust gas rate (kg/h)	68105	68207	68098	
Capacity load (%)	~~80~~ 53	53,1	53	
ME (% MCR)	50	50%	50	
AE1 (% MCR) (100% : 1600kW)	43% 700kW	4 720	700	
AE2 (% MCR)	0	0	0	
AE3 (% MCR)	0	0	0	
Aux. boiler (% load)	START / STOP	START / STOP	START / STOP	
EGCS SYSTEM PERFORMANCE				
SO_2 ppm	13,4	12,52	15,64	
CO_2 %	4,36	4,34	4,42	
SO_2 equivalence %	0,07	~~[illegible]~~ 0,069	0,081	
PAH discharge	0,09	0,14	0,05	
pH SW inlet	7,8	8	8	
pH discharge	5,77	5,75	5,84	
Turbidity SW inlet	1,86	3,45	12,41	
Turbidity discharge	10,49	9,59	14,56	
Nitrates in discharge water	N/A	N/A	N/A	
EGCS KEY PARAMETERS				
Pressure @ gas meeting point scrubber inlet	33 Pa	-16 Pa	4,6 Pa	
Pressure after Exhaust Fan	1053/1120 Pa	1042/1127 Pa	1043/1130	
Temperature Exhaust gas scrubber inlet	226,1	228,2	230	
Temperature Exhaust gas scrubber outlet	19,3	19.6	19.2	
Washwater flow rate, preinjection	20 m³/h	20 m³/h	20	
Washwater pressure, preinjection	9,82	9,83 bar	9,84	
Washwater flow rate	521	526	525	
Washwater pressure	2,33	2,32	2,34	
NaOH injection flow rate	40 L/h	28 L/h	26 L/h	

Remark! Auto gas analyser calibration from 17,52 - 17,55
UTA 9,52 - 9,55

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14 DEC 2014.

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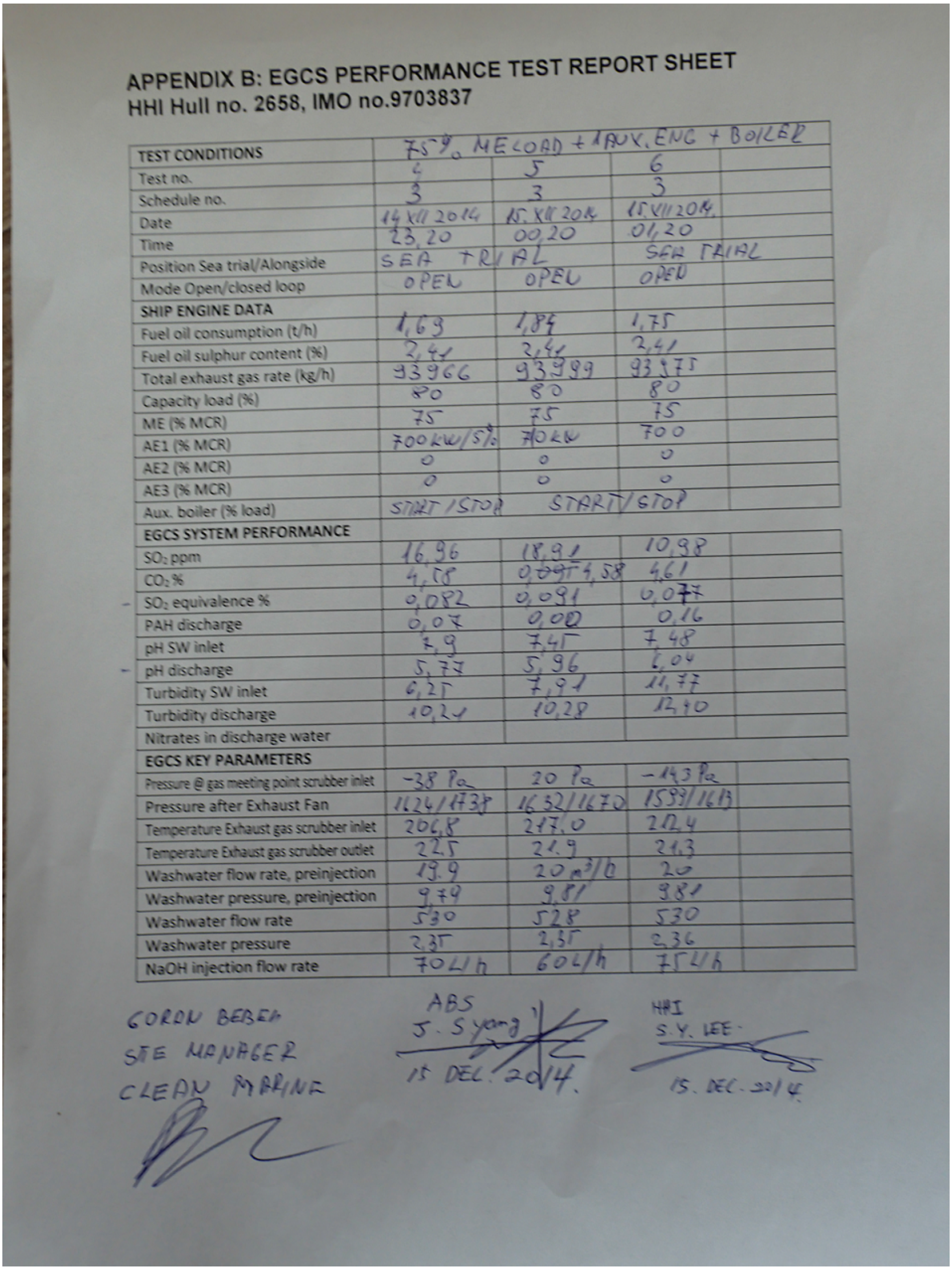
Figure C-1. EGCS performance sheet 1.



APPENDIX B: EGCS PERFORMANCE TEST REPORT SHEET
HHI Hull no. 2658, IMO no.9703837

TEST CONDITIONS	75 % ME LOAD + 1 AUX. ENG + BOILER			
Test no.	4	5	6	
Schedule no.	3	3	3	
Date	14 XII 2014	15. XII 2014	15. XII 2014	
Time	23,20	00,20	01,20	
Position Sea trial/Alongside	SEA TRIAL		SEA TRIAL	
Mode Open/closed loop	OPEN	OPEN	OPEN	
SHIP ENGINE DATA				
Fuel oil consumption (t/h)	1,69	1,84	1,75	
Fuel oil sulphur content (%)	2,41	2,41	2,41	
Total exhaust gas rate (kg/h)	93966	93999	93975	
Capacity load (%)	80	80	80	
ME (% MCR)	75	75	75	
AE1 (% MCR)	700kW/5%	710kW	700	
AE2 (% MCR)	0	0	0	
AE3 (% MCR)	0	0	0	
Aux. boiler (% load)	START/STOP	START/STOP		
EGCS SYSTEM PERFORMANCE				
SO_2 ppm	16,96	18,91	10,98	
CO_2 %	4,58	~~0,091~~ 4,58	4,61	
SO_2 equivalence %	0,082	0,091	0,077	
PAH discharge	0,07	0,00	0,16	
pH SW inlet	7,9	7,45	7,48	
pH discharge	5,77	5,96	6,04	
Turbidity SW inlet	6,25	7,91	11,77	
Turbidity discharge	10,21	10,28	12,40	
Nitrates in discharge water				
EGCS KEY PARAMETERS				
Pressure @ gas meeting point scrubber inlet	-38 Pa	20 Pa	-143 Pa	
Pressure after Exhaust Fan	1624/1738	1632/1670	1599/1613	
Temperature Exhaust gas scrubber inlet	206,8	217,0	212,4	
Temperature Exhaust gas scrubber outlet	22,5	21,9	21,3	
Washwater flow rate, preinjection	19.9	20 m³/h	20	
Washwater pressure, preinjection	9,79	9,81	9,81	
Washwater flow rate	530	528	530	
Washwater pressure	2,35	2,35	2,36	
NaOH injection flow rate	70 L/h	60 L/h	75 L/h	

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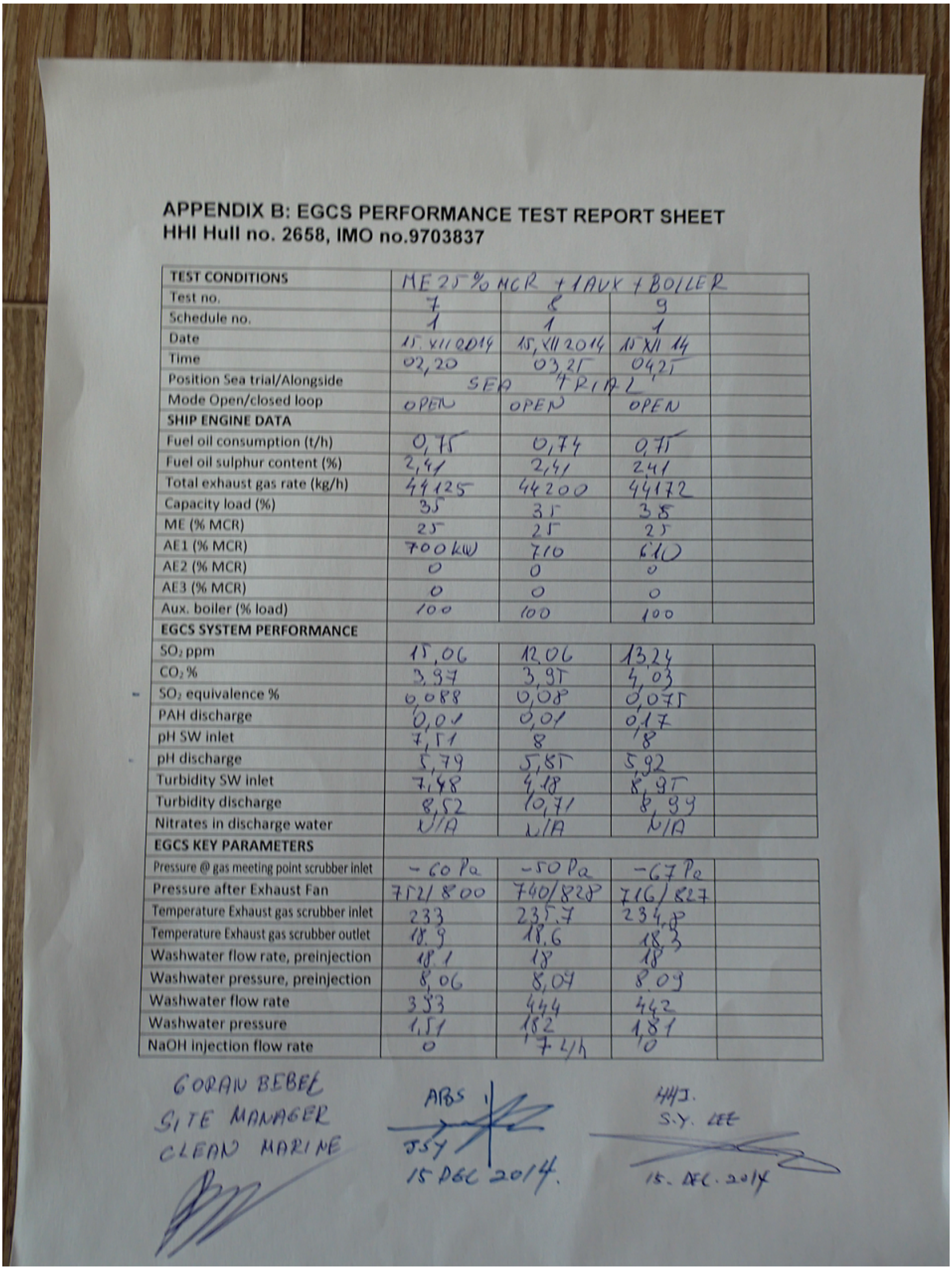
Figure C-2. EGCS performance sheet 2.



APPENDIX B: EGCS PERFORMANCE TEST REPORT SHEET
HHI Hull no. 2658, IMO no.9703837

TEST CONDITIONS	ME 25% MCR + 1 AUX + BOILER			
Test no.	7	8	9	
Schedule no.	1	1	1	
Date	15. XII 2014	15, XII 2014	15 XII 14	
Time	02,20	03,25	04,25	
Position Sea trial/Alongside	SEA TRIAL			
Mode Open/closed loop	OPEN	OPEN	OPEN	
SHIP ENGINE DATA				
Fuel oil consumption (t/h)	0,75	0,74	0,75	
Fuel oil sulphur content (%)	2,41	2,41	2,41	
Total exhaust gas rate (kg/h)	44125	44200	44172	
Capacity load (%)	35	35	35	
ME (% MCR)	25	25	25	
AE1 (% MCR)	700 kW	710	610	
AE2 (% MCR)	0	0	0	
AE3 (% MCR)	0	0	0	
Aux. boiler (% load)	100	100	100	
EGCS SYSTEM PERFORMANCE				
SO_2 ppm	15,06	12,06	13,24	
CO_2 %	3,97	3,95	4,03	
SO_2 equivalence %	0,088	0,08	0,075	
PAH discharge	0,01	0,01	0,17	
pH SW inlet	7,51	8	8	
pH discharge	5,79	5,85	5,92	
Turbidity SW inlet	7,48	4,18	8,95	
Turbidity discharge	8,52	10,71	8,99	
Nitrates in discharge water	N/A	N/A	N/A	
EGCS KEY PARAMETERS				
Pressure @ gas meeting point scrubber inlet	-60 Pa	-50 Pa	-67 Pa	
Pressure after Exhaust Fan	752/800	740/828	716/827	
Temperature Exhaust gas scrubber inlet	233	235,7	234,8	
Temperature Exhaust gas scrubber outlet	18,9	18,6	18,3	
Washwater flow rate, preinjection	18,1	18	18	
Washwater pressure, preinjection	8,06	8,07	8,09	
Washwater flow rate	353	444	442	
Washwater pressure	1,51	1,82	1,81	
NaOH injection flow rate	0	7 L/h	0	

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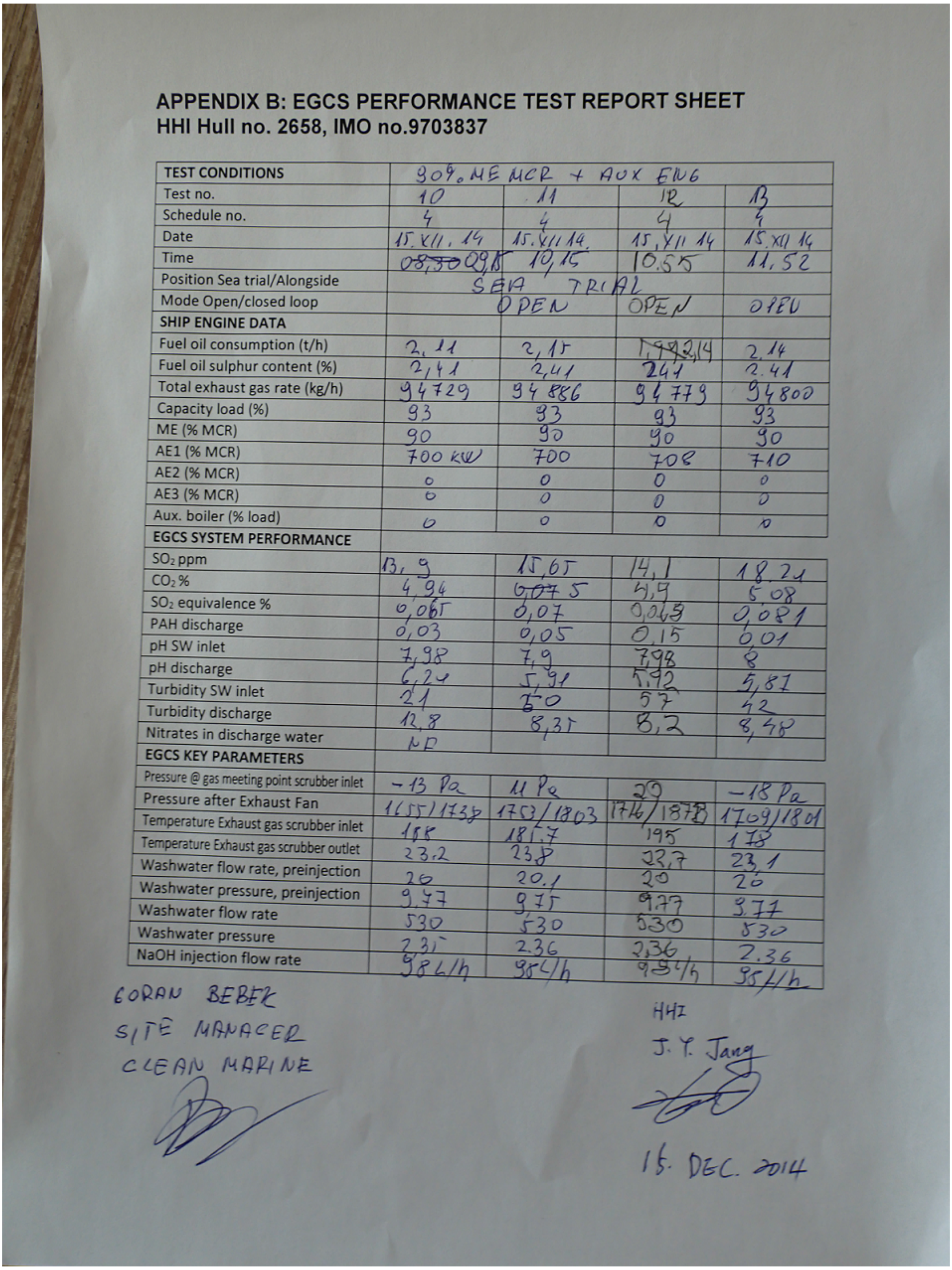
Figure C-3. EGCS performance sheet 3.



APPENDIX B: EGCS PERFORMANCE TEST REPORT SHEET
HHI Hull no. 2658, IMO no.9703837

TEST CONDITIONS	90% ME MCR + AUX ENG			
Test no.	10	11	12	13
Schedule no.	4	4	4	4
Date	15.XII.14	15.XII.14.	15,XII 14	15.XII 14
Time	~~08,30~~ 09,15	10,15	10.55	11,52
Position Sea trial/Alongside	SEA TRIAL			
Mode Open/closed loop		OPEN	OPEN	OPEN
SHIP ENGINE DATA				
Fuel oil consumption (t/h)	2,11	2,15	~~1,99~~ 2,14	2,14
Fuel oil sulphur content (%)	2,41	2,41	241	2.41
Total exhaust gas rate (kg/h)	94729	94 886	94 779	94800
Capacity load (%)	93	93	93	93
ME (% MCR)	90	90	90	90
AE1 (% MCR)	700 kW	700	708	710
AE2 (% MCR)	0	0	0	0
AE3 (% MCR)	0	0	0	0
Aux. boiler (% load)	0	0	0	0
EGCS SYSTEM PERFORMANCE				
SO_2 ppm	13,9	15,65	14,1	18,21
CO_2 %	4,94	~~6,07~~ 5	4,9	5,08
SO_2 equivalence %	0,065	0,07	0,063	0,081
PAH discharge	0,03	0,05	0,15	0,01
pH SW inlet	7,98	7,9	7,98	8
pH discharge	6,24	5,91	5,92	5,81
Turbidity SW inlet	21	50	57	42
Turbidity discharge	12,8	8,35	8,2	8,48
Nitrates in discharge water	ND			
EGCS KEY PARAMETERS				
Pressure @ gas meeting point scrubber inlet	-13 Pa	11 Pa	29	-18 Pa
Pressure after Exhaust Fan	1655/1738	1753/1803	1746/1878	1709/1801
Temperature Exhaust gas scrubber inlet	188	181,7	195	178
Temperature Exhaust gas scrubber outlet	23.2	23,8	23,7	23,1
Washwater flow rate, preinjection	20	20.1	20	20
Washwater pressure, preinjection	9,47	9,75	9,77	9,77
Washwater flow rate	530	530	530	530
Washwater pressure	2,35	2.36	2,36	2.36
NaOH injection flow rate	98 L/h	95 L/h	95 L/h	95 L/h

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16. DEC. 2014

Figure C-4. EGCS performance sheet 4.

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