NTNU
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The Compact Separation Laboratory

Design and Engineering of Phase 2

Sindre Nordås Fotland
Daniel Børsheim Hjørnevik

Subsea Technology
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Supervisor: Christian Holden, MTP

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

NTNU

Faculty of Engineering

Department of Mechanical
and Industrial Engineering

MASTER'S THESIS

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Oil and gas fields produce significant amounts of water as an unwanted by-product. This is especially significant in brown (old) fields; the percentage of water produced (the water cut) increases with the age of the field.

The increased water cut necessitates new solutions for water treatment offshore, and installations that can be used sub-sea rather than on platform have been of increasing interest in the oil and gas industry in recent years. However, there are still major scientific and technical challenges to overcome.

To study and improve the efficiency of compact separators, the Department of Mechanical and Industrial Engineering are constructing a small-scale laboratory. In this project, the students will complete the design of the Phase 2 expansion of the laboratory. Originally planned was a compact flotation unit (CFU); the project scope has expanded to also include a gas-liquid cylindrical cyclone (GLCC) and a scrubber vessel.

The main objectives of this thesis are:

1. Finalize engineering of Phase 2 components
    a) CFU, GLCC and scrubber vessel
    b) Gas reservoir
    c) Phase 2 process layout
    d) Instrumentation system including electrical and automation
2. Enable Phase 2 construction
    a) Find manufacturers and arrange for construction of CFU, GLCC and scrubber vessel
    b) Pick vendors and retrieve offers for all necessary equipment
    c) Mange project economy and revise the budget for Phase 2

At the end of the project, Phase 2 should be ready to begin construction, pending review of the plans and ordering parts and components.

Responsible supervisor:	Associate professor Christian Holden E-mail: christian.holden@ntnu.no Telephone: +47 735 93782

Preface

This master's thesis is submitted in partial fulfillment of the requirements for the M.Sc degree in Subsea Technology at the Norwegian University of Science and Technology (NTNU).

This thesis is carried out at the Department of Mechanical and Industrial Engineering, in the spring semester of 2017. Associate Professor Christian Holden has been our supervisor, and PhD Candidate Sveinung Johan Ohrem our co-supervisor.

The thesis is a result of the Center of Innovation-Driven Research (SFI) SUBPRO (Subsea Production and Processing). SUBPRO is a cooperation between the Norwegian University of Science and Technology and several industry partners, and aims to become a leading international subsea research center providing innovative technology, knowledge and candidates.

The industry partners of SUBPRO have expressed interest for compact separation technology, a partial fulfillment required for the future concept of complete subsea production and process systems. This thesis represent the development of a compact separation laboratory to facilitate research in advanced and novel control algorithms for compact separators.

This thesis is intended for all SUPBPRO partners involved in the research of compact separation technology, and particularly Associate Professor Christian Holden who administrates the compact separation laboratory. The thesis represents the basis for future personnel responsible for constructing Phase 2 of the laboratory.

Trondheim, June 11th 2017

Sindre N. Fotland

Sindre Nordås Fotland

Daniel B. Hjørnevik

Daniel Børsheim Hjørnevik

Acknowledgements

This project would not have been possible without valuable guidance and input from several individuals from both NTNU and the industry. We would like to thank the following persons:

All contributions made by our supervisor, Associate Professor Christian Holden. He has provided continuous feedback, technical knowledge and motivation above our every expectation.

The guidance made by our co-supervisor Sveinung Johan Ohrem. His technical support and input have helped greatly to the submission of this thesis.

Torstein Thode Kristofferen for his assistance regarding GLCC technology and involvement during the GLCC design process.

Andreas Hannisdal, and his colleagues at Fjords Processing. They have shown interest in out thesis and provided valuable input and knowledge, making us capable of designing a CFU vessel.

Gary Short at Transvac AS for taking a huge interest in our project and assisting the selection of mixer unit for the CFU liquid flow.

Olav Kristiansen at Statoil ASA for his contribution to the GLCC design process, and providing valuable input to the Phase 2 layout.

Rune Skarpenes at RadøyGruppen Engineering, who has set aside both time and interest to assist us in the later CFU design process and future manufacturing of the vessel.

Øystein Hagemo at the NTNU Finmekanisk for taking a interest in our project and future manufacturing of the GLCC vessel.

Arild Sæther and is crew at the MTP workshop for collaboration regarding manufacturing possibilities.

The Phase 1 project team, Jens Djupvik and Magnus Hellem. Their experience from constructing Phase 1 have been a valuable asset during our work. In addition, long office hours and longer lunch breaks are best enjoyed with company.

We also send our appreciations to all equipment suppliers consulted regarding the project. Your services have been both highly professional, finding the best technical solutions for our project and being patient during several iterations and design changes.

You have all contributed to our work, by providing us the necessary knowledge and motivation to submit this thesis. We are forever deeply grateful. Thank you.

Sindre Nordås Fotland

Daniel Børsheim Hjørnevik

Trondheim, June 11th 2017

Summary

Increased oil and gas production over the past decades have claimed most of the easily accessible offshore reservoirs. Developing new reservoirs in remote environments and at large water depths are challenging for topside production facilities. This empathizes the need for innovative subsea production and processing solutions.

Aging reservoirs require methods to maintain the desired pressure during operation, often by re-injecting produced water back into the reservoir. As oil and gas fields become depleted, more water is required in order to extend the flow from the reservoir. The increasing rate of produced water, combined with large costs associated with treating water, provides an economic incentive to create innovative solutions.

The SUBPRO (Subsea Production and Processing) Center of Innovation-Driven Research (SFI) cooperation have expressed interest in compact separator technology. The small size and reduced weight of a compact separator is favorable for installation at remote locations or at large water depths, compared to larger traditional separators. The disadvantage of compact separators is the decreased performance during flow irregularities when producing from a reservoir.

To improve compact separation technology, SUBPRO has funded 3,000,000 NOK for the development of a compact separation laboratory (CSL) at the Norwegian University of Science and Technology, Department of Mechanical and Industrial Engineering. Development of the CSL is divided into three phases: Phase 1 consist of three hydrocyclones in series, Phase 2 introduces a compact flotation unit (CFU) and a gas-liquid cylindrical cyclone (GLCC) and Phase 3 concerns the pump and reservoir system for the lab. Experiments and research carried out on the different separator technologies will facilitate the development of advanced novel control algorithms. This enables autonomous solutions, required to realize the *subsea factory* concept, where all production and processing equipment are placed on the seabed.

This thesis describes the design and engineering of Phase 2. A literature study on CFU and GLCC has been conducted to acquire necessary knowledge for design and functional engineering. The result of the study and recommendations from industry specialists, are the development of a complete design of the given separator vessels.

A large number of manufacturers and suppliers have been consulted in order to engineer the process layout and select relevant process and instrumentation equipment. Arrangements for the construction of the three vessels have been established with contractors, selected based on their experience with manufacturing similar units.

As the project is limited by the available funds, a detailed budget has been created to manage the project economy. The budget including all three phases of the CSL and the status of the economy have been discussed.

The finalized design presented in this thesis has been engineered in order to initiate the construction of Phase 2. All equipment are listed with model specifications. Respective suppliers and contractors are standing by, awaiting the initiation of the construction phase. All necessary documentation is provided to the supervisor, who is responsible for future planning and decisions regarding the CSL project.

This thesis will determine if the design of Phase 2 fulfills the requirements with regards to quality, functionality and economy. If the design is found sufficient, the construction phase can be initiated.

Sammendrag

Olje- og gassproduksjon de siste tiårene har primært produsert fra lett tilgjengelige reservoarer . Etablering av nye felt i mer krevende omgivelser og dypere vann er vanskelig for tradisjonelle produksjonsplattformer plassert top-side. Dette har ført til et økende behov for innovative produksjons- og prosesseringsløsninger på havbunnen.

Aldrende petroleumsreservoarer vill oppleve redusert reservoartrykk, noe som minker produksjonen. En metode for å opprettholde tilstrekkelig reservoartrykk er å injisere produsert vann i reservoaret for å utvide dets levetid. Det økende behovet for å injisere vann, kombinet med høye kostander assosiert ved rensing og injisering av produsert vann fremmer utviklingen av nye løsninger.

SUBPRO (Undervanns Produksjon og Prosessering) i samarbeid med Senter for Forskningsdrevet Innovasjon (SFI) har uttrykt interesse rundt kompakte separasjonsteknologier. Kompakte separatorer krever mindre plass og er enklere å transportere og er derav foretrukket for installasjon på havbunnen fremfor store tradisjonelle separator enheter. Den største svakheten for kompakte separatorer er separasjonsgraden under varierende strømningsforhold, som ofte er typisk for produksjonsstrøm fra reservoarer.

For å forbedre teknologien til kompaktseparatorer, har SUBPRO investert 3 millioner NOK for å utvikle et forsøkslaboratorium ved Norges Teknisk-naturvitenskapelige Universitet, Institutt for maskinteknikk og produksjon. Laboratoriet er inndelt i tre faser: Fase 1 inneholder tre hydrosykloner i serie, Fase 2 introduserer en kompakt flotasjonsenhet (CFU) og en gas-væske sylindrisk syklon (GLCC), mens Fase 3 inneholder pumpe- og reservoarsystemet til laben. Eksperimenter og forskning på de ulike separasjonsteknologiene vil tilrettelegge utvikling av nye kontrollalgoritmer som igjen vil tilrettelegge utvikling av autonome løsninger for å realisere *subsea factory* konseptet, der alle produksjons- og prosesseringsfasiliteter blir plassert på havbunnen.

Denne masteroppgaven beskriver utviklingen av Fase 2. Det har blitt utført en litteraturstudie på de aktuelle separatorteknologiene for å tilegne den nødvendige kunnskapen om design og operasjonsprinsipp av CFU og GLCC. På grunnlag av litteraturstudiet og konsultasjon med spesialister fra industrien har det blitt designet og utviklet en CFU og en GLCC.

Ulike leverandører og aktører har blitt konsultert for å utvikle prosessystemet og for å velge de beste løsningene for prosessutstyr og instrumentering. Det har blitt opprettet avtaler med kvalifiserte aktører for å bygge de tre separatorene.

Siden laboratoriet er underlagt økonomiske begrensninger har det blitt laget et detaljert budsjett for å håndtere økonomien. Den økonomiske statusen til hele laboratoriet har også blitt diskutert.

Denne oppgaven presenterer et ferdig design for Fase 2 som er klart for konstruksjon. Det nødvendige utstyret er spesifisert med modeller og leverandører, og alle leverandører og aktører står klare til å ta imot bestillinger når byggeprosessen starter.

All nødvendig dokumentasjon er blitt overlevert til Proffessor Christian Holden, som er ansvarlig for prosjektet i sin helhet. Holden vil avgjøre om designet tilfredsstiller kravene for kvalitet, funksjonalitet og økonomi.

Dersom designet tilfredsstiller alle krav kan byggeprosessen starte.

Contents

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Abbreviations & Nomenclature

Abbreviations

AC	Alternating Current
AI	Analog Input
AO	Analog Output
Bara	Bar absolute
Barg	Bar gauge
BIPT	Beijing Institute of Petroleum Technology
CAD	Computer Aided Design
CFC	Churn Flow Coalsecer
CFU	Compact Flotation Unit
CNC	Computer Numeric Control
CSL	Compact Separation Laboratory
DC	Direct Current
DGF	Dissolved Gas Flotation
DIN	German Institute for Standardisation
DN	Diameter Nominal
EEA	European Economic Area
ENS	Engineering Numbering System
EU	European Union
F&D	Flanged & dished
FEED	Front End Engineering Design
GCU	Gas Carry Under
GLCC	Gas-Liquid Cylindrical Cyclone
GMF	Gas Mass Fraction
GVF	Gas Volume Fraction
HHLL	High-High Liquid Level
HLL	High Liquid Level

HP	High Pressure
HRT	Hydraulic Retention Time
HSE	Health Safety & Environment
ID	Inner Diameter
IGF	Induced Gas Flotation
I/O	Input/Output
IS	Intrinsically Safe
ISE	Intrinsically Safe Earth
LCO	Liquid Carry Over
LJC	Liqud Jet Compressor
LLLL	Low-Low Liquid Level
LLL	Low Liquid Level
LP	Low Pressure
MTP	Department of Mechanical and Industrial Engineering
$\mathbf{N_2}$	Nitrogen gas
NCS	Norwegian Continental Shelf
NEA	Norwegian Environmental Agency
NI	National Instruments
NLL	Neutral Liquid Level
NOK	Norwegian krone
NORSOK	The Norwegian Shelf's Competitive Position
NTNU	Norwegian University of Technology and Science
OiW	Oil in Water
OD	Outer Diameter
P&ID	Piping and Instrumentation Diagram
PED	Pressure Equipment Directive
PMMA	Poly methyl methacrylate
PN	Pressure Number
ppm	Parts per million
PSV	Pressure Safety Valve
PVC	Polyvinyl Chloride
RTD	Resistance Temperature Detector
Sch	Nominal pipe schedule number
SFI	Center of Innovation-driven Research
$\mathbf{SF_6}$	Sulfur hexafluoride gas

SINTEF	The Foundation for Scientific and Industrial Research at the
SLR	Surface Loading Rate
SUBPRO	Subsea Production and Processing
USB	Universal Serial Bus
VAT	Value Added Tax
VOK	Vertical Knock Out Separator

Nomenclature

Symbol	**Description**	**SI Units**
Uppercase		
A	area	m^2
C_D	drag coefficient	-
E	probability	fraction
K_s	K-value for settling velocity	m/s
L	length	m
N	coefficient depending on $\Delta\rho$ of mediums	-
Q	volumetric flow rate	m^3/s
Re	Reynolds number	-
S_o	spread coefficient	-
V	volume	m^3
Lowercase		
d	diameter	m
g	gravitational acceleration	$\mathrm{m/s}^2$
k_1	static mixer constant	-
$\dot{m}$	mass flow	kg/h
r	radius	m
v	velocity	m/s
v_s	settling velocity	m/s
v_{SLR}	surface loading rate	m/s
Greek letters		
α_o	proportional factor depending on	-
	bubble-particle collision	-
γ	surface tension water	dyne/cm
ϵ	energy intensity	W/kg
ζ	swirl intensity	G
μ	dynamic viscosity	Pa s
ρ	density	$\mathrm{kg/m}^3$
σ	interfacial tension	N/m
τ	hydraulic retention time	s
ψ	turbulence intensity	%
Δ	incremental	-
Subscripts		
adhesion	thinning and rupture of liquid	
agglomerate	formation of stable aggregate	
b	bubble	
collision	bubble-particle collision	

cc	cross-section
cp	continuous phase
d	droplet
dp	dispersed phase
g	gas
go	gas-oil
max	maximum
min	minimum
$mixer$	in-line mixer unit
l	liquid
o	oil
ow	oil-water
p	particle
ps	pump system
t	tangential
tot	total multiphase flow

Chapter 1

Introduction

1.1 Background

Produced water from oil and gas reservoirs represents a large waste in the petroleum industry. After production, water is usually re-injected in the reservoir or discharged to sea. The operational costs and energy demands associated with transporting and treating produced water are high [38].

As a reservoir ages, the water cut of the produced fluids will increase and reservoir pressure will decrease, requiring more energy to extract hydrocarbons and gas. In a time with increased water cuts due to aging fields and oil- and gas reservoirs which are difficult to reach, the demand for flexible and compact water treatment facilities are more prevalent.

There is a large industrial and scientific interest in placing water treatment facilities subsea. By mitigating the extra distance pre- and post-treated water have to be pumped, large costs can be removed. Placing treatment facilities on the seabed enables construction of smaller rigs topside, which will lead to increased safety for the onboard personnel due to less man-machine contact.

The oil and gas industry strives to create an all-subsea production facility, where wells, production systems and storage tanks are all placed on the seabed, removing the need for a topside rig or production vessel. Automatic control of compact separation units is an important step in order to enable the development of such a facility. Compact and reliable separation vessels are necessary to achieve cost effective solutions that require low maintenance, as well as being able to sustain the hydrostatic pressure at the seabed.

A Compact Separation Laboratory (CSL) has been developed in cooperation with the Center of Innovation-Driven Research (SFI) and Subsea Production and Processing (SUBPRO), which is collaboration team where NTNU and several industrial partners are involved. The objective for the CSL is to facilitate the study and development of advanced and novel control algorithms to be implemented in subsea process installations.

The laboratory is divided into three phases and includes hydrocyclones, a Compact Flotation Unit (CFU), a reservoir system, low shear valves, instrumentation and sensors. In January 2017, the CSL was expanded to include a Gas Liquid Cylindrical

Cyclone (GLCC) and a gas-liquid scrubber to separate and measure outlet flow from the GLCC.

After construction and experiments with model oil, the laboratory is intended to be re-located to SINTEF multiphase flow facility at Tiller to conduct experiments with real hydrocarbons, which are prohibited at MTP Valgrinda due to health, safety and environment (HSE) regulations at the workshop.

A CFU is a vertical water treatment vessel utilizing centrifugal and viscous forces, combined with gas flotation to clean the produced water. Introduced in 2004 on the Norwegian Continental Shelf (NCS), this technology is preferable to conventional gravitational separators due to a small footprint, low residence time and high maintainability due to the lack of moving parts inside the vessel.

One of the main weaknesses of the separation unit is the small volume, which makes it sensitive to different flow regimes. A proficient separation efficiency is essential when the treatment facility is used as the final stage before discharge to sea, This can be done by dynamic control of the outlet valves.

A GLCC is a compact gas-liquid separator utilizing centrifugal and gravitational forces to separate gas and liquid. The first GLCC vessels were introduced in the 1990's and have gained popularity over conventional gravitational separators due to small footprint, low operational cost and high durability [49].

The shape of a GLCC is recognized as a pipe instead of a vessel, which simplifies pressure regulations and HSE requirements. The main problem for a GLCC separator is the small volume, causing flow variations to affect performance negatively. By developing robust control algorithms for GLCCs, reliability and consistent performance during flow variations can be ensured.

1.2 Previous work

In the spring semester of 2016, a tentative design of the CSL project was developed [64]. The tentative design includes a 3D-model for Phase 1 and Phase 3, and a piping and instrumentation diagram (P&ID) for all three phases.

Phase 1 consist of three deoling hydrocyclone liners arranged in series, where the separation efficiency is dynamically measured by the implementation of two Oil in Water (OiW) sensors. Phase 2, which is the focus of this thesis will extend the CSL with a CFU and a GLCC. Phase 3 consist of a pump and reservoir system, which purpose is to provide process feed to the CSL. The Cameron water and oil pumps located at NTNU MTP workshop were intended to function as a temporary feeding system until Phase 3 is implemented in later stages of the CSL.

Phase 1 was constructed during the fall semester of 2016 by Jens Djupvik and Magnus Hellem [42]. During construction, the initial plan of utilizing the Cameron water and oil pumps was abandoned, as the pumps where found problematic to serve as a temporary pump system for the CSL. As a result of this, the only solution to provide process feed to the CSL is the planned pump and reservoir system implemented in Phase 3.

Parallel to the construction of Phase 1, the design process of Phase 2 was initiated. During the design phase, a literature study of CFUs was conducted. Contact was established with Fjords Processing, a supplier of a CFU model that can operate within the given operational conditions for the CSL presented in [64]. As the given model from Fjords Processing is beyond the budgetary limitations of Phase 2, Andreas Hannisdal [V], at Fjords Processing offered to provide feedback in order for the authors to design and construct a CFU in-house.

Construction of a CFU turned out to be difficult, as the large diameter of the pressurized CFU is problematic to construct at the associated workshop at MTP Valgrinda. Regulations of pressurized equipment are strict regarding construction and certification, which caused the authors to regard outsourcing as the preferable solution. The engineering contractor RadøyGruppen Engineering was consulted and agreed to construct the vessel after it is designed.

A gas-injection and multiphase mixer solution for the CFU was investigated, and two suppliers of different mixing technologies was consulted. A tentative P&ID regarding the connection to Phase 1, relevant instrumentation and main process layout when only Phase 2 is in operation was constructed.

The tentative design provided by the authors proposes three gases for flotation in the CFU, namely sulfur hexafluoride (SF_6), nitrogen gas (N_2) and air. After investigating the different properties and solutions for the three gases, N_2 was selected as the preferred gas for injection into the CFU.

The design of Phase 2 was not fully completed during the fall semester of 2016, hence, the basis for this thesis is to continue and complete the design of Phase 2, facilitating the construction of both a CFU, GLCC, gas reservoir and associated instrumentation.

Figure 1.1: Phase 1 constructed facility [I].

1.3 Problem Description

The following problem description has been developed in collaboration with Mr. Holden

> *"To study and improve the efficiency of compact separators, the Department of Mechanical and Industrial Engineering are constructing a small-scale laboratory. In this project, the students will complete the design of the Phase 2 expansion of the laboratory. Originally planned was a compact flotation unit (CFU); the project scope has expanded to also include a gas-liquid cylindrical cyclone (GLCC)."*

1.4 Objectives

The main objectives of this thesis are:

1. Finalize engineering of Phase 2 components
    a) CFU, GLCC and scrubber vessel
    b) Gas reservoir
    c) Phase 2 process layout
    d) Instrumentation system including electrical and automation
2. Enable Phase 2 construction
    a) Find manufacturers and arrange construction of the CFU, the GLCC and the scrubber
    b) Pick vendors and retrieve offers for all necessary equipment
    c) Mange project economy and revise the budget for Phase 2

At the end of the project, Phase 2 should be ready to begin construction, pending review of the plans and ordering parts and components.

1.5 Approach

Based on the problem description and objectives, this master's thesis combines design and engineering of the CLS Phase 2. The following approach has been utilized:

1. *Design:* Conduct and finalize design process for CFU and GLCC process. Consult industry specialists for optimal design preferences and solutions.
2. *Engineering:* Engineering of Phase 2 layout and process equipment including piping, instrumental, electrical and automation. Requires collaboration with Phase 1 project team for integration of Phase 1 and Phase 2.
3. *Enable construction:* Contact external vendors for construction of CFU, GLCC and scrubber vessel. Locate vendors and procure all necessary process equipment for Phase 2. Provide documentation for equipment where calculations for dimensions is required.
4. *Documentation:* Writing the master's thesis.

1.6 Limitations

This master's thesis is limited by the following:

- An economical boundary of 3,000,000. NOK funded by SUBPRO.
- The CSL Phase 1 design and facilitation for Phase 2.
- The available open literature of CFU and GLCC research and technology.
- CFU design
- Decisions taken by the authors based on their best knowledge, regarding the different subjects and components implemented in the master's thesis.
- Electrical and automation system design is beyond the scope of the authors' knowledge. A proposed design is created to indicate a more comprehensive understanding, but should be revised during construction by more qualified personnel.
- Limited knowledge regarding advanced two-phase flow simulations, resulting in SolidWorks Flow Simulation^{TM} being utilized when analyzing flow in CFU iterations.

1.7 Structure of the thesis

This master's thesis follows the development of the CSL Phase 2 design without requiring the reader to have previous knowledge of the CSL project. The thesis is organized in the following chapters:

- Chapter 2 is a literature study of oil and water separation, with focus on compact separation by CFU and GLCC. This chapter is especially intended for readers without knowledge of produced water treatment or compact separation installations. Relevant literature for laboratory equipment that have not been covered is also included in this chapter.
- Chapter 3 addresses the Conceptual study of the CFU, the GLCC and the scrubber. This Chapter follows the design process from initial sketches to final design.
- Chapter 4 addresses the Front End Engineering Design (FEED) for the CSL Phase 2. The complete process system is presented, followed by structure, instrumentation, automation and electric system.
- Chapter 5 lists all the equipment required for the CSL Phase 2 and their order status.
- Chapter 6 describes the manufacturing process for the CFU, the GLCC and the scrubber vessels.
- Chapter 7 presents the economical budget for Phase 2 and the CSL project as a whole.
- Chapter 8 summarizes the work conducted in this master's thesis. A discussion of the work and recommendation for further work is also described here.

Chapter 2

Literature

To design a compact separation unit, it is important to understand the phenomena of multiphase separation and how the separation is affected by the design of the unit, as well as the composition of the fluid. This chapter presents CFU, GLCC and scrubber operating principles and technologies. Most effort is devoted to the CFU technology, due to the high level of complexity of flotation principles. A basic introduction to important laboratory equipment and certification is also included in this chapter.

2.1 Produced Water

Production from hydrocarbon reservoirs also includes the production of large quantities of water. The unwanted produced water is either re-injected into the reservoir or discharged to sea. Water is contaminated by hydrocarbons from the reservoir it is produced from, and will have different chemical compositions with regards to salinity, Ph-levels and acids. There are strict regulations for the oil concentration of discharged water, further described in Section 2.1.2.

As a reservoir ages, injected water can be utilized to maintain the required reservoir pressure for production, to improve a reservoirs life time.

The increase of water production is illustrated in Fig. 2.1, which presents the increasing trend of produced water due to aging reservoirs from 1990 to 2014. There are huge costs associated with handling and treating water and the treatment facilities requires a large area on the rig in order to handle the ever increasing production rate.

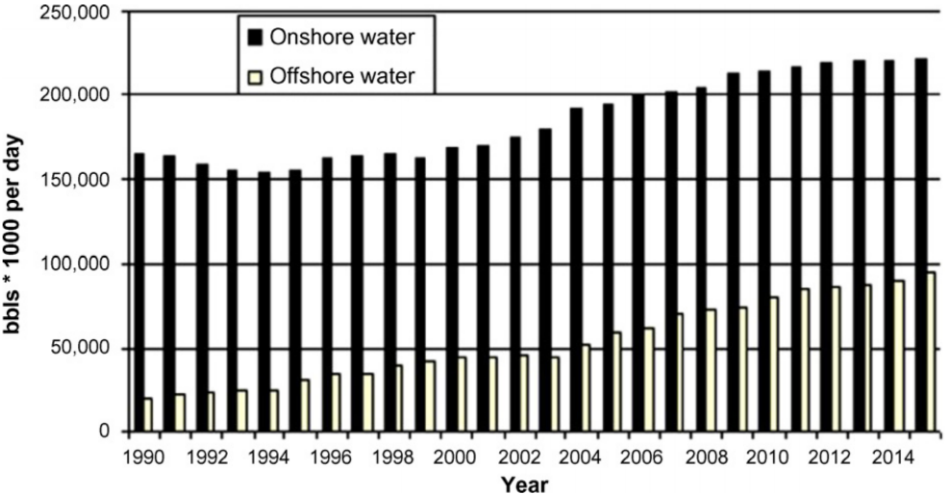


Figure 2.1: Increase in offshore produced water due to aging hydrocarbon production fields [43].

Improved treatment of produced water have economical, political and environmental impact. The regulations enforced by governments restricts the oil concentration of water discharged to sea. This motivated oil producers to innovate in the area of purifying produced water.

The results of the increased focus on produced water treatment resulted in enhanced extraction of hydrocarbons from produced fluids during operation. Hydrocarbons entrained in water, normally considered a waste can now be separated and further processed.

2.1.1 Oil in Water

Concentrations of oil in water can occur in two main ways, as either dispersed or dissolved oil, illustrated in fig 2.2. Dispersed oil are small oil droplets in water with a varying diameter from 0.5 μm to greater than 200 μm.

Dissolved oil is soluble and completely entrained in the water, due to being affected by the pressure of the surrounding liquid medium [64]. This type of oil in water generates extremely small droplet diameters which are difficult to remove. Oil droplets larger than 150 μm can usually be separated by conventional methods [52].

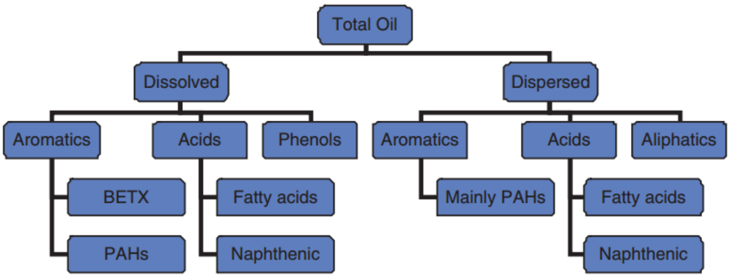


Figure 2.2: Overview of the different ways oil can occur in in water [63].

When treating produced water, separation efficiency S_{eff} is used as a measurement of the effectiveness of the separation process. It is given by

$$S_{eff} = \frac{C_{out}}{C_{in}} \tag{2.1}$$

where C_{in} and C_{out} are inlet and outlet concentration of contaminants in the separation vessel vessel.

2.1.2 Oil discharge regulations

Production companies operating on the NCS have a strict discharge policy in order to ensure environmental health. In 1997, a zero-discharge policy was established, targeting hazardous substances. Discharge of oil in produced water is regulated nationally by permits issued by the Norwegian Environmental Agency (NEA) under the Pollution Control Act [59].

Operating companies in the oil and gas industry are required to apply for permits before discharging oil into the environment. During the application process, the standards and procedures of the given company are investigated. The discharge policy are also regulated internationally through the OSPAR Convention [41].

When measuring oil concentration, either mg/l or parts per million (ppm) is used. The OSPAR convention states that the discharge of oil in produced water must not exceed a monthly average of 30 mg/l, and never exceed 100 mg/l at any point. This indicates that the discharged oil concentration in produced water can vary in the range of 0 to 99.9 mg/l as long as the monthly average not exceed 30 mg/l [64].

2.2 Compact Flotation Unit

A CFU is a vertical separation unit which utilizes gravitational and centrifugal forces, combined with gas flotation in order separate oil and gases from the produced water flow. Gas flotation is done by utilizing the gas entrained in the produced water or by injecting gas in the liquid flow prior to, or inside the CFU.

The main advantages of a CFU compared to conventional separation vessels are a small footprint, high reliability, low retention time, high separation efficiency and high maintainability [54]. These separation units are normally used in the final stage of separation, and can meet the discharge demands on the NCS, described in Section 2.1.2. Due to its simplistic design, a CFU can be scaled to handle flows varying from 1 m^3/h to 1150 m^3/h [51]. Several CFUs can be placed either in series or parallel to handle larger flow rates or ensure a more thorough treatment of produced water.

The CFU was developed by MI-Swaco in 2001 and introduced in the Norwegian Continental Shelf in 2004 [27]. This technology has been preferred over the more traditional technologies for water clarification due to reduced weight and footprint, combined with superior cleaning efficiency with regards to the time spent inside the vessel [38].

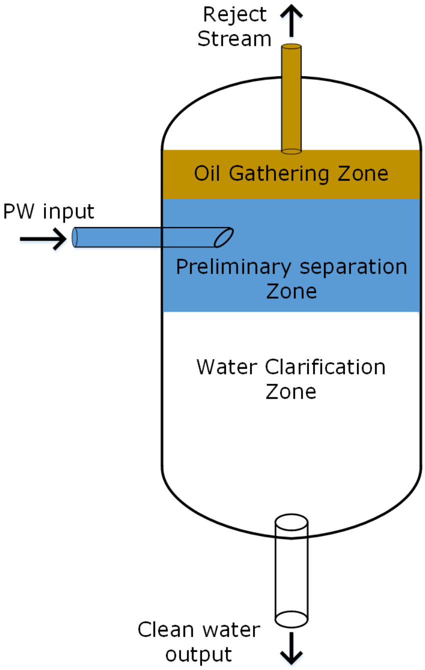


Figure 2.3: Separation Zones in a basic CFU, where produced water flows into the vessel and is separated.

2.2.1 Geometry

There are many different geometrical solutions for a CFU depending on the operational specifications of the vessel, but there are common denominators for each unit.

A CFU is divided into 3 regions where different separation processes will occur, illustrated in Fig 2.3. These regions are the preliminary separation zone, the water clarification zone and the oil-gathering zone [40].

2.2.1.1 Preliminary separation zone

The preliminary separation zone is where the bulk separation of produced water occurs. This area is defined by a tangential inlet for produced water flow and an inner cylinder implemented in the vessel. Bulk separation inside a CFU occurs due to swirl along the main walls of the vessel. Oil droplets will agglomerate and coalesce in the center due to centrifugal forces, and be led upwards in the inner cylinder and separated by viscous forces.

The CFU is designed according to the swirl- and turbulence intensity in the preliminary separation zone. Oil droplets will agglomerate and coalesce due to the rotational flow field generated by the tangential inlet.

Depending on their diameter, oil droplets will either migrate upwards along the outer walls of the vessel or agglomerate in the inner cylinder and use the difference in density between oil and water to be settled upwards. The introduction of gas flotation will attach gas bubbles to oil droplets in order to further increase this difference. This causes a CFU to be able to separate oil droplets with a diameter down to 3 μm [54].

2.2.1.2 Oil gathering zone

The oil gathering zone is defined by a primarily oil and gas filled zone above the inner cylinder in the CFU. After separation, a layer of oil establishes on top of the water level in the top part of the CFU. This layer flows through a reject outlet pipe at the top of the CFU by controlling the reject control valve and injecting flotation gas. A gas filled pocket will be established at the top of the CFU between the walls and reject pipe.

The optimal downward length of the reject outlet is defined by the desired water level inside the vessel. The flow through the reject outlet varies from 1 to 5 % of the total produced water flow, depending on the oil content and design of CFU [54] [36].

As stated in the Ospar convention in 2006, the oil content of the outlet can vary from 10 to 50 % of the total reject flow [54], while a case study conducted by S. Asdahl and K. Rabe states the gas flow of the reject outlet is 80 to 95 % of the total flow [37].

This indicates that the reject flow will primarily consist of gas, with some amount of separated oil and water. The ratio of volume flow is dependent on the given CFU and connecting equipment, which varies on a vessel by vessel basis.

Chemicals and other compounds can be added to the produced water flow in order to further promote flocculation and agglomeration of oil droplets. The main disadvantage of injecting chemicals is that it needs to be removed if water is recycled to the vessel or further routed to another separation unit. The chemicals must also be removed when if separated oil and water is to be further processed.

2.2.1.3 Water Clarification Zone

The water clarification zone is the area below the inner cylinder and defines an area which mainly consists of separated water. It consists of a vortex breaker, which main function is to disrupt the rotational flow field and creating a laminar flow profile towards the outlet at the bottom of the vessel. This prevents potential oil droplets or gas bubbles from being caught in the swirling water and exiting through the bottom outlet.

In more advanced CFUs, the three different zones can occur in different stages depending on the geometry of the vessel. The Cameron TST CFU MS3 illustrated in Fig. 2.4 has several distribution lines, that each generate distinct areas where the preliminary separation-, oil gathering- and water clarification zones occur. The number of internal stages that are required in the vessel is dependent on the quality of produced water with respect to OiW concentration, oil droplet size distribution. solid particles and use of chemicals. The technology is proven to be effective in treating produced water with high oil concentrations, and can remove droplets with a small diameter [39].

A CFU and can in general be divided into three types, differentiated by the components placed in the separation vessel. Type 1 has no inner components and is dependent on rotation along the walls of the main vessel. Type 2 and 3 both have an inner cylinder and vortex breaker to dictate the flow pattern inside the separator vessel. The main difference of these two types is the placement of the tangential inlet pipe. Type 2 CFUs guide the inlet flow inside the inner cylinder by placing the inlet pipe tangential to the cylinder and generates the preliminary separation at this area. Type 3 CFUs places the inlet pipe tangential to the main vessel and utilizes most of the volume inside the CFU for separation [40].

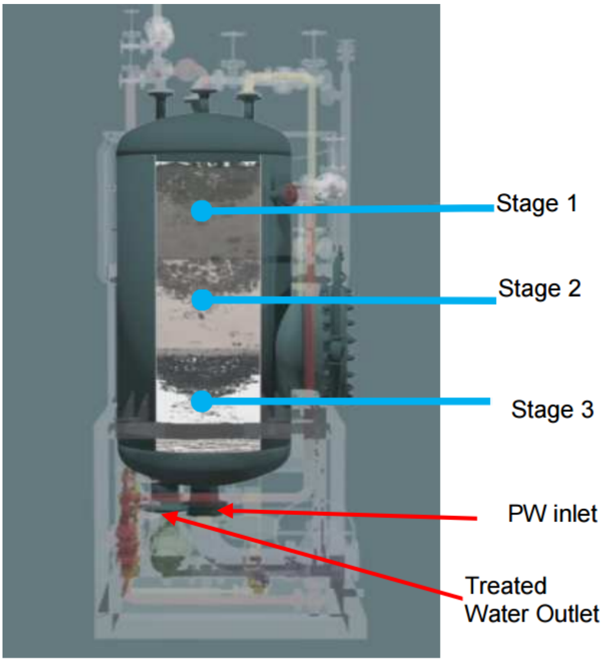


Figure 2.4: Cameron's TST CFU MS3 with three separation stages, where the produced water inlet indicated by red lines [39].

2.2.2 Physical Parameters

The main function of a CFU is utilize a rotational flow field to generate swirl inside the vessel, which causes oil droplets and gas bubbles to agglomerate in the center of the main vessel. The centered particles will be separated and flow through a suspended reject pipe, further promoted by gas flotation. According to M. Bhatgahar [39], the following parameters affects the performance of CFU:

- Quantity of gas bubbles
- Gas bubble size
- Distribution of gas bubbles across the cross-sectional area of the vessel
- Distribution of produced water across the cross-sectional area of the vessel
- Downward velocity of produced water
- Water chemistry to promote bubble-particle interaction
- Size of oil droplets

The performance of a CFU is highly dependent on the ability of gas bubbles and oil droplets to connect, further described in Chapter 2.3. Some operational parameters are presented by [54] and [39] are:

- Operational pressure: minimum 0.5 barg

- Flow in reject pipeline: 1–5 % of the total flow
- Retention time: 30-60 seconds

The operational pressure of a CFU does not affect the performance of the vessel in a significant degree, but must be larger than the outlets to ensure a correct and predictable flow pattern. The most important parameter is the swirl intensity (ζ), which gives an indication of the degree of rotation, given by equation

$$\zeta = \frac{v_t^2}{rg}. \tag{2.2}$$

Where v_t is the tangential velocity, r is the radius of the vessel and g is the gravitational acceleration. For a CFU, the swirl intensity range is normally between 20 and 30 [54].

While swirl intensity gives an indication of the degree of rotation in the vessel, turbulence intensity (ψ) defines defines the turbulence in the preliminary separation zone given by

$$\psi = 0.17 Re_l^{\frac{1}{8}} \tag{2.3}$$

where Re_l is Reynold's number of liquid flowing in a pipe. This value is defined by

$$Re_l = \frac{d_{pipe} v_l \rho_l}{\mu_l}, \tag{2.4}$$

where d_{pipe} is the diameter of the pipe, v_l is the velocity of the liquid, ρ_l is the density of the liquid and μ_l is the dynamic viscosity of the liquid.

Reynold's number affects the bubble-droplet collision during operation. A higher turbulence intensity will further promote connection between oil and gas, which will act as a driving force when the process of agglomeration and coalescing occurs. In the preliminary separation zone, the turbulence intensity can vary from 10 to 30 % [40]

With a given radius of the separation vessel, the required tangential velocity to achieve sufficient swirl can be calulated. With a predetermined maximum flow rate from reservoir and pump system, the required inlet pipe diameter, d_{pipe} can be calculated. It is given by

$$d_{pipe} = \sqrt{\frac{4Q_{tot}}{v_t \pi}} \tag{2.5}$$

where Q_{tot} is the total inlet flow rate. With regards to the inlet flow rate of a CFU, Q_{tot} is given by

$$Q_{tot} = A_{pipe} v_t \tag{2.6}$$

where A_{pipe} is the cross-sectional area of the inlet pipe, given by

$$A_{pipe} = \frac{\pi}{4} d_{pipe}^2 \tag{2.7}$$

Once produced water and gas enters the CFU, the majority of liquid flows downwards through the water outlet. The bulk downward velocity of this flow is defined as surface loading rate (SLR), which defines the volume flow rate per cross-sectional area. SLR is given by equation

$$v_{SLR} = \frac{Q_{pump}}{A_{cc}} \tag{2.8}$$

v_{SLR} is the SLR and A_{cc} is defined as the cross-sectional area of the separation vessel. The SLR gives a value of the necessary oil droplet and gas bubble diameters required in the laminar flow field inside the inner cylinder of the CFU.

The diameter affects the settling velocity of particles in a liquid, calculated using Stokes law. SLR will indicate the ranges of bubble- and droplet diameters that are able to counteract the bulk downwards velocity and flow upwards to the oil gathering zone.

Hydraulic retention time (HRT) is used as a measure of the amount of time a fluid spends inside the vessel before flowing through the outlet. HRT is given by

$$\tau = \frac{V_{CFU}}{Q_{pump}}, \tag{2.9}$$

where τ is the HRT and V_{CFU} is the volume of the CFU, dependent on the liquid level height of the vessel. For separator design, the retention time will give an indication of the required particle settling velocity of the fluid for separation, with regards to the height of the vessel. If a fluid has a predetermined HRT inside a vessel, it determines the required settling velocity for a particle to be separated within the confines of the vessel.

One of the main advantages of a CFU compared to other conventional separators is the low retention time. The OSPAR convention [54] states that the retention time of a conventional CFU is less than one minute, [39] states a retention of 30 s and consultation from Fjords Processing [V] stated a normal retention time between of 30 to 40 s. The retention time is much lower compared to a standard gravitational separator, which has a retention time of 2 to 3 h in order to achieve the same efficiency [54].

Stoke's Law describes the vertical settling velocity of a particle in a medium due to the difference in density between the two. Settling is the desired separation process to occur inside the inner cylinder of the CFU. Stoke's Law states that

$$v_o = \frac{d_o^2 g(\rho_w - \rho_o)}{18\mu_w}, \tag{2.10}$$

where v_o is the settling velocity of oil droplets, d_o is the diameter of the oil droplet, g is the gravitational constant, ρ_w and ρ_o is the densities of water and oil respectively and μ_w is the dynamic viscosity of water. This equation is specified for the relevant mediums, where oil is the particle being separated and water is the continuous phase.

For Stoke's law to be viable, the Reynold's Number for the particle is less than 0.1, and a laminar flow field must be present. Stoke's law describes the vertical settling velocity of a particle entrained in a liquid. Water is the primary medium, where oil and gas will settle upwards. Reynold's number for a particle in water is given by

$$Re_p = \frac{d_p v_t o t \rho_l}{\mu_l} \tag{2.11}$$

Where d_p is the diameter of the particle and v_{tot} is the total multiphase velocity. With regards to the CFU, the entrained particles are either oil droplets or gas bubbles, which are affected by different forces. This is due to the difference of Reynold's Number of the different phases.

The oil droplet is affected by viscous forces due to a small Reynold's number for the particle, while the gas bubble is affected by inertia forces, because of a high Reynold's number [51]. The equation of the upwards settling velocity of a gas bubble is given by

$$v_g = \sqrt{\frac{4}{3}\frac{(\rho_w - \rho_g)C_D}{\rho_w}}, \tag{2.12}$$

where ρ_g is the density of gas and C_D is the drag coefficient, dependent on the gas bubble diameter. Both factors are dependent on the given operational pressure. Note that the settling velocities only considers a single particle entrained in water and does not take into account the collision and coalescence of droplets and bubbles, likely to occur in a CFU [51]. As bubbles and droplets collide and coalesce the combined diameter of the newly formed particle will have a positive effect on the settling velocity.

2.2.3 Areas of scientific interest

There are limited resources available regarding scientific studies conducted on CFUs, which makes it an interesting area for further research. Most of the published works does not focus on the specifics of the inner geometry and characterization of flow fields inside the vessel. Most case studies performed utilizes a commercial unit, where the specifics of the CFU are not open research. The design process evaluates the change in geometries, which is not seen in papers published on CFUs.

Implementing a CFU in the already existing CSL will provide a unique opportunity to, for instance directly compare the separation efficiency with hydrocyclones, experience the change in separation efficiency with regards the flow pattern at the inlet and with different operational conditions.

CFUs are primarily used in the final stage of separation, and can normally handle a flow consisting of 500 ppm oil in a produced water flow. An interesting aspect of research is to operate the CFU outside the nominal operational conditions and observe the effect this has on the separation efficiency. The current solution for a reservoir system, as presented by [64], allows a concentration of oil in the produced water varying from 0 to 50000 ppm. This offers a wide range of oil concentrations where separation efficiency can be evaluated in correlation with the amount of oil in the produced water.

The main purpose of the CSL is to develop control algorithms for different separator units in order to enable automatic control when faced with varying flow and different concentrations of oil and gas. It is interesting to see if effective algorithms can be developed, as this can enable subsea installation of CFUs and similar water treatment vessels.

A small footprint, low retention time and maintainability makes the CFU a prime candidate, but due to strict regulations and demands from the offshore industry, sufficient separation must occur in the vessel. This makes dynamic control of valves at the inlet and outlets of the vessel an important area of research.

2.3 Gas flotation in CFU

Separation in a CFU occurs by using centrifugal forces in order to make oil droplets coalesce and agglomerate. The addition of flotation gas to attaches gas bubbles and oil droplets, which collides and rises through the reject outlet. The technique of gas flotation is the utilization of induced and dissolved gas in the separation process. With regards to a CFU, gas bubbles will be attached to the small oil droplets and flow through the suspended pipe at the top of the vessel.

When producing from a reservoir, natural gas will often be entrained and can be utilized as a separation agent in a CFU. With limited rates of naturally occurring gas, injected gas, often nitrogen can be supplemented in the flow line or vessel [39]. The difference of injection techniques will have an impact on the diameter of the gas bubble. While operating a CFU the gas bubble size can vary from 10 to 1000 μm [38], depending on the selected gas flotation solution.

Measurement of the amount of gas present in a system both Gas Volume Fraction (GVF) and Gas Mass Fraction (GMF) are used. These fractions describe the ratio of gas in a multiphase flow. GVF is defined as

$$\alpha = \frac{Q_g}{Q_g + Q_l} \tag{2.13}$$

where α is the GVF and Q_g and Q_l are the volume flow rates of gas and liquid, respectively. GMF is defined as

$$\beta = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} \tag{2.14}$$

where β is the GMF and $\dot{m}_g$ and $\dot{m}_l$ are the mass flow rates of gas and liquid, respectively [45]. The relationship between GVF and GMF is given by

$$Q = \frac{\dot{m}}{\rho} \tag{2.15}$$

The selected technique for injecting gas is dependent on the design of the CFU. It can be entrained in the liquid, injected in the process feed line before entering the vessel or inside it, either in one or several stages depending on the selected injection layout. An optimized CFU can remove dispersed oil droplets down to 3 μm in diameter from a produced water flow [54]. The separation efficiency of the flotation process is defined as the probability of flotation (E_{flot}), given by

$$E_{flot} = E_{collision} + E_{adhesion} + E_{agglomerate} \tag{2.16}$$

Where $E_{collision}$ is the probability of bubble-particle collision, $E_{adhesion}$ is the probability of thinning and rupture of the liquid film during contact time and $E_{agglomerate}$ is the probability of establishing a stable aggregate formation [60].
This indicates that the process of a bubble and droplet colliding, connecting and staying connected are of equal importance when introducing gas as a flotation agent. $E_{collision}$ is further defined as

$$E_{collision} = \alpha_o \left(\frac{d_p}{d_g} \right)^N , \tag{2.17}$$

where α_o is a proportionality factor depending on the number of particles laying along the cylindrical trajectory of the bubble, d_p and d_g are the diameter of particle and gas bubble respectively and N is an exponent which depends on the density difference between the mediums [60]. Smaller bubbles will have a smaller contact area on the surface of the droplet, which results in more bubbles being able to establish contact with the given oil droplet [39].

The different ways of injecting gas into a flow line is illustrated by Fig. 2.5. Induced gas flotation (IGF) is achieved by injecting the gas in the feed line or inside the vessel, whereas dissolved gas flotation (DGF) are gas bubbles entrained in pressurized fluids, which will expand with the decrease of pressure when bubbles enters the separation unit or flows through a restriction.

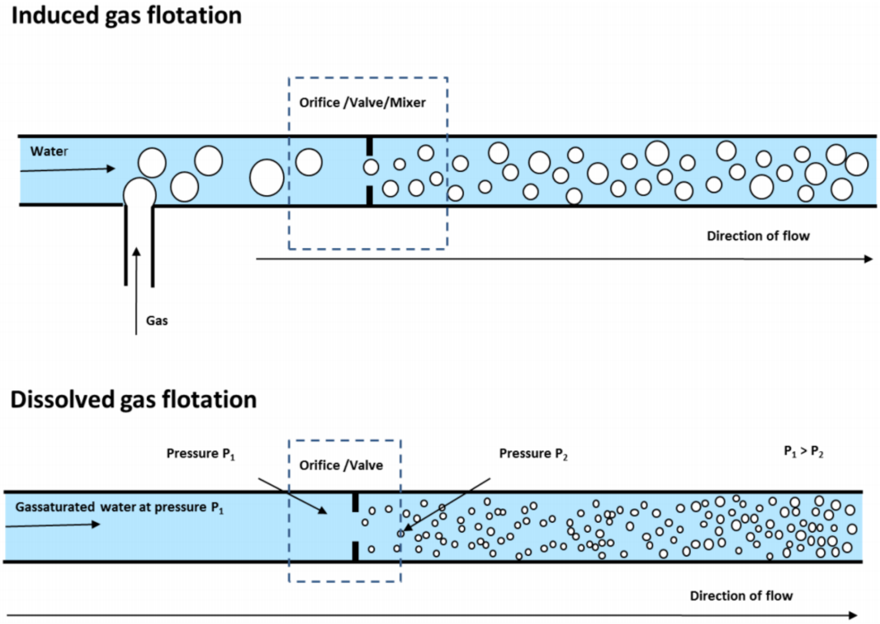


Figure 2.5: Illustrative difference between induced and dissolved gas flotation [38].

For a CFU, the use of both dissolved and induced gas to promote bubble-particle connection is the most preferable solution. If only one of the options are available, induced gas is a viable option as dissolved gas produces a very small bubble diameter. The small bubbles will have a tendency to follow the water feed through the bottom outlet due to the low retention time of the separator, which does not allocate sufficient time for the gas bubbles to expand to necessary diameter [39].

Gas bubbles have a tendency to collide and be attached to the oil droplets in a produced water flow [51]. There are three ways attachment can occur in a flotation process as illustrated in Fig. 2.6. With a downward bulk water flow and upwards gas flow, the smaller oil droplets can be spread around the gas bubble, be entrained inside it or attached to the bubble surface.

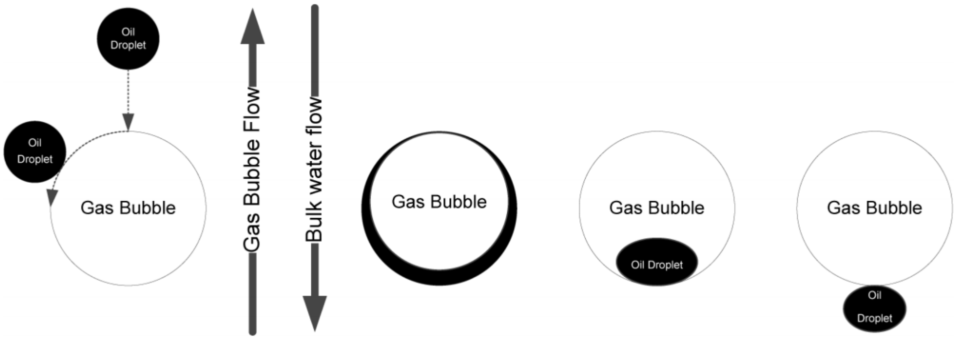


Figure 2.6: Oil-gas adhesion methods [51].

An important factor regarding gas flotation is the uniform distribution of gas-droplets across the cross-sectional area of the main flow. As described by 2.17, the increase of gas bubbles introduced in the injection process increases the probability of flotation.

A case study conducted by [36] evaluates the gas and liquid reject flow rates of a CFU. It concludes that the increase of injected gas has a positive impact on the separation efficiency.

The behaviour of droplets after attachment is defined by the low densities of the mediums involved in the collision, and the fact that a droplet is not a rigid body. The tendency of oil to spread as a film on the liquid-gas interface is dictated by the positive value of the spreading coefficient (S_o), given by

$$S_o = \gamma_{wg} - \gamma_{ow} - \gamma_{og}. \tag{2.18}$$

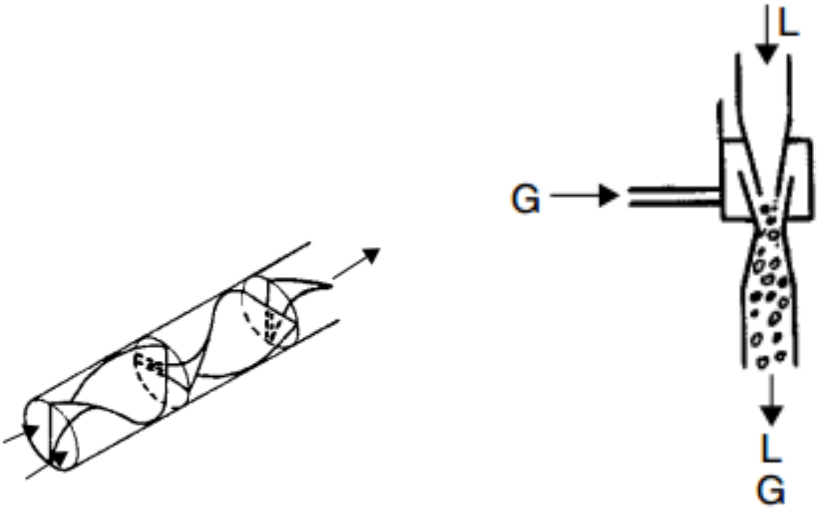
Here γ_{wg} is the surface tension between water and gas, γ_{ow} is the surface tension between oil and water and γ_{og} is the surface tension between oil and gas. The spreading coefficient is positive in most oil-water systems, whereas a negative S_o indicates an environment where droplet-bubble adhesion is not promoted. [60]

2.3.1 Gas Injection to CFU

When injecting gas to a CFU, on of the areas of importance is a stable and continuous feed of gas, which is distributed evenly across the cross-sectional area of the pipe or vessel. This combined with ability to predict the bubble size of injected gas and achieve uniform size distribution in the feed is best for the probability of flotation.

As described in chapter 2.3, there are different techniques of injecting gas in a CFU. Gas bubbles have a tendency to be attached to oil droplets in a produced water feed, and a mixer which can both induce gas in the liquid flow and mix the two mediums into a single phase is preferable during operation.

The book *"Handbook of Industrial Mixing - Science and Practice"* [57] describes different ways of achieving sufficient gas-liquid mixing. The easiest solution for the CSL is an in-line mixer unit, where the injection and mixing of gas occurs in the process flow lines, instead of requiring a dedicated vessel to perform the mixing operation. Two mixer units that fits this purpose are the in-line static mixer and ejector, illustrated in Fig. 2.7.



(a) Static mixer. Illustration of principle where two mediums are mixed to a homogenous phase by guide vanes.

(b) Gas-liquid Ejector. Utilizing the dynamic pressure of liquid to inject and mix gas and liquid.

Figure 2.7: Operating principles of a static mixer and a Gas-liquid ejector [57].

The static mixer and ejector are engineered for continuous operation and will achieve predictable mixing performance which correlates to the pressure drop over the unit. The motionless mixer units have no rotating parts, and utilizes the dynamic pressure of the mediums to create a homogeneous phase. With turbulent flow ($Re_l >$ 2300), static mixers and ejectors will achieve a close approximation to plug flow for the combined phase [57].

2.3.1.1 In-line static mixer

The primary components of a static mixer are the mixer elements, implemented in the process flow line. The mixer elements are guide vanes that forces several mediums through a predefined and restricted flow pattern, a process which promotes collision and dispersion of the injected medium, illustrated in Fig. 2.8. The use of static mixers is given by [57] as

> *"Static mixers are recommended for multiphase flow applications with a continuous liquid phase and a dispersed gas or immiscible liquid phase"*

Figure 2.8: Illustration of two separate phases mixed into a homogeneous phase by guide vanes [5].

The guide vanes can have different shapes depending on the viscosity of the mediums and rate of mixing required. The static mixer can be combined with a tee-connection and inlet nozzle to be used for both injection and mixing, illustrated in Fig. 2.9. It is the pressure of the injected medium relative to the main flow that indicates the degree of mixing [57]. The inlet nozzle can be constructed with small holes which generates a certain bubble size in the feed, mitigating some of the pressure required for injection.

Figure 2.9: Illustration static mixer with tee-connection and mixer elements [1].

Static mixers have a quick reaction time compared to other mixer vessels, and reaches the desired equilibrium droplet size quickly, usually after a few diameters of pipe length [57]. The maximum bubble size, $d_{b,max}$, of the injected medium after being mixed is given by

$$d_{max} = k_1 \left(\frac{\sigma}{\rho_c}\right)^{0.6} \left(\frac{\rho_c}{\rho_d}\right)^{0.2} \epsilon^{-0.4}. \tag{2.19}$$

Where k_1 is a constant dependent on the mixer type, σ is interfacial tension, ϵ is the energy intensity or power per unit mass, ρ_c and ρ_d are the densities of the continuous and dispersed phase, respectively. This indicates that the difference in density between the liquid continuous phase and the dispersed gaseous phase, in addition to pressure and energy will impact the bubble size of injected gas.

2.3.1.2 Gas-liquid Ejector

When a sufficient gas pressure for injection is not prevalent, an ejector is a possible solution. It has a similar application to the static mixer, but utilizes the dynamic pressure of liquid in order to infuse gas in the flow instead of using gas pressure to induce gas in the process flow.

This mixer technology utilize the venturi-principle as the primary force for mixing. High pressure (HP) motive flows through a restriction at the nozzle, which creates a decrease in pressure. The injected gas will enter through the low pressure (LP) suction inlet due to the vacuum generated in the restriction.

A combined gas-liquid mixture will be combiend through the diffuser and be discharged as a homogeneous phase with a given droplet size. Gary Short at Trensvac systems can supply an ejector in the range of 160 μm.

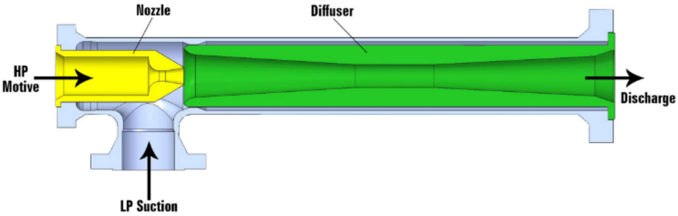


Figure 2.10: Illustration of main components of an ejector.

Shearing across upstream valves can create smaller oil droplets, and should be avoided [39]. Since the oil droplet diameter is of importance, it is not preferable to have any control valves between the mixer and CFU inlet.

The rate of rise of gas bubbles in water will eventually lead to migration on the top of the flow and create a stratified flow field. Because of this, the distance between the injector and mixer unit and the separator units are crucial in order to ensure the uniform distribution of gas before being entering the separator vessel. A pipe length of minimum 5 to 10 mixer diameters of pipe length is necessary to generate a uniform droplet size distribution.

2.4 Gas Liquid Cylindrical Cyclone

A Gas Liquid Cylindrical Cyclone (GLCC) is a compact gas-liquid separator in the form of a vertical pipe. A multiphase upstream flow enters the separator through a downward inclined tangential inlet.

The tangential inlet creates a swirling flow behavior and exposes the inflow to strong centrifugal forces. The centrifugal forces will separate the liquid and gas because of their difference in density, which causes the low density gas phase to move towards the center and create a gas core that will flow through the top outlet.

The heavier liquid phase will be forced to rotate along the walls of the cylinder, creating a liquid film. The liquid is affected by gravitational forces and will accumulate at the bottom before exiting through the bottom outlet [61]. A typical GLCC is illustrated in Fig. 2.11.

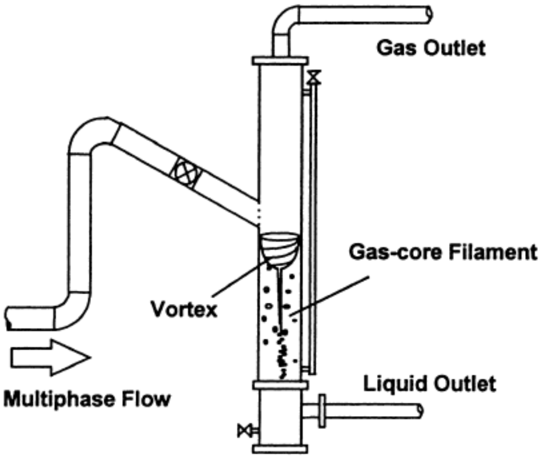


Figure 2.11: Typical GLCC vessel [53].

Since the early 1990's the oil and gas industry have shown increased interest for GLCC development and application, because of its several advantages over conventional gravity separators. The main advantages are a simplified and compact design, low weight, low operation cost and high maintainability. The GLCC is specially suited for both offshore and onshore installations with limited capacity or available area. According to [29], over 6000 GLCC vessels have been installed on a global basis.

The first GLCC separators where used as gas knock out systems in upstream production systems. Later, the application expanded to gas-liquid ratio control for multiphase metering, well testing meter systems, pumps and de-sanders, gas scrubbing and external pre-separation upstream for conventional separators. In 2006 a GLCC was installed subsea at the Marlim Field in Brazil, as a part of a multiphase pumping system [49], [53], [46].

The GLCC has no internal moving parts, meaning the liquid level inside the vessel is controlled by flow control valves. The performance of a GLCC is described by two phenomenas, namely liquid carry over (LCO) and gas carry under (GCU).

2.4.1 Liquid carry over

LCO occurs when liquid droplets attaches to gas bubbles due to interfacial forces. As the velocity of the liquid and gas increases relative to each other, more droplets are entrained. When the swirling gas core is moving axially upwards, the entrained droplets are counteracted by centrifugal forces due to the tangential forces.

The ratio between the axial and tangential velocity determines if the droplet will follow the gas and be carried over in the gas outlet, or separated from the bubble and forced along the cylinder wall in a downward direction.

Increasing the inlet velocity will increase the centrifugal forces inside the vessel. In theory this will reduce LCO, but increasing the inlet velocity will also increase the liquid level, and thereby shortening the axial distance gas bubbles travels before exiting at the gas outlet [50].

2.4.2 Gas carry under

GCU occurs when gas bubbles follows the liquid agglomeration in the bottom of the GLCC. This phenomena occurs in two scenarios. If the smaller gas bubbles have a low radial velocity, the centrifugal forces becomes to low, and unable to force the gas bubble into the swirling gas core. The bubble will follow the liquid to the liquid bulk towards the bottom and exit through the water outlet.

The other possibility for GCU occurs if the swirl intensity of the gas core is too low, creating an unstable gas tail. If the gas tail breaks, the gas bubbles will enter the liquid bulk flow and exit the GLCC through the liquid outlet [50].

Note that the complex mechanisms responsible for LCO and GCU are inversely related [50], making them difficult to control.

2.4.3 Areas of scientific interest

As described in Section 2.4, the main challenge for GLCC separation is the disadvantages related to irregular flow behavior. To enhance performance and flow capacity, it is interesting to investigate the LCU and GCO phenomenas responsible for the overall separation performance of the GLCC.

The operating principle for a GLCC have been well studied at the University of Tulsa. Systematic research and experiments presented in [44], [49] and [61] have accumulated detailed mechanical models for the LCO and GCO phenomenons. These models are unfortunately less suited for developing control algorithms, which can improve performance during irregular flow conditions.

In [50], a control oriented model based on the physical mechanisms of GCU and LCO is developed. The control oriented model combines dynamic mass balances with online steady-state separation calculations of LCO and GCU. The model can be further utilized to facilitate the development of advanced novel control algorithms. The construction of a GLCC vessel will facilitate the development of such control algorithms.

2.5 Sepration of gas-liquid flow from GLCC outlet

Gas flow from the GLCC upper outlet contains liquid and gas and is defined as a wet gas, which is a fluid with GVF greater than 0.95 of the total flow [45].

In order to correctly measure the gas and water flow separately, Olav Kristiansen [IV] suggested to implement a gas-liquid scrubber in the process line in order to physically separate the multiphase flow. This is a common solution and allows the separated gas and liquid phases to be measured by simpler one-phase flow meters.

Other solutions for measuring gas-liquid flow are done by either calculating the pressure drop over a valve to give an indication of gas compression, or implmenting a multiphase flow meter. Pressure drop calculation is often inaccurate and requires a error function to be used, while multiphase flow meters are costly.

The scrubber uses gravitational forces and Stoke's Law for gas-in-water and water-in-gas settling to separate the two phases. A mist exstractor is implemented in the vessel to prevent water droplets that are entrained in gas to flow through the gas outlet.

A scrubber illustrated in Fig. 2.12 usually consists of an inlet diverter, a mist extractor and a vortex breaker to disrupt a potential rotational flow field.

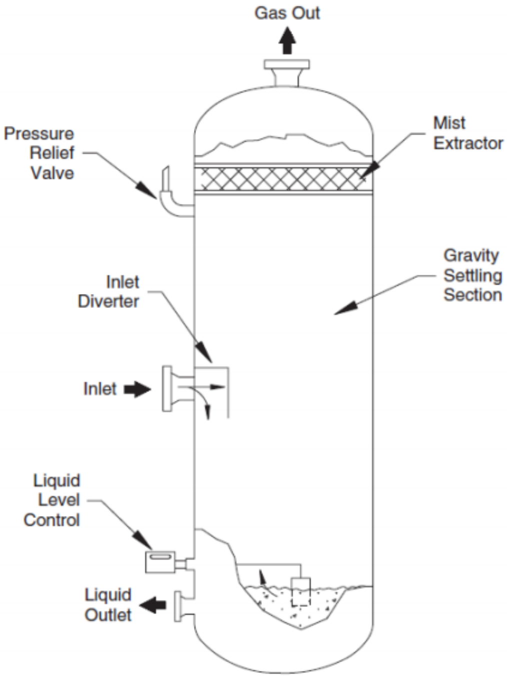


Figure 2.12: Vertical Gas-liquid separation unit [58].

When calculating the necessary diameter and height of the scrubber, an industry standard known as the K-value (K_s) is introduced. The K-value gives an indication of the maximum gas bubble velocity inside the vessel. Given that the amount of water from the GLCC gas outlet flow represents a minimal amount of the total flow, the gaseous phase is the primary medium in which the separator is designed about. The maximum bubble velocity is given by

$$v_{b,max} = K_s \sqrt{\frac{\rho_l - \rho_g}{\rho_g}} \tag{2.20}$$

where ρ_l and ρ_g are the densities of the liquid and gaseous phases respectively. The K-value simplifies the velocity estimation in the design phase of a separator. It is derived from

$$K_s = \sqrt{\frac{4}{3}\frac{C_D}{\rho_g}}. \tag{2.21}$$

The drag coefficient is dependent on the droplet diameter and pressure of the given medium. The maximum upwards gas velocity, $v_{g,max}$, is calculated using a given flow rate and cross sectional area. This is given by

$$v_{g,max} = \frac{Q_g}{A_{cc}} \tag{2.22}$$

where Q_g is the gas flow at the operation conditions and A_{cc} is the cross-sectional area of the vertical separator. The minimum diameter for a scrubber vessel, d_{min}, is given by

$$d_{min} = \sqrt{\frac{4}{\pi}\frac{Q_g}{v_{g,max}}}, \tag{2.23}$$

This equation defines the minimum cross-sectional area for separation to occur. The length of scrubber is normally given by the ratio

$$\frac{L_{vessel}}{d_{vessel}} = 3 \tag{2.24}$$

where L_{vessel} and d_{vessel} are the length and diameter of the scrubber vessel [6].

2.6 Laboratory equipment

A process laboratory requires different types of equipment for control and measurement purposes. For the CSL Phase 2, the main supporting equipment will be different types of valves, flow meters and pressure and temperature transmitters. The following sections describes the principle and function of the different equipment.

2.6.1 Flow meter

Measurement of the mass flow rate is a critical design parameter in a process system for control and HSE purposes [32]. Several technologies for mass flow measurement exist, depending on application and process data. The CSL Phase 2 utilize water, oil and gas for operation and require multiple mass flow measurements. As stated by [64], Coriolis mass flow measurement is preferred for liquid phases containing water and oil, while magnetic mass flow measurement is preferred for water measurement. This is because a magnetic flow meters requires a conductive medium in order to measure flow.

After consulting with industry suppliers, vortex mass flow measurement is most applicable for gas measurement. Flow rate in a specific application can be measured by several different technologies. By consulting different mass flow measurement suppliers, the CSL Phase 1 project team and Mr. Holden, the preferred mass flow measurement technologies for Phase 2 are Coriolis, magnetic and vortex mass flow meters.

2.6.1.1 Coriolis flow meter

The Coriolis mass flow meter utilize the Coriolis force to measure flow rate. The Coriolis force occurs from the acceleration of a mass moving toward (or away from) the center of rotation. In a typical Coriolis mass flow meter the accelerated mass is divided into two equal and parallel pipes, which is vibrating at a given frequency and fastened at the inlet and outlet. Due to the Coriolis effect, the parallel pipes will bend as the mass resist acceleration and deceleration. Sensors placed at the inlet and outlet of the pipes measures the magnitude of the bends, which is proportional to the mass flow rate. Fig. 2.13 illustrates the Coriolis mass flow meter principle [64], [3].

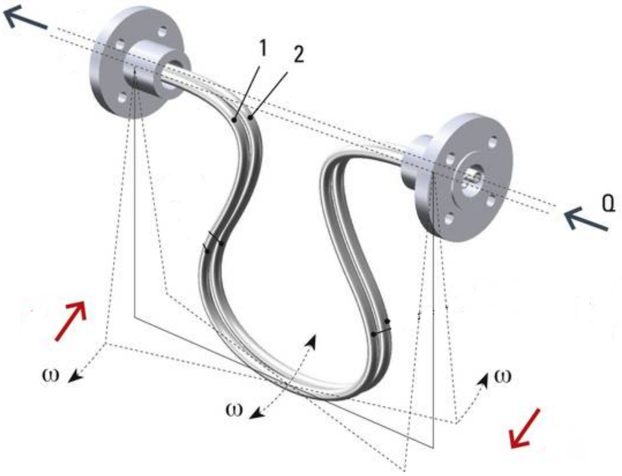


Figure 2.13: Coriolis mass flowmeter principle [13].

The Coriolis mass flow technology is applicable in a wide range of scenarios and are known for high accuracy and maintainability. By measuring the resonance frequency of the vibrating pipes, density can be measured. This makes Coriolis mass flow meters preferred in multiphase measurement where phase composition is unknown.

The main disadvantages of Coriolis mass flow meters are the high cost when procuring the unit and a possible pressure drop over the unit. High viscosity fluids are especially exposed to this pressure drop. Coriolis mass flow meter can cause slug flow behavior in gas-liquid applications [3]. For large components, vibration from the Coriolis mass flow meter can cause operational issues.

2.6.1.2 Magnetic flow meter

Magnetic flow meters utilize Faraday's law of electromagnetic induction to measure flow rate. Magnetic flow meters generates a magnetic field in the liquid flow. As the conductive liquid flow enters the magnetic field, a voltage signal is generated. When inside the electrical field, electrodes in the pipe measures the voltage signal.

Faraday's law states that the generated voltage is proportional to the flow movement. Higher liquid flow will result in a stronger voltage signal. Fig. 2.14 illustrates the magnetic flow meter principle [7].

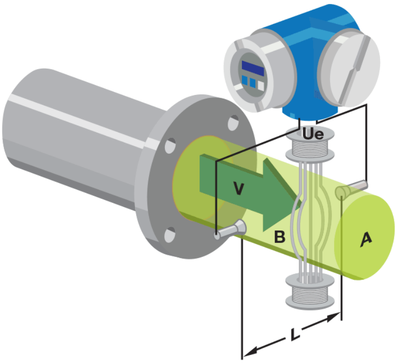


Figure 2.14: Magnetic flow meter principle [14].

The magnetic flow meter technology is available at large sizes and has a low pressure drop over the unit. The flow meter can handle dirty liquids contaminated with mud or other solid particles. The accuracy is intermediate, which limits the technology to applications where high accuracy is not required.

The main disadvantage of magnetic flow meters is the requirement of a conductive medium to flow in the process line. Hence, the technology can not be used for gases, or non-conductive liquids such as oil [7].

2.6.1.3 Vortex flow meter

Vortex flow meters utilizes the von Karman effect to measure flow rate. The von Karman effect occurs when a mass flow passes through a bluff body and generates a repeating pattern of alternating vortices. The pattern of vortices is also called a Karman vortex street.

In a vortex flow meter the bluff body is inserted vertical into the flow. The body have a flat front facing the flow direction, which creates the vortices. The vortices will oscillate at specific frequencies that can be measured. This frequency is directly proportional to the flow velocity, which is used to calculate mass flow. Fig. 2.15 illustrates the principle of a vortex flow meter [31].

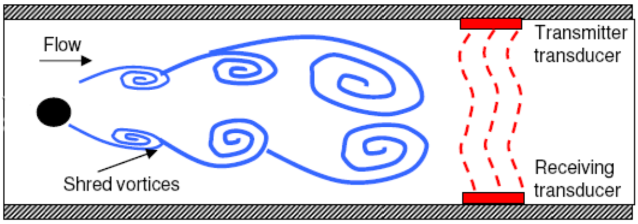


Figure 2.15: Vortex flowmeter principle. Bluff body is indicated by a black circle [11].

Vortex flow meters have a medium to high accuracy and are well suited for liquid and gas measurement. In addition, vortex flow meters are widely used for measuring steam flow, which is normally difficult due to high pressures and temperatures. The main limitation of vortex flow meters is low flow rates, which generates irregular vortices. Slug flow is also a problem due to interference of the vortices [30].

2.6.2 Valves

Valves have two essential functions in any pipeline or process systems; process control and to function as a safety barrier between the system and the surroundings. A wide range of different valve types for different applications are available.

Valves can be divided into two main categories, manual valves and control valves. Manual valves are manually operated, by a shaft or a top wheel. Manual valves are most commonly used as shut off valves, to divert process flow in a bypass. Well designed shut off valves does not affect the flow pattern when fully opened, and are called full bore valves [64].

Control valves are controlled by electrical or pneumatic actuators. The actuator must have a high operational velocity to ensure desirable feedback control of the system. Control valves operate at a given percentage of fully open or closed, and must be calibrated carefully for each application. This is especially important for multiphase process system where droplet sizing is of importance [64].

2.6.2.1 Manual Ball Valves

Manual ball valves have an outer casing and a perforated ball inside. The casing can be constructed in one, two or three pieces. The ball is controlled by turning the top handle or wheel. When the valve is in open position, the hole of the ball is in line with the flow direction. In closed position, the hole is perpendicular to the flow direction. Ball valves are designed to be full bore, and therefore often preferred as shut-down valves [35]. Fig. 2.16 illustrates a typical manual ball valve.

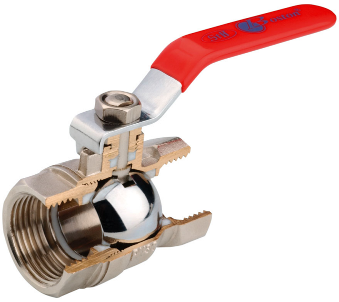


Figure 2.16: Illustration of manual ball valve [19].

2.6.2.2 Choke Valves

Choke valves are designed to control the pressure in a pipeline. If the inlet pressure is too high, the choke valve can relieve the pressure and thereby regulate the outlet pressure. Pressure control is achieved by allowing the fluid to flow through a small opening, which generates a predetermined pressure. Choke valves are often used to bleed down the pressure if it exceeds the maximum design pressure of a system [64]. Fig. 2.17 illustrates a typical choke valve.

Figure 2.17: Illustration of Choke Valve [12]

2.6.2.3 Pressure Safety Valves

Pressure safety valves (PSVs) are used as a final safety device to prevent pressure levels above the design limits in a vessel or pipeline. The valves are set to a predetermined pressure, and opens automatically if the pressure exceeds the set pressure. As the pressure decreases below the set pressure, the valve will close.

PSVs can be operated by a spring load, a pilot operator or dead weight. Common for all PSVs is the ability to function without any electric power support [33]. Fig. 2.18 illustrates a typical pressure safety valve.

Figure 2.18: Illustration of Pressure Safety Valve [22].

2.6.2.4 Globe Valve

Globe valves uses an adjustable plunger to control the flow rate. The plunger can be raised or lowered into a seat to increase or decrease the flow. Because of the plunger and the seat, a globe valve will affect the flow pattern and cause turbulent flow.

The plunger can be operated manually by top wheel or automatic by an actuator. For the CSL, globe valves are used with pneumatic actuators for flow control in the system [17]. Fig. 2.19 illustrates a typical globe valve.

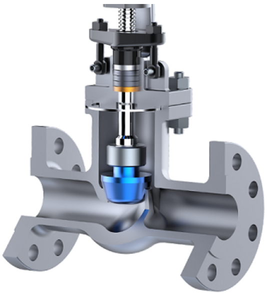


Figure 2.19: Illustration of Globe Valve [16].

2.6.2.5 Needle Valve

Needle valves uses the same principle as the globe valve with an adjustable plunger to control the flow rate. The difference is the size of the plunger, where needle valves use a smaller plunger shaped as a needle. The small plunger allows the needle valve to be more retuned, for improved flow control [20]. Fig. 2.20 illustrates a typical needle valve.

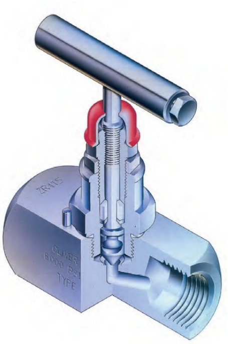


Figure 2.20: Illustration of Needle Valve [21].

2.6.3 Instrumentation

2.6.3.1 Pressure measurements

Pressure levels in a process system is one of the most important factors for process control and HSE, and should be one of the design parameters in any process system. All pressure measurements can only be measured related to a known pressure.

Absolute pressure sensors measures the pressure relative to vacuum, where the pressure is absolute zero. Absolute pressure measurements is indicated by the unit bar absolute (bara). Gauge pressure sensors measures the pressure relative to the atmospheric pressure, which is equivalent to standard sea level pressure of 101 325 Pascal. Gauge pressure measurements is indicated by the unit bar gauge (barg). Differential pressure sensors have the abolity to measure the pressure in two given points, and then calculates the difference [I].

Pressurized pipelines and vessels usually have at least one pressure sensor to monitor the process. Differential pressure sensors are often installed upstream and downstream equipment to measure the pressure drop (or increase) over an equipment [I].

When designing pressurized systems it is normal to include an additional safety factor in the calculation, in case the pressure exceeds the design limit for the system. NTNU requires a safety factor of 1.6, which means all pressurized equipment must be capable of handling a pressure of 1.6 times the maximum operational pressure for the equipment [I].

2.6.3.2 Temperature measurements

Temperature measuring in a process system is important for both process control and HSE. Liquids and gases have a different phase behavior depending on temperature. Temperature can also affect the structural integrity of process equipment if the temperature exceeds the design limits.

There are two main technologies used for measuring temperature, resistance temperature detectors (RTD) and thermocouple. RTD utilize the principle of electrical resistance for a material, where the resistance changes with temperature. A thermocouple utilize the seebeck effect, where the temperature difference between two dissimilar electrical conductors will produce a voltage. The voltage can be measured and is proportional to the temperature [34]. For temperatures from 200 to 500 °C, (RTD) are preferred, while thermocouple are used for temperatures above 500 °C. The CSL will operate in temperatures from 20 to 70 °C, making RTD the preferred measuring technology [26], [47].

2.7 Pressurized equipment certification

The Pressure Equipment Directive (PED) is a European legislative framework to ensure the quality of pressurized equipment. Equipment restricted to the PED is described by [55]:

> *"This Directive should apply to pressure equipment subject to a maximum allowable pressure PS greater than 0.5 bar. Pressure equipment subject to a pressure of not more than 0.5 bar does not pose a significant risk due to pressure."*

The first directive, named 1997/23/EC was introduced to all EU member states on November 29th 1999. In April 20th 2016, the original directive was replaced by the new directive named 2014/68/EU. The purpose of the directive is to create a general standard of safety for all pressurized equipment sold within the EU. By a general PED approval, technology and equipment is recognized as safe to operate and can be distributed within the EU. This decreases the cost of marketing products across EU significantly [9], [10]. Norway is not a member of the EU, but is committed to the PED through the European Economic Area (EEA) agreement [25].

To acquire PED approval the equipment must be examined and approved by a independent contractor. In Norway, Kiwa Technologist Institute is designated to preform technical control by the Norwegian Government. Manufacturers must select the most suitable PED module for the selected equipment and apply for a technical control.

The technical control is conducted by reviewing all documentation relative to design and manufacturing. If the application is approved, certification of the equipment can be issued [2].

Chapter 3

Conceptual design

This chapter consists of a conceptual study for the main components in the CSL Phase 2. After the feasibility study conducted in [64], a conceptual study is the natural next step in the engineering process. The conceptual study involves exploration of different ideas and comparison of pros and cons for different solutions. This stage intend to minimize future mistakes in the design process and manage cost and risk, by presenting the evolution of the design process for the CFU, the GLCC and the scrubber.

3.1 CFU design process

The design process of the CFU is based on the work conducted by [40], who performed a computational flow dynamic (CFD) analysis on the Beijing Institute of Petroleum Technology's BIPT-CFU [40].

The geometry of the model is considered open research and used as the basis for developing the final design of CFU. The BIPT-CFU geometry is illustrated in Fig. 3.1. The main components of this type of CFU are the tangential inlet pipe, inner cylinder, vortex breaker and suspended reject outlet.

As described in Section 2.2, there are in general three types of CFUs. The designed CFU will utilize a type 3 CFU design, which implements an inner cylinder inside the main vessel. Stated by [40], it is the geometry which achieves the best separation efficiency.

This is due to the ability to more heavily affect the flow pattern inside the vessel, as well as utilizing the entire CFU for separation. It clearly distinguishes the high turbulence area in the preliminary separation zone and the laminar flow field inside the inner cylinder.

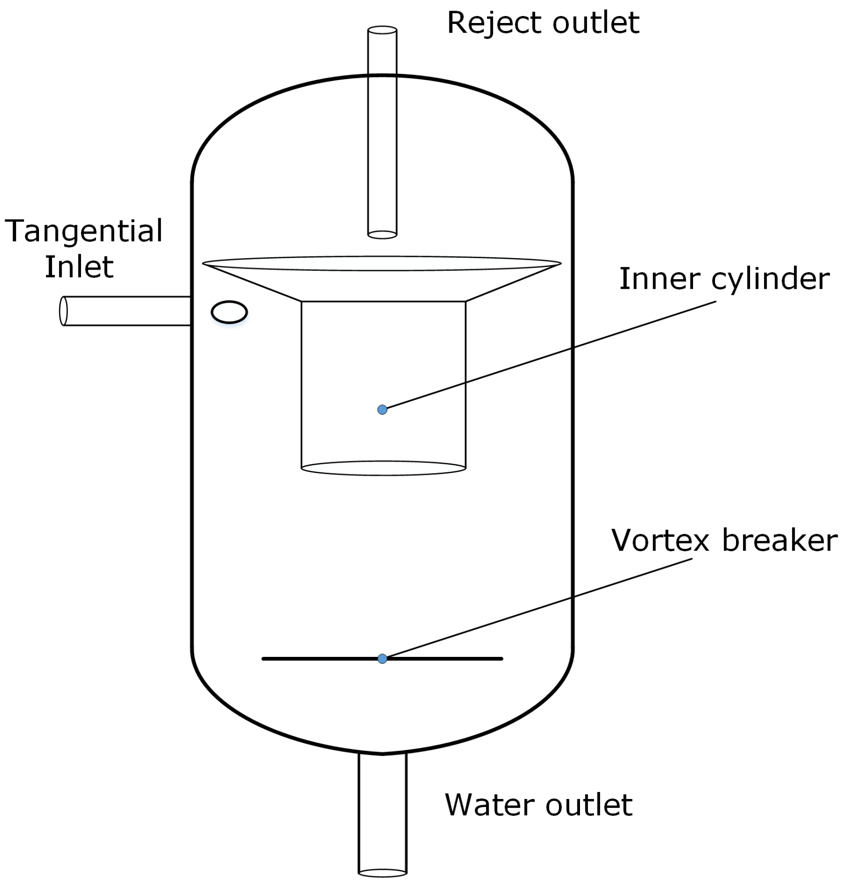


Figure 3.1: BIPT-CFU design sketch.

3.1.1 CFU design parameters

The design parameters for the given CFU are presented in Tab. 3.1. Gas and liquid flow rates are limited by the systems that are supplying the different mediums. The pump system proposed in the original design can supply 5 m^3/h at 25 barg [64]. A gas reservoir of four nitrogen bottles provides continuous gas feed.

Each gas bottle contains 50 l at 200 barg or 11.49 kg, which is equivalent to one hour of operation at maximum gas flow rate 1.25 m^3/h at 8 bara. The gas reservoir is further described in Section 4.1.8

Although the proposed pump system can supply 25 bara pressure, Phase 2 is designed with a pressure rating of PN16. This is due to the required operational pressure of 0.5 barg, which makes construction with a higher pressure rating unnecessarily costly.

Mr. Holden requested the possibility to manufacture the CFU in a transparent material, so the separation process could be visualized. Tor Erling Uander [XIII], research manager at SINTEF was consulted regarding transparent materials for pressurized vessels, and recommended to use transparent polyvinyl chloride (PVC) material. PVC has strong material properties relative to other plastic materials. If a PVC pipe is exposed to high pressure levels, the material would rupture instead of explode. PVC is the preferred material for pressurized application, due to HSE concerns [XIII].

Table 3.1: CFU design parameters.

Design Parameters	**Value**
Q_l	1–5 $\mathrm{m^3/h}$
Liquid selection	Freshwater ($\rho_w = 1000$ $\mathrm{kg/m^3}$) Model oil ($\rho_o = 824$ $\mathrm{kg/m^3}$
Q_g	0–1.25 $\mathrm{m^3/h}$
Gas selection	N_2 ($\rho_g = 5.7$ $\mathrm{kg/m^3}$ at 7.5 barg)
GVF	0.01–0.2
Operational pressure	0.5–10 barg
Operational temperature	20 °C
Material selection	Transparent PVC 316L

3.1.2 CFU operation

The operational area for the CFU is given by a maximum liquid flow of 5 $\mathrm{m^3/h}$ and a varying GVF of 0.01 to 0.2 added to the produced water, illustrated in Fig. 3.2. With a GVF of 0.2 the combined inlet velocity of the combined phase becomes too large with regards to swirl intensity, so the liquid flow rate must be decreased.

In order to prevent variations in flow, which will negatively affect the flow pattern, the input flow and injected gas must remain constant during operation. Liquid level is established by dynamically controlling the control valves at the water- and reject outlets.

After separation, the clarified water outlet will amount to 95 to 99 % of the total flow. The multiphase reject will have a slug flow pattern and vary during operation due to the compression of injected gas [51].

Although the operational pressure has a minimum value of 0.5 barg, it is interesting to investigate the effects of increasing pressure with regards to separation efficiency and probability of flotation.

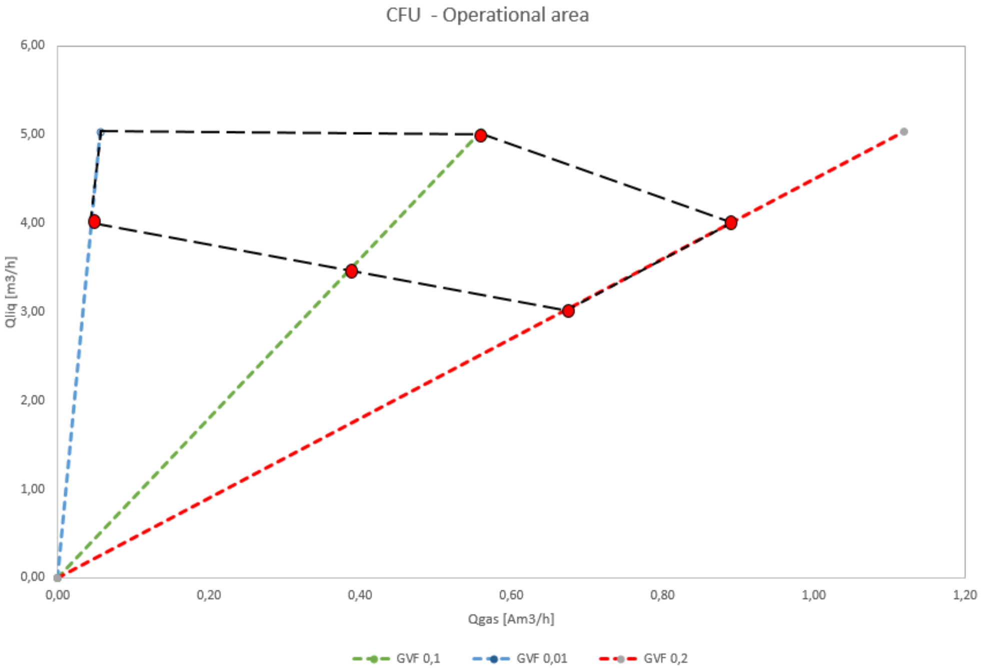


Figure 3.2: Operation envelope for the CFU. The blue, red and green dashed lines represents different GVF values. The red dots represents the selected design points, and defines the operation area for the CFU, indicated by the black dashed lines.

3.1.3 Initial design

The initial design of CFU is based on the BIPT-CFU solution presented by [40] as well the equations described in Section 2.2. Fig.3.3 illustrates the design with main dimensions of the main vessel, the inner cylinder and the vortex breaker. The values for the main dimensions are listed in Tab 3.2. The importance of implementing a inner cylinder is to differentiate the rotational flow field along the walls of the outer vessel and the area inside the inner cylinder.

In order for the settling of oil droplets and water to be promoted, a laminar flow field must be prevalent. The inner cylinder will isolate the oil droplets which have agglomerated due to centrifugal forces, allow them to settle due to a laminar flow field. The separated oil will flow through the reject pipe due to the injected gas.

The inlet diameter is $1/2''$, due to the need of high inlet velocity with the given flow rates. Swirl intensity is the main parameter in which the design is based around. When the diameter is given, the necessary inlet liquid flow range to generate sufficient swirl is used. HRT and SLR for the given design are calculated by the necessary flow rates.

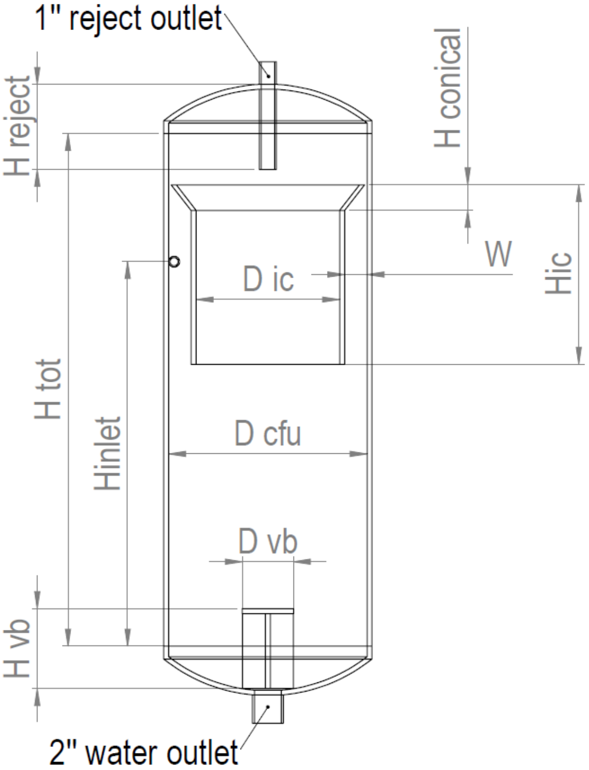


Figure 3.3: Initial design of CFU with key geometries illustrated and described.

Table 3.2: Initial CFU design with key geometries indicated.

Annotation	**Description**	**Value [mm]**
D_{CFU}	Inner diameter of CFU	400
D_{ic}	Diameter of inner cylinder	300
W	Distance between inner cylinder and CFU	40
$H_{conical}$	Height of conical geometry of inner cylinder	50
D_{vb}	Diameter of vortex breaker	45
H_{ic}	Height of inner cylinder	400
H_{tot}	Total height of CFU	1700
H_{inlet}	Height from inlet pipe to CFU bottom	1300
H_{reject}	Length from reject pipe end to pressure vessel head	200
H_{vb}	Height of vortex breaker	200

Tab. 3.3 presents the values of the key parameters of CFU operation. SLR and HRT are defined from the inlet down to the water outlet, given that water is the primary phase being calculated. The total height of the vessel is defined from tangent to tangent of the main cylinder.

Note that the actual height of the CFU will be larger in practice, due to the height of the pressure vessel heads at the bottom at the vessel. This extra height will have a positive effect on HRT and SLR, as liquid spending more time in the vessel will allow more time for oil droplets to settle upwards towards the oil gathering zone.

Table 3.3: Initial CFU calculation results.

Initial CFU performance parameters	**Value**
Q_l	4.4–5 m^3/h
v_{SLR}	0.009–0.01 m/s
τ	99.8–79.84 s
ζ	19.82–25.6 G
v_t	6.23–7.08 m/s
Inlet pipe diameter	15.8 mm (1/2″)

3.1.4 First design iteration

The first iteration was made after consultation with engineers at Fjords Processing [V]. Valuable feedback was provided after the initial CFU was presented to them.

The main concerns were centered around the diameter of the inner cylinder and the geometry of the vortex breaker. The proposed solution was to make the radius of the plate close to the diameter of the vessel and apply a conical shape to the plate. The HRT and Swirl intensity is larger than that of a conventional CFU, which indicates a decrease in produced water flow or increase in vessel diameter can be examined.

A new design of the CFU was created in correlation with the feedback given, illustrated in Fig. 3.4. The iterated CFU vessel has a smaller height and diameter, and the reiterated inner cylinder has a wider gap between cylinder and the walls of the main vessel. This promotes larger amounts of bulk flow to be rotated upon entering the vessel, instead of being forced in vertical directions inside the CFU.

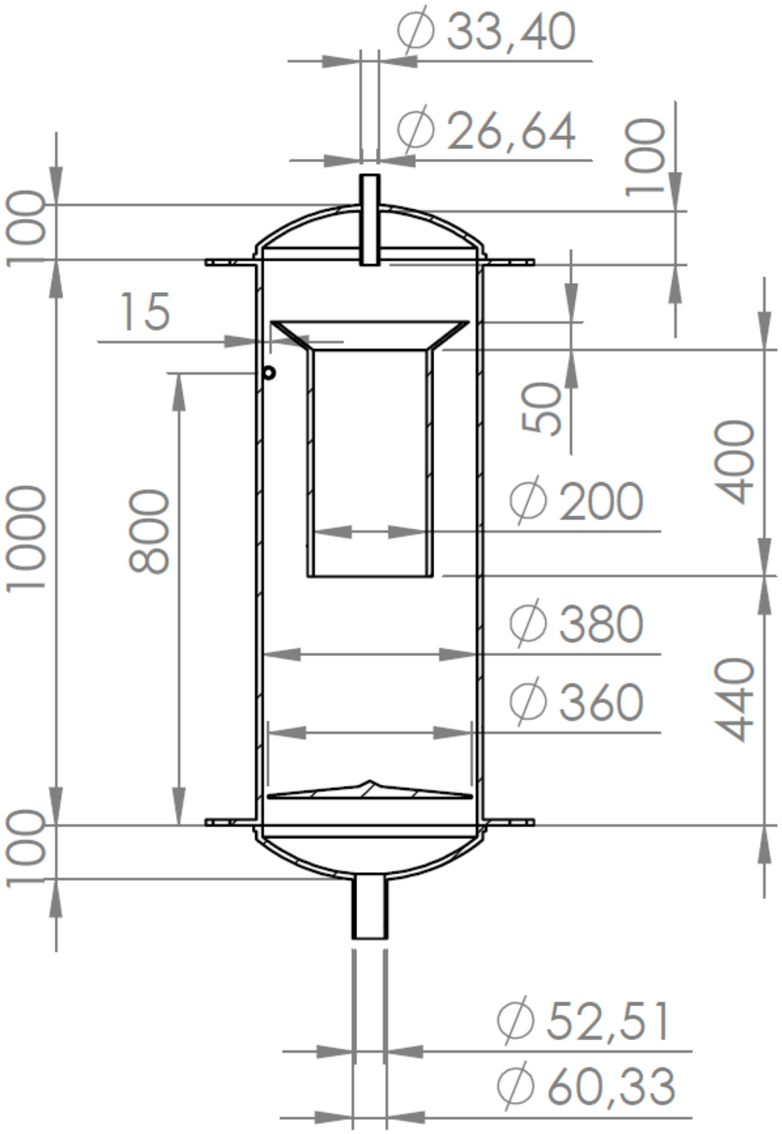


Figure 3.4: First iteration of the CFU design with key geometries illustrated.

The newly designed vortex breaker is illustrated in Fig. 3.5. Its main functions are to create a laminar flow field below it and prevent potential gas bubbles or oil droplets that are entrained in water phase from flowing through the bottom outlet. The conical shape is relevant in order to ensure that the center of the vortex, generated by the rotational flow field rotates around the vertical axis of the CFU.

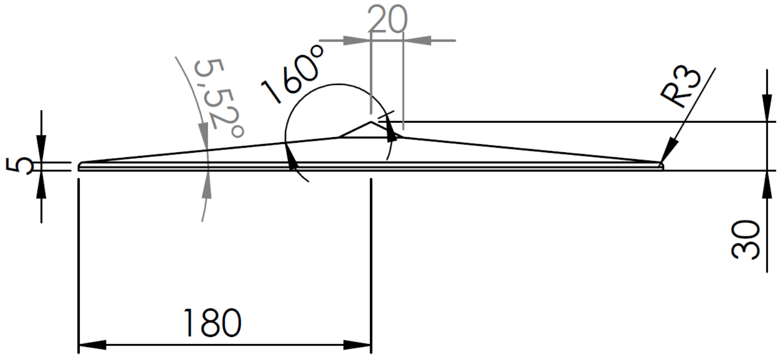


Figure 3.5: First iteration of the vortex breaker design.

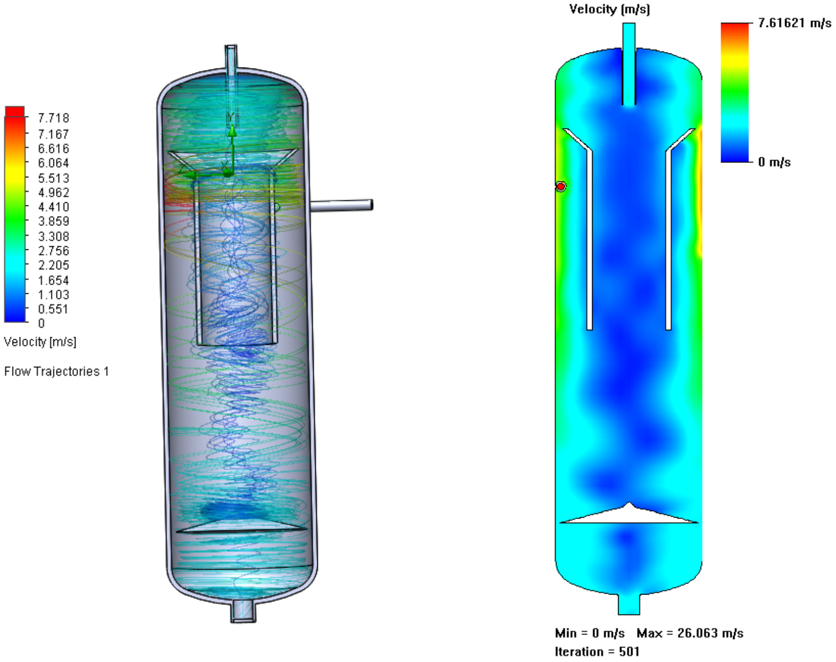
After consultation with Mr. Holden [I], a smaller vessel diameter is preferable as it allows the CFU to be operated at a lower liquid flow rate and achieve sufficient swirl in the preliminary separation zone. As the calculated retention time presented in Tab. 3.3 is larger than that of a conventional CFU, the vessel height can be decreased. The calculated performance values for the newly designed CFU is presented in Tab. 3.4.

Table 3.4: CFU calculation results after first iteration.

2nd CFU performance parameters	**Value**
Q_l	4.1–5 m^3/h
ζ	18.12–26.94 G
v_{SLR}	0.0095–0.012 m/s
τ	80.42–65.95 s
v_t	5.97–7.86 m/s

To verify the assumed flow field inside the vessel, a simplified flow simulation was conducted using SolidWorks Flow Simulation^{TM}. The main limitation of using this software is that it is only able to simulate 1-phase flow. Water will be the primary medium during operation, with oil concentrations in the produced water during operation not exceeding 5,000 ppm, hence it is negligible during this simulation. The injected gas is assumed to flow upwards through the reject outlet [36], and is not the phase of main concern in the vessel.

The software gives a quantitative indication of the flow pattern inside the vessel, due to the simplified mesh generated by the program. Although the program is not qualitative viable, it generates a visual representation of the flow behaviour of the water phase, in order to investigate if swirl about the center of the vessel occurs. The conducted flow simulation is illustrated in Fig. 3.6, with mesh generation, boundary conditions and set values given in Electronic Appendix 3.



(a) Flow lines of first iteration of CFU.

(b) CFU velocity profile of first iteration of CFU.

Figure 3.6: Results of flow simulation using 5 m^3/h water, 5 bar at the inlet and athmospheric pressure at the outlets indicating the flow lines and velocity profile of CFU during operation.

A rotational flow pattern is present due to the tangential inlet of the vessel as seen in Fig. 3.6a. The flow line colors indicates the variation of fluid velocity velocity, with a set cap of ~7.7 m/s. The velocity in the preliminary separation zone is faster than in the rest of the vessel, with the smallest velocities occurring inside the inner cylinder.

The range of velocities in the different areas of CFU enables the intended separation processes. For further design analysis, the components inside the CFU is varied to evaluate a change in flow pattern in order to further differentiate the preliminary separation zone, water clarification zone and oil gathering zone.

3.1.5 Second design iteration

Flow simulations of the first iteration illustrates vortices inside the vessel, which is the preferable flow pattern of water during operation. The second iteration investigates the distance between the inner cylinder and walls of the main vessel, length of reject pipe and shape of the vortex breaker, and is illustrated in Fig. 3.7.

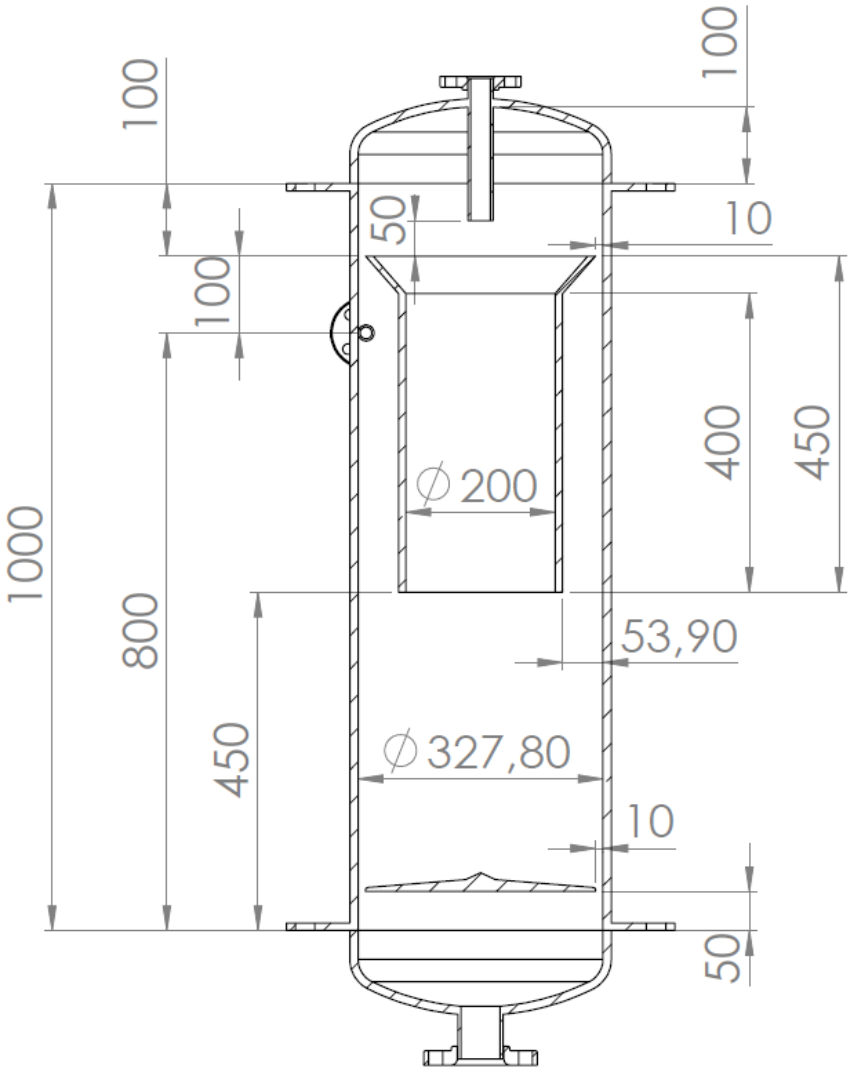


Figure 3.7: Second design iteration of the CFU with key geometries illustrated and described.

The downwards length of the reject pipe defines the liquid level of the CFU during operation. It is preferable with a smaller distance between inner cylinder and reject pipe in order to prevent the skimmed oil layer from being disrupted and re-entrained in the rotational water flow. As a result of this the distance between the inner cylinder and reject pipe is changed from 100 mm to 50 mm.

The first iteration of CFU design narrows the diameter of the vessel, but after the first iteration was presented to Mr. Holden, a further decrease is preferable. As the

CFU is created to perform experiments, flow rates shall only facilitate the required swirl in the vessel, which allows a further decrease in vessel diameter rounded down to the nearest nominal pipe size.

The distance between inner cylinder is reduced to 10 mm in order to force more of the produced water flow downward to further distinguish the preliminary separation zone and oil gathering zone. The calculated flow range and values are presented in Tab. 3.5

Table 3.5: CFU calculation results after second iteration.

3rd calculated CFU performance	**Value**
Q_l	4–5 $\mathrm{m^3/h}$
ζ	19.99–31.24 G
v_{SLR}	0.0125–0.015 m/s
τ	61.34–49.08 s
v_t	5.67-7.09 m/s

The inlet pipe height is defined by the retention time of produced water in the vessel and is placed 800 mm from the main cylinder, illustrated in Fig. 3.7. The calculated retention time, is within the preferred time spectre of 30 to 60 s for a conventional CFU.

Flow simulations conducted on the first iteration of the vortex breaker illustrated in Fig. 3.5 visualized a problem with the geometry. The conical design of the vortex breaker was too steep, and caused the center of rotation to occur away from the center of the CFU.

A smaller angle of 4.63 % is implemented by decreasing the total height of the vortex breaker, illustrated in Fig. 3.8. The new design creates a more centered rotational flow pattern of water in the CFU. The effect of changing the vortex breaker dimensions is established by flow simulations at the maximum flow rate, illustrated in Fig. 3.9.

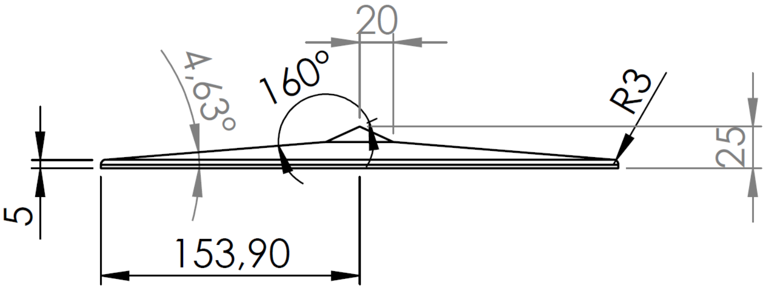
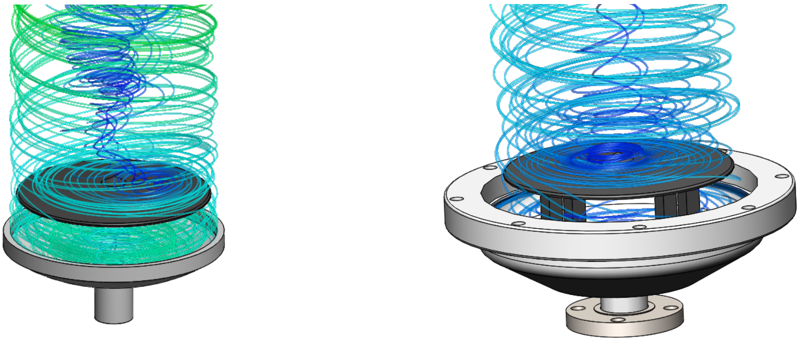


Figure 3.8: Second iteration of the vortex breaker.



(a) Rotational flow field about the 2nd vortex breaker design.

(b) Rotational flow field about 3rd vortex breaker design.

Figure 3.9: Difference in flow field when changing vortex breaker dimensions, with main cylinder hidden.

3.1.6 Third design iteration

For a final evaluation of the CFU design, Rune Skarpenes [VI] at RadøyGruppen Engineering was consulted. RadøyGruppen Engineering is a producer of subsea production associated equipment, well recognized in the industry for manufacturing steel constructions for subsea facilities.

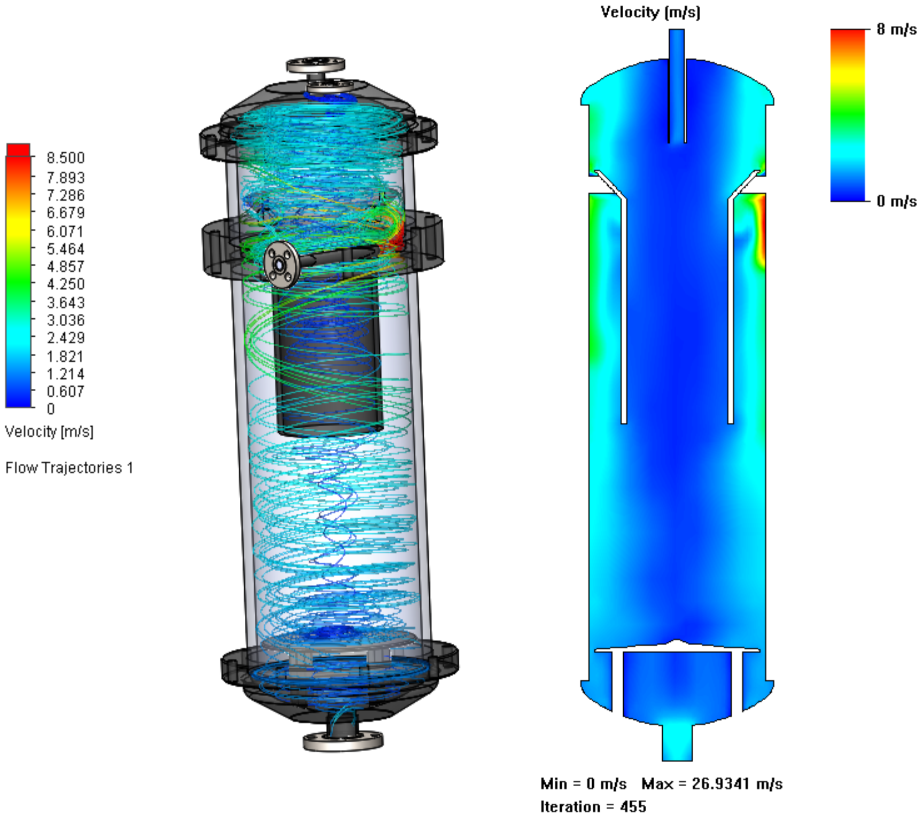
Mr. Skarpenes expressed interest in the project, and proposed some changes to the design, material supplier and assembly method for the vessel. In addition, RadøyGruppen Engineering agreed to be hired for manufacturing of the CFU vessel when the constriction phase is initiated.

For practical purposes when acquiring the construction material, the diameter of the main cylinder has been reduced to 315.83 mm. A smaller diameter is more preferable than a larger, as it allows a lower liquid flow rate during CFU operation. The new calculations for the CFU performance are presented in Tab. 3.5

Table 3.6: CFU calculation results after third iteration.

Final calculated CFU performance	**Value**
Q_l	3.9–5 $\mathrm{m^3/h}$
ζ	20.75–32.42 G
v_{SLR}	0.0135–0.017 m/s
τ	56.95–45.56 s
v_t	5.53–7.09 m/s

A flow simulation of the third iteration of CFU is illustrated in Fig. 3.10, using a water flow of 5 $\mathrm{m^3/h}$ and 5 bar at the inlet. Mesh generation, boundary conditions and set values can be found in Electronic Appendix 3.



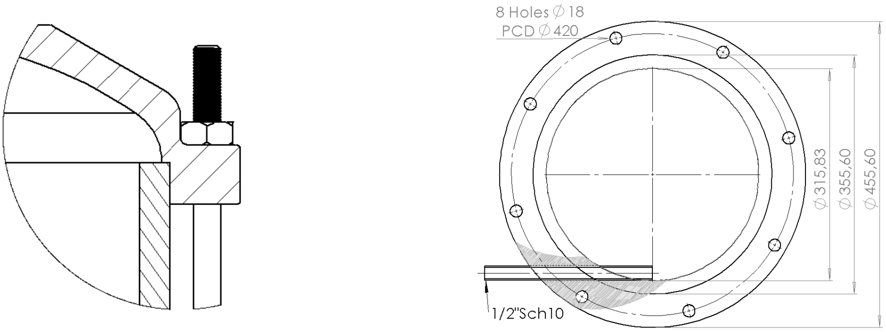
(a) Flow lines of the third iteration of CFU

(b) CFU velocity profile of the third iteration of CFU

Figure 3.10: Results of flow simulation using 5 m^3/h water, 5 bar at the inlet and athmospheric pressure at the outlets. The flow lines and velocity profile of CFU during operation are presented.

The new design of the main cylinder is separated in two sections by a metal belt. Instead of using flange connections, the main cylinder sections, metal belt and pressure vessel heads will be assembled by eight tension rods.

The use of tension rods simplifies the construction of the tangential inlet pipe without compromising the structural integrity of the main cylinders. A hole tangential to the main cylinder will be manufactured in the metal belt, where the inlet pipe can be inserted. This allows the inlet pipe to be replaced if the effect of varying its diameter is of interest. Fig. 3.11 illustrates the new assembly method and the metal belt.



(a) Illustration of the assembly of the top main cylinder, the top pressure vessel head and a tension rod

(b) Illustration of the metal belt with inserted tangential inlet pipe

Figure 3.11: Revised CFU design for assembly method and inlet pipe.

As a result of the decrease diameter, both the vortex breaker and inner cylinder are reduced to maintain the same distance between the components and walls of the CFU. This iteration represents the final changes to the design of the CFU.

3.1.7 Final CFU Design

The final design of CFU has a main diameter of 315,83 mm and a total height of 1025 mm. The vertical water outlet pipe has a diameter of $2''$ and the vertical reject pipe has a diameter of $1''$. The inlet pipe has a diameter of $1/2''$ and is inserted tangentially in the metal belt. The main cylinder is divided in two sections, and tensioned between the two pressure vessel heads and metal belt by eight tension rods. The CFU is a pressurized tank, which requires a PSV to be installed to redirect the fluids inside the vessel if the pressure exceeds a given value. The $1/2''$ outlet for the PSV is placed on the top pressure vessel head.

The manufacturing of the CFU is arranged to be outsourced RadøyGruppen Engineering. Fig. 3.12 presents an exploded view of the finalized CFU sections with a description. The two main cylinder sections and the inner cylinder will be manufactured in transparent PVC, while the pressure vessel heads, the metal belt, the vortex breaker and the tension roads will all be manufactured in 316L. Detailed construction drawings of the CFU can be found in Appendix C.

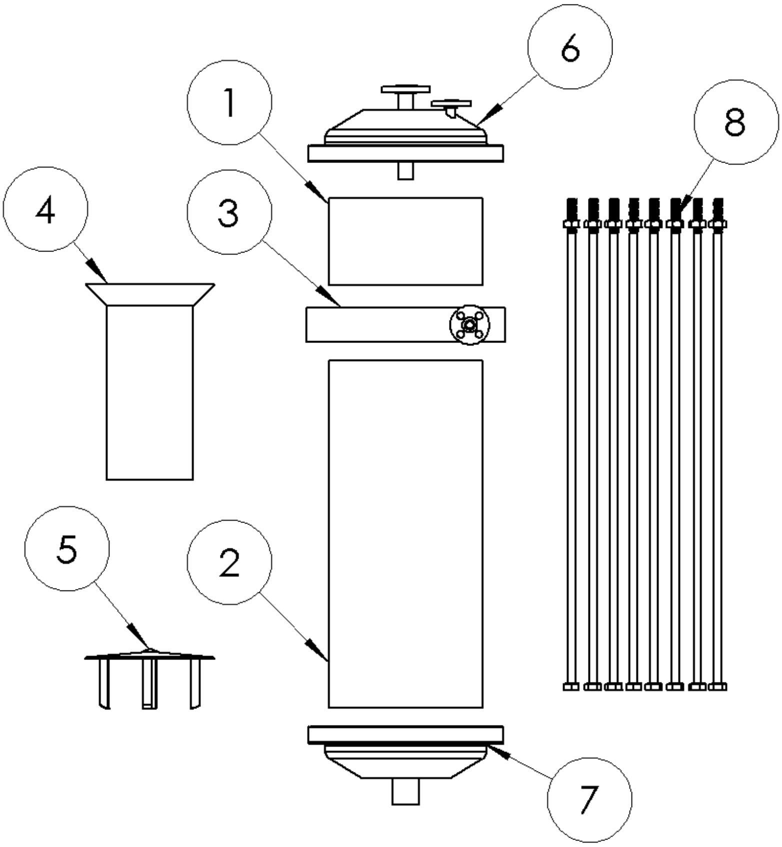


Figure 3.12: Exploded view of the final CFU design.

Table 3.7: CFU assembly sections.

Section	Description	Material
1	Top main cylinder with ribs to install inner cylinder	Transparent PVC
2	Bottom main cylinder	Transparent PVC
3	Metal belt with 1/2″ inlet pipe and flange	316L
4	Inner cylinder	Transparent PVC
5	Vortex breaker with support legs	316L
6	Top pressure vessel head with 1″ reject outlet, PSV outlet and flange	316L
7	Bottom pressure vessel head with 2″ water outlet and flange	316L
8	Tension rods with bolted connection	316L

The vortex breaker is installed at the bottom of the CFU. The four legs of the vortex breaker is welded to the bottom pressure vessel head. Fig. 3.13 illustrates the final design of the vortex breaker.

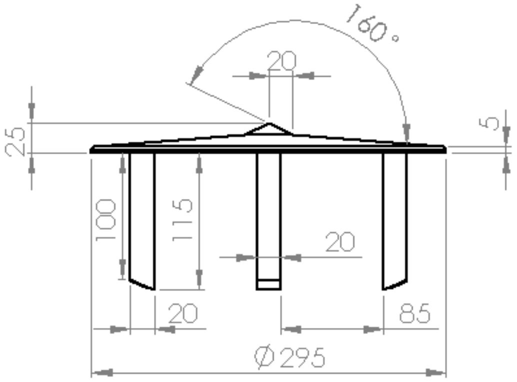


Figure 3.13: Final design of the vortex breaker with support legs.

The inner cylinder is rested on four ribs glued to the walls of the top main cylinder. Fig. 3.14 illustrates the final design and dimensions of the inner cylinder.

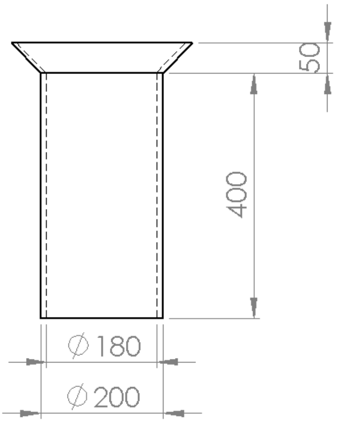


Figure 3.14: Final design of the inner cylinder.

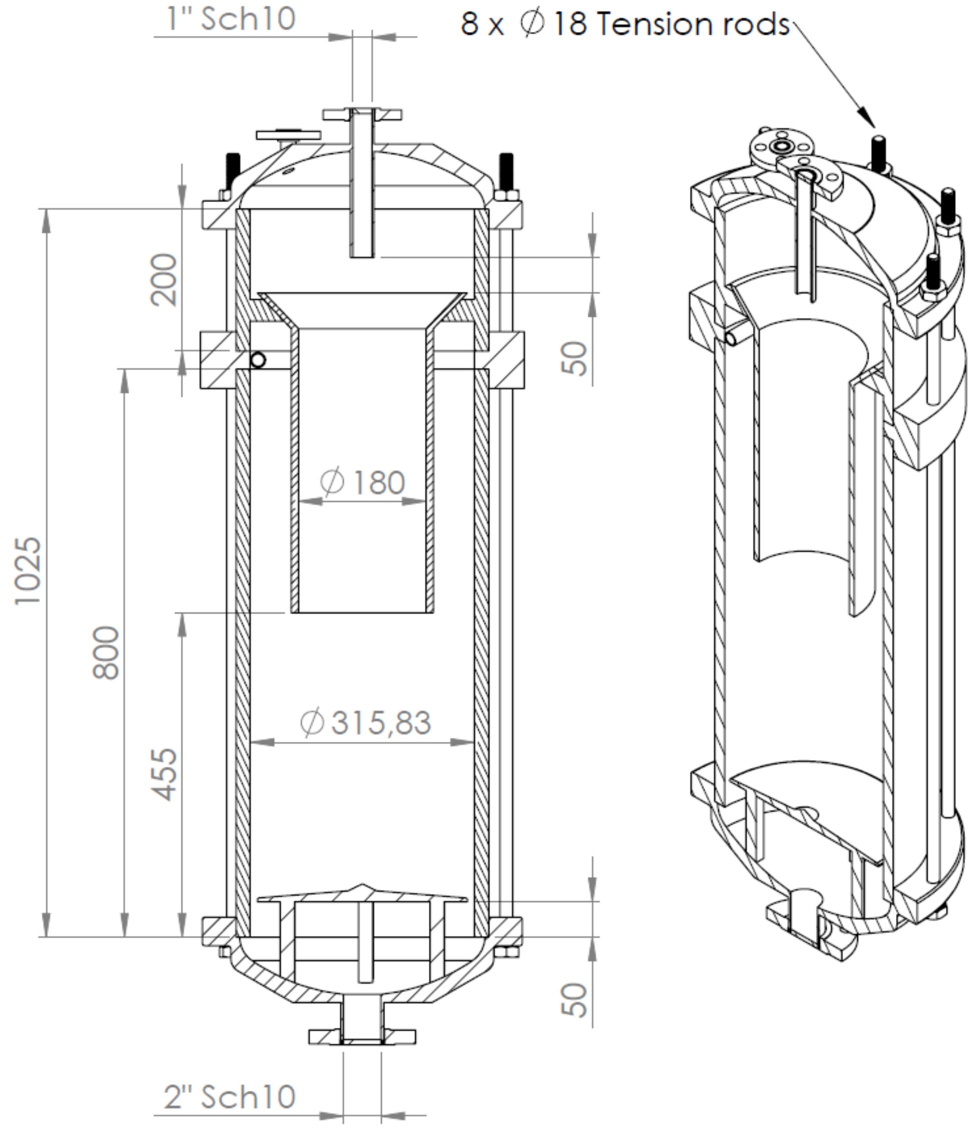


Figure 3.15: The final CFU design with dimensions.

Figure 3.16: The final CFU constructed in transparent PVC and 316L.

3.1.8 Gas-injection design

The injection of gas will have a positive effect on the separation efficiency, and is a vital part of operating both the CFU and GLCC. In the original design of the CSL, it is stated by [64] that a GVF of 0.01 inside the hydrocyclones of Phase 1 will increase the separation efficiency of the given unit. In order to facilitate gas injection of the hydrocyclones, a solution for a common injection method was investigated.

After consulting Hank Rawlins, director of eProcess Technologies [XII], it is established that gas injection in hydrocyclones can be regarded as counterproductive. There are complications when ensuring that gas will flow into the inner cylinder, which can cause gas to be trapped inside the outer housing. As a result of this, injection of gas to hydrocyclones was abandoned from further design.

The issue when deciding a common solution for injecting gas in both the GLCC and the CFU is the nature in which the gas is to be utilized, and the magnitude of injection flow rate of nitrogen gas.

The main purpose of the GLCC is to perform bulk separation of gas and liquid, whereas the CFU uses gas flotation as a flotation agent to separate small concentrations of oil droplets. The method of injecting gas to the GLCC is further described in Section 3.2.1.

In Section 2.3.1, an ejector and a static mixer are presented as viable in-line injection and mixer units. The CFU specialists at Fjords Processing [V] recommended the use of a static mixer, and Gary Short at Transvac Systems [VIII] presented an liquid jet compressor (LJC) ejector which is suitable for the CFU. It is an area of interest to investigate how the separation efficiency will be affected by changing the mixer unit. Due to this, the solution for mixer technology is to implement both a static mixer and an LJC ejector at different stages of CSL operation.

Due to budgetary constraints, the ejector will not be available for testing before spring 2018. In absence of the ejector, a static mixer will be supplied and used for lab operation.

3.2 GLCC design process

The design process of the GLCC vessel is not a part of the objectives listed in Section 1.4, and have been outsourced to Statoil ASA. The design described in the Sections 3.2.1 to 3.2.4 is presented by Statoil, using internal proprietary tools and test results. The specific design model details cannot be disclosed in this thesis.

The engineering process of the GLCC is conducted by the authors. This include material selection, enable manufacturing and preparing detailed manufacturing drawings. It is important to include some level of insight of the evolution of the GLCC design process in the master's thesis. Access to the designed models and sketches are necessary to enable construction of the GLCC vessel, which is one of the objectives for the thesis.

Decisions regarding the final design of the GLCC will also affect the remaining process equipment required for GLCC control and overall system layout, which is natural to include in this master's thesis.

3.2.1 GLCC design parameters

The operation capacity of the GLCC is limited by the available feed resources for liquid and gas. The future pump and reservoir system for the CSL will have a maximum feed capacity of 5 m^3/h and a maximum operational pressure of 25 bar. As the overall pressure rating of CSL Phase 2 is set to PN16, the maximum operational pressure for the GLCC vessel is limited to 10 bar.

For experiments at MTP Valgrinda, the GLCC will operate using freshwater as the liquid phase. Freshwater is applicable for gas-liquid separation experiments to validate the design and manufacturing quality of the GLCC, and suitable from both an HSE and economical point of view. When the CSL is relocated to SINTEF Tiller facilities, experiments with oil representative of real hydrocarbons can be conducted.

Gas feed for the GLCC can be provided either by the nitrogen gas reservoir or the MTP central pressurized air distribution system. A typical GLCC vessel operates with a GMF range from 0.05 to 0.4 [III]. For the intended liquid flow and typical GMF range, the GLCC will require a gas feed in the range from 0.98 to 0.134 kg/s. These feed values are not available for the nitrogen gas reservoir, and leaves the MTP central distribution system the preferred gas feed solution. The central distribution system can provide 16.05 kg/s feed with a maximum pressure of 8.5 bar [X], which is sufficient for the GLCC requirements.

Early in the design process Mr. Holden requested the possibility to manufacture the GLCC in transparent material, equal the to CFU vessel. The simple geometry of a GLCC vessel is described in Section 2.4, and should be applicable for manufacturing in PVC transparent material [VII]. The design parameters for the GLCC are listed in Tab. 3.8

Table 3.8: GLCC design parameters.

Design Parameters	**Value**
Max liquid flow rate	5 m^3/h
Max gas flowrate	16 kg/min
Liquid selection	Freshwater $\rho_w = 1000$ kg/m^3
Gas selection	Air $\rho_g = 9$ kg/m^3 at 10 bar
Max operational pressure	10 bar
Max operational temperature	70°C
Material selection	Transparent PVC 316L

3.2.2 GLCC operation envelope

By utilizing the design parameters as a base, an operation envelope could be calculated. The operation envelope plots the volume flow for the liquid phase versus the volume flow for the gas phase, and is used to identify the operational range for the GLCC. The operation envelope is illustrated in Fig. 3.17. The operation envelope can also by used to estimate LCO and GCU from the GLCC, which is illustrated in Fig. 3.18 and Fig. 3.19.

All calculations and illustrations for the GLCC operation envelope, LCO and GCU is designed by Statoil. Further details are not described in this master's thesis, in compliance with the non-disclosure agreement.

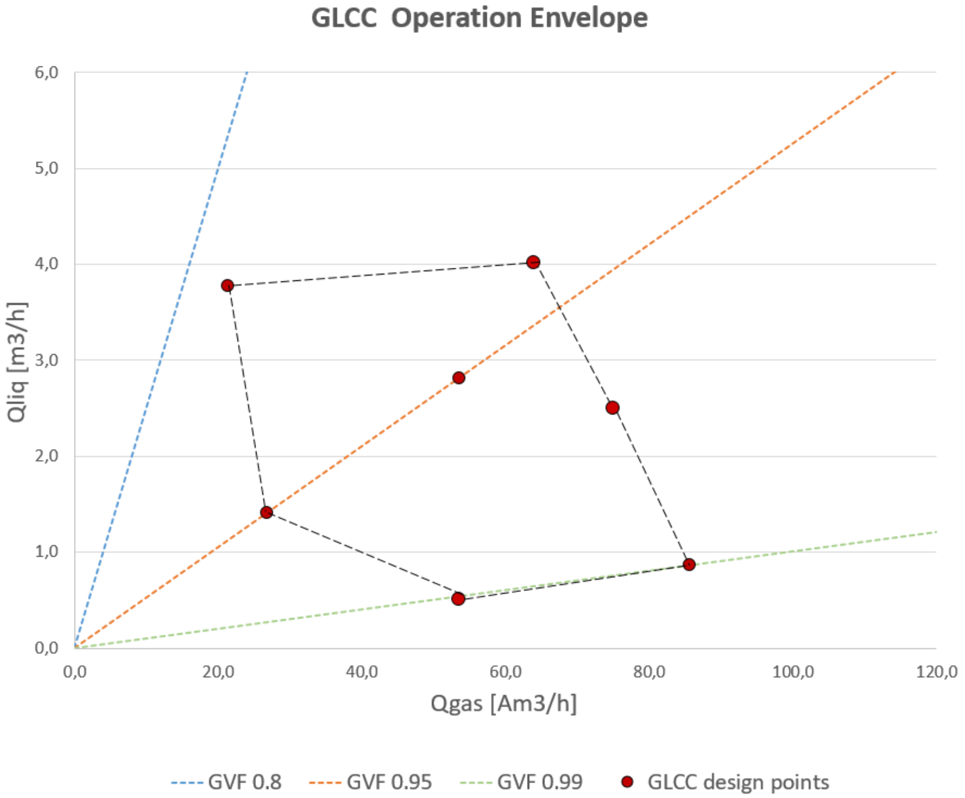


Figure 3.17: Operation envelope for the CSL Phase 2 GLCC vessel. The blue, orange and green dashed lines represents different GVF values. The red dots represents the selected design points, and defines the operation area the GLCC will be designed for. The illustration is provided by Statoil.

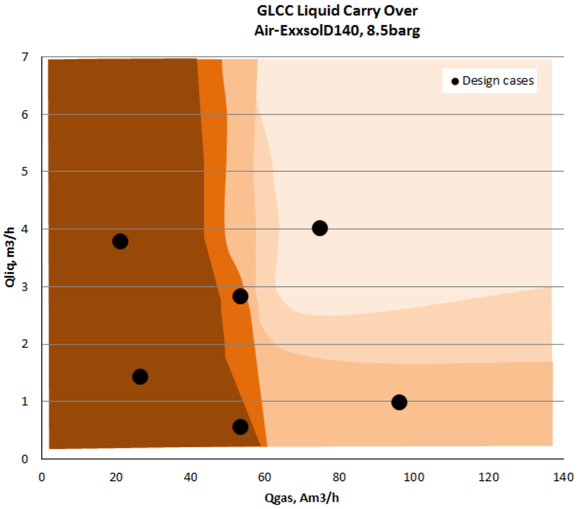


Figure 3.18: Estimated LCO during GLCC operation for the different design points in the operation envelope. The lighter brown color indicates decreased GVF and thereby increased LCO. The illustration is provided by Statoil.

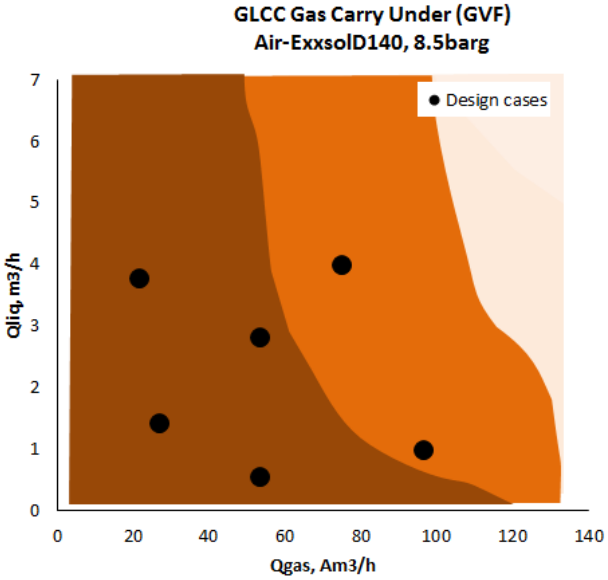


Figure 3.19: Estimated GCU during GLCC operation for the different design points in the operation envelope. The lighter brown color indicates increased GVF and thereby increased GCU. The illustration is provided by Statoil.

3.2.3 Initial design

The initial GLCC design is based on a 6″ diameter main pipe with a total length of 2.2 m. The inlet pipe diameter is equal to the main pipe diameter, and assembled in a Y-connection where the inlet pipe have a 27° inclination relative to the horizontal plane.

To create a tangential inlet flow, a vertical inlet diverter plate will be installed at end of the inlet pipe. The inlet diverter plate will cover approximately 71 % of the inlet cross section and create the tangential flow pattern. The inlet diverter plate will also increase the inlet flow velocity, as the cross section area is reduced.

The inlet pipe is 1 m, with a vertical churn flow coalsecer (CFC) pipe installed vertically upstream of the inlet pipe. The long inlet pipe will promote a stratified flow pattern in order pre-separate the flow before entering the main vessel. The intention of the CFC is to generate churn flow and promote bubble coalescence. Fig. 3.20 illustrates the initial design sketch including main dimensions and recommended sizes for the reject pipes. The blue lines indicates recommended locations for flange connections, to enable future extension of the GLCC and to simplify the manufacturing process.

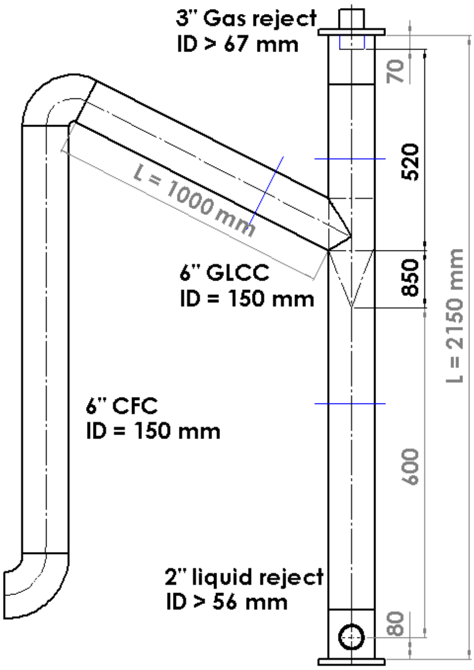


Figure 3.20: Initial GLCC design and dimensions.

3.2.4 First design iteration

After the initial sketches was presented to Mr. Holden, a discussion regarding the expected GLCC performance occurred between Mr. Holden and Mr. Kristiansen. As stated in Tab. 3.8, the GLCC will operate using water and air during experiments at MTP Valgrinda. The separation process for water and air have a low level of complexity in reference to hydrocarbons and natural gas, and occurs more easily [IV].

Mr. Holden expressed concerns regarding the separation performance being unrealistically high, relative to existing GLCCs separating oil and gas. Due to the easy separation process between water and air, the estimated LCO and GCU values will be close to zero. If the GLCC performs at its optimal level, the scientific research value is limited due to no possibility for improvements. If the GLCC where to be designed sub-optimally, increased LCO and GCU values will increase the scientific value and contribute to the CSL overall objective, which is to develop control algorithms for separator units. Mr. Kristoffersen expressed concerns for the experimental validity if the GLCC where designed sub-optimally. After a consultation with Statoil ASA, it was decided to re-design the GLCC vessel to the outer limit of the existing design models.

The revised GLCC design have reduced the diameter of the main pipe and inlet pipe from 6″ to 4″. The respective length and angle of the inlet is unchanged. The revised inlet diverter plate has been increased and will now cover 75 % of the cross section area. The total length of the GLCC has been increased from 2.2 m to 2.6 m, by extending the top section of the main pipe. The size of the liquid reject have been increased from 2″ to 3″, equal to the gas outlet. The revised GLCC design and geometry is illustrated in Fig. 3.21.

The reduced diameter of the inlet and main pipe will increase the inlet velocity and shear forces between the gas bubbles and water droplets. The increased inlet velocity generates a more turbulent flow and counteract the pre-separation. Increased shear forces will increase the number of liquid droplets and decrease the size of each droplet. Because of the turbulent flow, more gas bubbles will interact with the liquid phase and attach to the liquid droplets. The reduced diameter will also increase the liquid level at the bottom and increase tangential velocity [IV].

The revised dimensions and geometry of the GLCC is designed at the outer limit of the design models for more experimental operation. All the described effects of reducing the diameter, except increased tangential velocity, will result in a more experimental GLCC. The experimental GLCC design have increased scientific value as it requires increased level of control for optimal performance. The increased tangential velocity will increase separation performance and counteract the negative effects, but only to a certain level [IV].

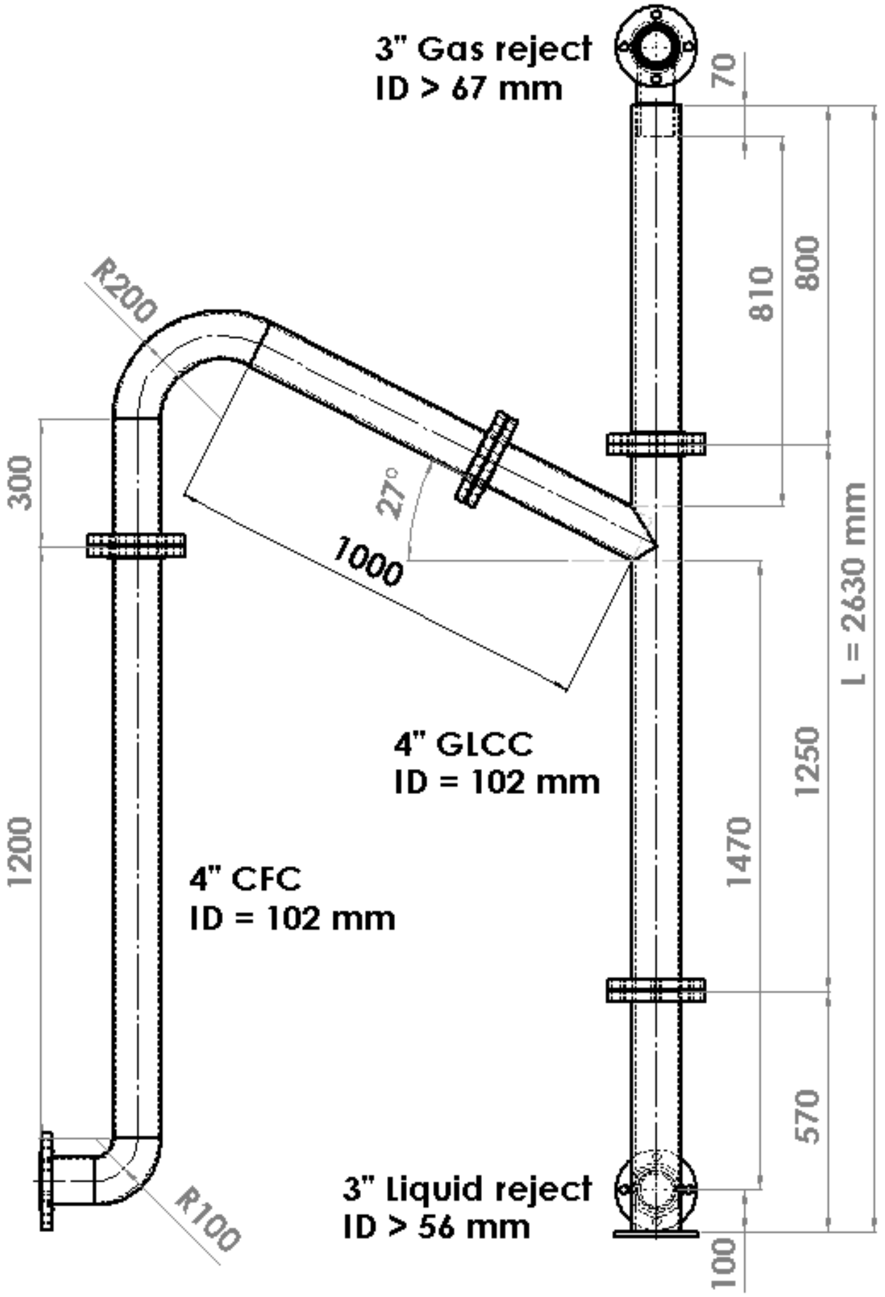


Figure 3.21: Second GLCC design and dimensions, including flanges for assembly, inlet and outlets.

3.2.5 Second design iteration

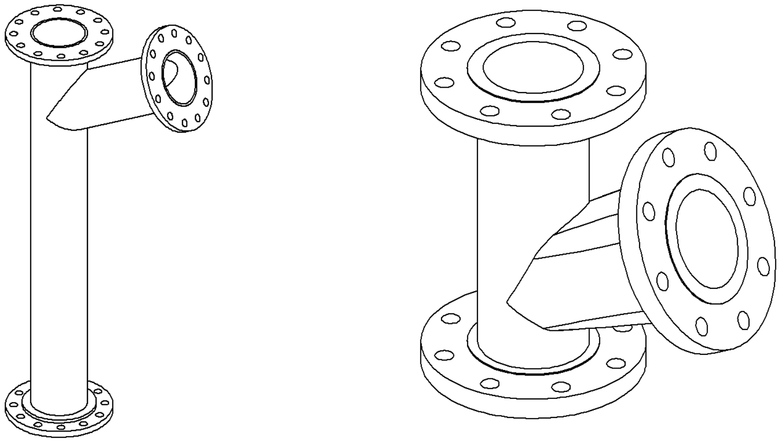
After the revised design was presented, Øystein Gjervan Hagemo [VII], staff engineer at the NTNU Finmekanisk workshop was contacted for consultation and detailed re-engineering of the design from a manufacturing point of view.

The NTNU Finmekanisk workshop is located at NTNU Gløshaugen campus, and specializes on high accuracy manufacturing of small-scale objects. Mr Hagemo has previous experience in manufacturing PVC, and was recommended from one of the PVC material suppliers.

Mr. Hagemo found the project both interesting and applicable for manufacturing at the NTNU Finmekanisk workshop. He had some concerns regarding the construction and assembly method of the GLCC, especially the main cylinder and inlet pipe. The Y-connection of the pipes constitutes a weak point of the structure, which can compromise the GLCC integrity when the intended operational pressure is applied. Finding a suitable adhesive to connect the given parts and handle the stress levels is a challenge.

To solve the manufacturing problem, a new design for the main cylinder was proposed, where the main cylinder and inlet connection is manufactured as a single section. With the new design, the potential weak points and use of adhesives for assembling is eliminated.

To simplify the manufacturing process the length of the main pipe/inlet connection section is reduced, and the bottom pipe is extended. With this solution, the overall GLCC dimensions are unchanged, but weak points are eliminated. Fig. 3.22 illustrates the previous design and the new design of the main pipe.



(a) Original GLCC main body design.

(b) New GLCC main body design.

Figure 3.22: GLCC main body revision.

In addition to the re-designed main pipe, some modifications to the flange locations were made. The 90° elbow bend at the CFC inlet and the 117° bend at the inlet pipe are difficult to manufacture in PVC material. These sections does not require transparency, resulting in the decision manufacture these bends in 316L instead of PVC. Flange connections were added to both sides of the bends for connection to the straight PVC pipes. These changes represents the final iteration of the GLCC vessel, which is presented in Section 3.2.6.

3.2.6 Final design

The final design of the GLCC vessel has a diameter of 4″ and a vertical height of 2.6 m. The inlet pipe has a diameter of 4″ and a length of 1 m with an inclination of 27° relative to the horizontal plane. The inlet pipe is designed with a inlet diverter plate covering 75 % of the inlet cross section area to provide a tangential inlet flow pattern. The CFC and inlet pipe churn the flow and promote bubble coalescence for pre-separation. The liquid outlet extends horizontally from the GLCC bottom pipe and has a diameter of 3″, while the gas outlet extend vertically from the top, also with a diameter of 3″.

The GLCC vessel is designed as an assembly of eight sections. The main reason for this design is the possibility to extend the GLCC in the future by replacing the different sections. The section design philosophy also simplifies the manufacturing process.

Five of the eight sections will be manufactured in transparent PVC material. This enables the operator to see the separation process during operation, which is one of the of requirements for the design. The remaining three sections will be manufactured in 316L due to geometry and manufacturing complications with PVC material.

The different sections of the GLCC are illustrated in Fig. 3.23 and listed in Tab. 3.9. The final GLCC dimensions and geometries are illustrated in Fig. 3.26 and 3.27. The complete set of construction drawings for the GLCC can be found in Appendix D

Table 3.9: GLCC assembly sections.

Section	**Description**	**Material**
1	Bottom pipe with liquid outlet	PVC
2	Main pipe with inlet connection and diverter plate	PVC
3	Top pipe	PVC
4	Top cap with immersed pickup pipe	316L
5	Inlet pipe	PVC
6	117° pipe bend between CFC and inlet pipe	316L
7	CFC pipe	PVC
8	90° elbow bend for CFC inlet	316L

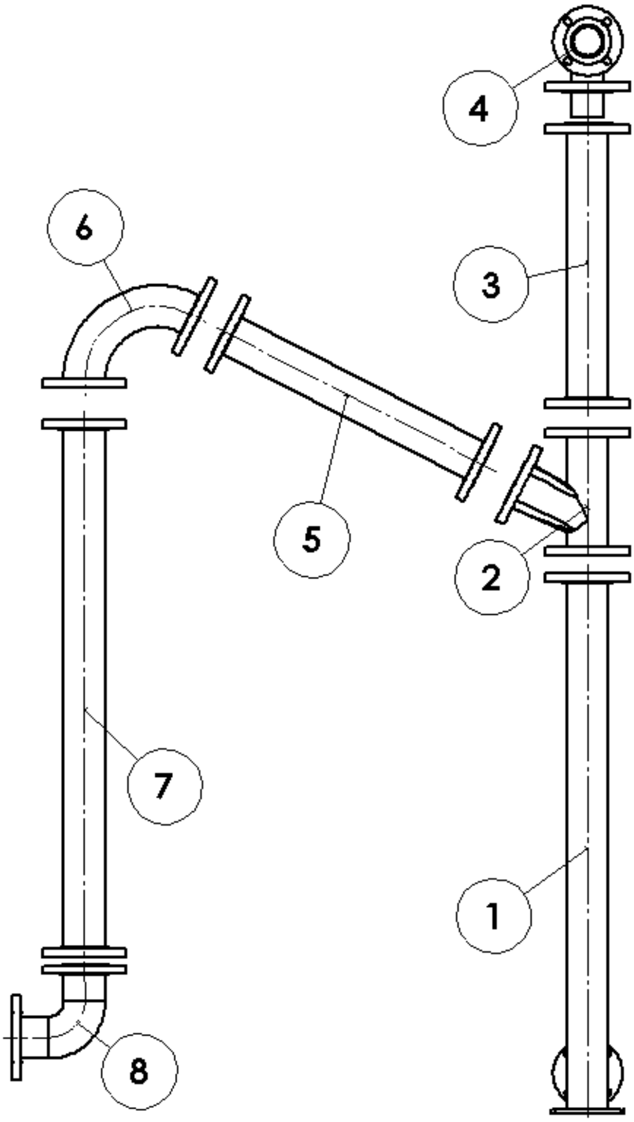


Figure 3.23: Final GLCC sections.

The GLCC main pipe and inlet is designed with equal diameter with a inlet diverter plate, will create a tangential flow pattern in the main vessel. The plate covers 75 % of the cross section areal of the inlet pipe, declining backwards into the inlet pipe until the inlet pipe is fully open. In addition to create the tangential inlet, the diverter plate will increases the inlet velocity due to reduced cross-sectional area. The main pipe with diverter plate is illustrated in Fig. 3.24

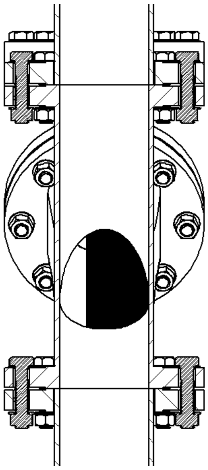


Figure 3.24: GLCC main pipe section view. The inlet slot is indicated by solid black.

The 3″ gas outlet is designed with an additional pickup pipe suspended vertically into the GLCC top pipe. The remaining cross-sectional area is sealed off by the top flange connection. The function of the pickup pipe is to allow gas flow to exit and restrict LCO from flow through the gas outlet. The pickup pipe is 3′ and has the same dimension as the gas outlet pipe, illustrated in Fig. 3.25.

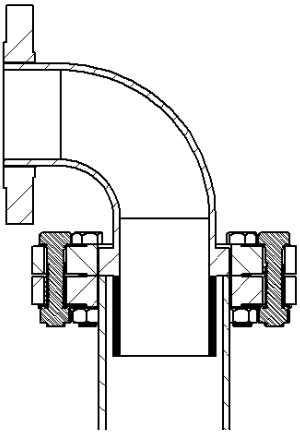


Figure 3.25: GLCC top pipe section view. The edges of the immersed pickup pipe is indicated by solid black.

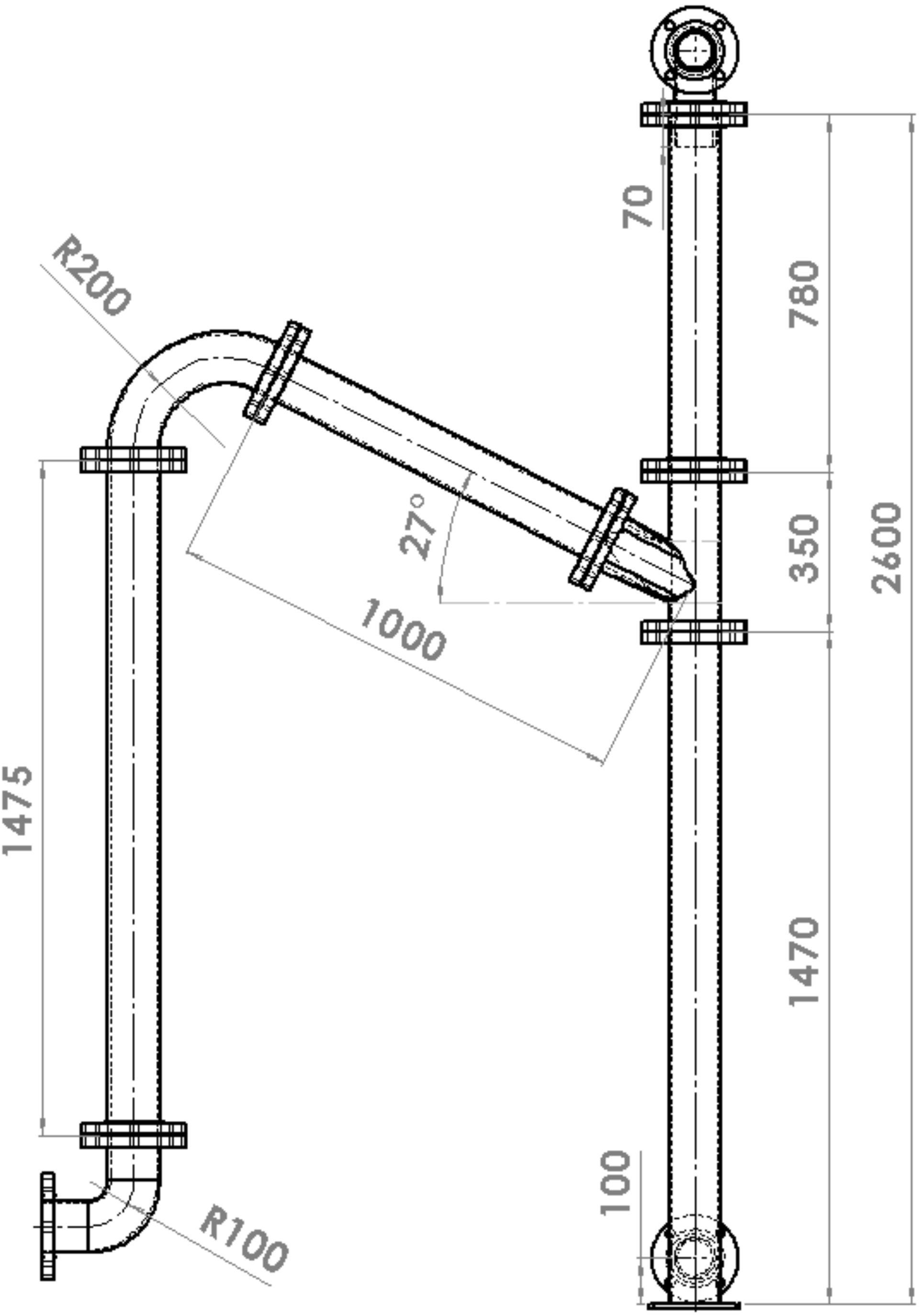


Figure 3.26: Final GLCC design with dimensions.

Figure 3.27: The final GLCC constructed in transparent PVC and 316L.

3.3 Scrubber design process

A scrubber is a vertical gas-liquid separator, consisting of an inlet, a mesh pad and two outlets for gas and liquid respectively, illustrated in Fig. 3.28. The scrubber design is correlated to the settling velocity of gas-in-liquid (v_g) and liquid-in-gas (v_l). When $v_g = v_l$, the maximum velocity of gas inside the vessel is calculated.

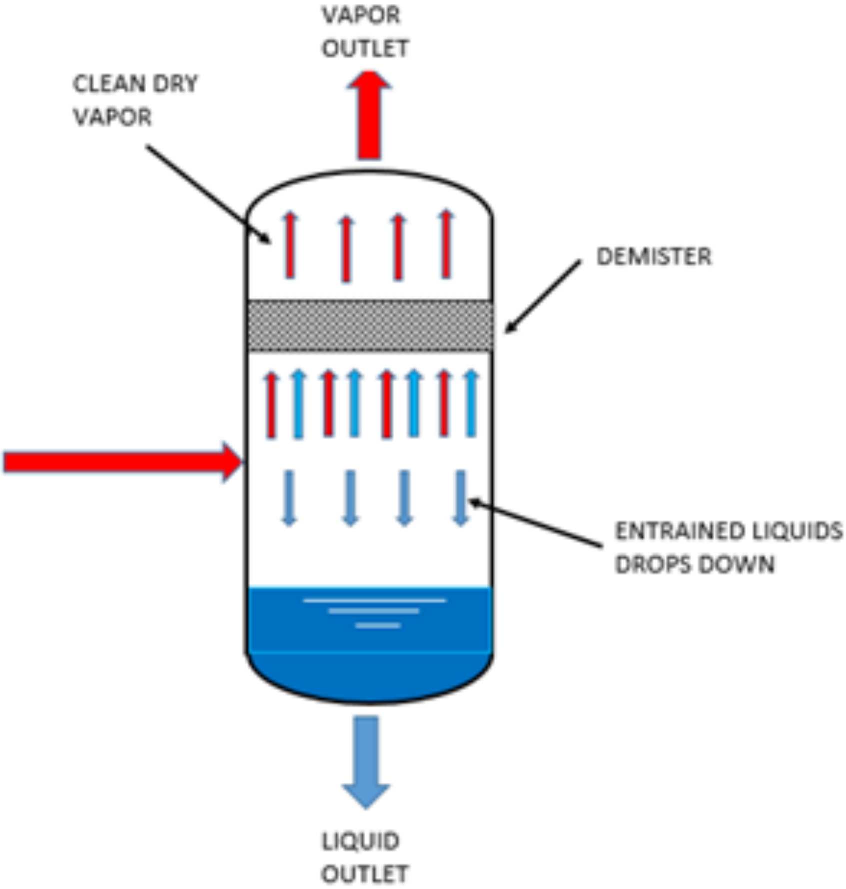


Figure 3.28: Principle scrubber layout with demister [23].

The process of designing a scrubber is done utilizing the equations described in Section 2.5. The K-value is defined by the implementation of a mesh pad, also referred to as mist eliminator or demister. The mash pad has a predefined area between, which allows liquid drop with diameter smaller than 5μm to flow through. The larger droplets will coalesce in the mesh pad and fall down when enough mist have agglomerated. An illustration of a standard mesh pad is presented in Fig. 3.29.

The implementation of a mesh pad create a restriction in the scrubber vessel, and defines the maximum gas velocity inside the vessel. For a standard mist eliminator the K-value is 0.107 m/s and is used for further calculation.

Figure 3.29: Illustration of a mist eliminator made with stainless steel [48].

3.3.1 Initial design

Using the equations described in Section 2.5, an initial design was constructed. The design is illustrated in Fig. 3.30 based on the design parameters presented in Tab. 3.10.

Using K-value as the defining parameter, the required diameter of the vessel required to ensure gas-liquid separation is calculated. The gas outlet is open to air, which makes the scrubber design pressure equal to 1 atm.

This results in the compression of gas to be negligible, and the settling process will be faster due to a larger difference in density between gas and water. The calculated diameter of the scrubber is ~ 150 mm, and increased to 250 mm to assure the separation process will be completed inside the vessel. The height of the vessel is given by the ratio $\frac{L_{vessel}}{d_{vessel}} = 3$.

Table 3.10: Scrubber design parameters.

Design Parameters	**Value**
Max. liquid flow rate	0.42 m^3/h
Max. gas flow rate	85 m^3/h
K-value	0.107 m/s
Liquid selection	Freshwater $\rho_w = 1000$ kg/m^3
Gas selection	Air $\rho_g = 1.184$ kg/m^3
Max. operational pressure	1 bara
Max. operational temperature	25°C
Material selection	Transparent plastic Aluminum

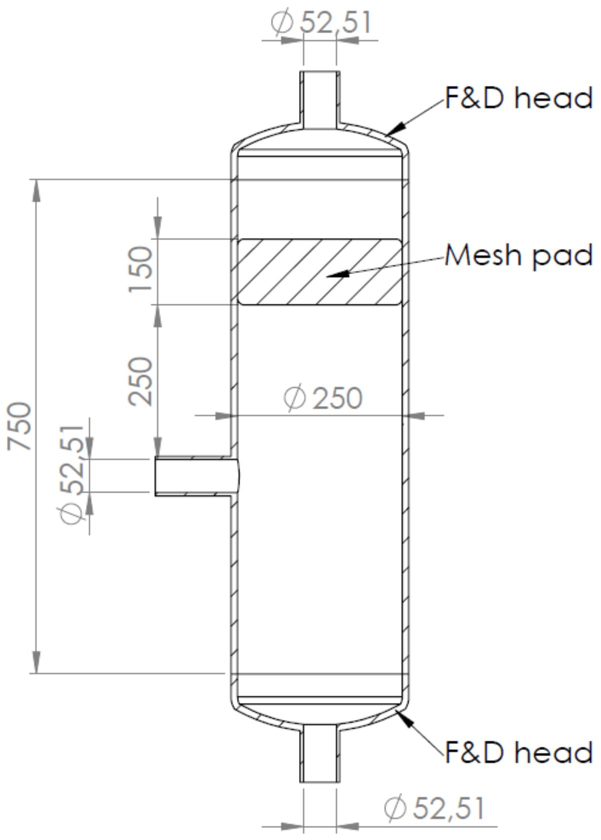


Figure 3.30: Illustration of initial design of Scrubber with two flanged and dished (F&D) pressure vessel heads and location of mesh pad indicated.

3.3.2 First Iteration

After consultation with Olav Kristiansen [IV] regarding the proposed design of the scrubber, a few changes was proposed.

The height between the scrubber inlet and the mesh pad is increased to 400 mm in order to facilitate gas-liquid separation. The height between inlet and a definable liquid level is increased to 300 mm to prevent liquid to re-exit the scrubber through the inlet if the liquid level exceeds the height of the inlet. The inlet and outlet pipe diameters are increased to 3″. According to NORSOK, a vertical separator must have a minimum of 150 mm distance between each liquid level, and a minimum brim time of 30 s between each liquid level [IV]. This iteration will have a final revision regarding the practicalities of constructing the scrubber. The revised design of Scrubber is illustrated in Fig. 3.31.

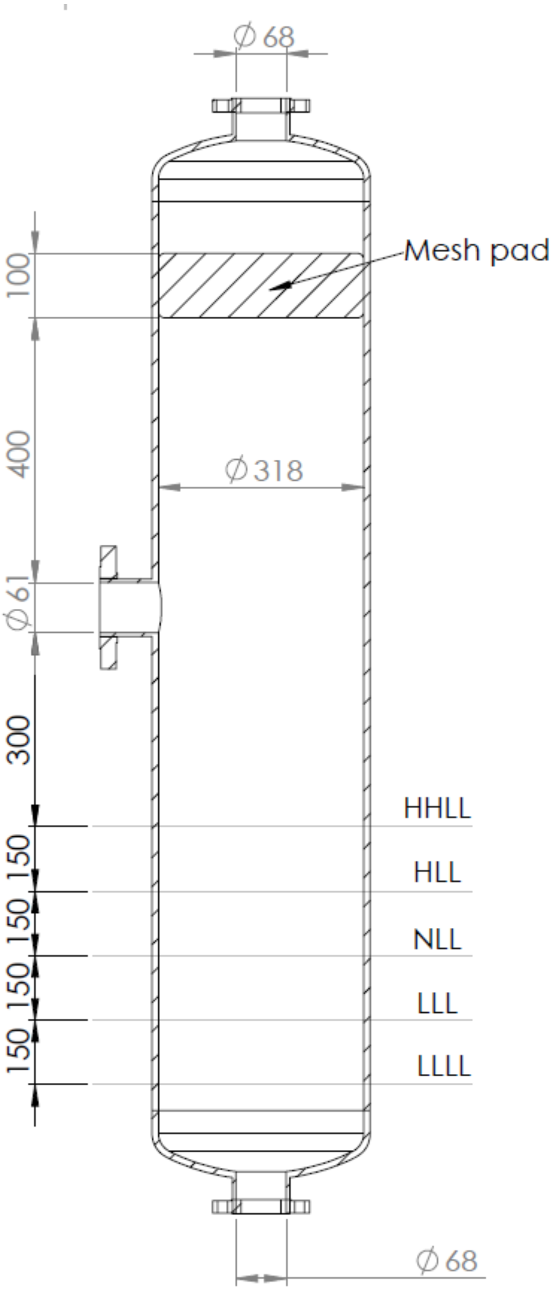


Figure 3.31: Illustration of the first iteration of scrubber design.

3.3.3 Second iteration

The second iteration of the scrubber design is made after revising the set point of liquid levels inside the vessel, scaling the diameter of inlet- and outlet pipes and revising the end caps of the scrubber.

After consulting with Mr. Holden, the initiate design with pressure vessel heads was found oversized for an vessel open to atmosphere. Hence, the pressure vessel heads were replaced by two simple cover plates with grooves for the main cylinder.

Arild Sæther [XIV], staff engineer at the MTP Workshop was consulted regarding manufacturing of the cover plates. Mr. Sæther recommended to manufacture the cover plates in aluminum for reduced cost and weight. Holes for the bolted connections and outlet pipe, as well as grooves for cylinder assembly can be machined at the MTP workshop. The outlet pipes and flange connections can be welded to the plates. The design and dimension of the end plates are illustrated in Fig. 3.32

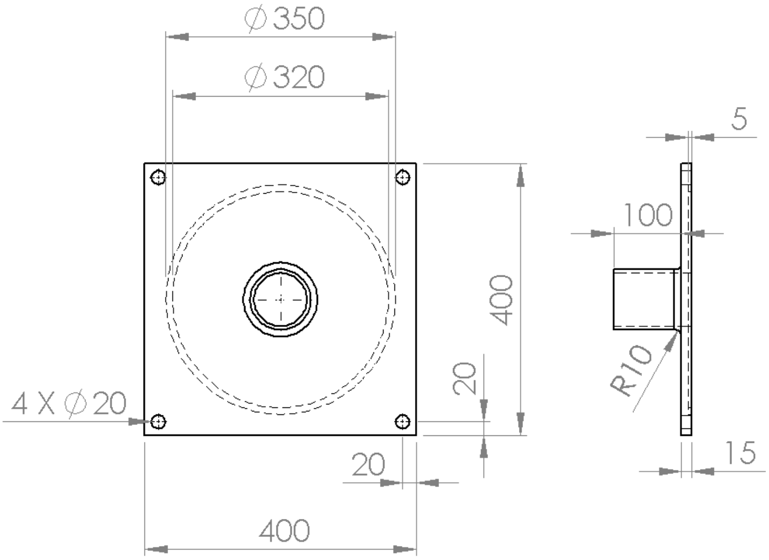


Figure 3.32: Scrubber cover plates with dimensions.

After contact with Astrup, the supplier of a the main cylinder made in transparent plastic, the authors were informed that polymethyl methacrylate (PMMA) plastic is the only transparent material available such a large extruded cylinder.

Selecting PMMA is not preferable due to the materials shattering behavior when being exposed to over pressure, but deemed acceptable in collaboration with Mr. Holden [I] due to the scrubber being open to air, indicating atmospheric pressure during operation. Fig. 3.36 illustrates the final manufactured scrubber. Detailed construction drawings of the scrubber assembly can be found in Appendix E.

3.3.4 Final Design

The final design of the scrubber has a diameter of 320 mm and a total height of 1430 mm. The two vertical outlets and the horizontal inlet has all a diameter of 3″ and connects to the process lines by flange connections.

The main cylinder is intended to be constructed in transparent plastic, with a level indicator to be installed. Installing a level indicator gives both a visual and digital representation of the actual liquid level inside the vessel. The choice of level indicator is further described in Section 4.1.7. The mesh pad is supported by a orifice plate, which in turn rests on four plastic ribs glued to the main cylinder.

To assemble the scrubber, four tension rods is used. An exploded view of the assembly with the associated sections is illustrated in Fig. 3.33 and described in Tab. 3.11.

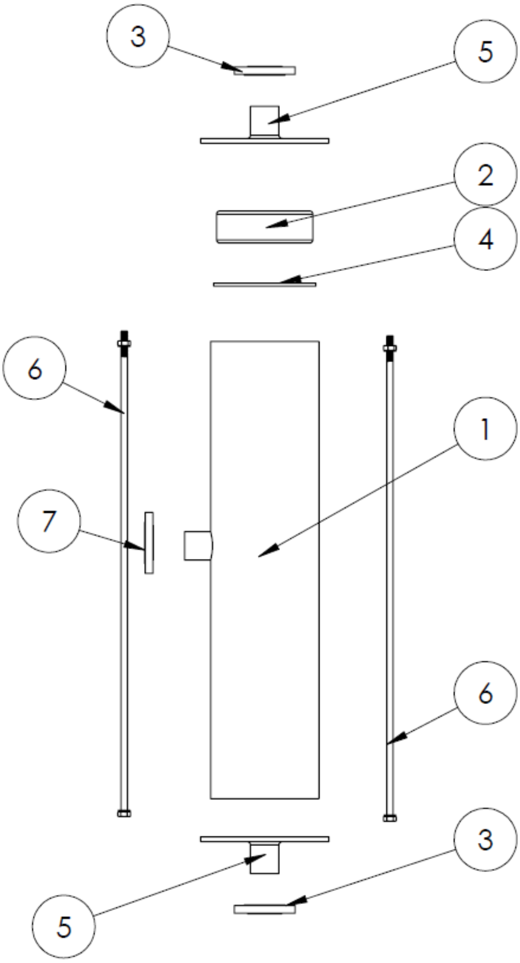


Figure 3.33: Exploded view of final scrubber design with main components marked.

Table 3.11: Scrubber assembly sections.

Section	Description	Material
1	Main cylinder with inlet pipe and ribs	Transparent Acryl
2	Mesh Pad	316L
3	3″ flanges	Aluminum
4	Orifice plate	PVC
5	Cover plates with welded outlet pipe	Aluminum
7	Inlet flange	Transparent PVC

The maximum theoretical flow rate of liquid from the GLCC to the scrubber is 0.42 m^3/h, resulting in rapid rise between the set liquid levels being unlikely to occur. As a result of this, the low-low liquid level (LLLL) is set at the outlet pipe of the vessel.

At the maximum theoretical flow rate, the estimated brim time between each liquid level is ∼100 s, which indicates a elapsed time from LLL to HHLL of ∼300 s. It is determined that this amount of time is sufficient to adjust a level control valve at the liquid outlet before liquid re-enters the inlet of the scrubber. Fig. 3.34 illustrates the final liquid levels in the scrubber. The final dimensions and design of the scrubber are illustrated in Fig. 3.35 and Fig. 3.36

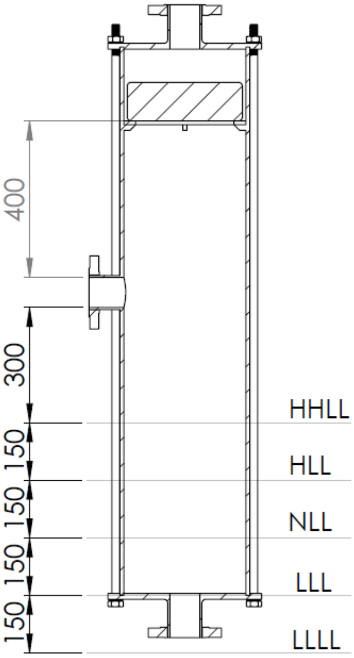


Figure 3.34: Finalized scrubber design with liquid levels.

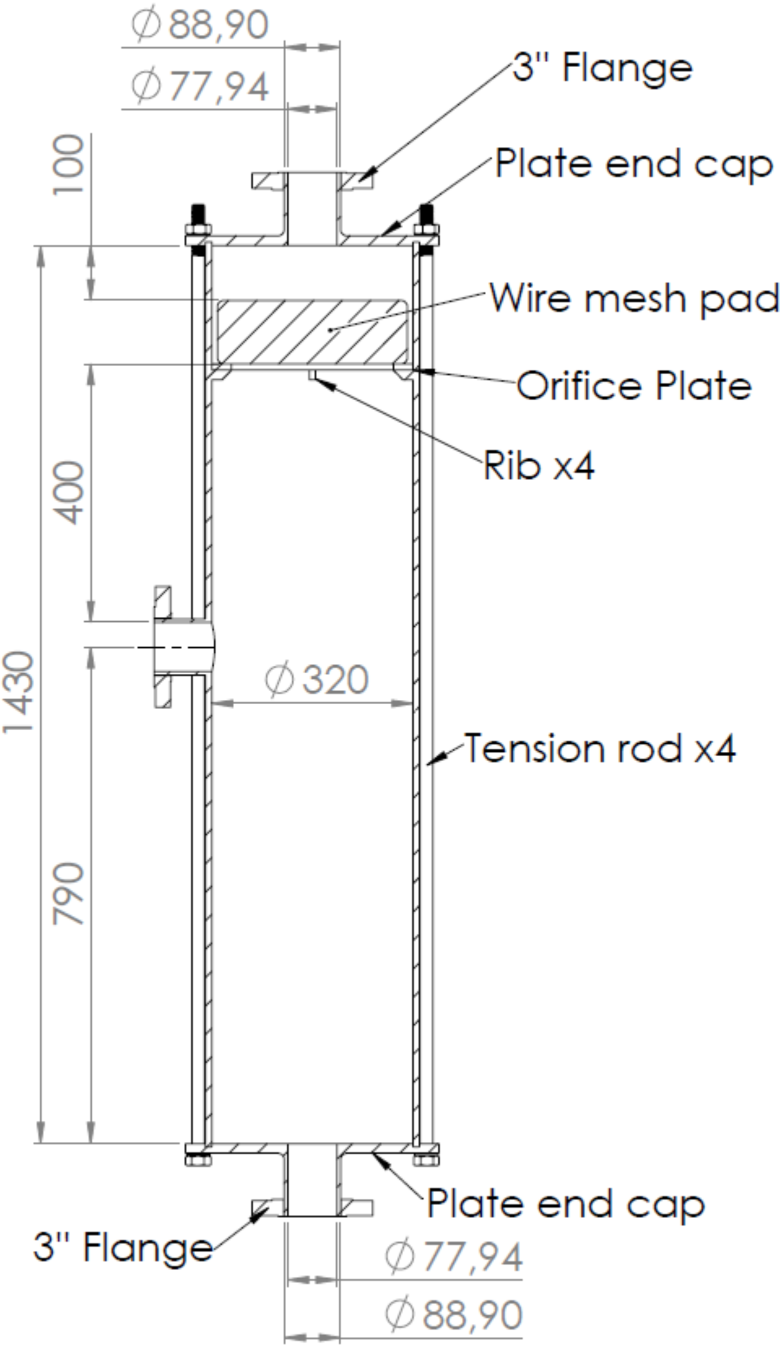


Figure 3.35: Final design of the scrubber, including main components and dimensions.

Figure 3.36: The final Scrubber constructed in transparent PVC, 316L and aluminum.

Chapter 4

Front End Engineering Design

The Front End Engineering Design (FEED) is an engineering study carried out after the conceptual design [4]. At this stage, the overall system configuration is defined including schematics and diagrams. The main intention of the FEED is to present a finalized design according to the requirements of the task. By conducting an extensive and detailed FEED study, significant changes during the construction phase can be avoided. For the CSL Phase 2 the overall system configuration is first presented, followed by a detailed engineering process for the different components of Phase 2.

4.1 Process

4.1.1 Laboratory Number System

To maintain good laboratory structure and identification of equipment, an Engineering Number System (ENS) has been developed by the CSL Phase 1 project team. The ENS provide information for location, type and serial number for all main equipment, instrumentation and cables in the CSL. Phase 2 continues the same ENS for consistent integration between Phase 1 and Phase 2. Details of the ENS can be found in Appendix A.

4.1.2 Phase 2 Piping and Instrumentation Diagram

A piping and instrument diagram (P&ID) is a common industry standard, which illustrates piping, process directions and instrumentation for a system [28]. The P&ID gives a realistic illustration of the laboratory functionality, flow directions and equipment. Fig. 4.1 illustrates the complete P&ID of the CSL Phase 1 and 2, while Fig. 4.2 illustrates the P&ID of Phase 2 only.

In Tab. 4.1 the Phase 2 components are listed with tags and descriptions. The unique tag numbers are also used for reference and description in the following sections. Tags and descriptions of the Phase 1 process equipment can be found in Appendix B.

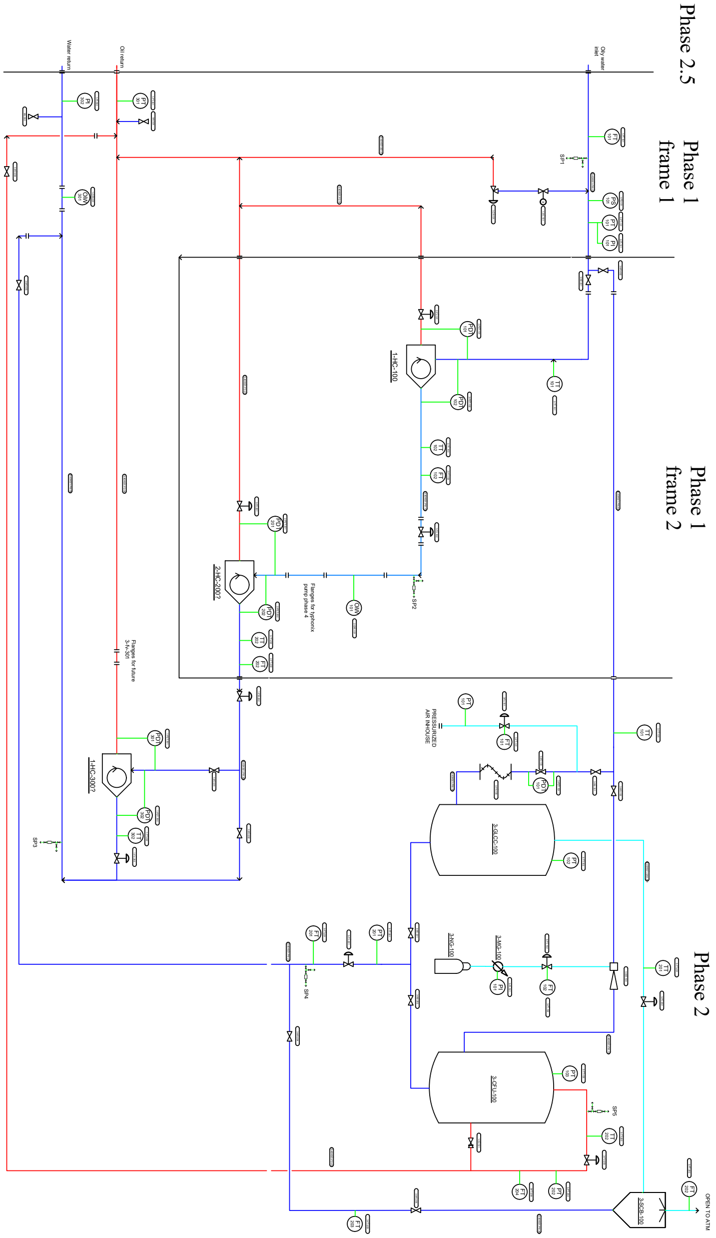


Figure 4.1: P&ID for all process lines and equipment in Phase 1 and Phase 2 of the CSL.

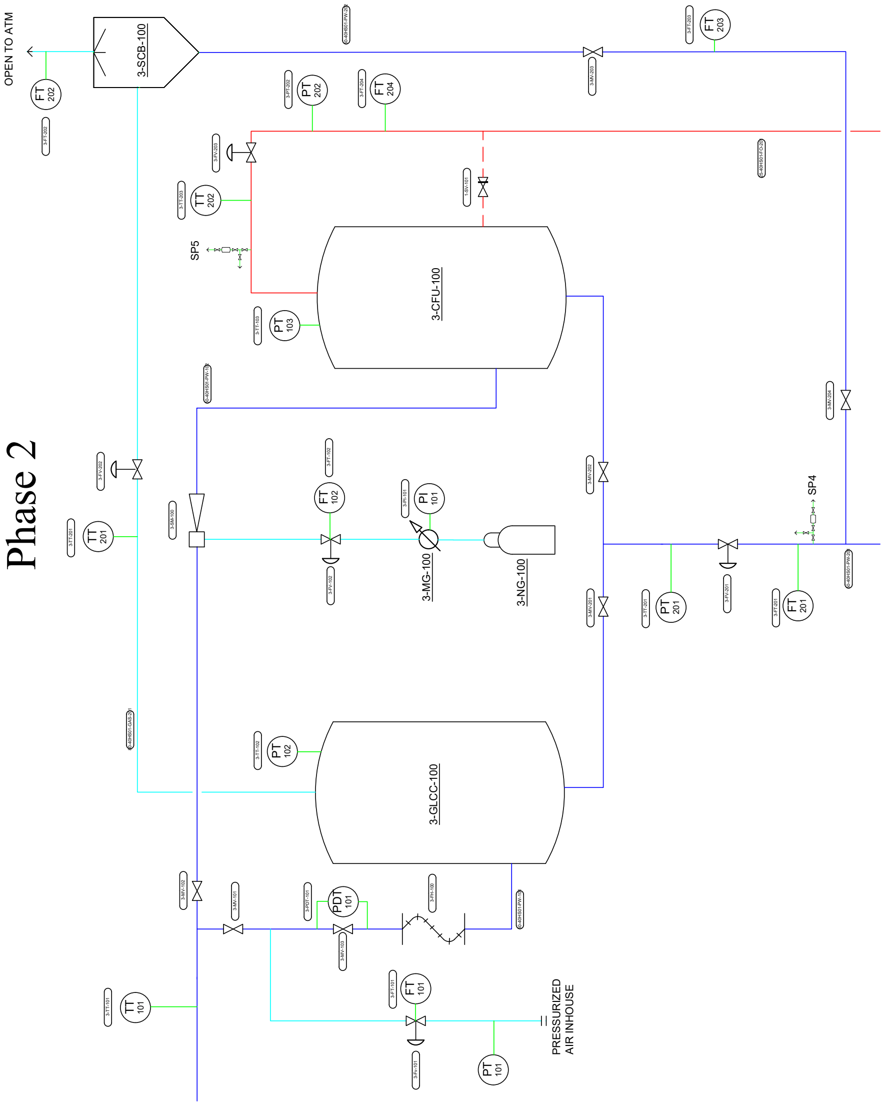


Figure 4.2: P&ID for all process lines and equipment in Phase 2 of the CSL.

P&ID tag	**Description**
3-MV-001	Manual valve for flow diverting to Phase 1
3-MV-002	Manual valve for flow diverting to Phase 2
3-TT-101	Temperature Phase 2 inlet feed
3-MV-101	Manual valve for flow diverting to GLCC
3-MV-102	Manual valve for flow diverting to CFU
3-PT-101	Absolute pressure air supply
3-FV-101	Ex-flow control valve for air
3-FT-101	Ex-flow mass flow for air
3-MV-103	Manual valve for air and water mixing
3-PDT-101	Differential pressure at GLCC inlet
3-FH-100	Flexible hose
3-GLCC-100	GLCC Vessel
3-PT-102	Absolute pressure GLCC
3-NG-100	Nitrogen gas reservoir
3-MG-100	Manual Regulator for Nitrogen gas
3-PI-101	Pressure indicator for nitrogen gas reservoir
3-FV-102	Ex-flow control valve for nitrogen
3-FT-102	Ex-flow mass flow for nitrogen
3-SM-100	Static mixer for nitrogen and oily water
3-CFU-100	CFU Vessel
3-PSV-101	CFU pressure safety valve
3-PT-103	Absolute pressure CFU
3-MV-201	Manual valve for diverting GLCC liquid outlet
3-MV-202	Manual valve for diverting CFU water outlet
3-PT-201	Absolute pressure joint water outlet
3-FV-201	Control valve with positioner at joint water outlet
3-FT-201	Mass flow at joint water outlet
3-TT-201	Temperature GLCC gas outlet
3-FV-202	Control valve with positioner GLCC gas outlet
3-SCB-100	Scrubber vessel
3-FT-202	Mass flow scrubber gas outlet
3-MV-203	Manual valve for scrubber liquid control
3-FT-203	Mass flow scrubber liquid outlet
3-MV-204	Manual valve scrubber-joint water outlet
3-TT-202	Temperature sensor CFU reject
3-FV-203	Control valve with positioner CFU reject
3-PT-202	Absolute pressure sensor CFU reject
3-FT-204	Mass flow sensor CFU reject
3-MV-003	Manual valve for water outlet to Phase 1
3-MV-004	Manual valve for oil reject to Phase 1
SP4	Sampling point at joint water outlet
SP5	Sampling point CFU reject

Table 4.1: Tag numbers and description for Phase 2 P&ID.

4.1.3 Computer Aided Design

During the development of the Phase 2 design, a great effort has been devoted into building a detailed 3D model with Computer Aided Design (CAD) tools. The use of CAD tools is common industry practice during an engineering process for several purposes. CAD is described by [62] as

> *"Computer aided design and manufacturing form the core of the engineering subjects. The engineering curriculum and the engineering academic process attempt to provide students and engineer, with a sufficient number of tools to perform, among other things, design and manufacturing."*

A 3D model provides a representative illustration of the design in the correct scale. This helps the engineering process with regards to the physical layout, dimensions and scaling the project. A digital model is also highly flexible and can be iterated without severe effort. Most CAD software have the ability to perform different analysis of the project. An interactive 3D-model of Phase 2 can be found in Electronic Appendix 1.

The analyses can vary from simple strength and stress tests to complex flow and power calculations. CFU flow analysis in chapter 3.1.4 is an example using CAD models for analysis. CAD models are used in construction to provide detailed manufacturing drawings, calculations of mass and material fabrication. The main reason to build a comprehensive model of Phase 2, is to enable pre-fabrication of process pipes instead of hiring external welding personnel, described in Section 4.3.

All 3D-models presented in this thesis are created using SolidWorks 3D CAD software. For more realistic illustrations, the models have been rendered using Keyshot rendering & Animation software. Information and procurement of SolidWorks and KeyShot 6 software can be found at [24] and [18] respectively.

The CSL Phase 2 CAD model is illustrated in Fig. 4.3, including all process equipment, the steel frame and the nitrogen gas reservoir. Fig. 4.4 illustrates the process equipment for Phase 2 without the steel frame and the nitrogen gas reservoir. Since Phase 2 contains a CFU separator and a GLCC separator in parallel, the two different systems has been described independently in Sections 4.1.5 and 4.1.6.

The P&ID of both Phase 1 and 2, as well as drawings presented in Sections 4.4 and 4.5 are made using AutoCAD drawing software.

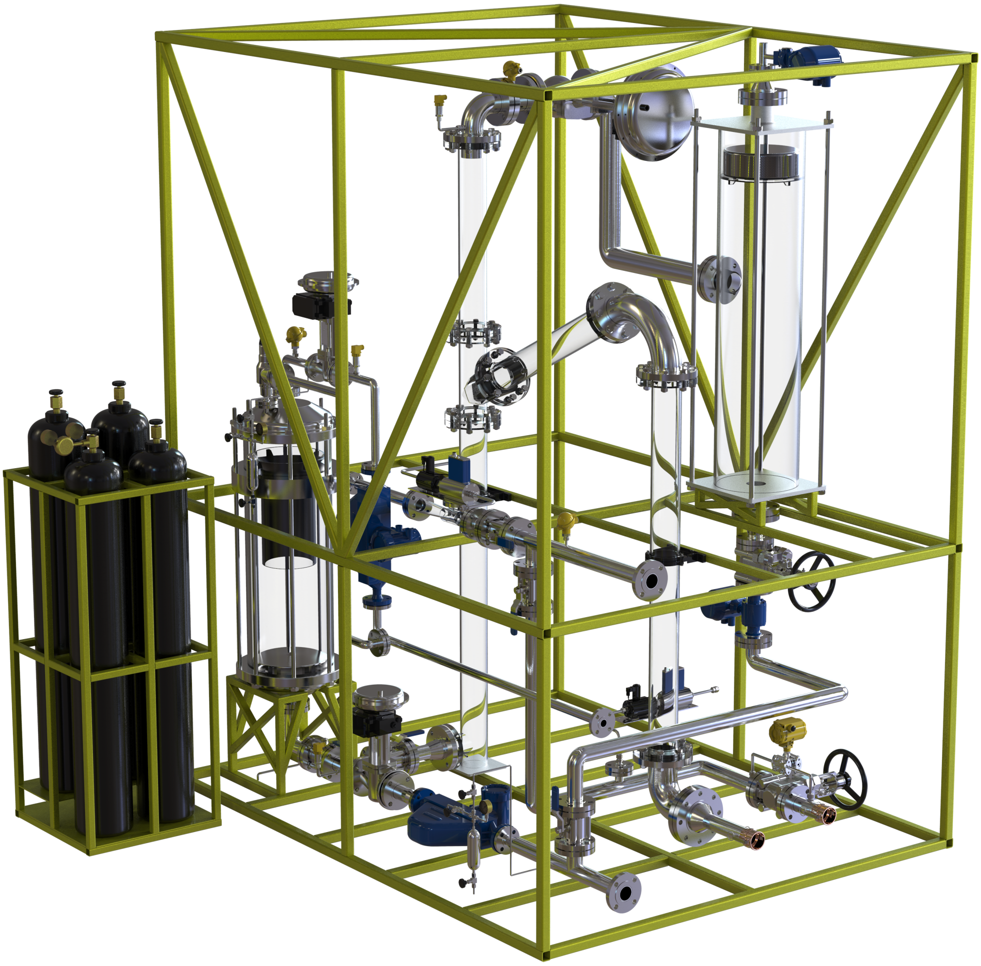


Figure 4.3: Final design of Phase 2 including steel frame, process equipment and gas reservoir.

Figure 4.4: Phase 2 process equipment illustrated without steel frame or nitrogen gas reservoir.

4.1.4 CFU and GLCC parallel configuration

The CFU and GLCC vessels in Phase 2 are configured in parallel process systems. Due to the limitations of the future pump and reservoir system and practical system configurations, the two separator units are not designed for simultaneous operation. Despite the separators' differences, the required process equipment for the separators have several similarities. Due to this, the possibility for joint process equipment and pipe layout for the CFU and GLCC have been investigated. A joint solution is a cost reducing solution and simplifies the total pipe-layout of Phase 2.

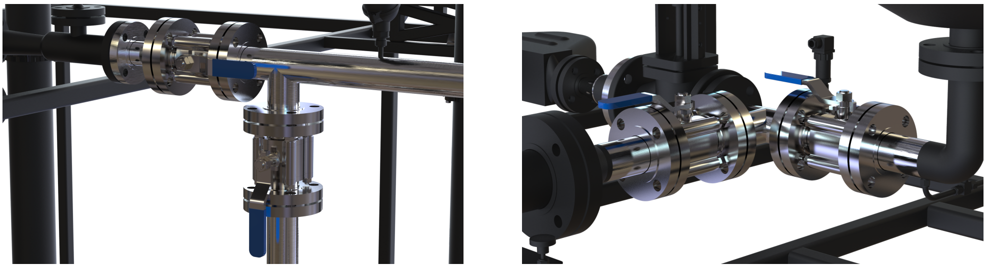
During the development of Phase 2, several industry contacts and manufacturers of process equipment have been consulted regarding joint process equipment of the CFU and GLCC. The differences in gas flow rates for the separators were revealed as the major obstacle for joint process equipment, with regards to injection and outlet flow measurement. Hence, different gas injection solutions have been designed and the inlet feed to the CFU and the GLCC is diverted before gas is injected to the given separator.

The inlet feed from the reservoir will be diverted by a tee-connection in the process line. The manual valves 3-MV-101 and 3-MV-102 are used to divert inlet feed to the desired separator, illustrated in Fig. 4.5a.

The liquid flow rates and operational pressures are similar for both separators, which enables joint process lines at the liquid outlets. The intgrated process line with connected process equipment will be used for both CFU and GLCC operation.

A tee-connection is used to connect the two outlets to the joint process line. Manual valves 3-MV-201 and 3-MV-202 are used to enable flow from the given separator during operation. Fig. 4.5b illustrates the tee-connection and valves for the outlet pipes and joint process line.

The presence of oil in the CFU reject, combined with the difference in gas flow restricts the possibility for joint process equipment of CFU reject outlet and GLCC gas outlet. Hence, the outlets have been separated in different process lines and equipment. The individual process equipment for the CFU and the GLCC are described in Sections 4.1.5 and 4.1.6 respectively.



(a) Tee connection and 3-MV-101 and 3-MV102 manual valves to divert inlet flow to GLCC or CFU respectively.

(b) Tee connection and 3-MV-201 and 3-MV202 manual valves to divert water outlet flow from GLCC or CFU respectively.

Figure 4.5: CFU and GLCC diverting tee-connections and valves.

4.1.5 CFU process equipment

The process equipment associated with the CFU and the GLCC are illustrated by the P&ID in Fig. 4.1 and described in Tab. 4.1. The ENS is further utilized to describe the CFU operation system. The complete CFU process system including vessel, process equipment and process lines is illustrated in Fig. 4.9.

The CFU is operated by the flow control valves 3-FV-201 and 3-FV-203. The purpose of the are to control the flow at the water- and oil reject respectively. The nitrogen injection and mixing solution is described in further detail in Section 4.1.5.1.

The control valves 3-FV-201 and 3-FV-203 have a globe valve design with pneumatic actuators, supplied by Samson-Matek. Control valve 3-FV-201 is located at the joint water outlet, to be used during CFU and GLCC operation. The tee-connection to connect the CFU water outlet and GLCC liquid outlet has been described previously in Section 4.1.4. Fig. 4.6 illustrates the two control valves for the CFU.

(a) 3-FV-201 control valve located at the joint water outlet.

(b) 3-FV-203 control valve for the CFU multiphase reject.

Figure 4.6: Control valves for level control of the CFU.

The mass flow meters 3-FT-201 and 3-FT-204 are installed at the joint water- and multiphase reject outlet, respectively. Depending on the separation efficiency of the CFU, the water outlet may contain oil droplets and gas bubbles. As a result of this, Emerson Coriolis mass flow meters are selected at both outlets, due to the ability to measure multiphase flows and densities regardless of conductivity.

Flow meter 3-FT-201 is rotated 90° relative to a horizontal axis due to spacial constraints defined by the geometry of the steel frame. The flow meter 3-FT-204 is installed vertically downwards to avoid oil agglomeration and slug flow, after recommendation by [IV]. Note that the use of the given flow meters will only measure the total flow rate and density, and does not measure mass flow rate of the individual phases.

The three pressure transmitters 3-PT-103, 3-PT-201 and 3-PT-202 are installed at the joint water outlet,on top of the CFU vessel and CFU multiphase reject line respectively. Pressure transmitter 3-PT-103 will measure the pressure at the top of the CFU vessel, where gas is likely to agglomerate.

Pressure transmitter 3-PT-202 measures the pressure downstream of the control valve 3-FV-202, in order to calculate the pressure drop over the control valve. Pressure transmitter 3-PT-201 is installed at the joint tee-connection and used for liquid level indication. By using the hydrostatic pressure, the liquid height can be determined if the liquid density and total volume of the pipe and vessel is known. When calculating the height, the dynamic pressure generated by the water flow must be subtracted. All transmitters are supplied by OEM automatics.

The temperature transmitter 3-TT-203 is installed at the CFU multiphase reject, upstream the control valve 3-FV-202. The temperature measurement is used to understand the behavior of the gas phase in the oil reject. The selected temperature transmitter is supplied by OEM automatics and utilizes the RTD temperature measurement principle described in Section 2.6.3.

To satisfy PED and HSE requirements, a PSV is installed at the top of of the CFU. The PSV is mechanically sealed by a spring load, and will open at a pre-determined pressure. The CFU has a maximum operation pressure of 10 bar and a PN16 pressure rating as a result of this, the pre-determined pressure for the PSV is set to 13 bar. If the CFU pressure exceeds the pre-determined pressure, the PSV will open and relive the pressure by re-routing the flow trough an open process line downstream of control valve 3-FV-202 and mass flow meter 3-FT-204. Fig. 4.7a illustrates the PSV installed at the CFU.

To remove water after CFU operation, a drain point is installed at the water outlet. The drain point is connected to the process line by tubing and fittings and controlled by a needle valve. After operation, the system should be drained for liquid and pressurized by air to flush the process pipes. This procedure is conducted to avoid agglomeration of unwanted particles in the system while it is not operational. The CFU drain point is illustrated in Fig. 4.7b

(a) 3-PSV-101 pressure safety valve for the CFU, with open process line routed back to the reservoir.

(b) Needle valve at the bottom of the CFU water outlet.

Figure 4.7: PSV valve and drain point for the CFU.

After the separation processes is completed in Phase 2, water and multiphase flow are returned to Phase 1 in their respective process lines. The multiphase flow will enter Phase 1 and be sent directly to the reservoir, while the separated water is analyzed by an OiW sensor. If the design, manufacturing and operation of Phase 2 is successful, the OiW content should be less than 30 ppm. Connection between the Phase 1 and 2 water- and reject lines is further described in Section 4.3.4

The sampling points SP4 and SP5 are installed in the process lines for the possibility to extract water and oil samples for laboratory tests. Sampling points can also be used to verify the measurements from the OiW sensors. SP4 and SP5 are located at the end of the joint water outlet and at the CFU multiphase reject respectively, as illustrated in Fig. 4.8.

(a) Sampling point SP4 arrangement.

(b) Sampling point SP5 arrangement.

Figure 4.8: The sampling points 4 and 5 of the CSL.

Each sampling point consists of three needle valves, a sampling bomb and a manometer, connected by tubing and fittings. This arrangement allows safe extraction of samples by the sampling bomb. Note the sampling bombs can only be used to extract liquids, as the gas will be difficult to measure accurately.

Figure 4.9: CFU process equipment.

4.1.5.1 Gas injection to CFU

As described in Section 3.1.8, the CFU will operate with gas injection from a nitrogen gas reservoir. The reservoir is described in further detail in Section 4.1.8. The literature presented in Section 2.3 describes that mass flow, pressure and method of gas injection affects the CFU separation efficiency. To control mass flow and pressure during injection, an Ex-flow unit is installed. The Ex-flow unit is a combined mass flow meter and control valve designed specifically for gas applications, ideal for CFU gas injection.

In the Phase 2 P&ID and Tab. 4.1 the Ex-flow unit for nitrogen gas is tagged 3-FT-101 and 3-FV-101, to indicate the capability of mass flow measurement and flow control. Ex-flow is connected by 12 mm tubing and fittings between the nitrogen gas reservoir and the static mixer.

To inject nitrogen gas in the process line, both a static mixer and an ejctor are solutions to be implemented in at different stages of CSL operation The mixers and gas injection methods are described in Section 2.3.

The mixer is installed in the process lines by flange connections. The mixers are manufactured with 1 1/2 ″ flanges, requiring reducers to be installed from the 2″ main process lines. The mixer gas inlet is manufactured with a 1″ flange, which is connected to the nitrogen feed by an adapter. Swagelock provides flange adapters from 12 mm tubing to a DN25 flange. Fig. 4.10 illustrates the Ex-flow unit and placement of the given mixer.

Figure 4.10: CFU nitrogen gas injection by mixer and Ex-flow unit. The homogeneous mixed phase flows to the right.

The mixer is to be placed a given length from any pressure reducing obstacle, in order to achieve a homogeneous and even bubble size distribution. For the selected mixer the minimum required length is

$$L > 5d_{mixer} \tag{4.1}$$

where d_{mixer} is the diameter of the mixer. With a d_{mixer} of 40 mm, the required free length after the mixer is 200 mm. This has been taken into account when designing the inlet process line to the CFU.

4.1.6 GLCC process equipment

The process equipment connected to the GLCC vessel is illustrated by the P&ID in Fig. 4.1 and described in Tab. 4.1. The ENS is further utilized to describe the GLCC operation system. The complete GLCC process system including vessel, associated equipment and process lines is illustrated in Fig. 4.13.

The GLCC vessel is operated by the control valves 3-FV-201 and 3-FV-203. The valves are individually responsible for controlling the flow at water outlet and gas outlet respectively. Air injection to the GLCC is controlled by the mass flow control unit 3-FV-101/3-FT-101 and described in further detail in Section 4.1.6.1.

The flow control valves 3-FV-201 and 3-FV202 are globe valves operated by pneumatic actuators manufactured by Samson-Matek. Note that the control valve 3-FV-201 is located at the joint water outlet and operates both the GLCC and the CFU. The process equipment at the joint water outlet have previously been described in Section 4.1.5 and is not repeated.

The control valve 3-FV-202 must be rotated 90° relative to the normal vertical installation procedure, due to spacial limitations defined by the steel frame. The rotated installation will not affect the performance. Fig. 4.11 illustrates the rotated control valve 3-FV-202.

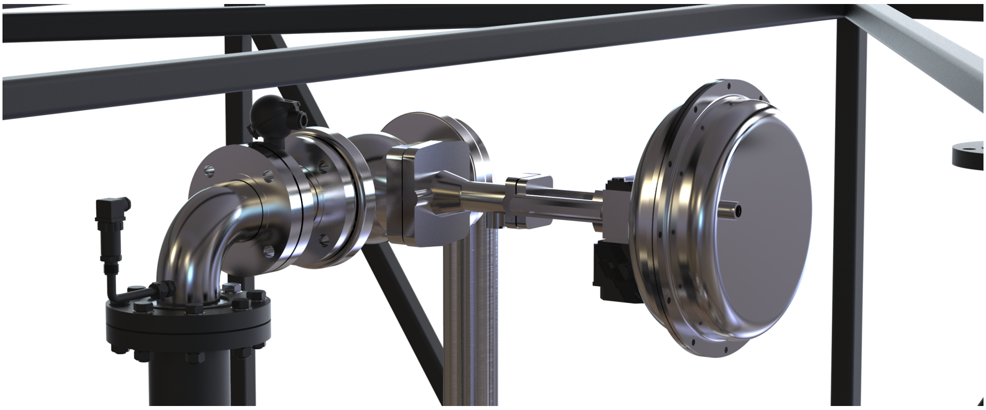


Figure 4.11: 3-FV-201 control valve installed at GLCC gas outlet and rotated 90°, limited by the steel frame.

The absolute pressure transmitter 3-PT-102 is installed in the gas outlet pipe of the GLCC. The pressure transmitter provides measurements of the gas phase in the GLCC during operation and is important for HSE procedures, used to indicate critical pressure if it occurs.

The temperature transmitter 3-TT-202 is installed upstream the control valve 3-FV-202. The temperature transmitters are manufactured by Apliens, and utilizes the RTD temperature measurement principle described in Section 2.6.3. Both the pressure transmitter 3-PT-102 and the temperature transmitter 3-TT-202 are illustrated in Fig. 4.12.

Figure 4.12: Pressure transmitter3-PT-102 and the temperature transmitter 3-TT-202 located at the gas outlet of the GLCC.

As described in Section 3.2 the air flow from the GLCC gas outlet will contain some amount of liquid, which makes accurate mass flow measurement difficult. Hence, the scrubber vessel 3-SCB-100 is installed to separate the gas and liquid, in order to individually measure the different phases. Process equipment for the scrubber vessel is described in Section 4.1.7

Figure 4.13: GLCC process equipment.

4.1.6.1 Gas injection for GLCC

As described in Section 3.2.1 the GLCC will operate with pressurized air from the MTP central distribution system. Before entering the GLCC inlet flow, the gas must be regulated to meet the design parameters. The Ex-flow mass flow control unit 3-FV-101/3-FT-101 is installed to control the air flow. This unit is essentially the same as the Ex-flow 3-FV-102/3-FT-102 installed to control nitrogen gas for the CFU vessel, but calibrated for the flow values of GLCC air injection.

The Ex-flow 3-FV-101/3-FT-101 is connected by 12 mm tubing and G1/2″ fittings. After the air is regulated to intended level, the air will be injected to the liquid flow by a simple tee-connection. Fig. 4.14a illustrate the Ex-flow unit and tee-connection.

The intended tee-connection does not perform sufficient mixing of the air and water phase. Olav Kristiansen [IV] was consulted regarding phase mixing, and proposed using a manual globe or choke valve to mix the air and water. When the multiphase flow enters a valve which is not full bore, a pressure drop will occur and create shear forces. The shear forces will create turbulent flow and thereby mix the two phases into a homogeneous multiphase flow. Hence, the manual globe valve 3-MV-103 is installed. Due to the spacial limitations by the frame and process piping, the valve must be rotated 90° relative to the normal vertical installation procedure. The rotated installation will not affect the performance.

For process control is it important to know the pressure characteristics over the valve. Hence, the differential pressure transmitter 3-PDT-101 is installed. The manual globe valve 3-MV-103 and differential pressure transmitter 3-PDT-101 are illustrated in Fig. 4.14b.

(a) Ex-flow connected to GLCC liquid flow by tee-connection and flange adapter.

(b) Manual globe valve 3-MV-103 and differential pressure transmitter 3-PDT-101.

Figure 4.14: GLCC gas injection equipment.

Mr. Kristiansen also suggested the possibility to vary the flow time between the mixing point and GLCC inlet to study the effect on separation performance. By varying the flow time between mixing at the manual valve 3-MV-103 and the GLCC inlet, the flow characteristics will change due to pre-separation and possible slug flow. This can affect the separation performance of the GLCC and is desirable to investigate.

One possible solution to vary the flow time is to extend the pipe length from the mixing point to the GLCC inlet. Flow time can be found by

$$t = \frac{L_{pipe}}{v_{mix}} \tag{4.2}$$

where L is the pipe length, v_{mix} is the flow velocity and t is the flow time. Flow velocity is given by

$$v_{mix} = \frac{Q_{mix}}{A_{pipe}} \tag{4.3}$$

where Q_{mix} is the mixed volume flow and A_{pipe} is the cross section areal of the pipe. For $Q_{tot} = 5$ m^3/h and a 2″ pipe, $v_{mix} = 12.2$ m/s. To study the effect of varying flow time in separation performance it is interesting to vary flow time in the range from 0 to 1.2 seconds. For slug flow behavior to occur, a flow time greater than 2.05 seconds is required [IV]. To design the pipe extensions, five design cases listed in Tab. 4.2 has been established.

Table 4.2: Flow time design cases.

Case	**Ratio**	**Pipe extension [m]**	**Flow time [s]**
1	L/d ≈ 0	∼ 0	∼ 0
2	L/d = 30	1.5	0.1
3	L/d = 100	5	0.4
4	L/d = 300	15	1.2
5	L/d = 1200	60	4.9

When designing the pipe extension system, practical considerations have been emphasized. Changing the pipe length will be conducted manually by the operator, and should require as little effort as possible. The pipe extension must be routed somewhere, preferable inside the steel frames of CSL Phase 1 and Phase 2. Mr. Holden also requested the possibility for a transparent pipe, so the flow behavior can be visualized during operation.

Vacupress Cristial is a flexible hose for suction and delivery of pressurized liquids and gases. The hose is made in transparent PVC embedded with galvanized steel spiral. For 2″ size the hose has as max pressure of 42 barg, bending radius of 170 mm and weight of 1600 g/meter. The low weight, flexibility and transparency makes the Vacupress Cristial well suited to extend the pipe lines.

To connect the pipes and Vacupress hose lengths to each other, standard clamps and Camlock couplings can be used. Camlock couplings connects by two clamps and tolerates a working pressure of 17 bar. Fig. 4.15 illustrates how the Camlock couplings are connected. Vacupress Cristal and Camlock couplings are delivered by Hydroscand. The flexible hose system is tagged 3-FH-100 in the P&ID in Fig. 4.1.

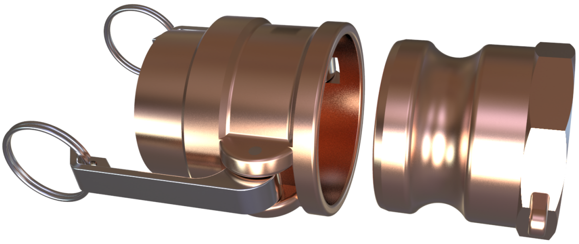


Figure 4.15: Male and female camlock connection.

4.1.7 Scrubber process equipment

The GLCC design process described in Section 3.2 states the need for a scrubber vessel to separate liquid and gas from the GLCC gas outlet. The design process for the scrubber vessel is described in Section 3.3.

The scrubber vessel is installed at the GLCC gas outlet, downstream the temperature sensor, control valve and absolute pressure sensor. The scrubber will separate the and LCO into two separate phases for mass flow measurement. The scrubber is open to air, resulting in the operation pressure to be 1 atm. During operation, some increased pressure will occur due to the dynamic pressure of liquid and gas during operation.

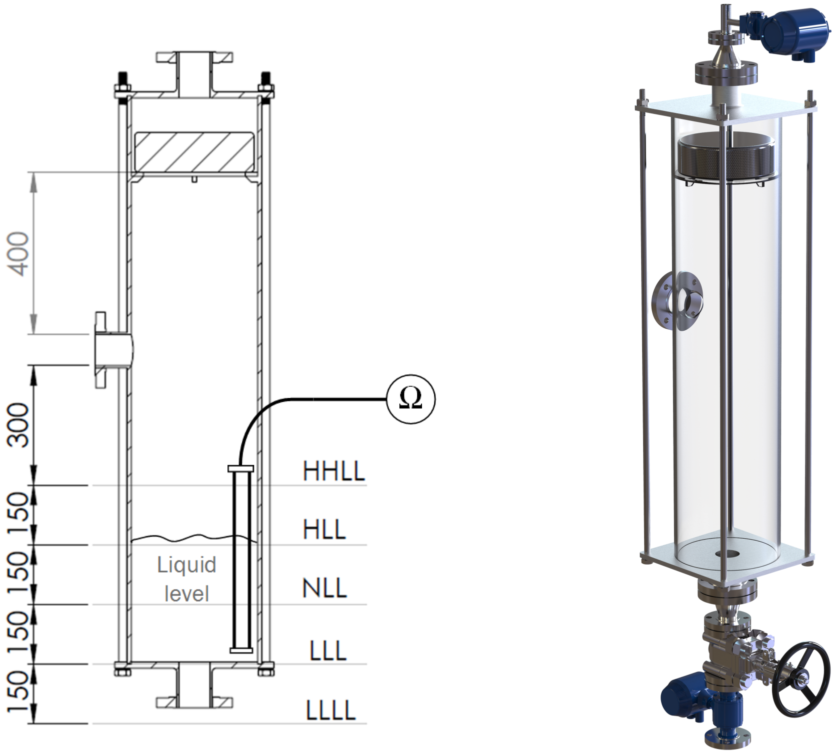
The separated dry air will exit the scrubber top outlet and be measured by 3-FT-203 vortex gas flow meter. Downstream the flow meter, air is released into the surroundings.

Water will exit the scrubber at the liquid outlet and is measured by a Emerson magnetic flow meter, listed in the P&ID with tag number 3-FT-204. During operation, the liquid level inside the vessel is intended to be at a neutral liquid level (NLL), illustrated in Fig. 3.34. It is important to maintain a stable liquid level in the scrubber for optimal separation and flow measurement.

Liquid level is maintained by a 3-MV-204 manual ball valve which creates a restriction depending on the valve position. At the start of GLCC operation the valve is closed to allow liquid level to agglomerate until it reaches NLL level. When the preferred liquid level is established, the valve is opened until steady state flow is present.

Liquid level is indicated by 3-LT-203, which is an electrical conductivity level transmitter. It is created by installing two metal rods or other conductive materical in parallel connected to a power source, illustrated in Fig. **??**. The liquid level inside the scrubber short circuits the electrical current, and the resistivity is measured by a Ohm-meter. Note that this figure is only illustrative, meaning cable placement and rod assembly must be reviewed during constructing of the scrubber assembly.

After separation and measurement, water is diverted into the joint water outlet by a tee-connection. Manual valve 3-MV-204 is installed at the tee-connection to prevent flow to the scrubber water outlet during CFU operation. Fig. 4.16b illustrates the scrubber vessel with associated process equipment. Fig. 4.17 illustrates the manual valve 3-MV-204 and tee-connection.



(a) Illustration of Scrubber LT placement with metal rods being short circuited at the liquid level in the vessel.

(b) Scrubber vessel with manual valve 3-MV-203 for liquid level control with 3-FT-203 vortex-, and 3-FT-204 magnetic flow meters.

Figure 4.16: Scrubber process equipment

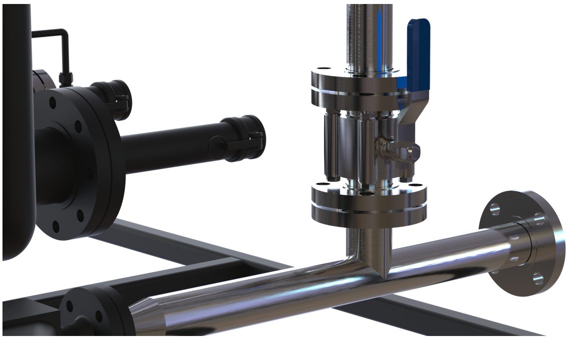


Figure 4.17: 3-MV-204 manual valve to restrict water flow to scrubber outlet when the GLCC and scrubber are not operated.

4.1.8 Nitrogen gas reservoir

The gas reservoir will supply the CFU with required gas to the separation process. In the Phase 2 feasibility study conducted by [64], sulfur hexafluoride gas (SF_6), nitrogen gas or air were proposed as possible gases to be used for injection. In the specialization project conducted by the authors in the fall semester 2016, pressurized bottles of nitrogen gas was selected as the preferred solution.

As described in Section 3.1, a gas reservoir of four 50 l bottles pressurized at 200 bar will be sufficient to operate the CFU at max capacity for 4 hours. The four bottles will be secured by a holding cage manufactured in steel, which prevents the bottles from tipping over. Fig. 4.18a illustrates the holding cage and Fig. 4.18b illustrates the complete gas reservoir.

The design of the holding structure is a steel frame intended to store four gas bottles. There are no specific restrictions on holding cage structure as long as the bottles do not fall over. As a result of this a simple cage is the proposed solution.

(a) Gas reservoir holding cage. The cage can contain four bottles of 50 liter nitrogen gas pressurize at 200 bar.

(b) Gas reservoir with nitrogen bottles. Two bottles are elevated by 100 mm offset to enable easy access during switch in operation bottle.

Figure 4.18: Gas reservoir

The cage will have the dimensions 0.56 m x 0.56 m x 1.4 m for length, depth and height respectively. 30 mm x 30 mm x 3 mm hollow steel profiles provides sufficient strength to the cage. A 10 mm thick steel plate will be used as bottom deck. An additional plate will be installed with 100 mm offset from the bottom, covering half of the bottom deck. This plate will elevate two of the gas bottles for easy access when installed the regulators on the different bottles. The specifications of the holding cage is listed in Tab. 4.3.

Table 4.3: Holding cage specifications.

Steel selection	316L
Main dimensions	0.56 m x 0.56 m x1.4 m
Steel dimensions	30 mm x 30 mm x 3 mm
Total length of steel profiles	17 m
Estimated weight	280 kg
Colour	Yellow

The gas regulator 3-MG-100 will be used to extract and regulate the pressurized nitrogen gas. The regulator will be connected to a flexible hose, allowing the possibility to change the operational bottle. The hose is further connected to the process lines by tubing, as described in Section 4.1.5.1. To recycle the gas bottles, the MTP workshop transverse crane is used to lift the bottles free from the holding cage. The empty bottles are then collected by Würth, and replaced if needed. The capacity and operation of the reservoir is summarized in Tab. 4.4.

Table 4.4: Gas reservoir summary.

Number of bottles	4
Bottle size	50 l
Total capacity	200 l 46.4 kg
Total operational time	14.5 h
Gas extraction and depressurization	Manual regulator
Gas bottle recycle	Transverse crane

4.2 Structure

The Phase 2 process equipment is designed to fit into a modular steel frame. The frame will secure the equipment during operation and enable transportation. The frame dimensions are set to be 2 m x 2.5 m x 3.1 m for length, depth and height respectively. The frame is illustrated in Fig. 4.19. and summarized in Tab. 4.5.

4.2.1 Frame design

The design of the steel frame is based on the Phase 1 frame design by [64] and [42], and further modified to fit the Phase 2 process equipment. The geometry of the frame is heavily depended on its location at the MTP Valgrinda workshop, described in Section 4.2.2.

A rectangular geometry is selected, where process equipment will be installed at the bottom and middle deck. Four ribs are included in the bottom deck to provide sufficient strength to support the process equipment. The top deck will protect the equipment during operation and transportation. Each deck is constructed solely by horizontal profiles. In this way, each deck can be welded on the ground separately and later be assembled with vertical profiles in between. Diagonal profiles at the top and sides will ensure sufficient torsional rigidity when lifting and tilting the frame and connected process equipment.

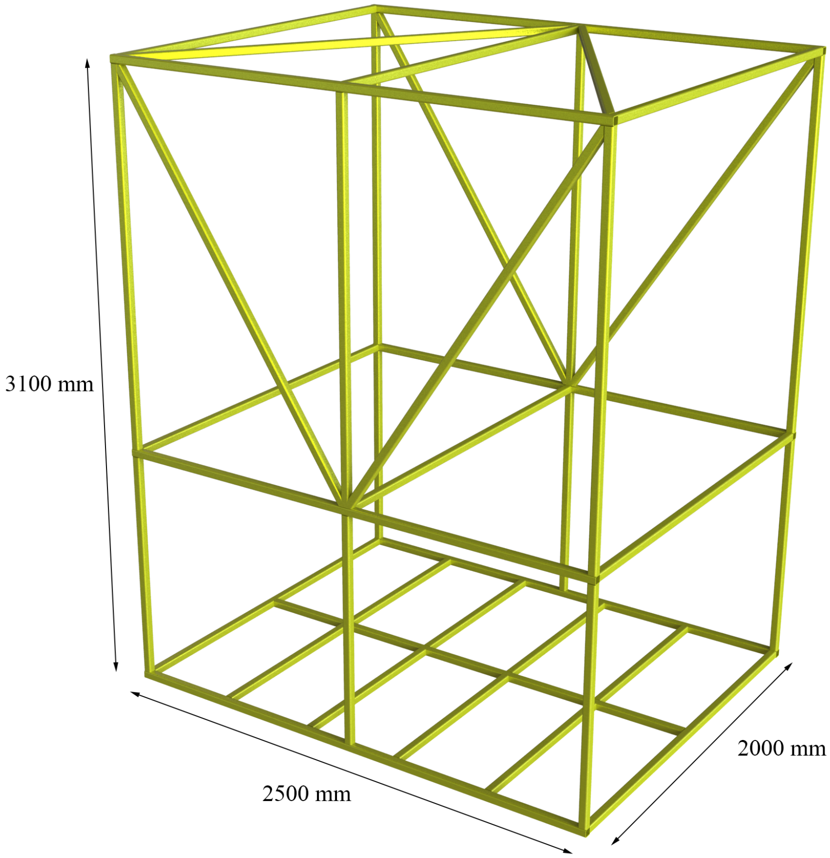


Figure 4.19: Phase 2 frame design.

The hollow steel profiles of the frame will have 40 mm x 40 mm x 4 mm dimensions. This will provide sufficient strength and integrity to the frame when lifted and rotated for future re-location and transportation, which is described in Section 4.2.3. To support the separation vessels, process pipes and equipment, extra pipe support will be added to the frame during the construction phase. The frame will be located in a non-corrosive environment, but occasionally the area is flooded due to experiments [XIV]. To distinct the steel frame from the rest of the process equipment, the frame will be painted yellow. The frame is summarized in Tab. 4.5.

Table 4.5: Steel frame specifications.

Steel selection	316L
Main dimensions	2 m x 2.5 m x 3.1 m
Steel dimensions	40 mm x 40 mm x 4 mm
Total length of steel profiles	76 m
Estimated weight	327 kg
Colour	Yellow

4.2.2 Location of Frame in the Laboratory Area

When deciding the optimal location for the steel frame of Phase 2 at MTP Valgrinda workshop, the following factors needs to be accounted for:

1. Process lines connecting Phase 1 and Phase 2 within the confines of the steel frame
2. Transport zone cannot be obstructed
3. HSE concerns for construction, pressure testing and operation
4. Visibility to the transparent CFU-, GLCC- and Scrubber vessels
5. Location of pump and reservoir system
6. Access to manual equipment and transmitter displays

Since Phase 2 extends and diverts process feed from Phase 1, it is not designed to operate independent from Phase 1. The process feed, water outlet and oil reject flanged connections are all located in fixed positions in frame 1 of Phase 1. It is therefore convenient to locate the frame of Phase 2 as close as possible to these connections. It is also important to allocate adequate space between the CSL and other laboratories to maintain safe and functional operations.

After inspection of the workshop area at MTP Valgrinda, two alternative locations for Phase 2 are suggested, illustrated in Fig. 4.20 and 4.21.

Objects with a red frame are not able to be moved, while objects with a green frame are not placed in a fixed location. The SINTEF facility located in the bottom right corner is scheduled for removal at some point in 2017, but this can not yet be accounted for. Therefore, the facility is treated as fixed. The three arrows represents connections to the control desk, process feed to Phase 2 and outlet flow from Phase 2.

Alternative 1 locates the Phase 2 in parallel with Phase 1, with a adequate offset along the length side determined by the process connections. This solutions locates Phase 2 as close as possible to the process connections between Phase 1 and Phase 2. This was also the intended solution when Phase 1 was constructed.

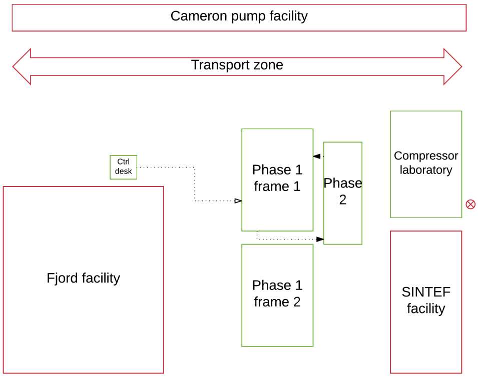


Figure 4.20: Phase 2 location alternative 1.

Alternative 2 aligns Phase 2 with Phase 1 and places them in series. This solution will require the process lines to run through the second frame of Phase 1 before entering Phase 2. This solution provides more area around Phase 2, and increase the design possibilities for the Phase 2 frame and layout.

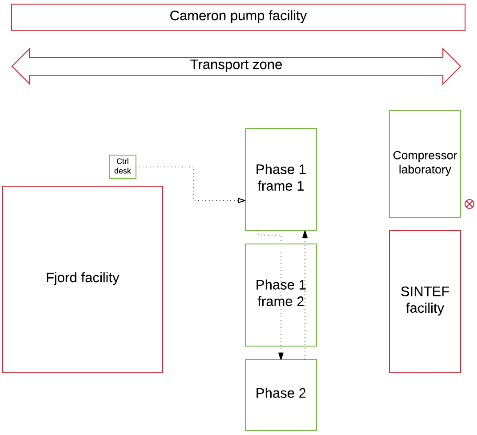


Figure 4.21: Phase 2 location alternative 2.

Each alternative have different advantages and disadvantages affecting the overall design of the Phase 2. After consulting with the Phase 1 project team and Mr. Holden, the location in alternative 2 is preferred. Important factors affect the decision were to not block sampling points in Phase 1 and improve process lineup for Phase 2, due to the increased available area. Utilizing alternative 2 decision requires increased process lines in connect Phase 1 and Phase 2, further described in Section 4.3.4.

4.2.3 Re-location and Transportation of Laboratory

Experiments conducted in the MTP workshop, will use Exxsol D140 model oil during operation due to HSE regulations. At a later stage, it is intended for the CSL to be moved to SINTEFs multiphase facility, in order to conduct experiments using hydrocarbons. The facility is located at Tiller, Trondheim, approximately 10 km from NTNU MTP. It offers the possibility to rent laboratory space and utilize the multiphase feeding pump using hydrocarbons.

Edgar Kaasboell [V], Transport Manager at NTNU Operations has been consulted regarding the possibility to relocate the CSL to SINTEF Tiller facility. Mr. Kaasboel ensured that the CSL can be relocated if the construction does not exceed the dimensions of 3.5 m x 2.5 m x 2.8 m. These dimensions have been accounted for in the design process of Phase 1 and 2 of the CSL. Phase 2 can be transported if it is tilted on its side before being moved.

Inside the MTP workshop area the CSL can be moved by either forklift or transverse crane. Transverse crane is the preferred solution due to the length limitation of 1.8 m for the forklifts [IX] and the need to tilt Phase 2 to satisfy the dimension transportation limitations.

4.3 Piping

4.3.1 Pre-fabrication of pipes

The design process is comprehensive with regards to the exact placement of separators, associated equipment and length of process pipes. This process enables pipe lengths to be prefabricated, which is cost- and time beneficial as each individual pipe does not have to be welded on site by hired personnel. The prefabricated pipes are constructed with flange connections, to be connected to the given process equipment and separator units.

The selected equipment for the CSL follows the German Institute of Standardisation (DIN) standard and a minimum pressure number (PN) 16. The diameter nominal (DN) of each equipment, combined with the pressure number determines the size and class for the flange connections.

The dimensions of the process lines is determined by the size of the outlet and inlet pipes of the separators, process equipment and the process lines from Phase 1. [64] recommends the use of pipe schedule number (Sch) 10, which will also be used in Phase 2.

4.3.2 Welding of Pipes

Because no detailed 3D model of the CSL Phase 1 exist, all pipe dimensions and geometries were extracted from a simple sketch. During construction of this phase, standard pipe lengths, elbow bends and flanges were bought and field-welded. This makes pre-fabrication of the process pipes connecting Phase 1 and 2 difficult, due to uncertainty regarding the placement of the Phase 1 flange connections, described in Section 4.3.4.

Because of the uncertainty of Phase 1 flange connections, the process pipes between the phases will be field welded. The sketches presented in Section 4.3.4 are only for illustrative purposes, but could be used for pipe length assessment. Standard pipe lengths, elbows, tee-connections and flanges are acquired from Ahlsell. For installation, a plumber company will be hired. K. Lund was contracted for Phase 1 process line installation, and is recommended by NTNU Operation and the Phase 1 project team.

K. Lund will be hired for the welding of connection process lines between Phase 1 and 2, and the required fittings for transmitters and sampling points, given that they are still under contract with NTNU as the preferred company.

4.3.3 Tubing

Pipes and tubes are often mistaken as the same in the industry because of their similarities, but some minor distinctions exists. The term pipe often imply a higher level of durability, rigidity and permanence relative to tubing. The lower mechanical properties than that of pipes, makes tubing more affordable and easier to install relative to pipes.

In Phase 2 of the CSL, 12 mm tubing will be used for all temperature transmitters, pressure transmitters and gas injections. 6 mm tubing will be used for sampling points and drain points. Because of the 1 mm thin wall of the selected tubing dimensions, the tubes can not be welded. Instead G1/2″ and G1/4″ fittings will be welded into the process lines and used to connect the tubes. Fitting and tubing can easily be field routed by the students constructing Phase 2, meaning no external contractor is required.

4.3.4 Phase 1 and 2 process lines connection

Phase 2 is designed as an extension of Phase 1, which diverts the flow lines to a separate skid. The process feed from the future pump and reservoir system will be routed through Phase 1 and connect to the Phase 2 process lines, disabling the ability for simultaneous operation of both phases. This is not an issue, as separation efficiency of the given separator units are not affected by the different phases.

This integration enables the inlet feed for Phase 2 to be measured by the Phase 1 Coriolis mass flow meter. The water- and multiphase rejects from Phase 2 are routed through Phase 1 and back to the reservoir system, enabling the separated water from Phase 2 to be analyzed by the OiW sensor, scheduled to be installed in Phase 1.

The OiW sensor represents nearly one third of the total available founds for the CSL project, meaning a similar component is unable to be procured just for Phase 2. Figs. 4.22 and 4.23 illustrates the process lines connecting the Phase 1 and the Phase 2.

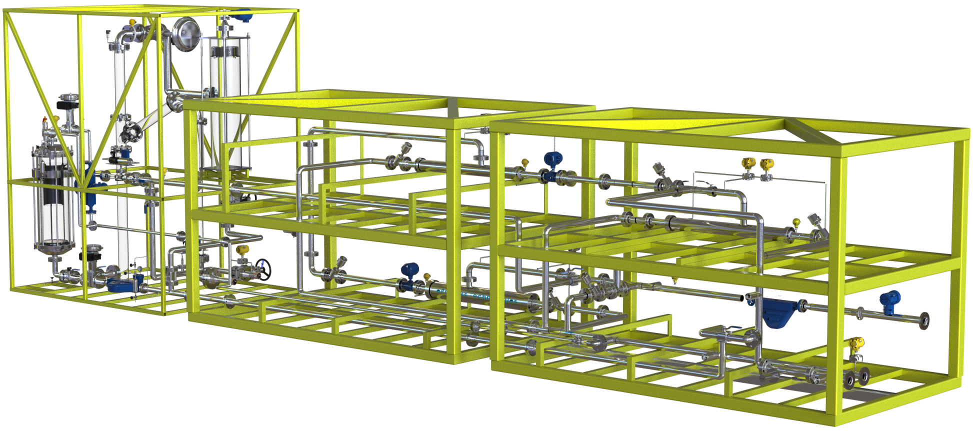


Figure 4.22: CSL Phase 1 and 2 with connecting process lines.

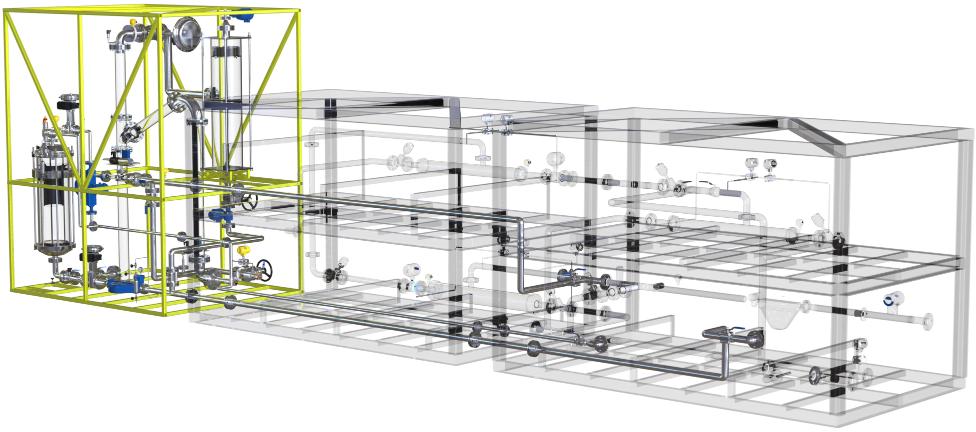


Figure 4.23: CSL Phase 1 and 2 with connecting process lines. Phase 1 transparent for illustrative purposes.

The process feed from the pump system is diverted to Phase 2 at the pipe connections between the steel frames of Phase 1. The process pipes between frame 1 and 2 are connected by 0.4 m long interchangeable pipe sections with flange connections. To allow process feed diversion, new pipe sections of 0.7 m will be installed. A tee-connection and manual valves 3-MV-001 and 3-MV-002 will enable the process feed to be diverted either to the Phase 1 hydrocyclones or Phase 2. Fig. 4.24 illustrates the rerouting tee-connection to Phase 1 and 2, which will supply produced water upstream the desired separators for operation. The replaced 0.4 m pipe sections will be reused to connect Phase 2 inlet- and outlet feed pipes from frame 2 in Phase 1.

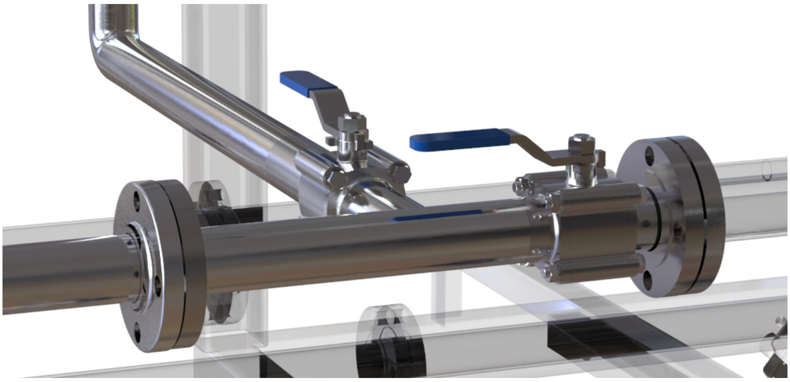
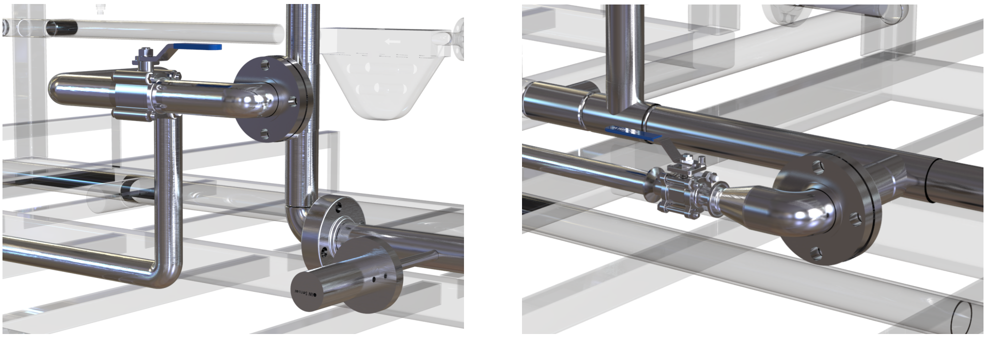


Figure 4.24: Process feed diverting between Phase 1 and Phase 2. Phase 1 pipes are transparent for illustrative purposes.

Phase 1 is facilitated the routing the Phase 2 water- and multiphase rejects by flange connection points, located at the end of the Phase 1 process lines. The water outlet enters the Phase 1 process lines upstream the OiW sensor location. The multiphase reject enters the Phase 1 process line and is routed directly to the reservoir system. Manual valves 3-MV-003 and 3-MV-004 are installed before the flange connections to restrict back flow in the water- and multiphase reject outlets, respectively, during Phase 1 operation.

Figs. 4.25a and 4.25b illustrates the water outlet- and multiphase reject connection. Note that Phase 1 and Phase 2 have PN40 and PN16 pressure rating respectively, so the welded pipes on either side of the shut-off valve needs to fulfill their respective pressure rating.



(a) Phase 2 water outlet connection to Phase 1, with manual valve 3-MV-003 to restrict back flow.

(b) Phase 2 multiphase reject connection to Phase 1, with manual valve 3-MV-004 to restrict back flow.

Figure 4.25: Phase 1 and 2 outlet and reject connections.

4.4 Instrumentation

When designing the instrumentation and automation process, the work conducted by Mr. Djupvik and Mr. Hellem in the Autumn of 2016 is the basis for design. Decisions have been made regarding field cable selection, software and hardware for automatic control, described in [42]. As Phase 2 will operate in the same environment and have similar requirements regarding certification, solutions for Phase 1 are viable when designing the current system. Compatibility is an important factor when proposing software and hardware for Phase 2, as implementing automatic operation to the existing script is preferred to be done as easily as possible.

4.4.1 Ex certification

In the Master Thesis [64] the CSL Phase 1 is designed to be classified as Ex zone 1, which is the required classification at SINTEF Tiller facilities. Ex zone 1 classification is described by [56] as

> *"A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapor or mist is likely to occur in normal operation occasionally."*

To satisfy the Ex zone 1 classification requirements, the instrumentation and automation equipment must have Ex protection. Most of the equipment of Phase 1 all have $Ex - ia$ protection or $Ex - d$ protection.

- *Ex-ia* is intrinsically safe (IS), meaning the equipment only contains intrinsically safe circuits. IS circuits are energy restricted to prevent sparks or thermal effects from igniting explosive gases or vapours. The energy restriction is achieved by implementing safety barriers [15].
- *Ex-d* is an enclosure that can withstand the pressure from an inner explosion and prevent the explosion from unfolding to the surroundings. To ensure proper $Ex{-}d$ protection, the enclosures should be designed with a predetermined safety factor [15].

4.4.2 Cable Selection

The selected field cable for Phase 1 and 2 is an RFOU(i) cable. This can be used for both IS and non-IS circuits, since the given cable is self-extinguishing. The cable has metal sleeves which protecst against disturbances from other signals. The electrical values for RFOU(i) cables are presented in Tab. 4.6. Note that RFOU(i) is not an abbreviation, but defines the construction material of the cable.

Table 4.6: Approximated electrical values for RFOU(i) cable [42].

Capacitance [nF/km]	**Inductance [mH/km]**	**Resistance at 20°C, max. [Ohm/Km]**	**L/R ratio [microH/Ohm]**
110	0.67	26.3	12.7

4.4.3 Field Junction Box

Input signals signals from the transmitters and output signals to control valves is connected in an on-site junction box illustrated in Fig. 4.26.

As stated by [42], the practice for instrument cabling is done by placing a field junction box near the equipment. The skid is intended to be constructed in a *"Ex-e"*, meaning no ignition or heat emitting equipment can be placed inside the selected unit. As a result of this only IS circuits can be placed in the junction box. This is not a problem in Phase 2, as all circuits are intended to comply with *"Ex-d"* regulations, resulting in all cables being routed through the junction box.

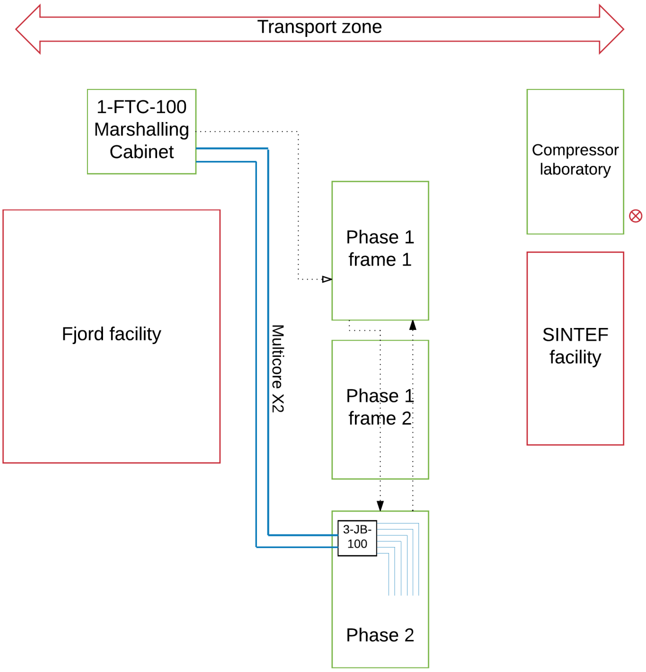


Figure 4.26: Illustration of junction box placement and connected field cables, including two multicores to 1-FTC-100 marshalling cabinet

The proposed design of Phase 2 has in total 15 transmitters and 5 valves which will transmit input signals and receive output signals. Each unit has a cable pair and a connection to earth, resulting in the need for 60 terminals. The selected junction box is illustrated in Fig. 4.27, with 98 terminals available. This allows some spacial flexibility when connecting equipment, as well as allowing more components to be added to the junction box at a later time, given that they comply with the described Ex regulations. The specific model is presented in Section 5.3.3.

A multicore cable contains several circuit pairs inside it, resulting in a practical routing from junction box 3-JB-100 to marshalling cabinet 1-FTC-100. The multicore can only supply 16 circuit pairs, which means that two multicores must be acquired in order to facilitate the components of Phase 2. The junction box and multicore cables are supplied by Stahl-Syberg AS.

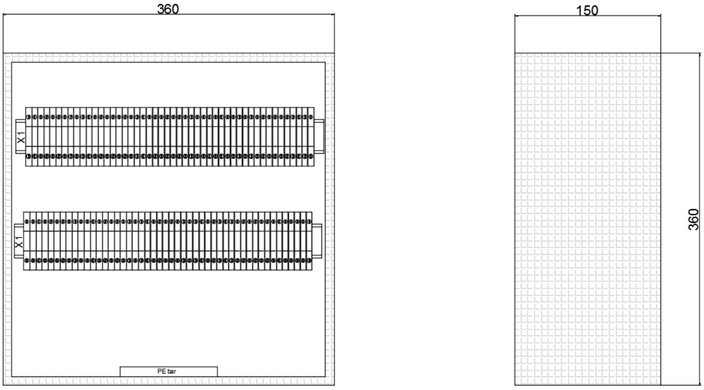


Figure 4.27: Illustration of selected junction box.

4.4.4 Cable Trays

Phase 2 will have one set of cable trays, where all the low voltage and pneumatic lines are routed. All field cables have metal sleeves around them, preventing disturbances from each other, resulting in all cables being able to be placed close to each other without complications. The cable tray is installed by the students constructing the Phase 2 instrumentation system. No proposed drawing is made of cable tray placement, as the design and construction of Phase 2 may vary from each other.

4.4.5 Pneumatic Air Supply System

The control valves at the CFU and GLCC rejects are all operated by pneumatic actuators, that requires pneumatic supply. During construction of Phase 1, a pneumatic air supply system was constructed, which can be extended to supply the Phase 2 actuators as well. The pneumatic system contains a pressure regulator, air filter and distribution to each actuators by tee-connections. The only required equipment to extend the system too Phase 2 will by additional tee-connections, pneumatic hose and snap-on fittings for connecting the hoses.

The central supply system can deliver approximately 8.5 bar, while the Samson pneumatic positioner has a maximum air supply pressure of 7 bar. Hence, the pressure is adjusted by the pressure regulator. It is important to consider the capacity of the pneumatic system as pressure drop can occur during operation. Since Phase 1 and 2 will not operate simultaneously, the original system capacity is found suitable for Phase 2 as well. This ensures thst the operation of the pneumatic positioner is not limited by the capacity of the pneumatic supply system. The extended pneumatic system for Phase 1 and 2 is illustrated in Fig. 4.28.

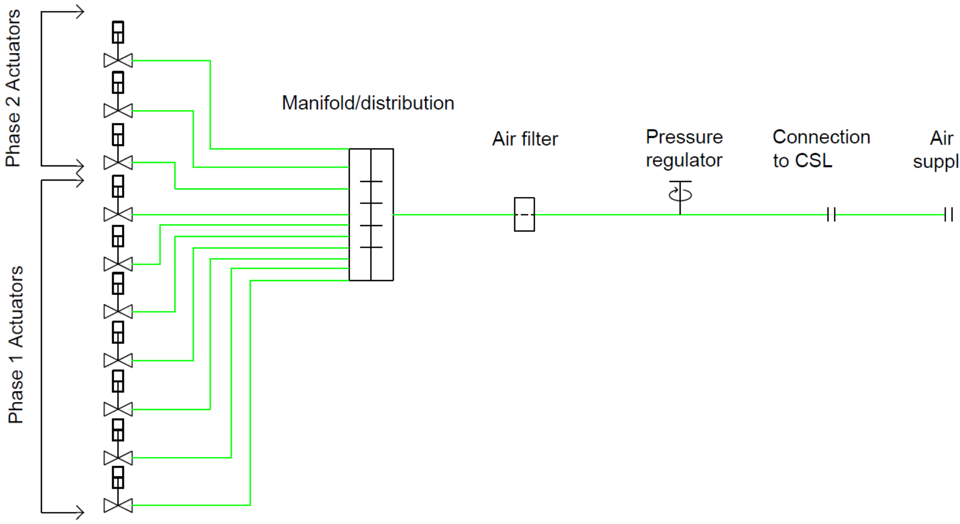


Figure 4.28: Pneumatic air distribution for Phase 1 and 2.

4.4.6 Installation of pressure transmitters

The two types of pressure transmitters can not be connected directly into the process lines, and will be connected to the process by the use of 12 mm tubing. Small size tubing is not suitable for welding due to the wall thickness. Hence, G1/2″ fittings will be welded into the process pipes for tubing connections. This solution allows pressure measurements without interfering the process flow.

The pressure transmitters 3-PT-101, 3-PT-102, 3-PT-103, 3-PT-201 and 3-PT-202 will be connected by one single tubing line. The differential pressure transmitters 3-PDT-101 will be connected by two tubing lines, upstream and downstream the 3-MV-103 manual valve.

4.4.7 Installation of temperature transmitters

The three temperature transmitters 3-TT-101, 3-TT-201 and 3-TT-202 will be installed at the inlet feed to Phase 2, GLCC gas outlet and CFU oil reject respectively. The Apliens CTGB1 measures the temperature utilizing RTD technology by a Pt100 element inserted in the process pipe. To get accurate temperature measurement, it is essential to install the end of the Pt100 element in the middle of the process pipes.

The CTGB1 model is delivered with G1/2″ process connection, which will be installed with a 12 mm tubing adapter. A 12 mm fitting will be welded to the process pipes, equally to the procedure for pressure transmitter installation. The Pt100 element is then inserted in to the process pipes and connected to the fitting.

4.5 Automation and Electrical system

4.5.1 Software

The software used to operate Phase 2 is either MATLAB or LabView. Both uses the programming language C and are suitable for data logging. LabView utilizes a graphical interface for data acquisition and control, making it easier to develop a program for operation.

The project thesis conducted by Mr. Djukvik and Mr. Hellem uses LabView as the proposed solution, which is utilized in the Spring of 2017 for control of Phase 1. It is logical to propose the same solution for Phase 2 in order to preserve continuity and enable implementation of Phase 2 to the existing Labview-script for the CSL.

4.5.2 Hardware

Hardware from National Instruments (NI) is used in the Phase 1 automation system, as input/output models from NI is easily implemented in LabView. The estimated quantity of signal types is presented in Tab. 4.7. By using similar equipment in Phase 2 as in Phase 1, spare I/O channels can be used, resulting in fewer devices needing to be acquired for Phase 2 automatic control and logging. The transmitters are connected to Analog Input (AI) devices and Analog Output (AO) devices are connected to valves. After consultation with Mr. Djupvik and Mr. Hellem, the required communication device is a NI9265 AO device [8], further specified in Section 5.3.2.

Table 4.7: Quantity of signal types in Phase 1 and estimated values for Phase 2 and 3 [42].

Section of CSL	**Signal type**	**Number of channels**
Phase 1	AI	17
Phase 1	AO	7
Phase 2 transmitters	AI	15
Phase 2 valves	AO	5
Phase 3 estimate	AI	5
Phase 3 estimate	AO	5

4.5.3 Marshalling cabinet layout

The marshalling cabinet containing barriers, fuses, communication devices and connection to earth was assembled during the construction of Phase 1. It is constructed to implement later phases of the CSL in the same cabinet. An illustration of the marshalling cabinet, updated to facilitate Phase 2 is presented in Fig. 4.29 with description of the different terminator rows in Tab. 4.8

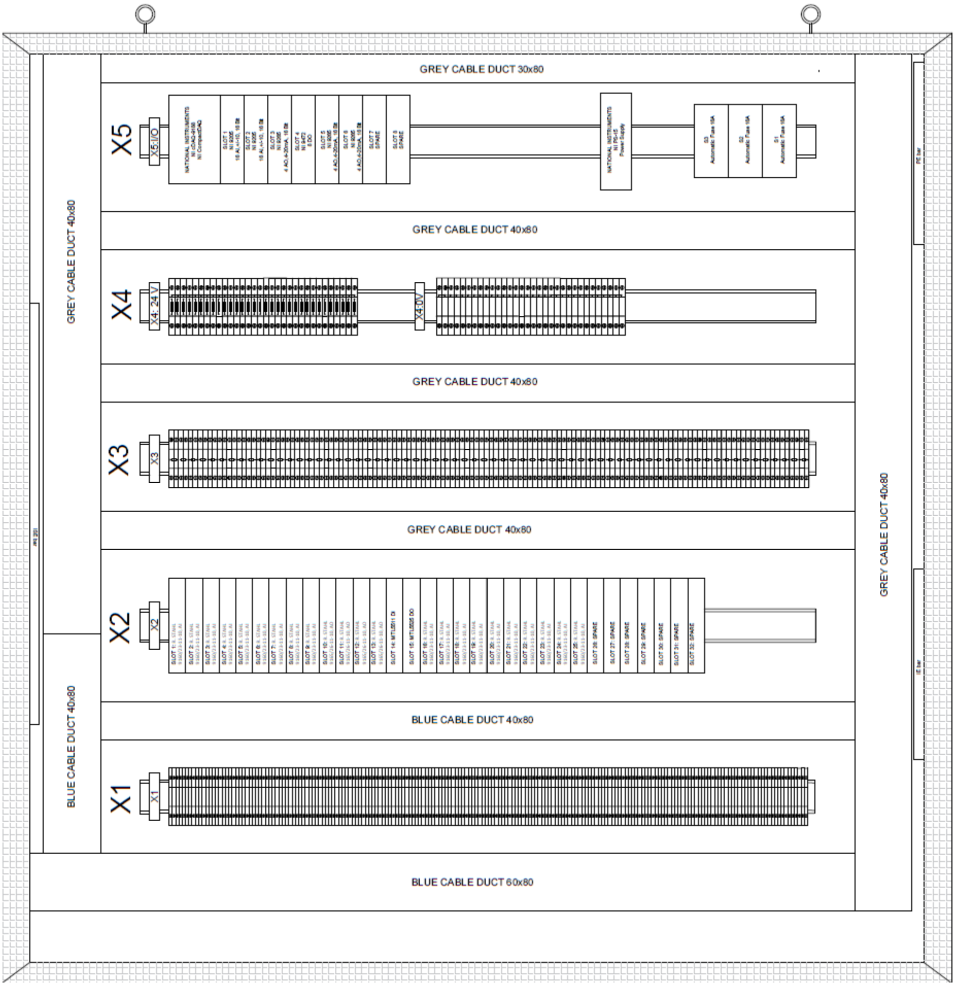


Figure 4.29: Design of marshalling cabinet, updated to facilitate Phase 2 [42].

Table 4.8: Sections of 1-FTC-100 Marshalling Cabinet [42].

Section	Description
X1	198 knife terminals for termination of field cables
X2	32 slots for safety barriers or galvanic isolators
X3	192 feed through terminals with resistance, to convert 4-20 mA to 2-10 V
X4	36 fuse modular terminal blocks for 24 V and 36 feed through terminals for 0 V
X5	8-slot chassis, power supply and three 16 A fuses for 230 VAC supply

The CSL marshalling cabinet with support was constructed by the Phase 1 project team during construction of Phase 1 [42]. The geometries of the marshalling cabinet and support structure is illustrated in Fig. 4.30.

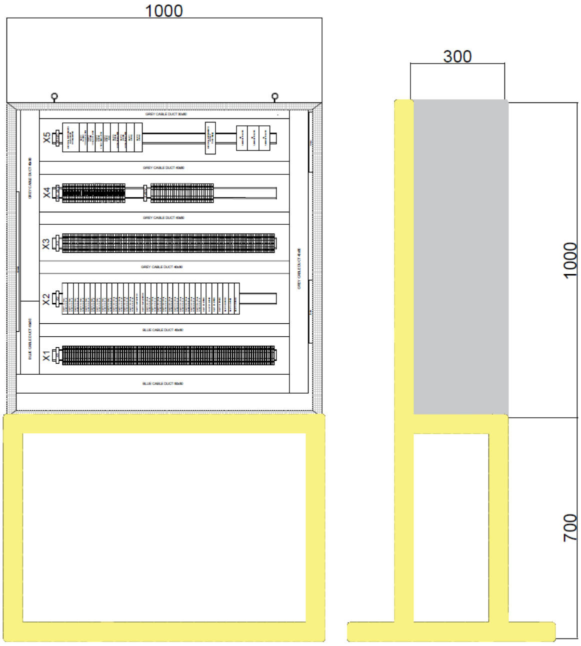


Figure 4.30: Illustration of the marshalling cabinet with support structure [42].

The slots proposed used in Phase 2 are presented in Tab. 4.9. The numbers presented are generated by utilizing the spare slots inside the 1-FTC-100 marshalling cabinet not being used in Phase 1. As the estimated usage of terminals in Phase 2 exceeds what was presented in [42], the possibility of constructing a second marshalling cabinet must be evaluated during the continued development of the CSL.

Table 4.9: Proposed placement of Phase 2 electrical wiring in 1-FTC-100 Marshalling cabinet [42].

Section	Slots to be used
X1	97–157
X2	16–25
X3	78–117
X4	17–26
X5	6

4.5.4 Loop Diagrams

Loop diagrams are used as a method for displaying electronic circuits. It illustrates the connection from a component to the control system located in the marshalling cabinet, illustrated in Fig. 4.31.

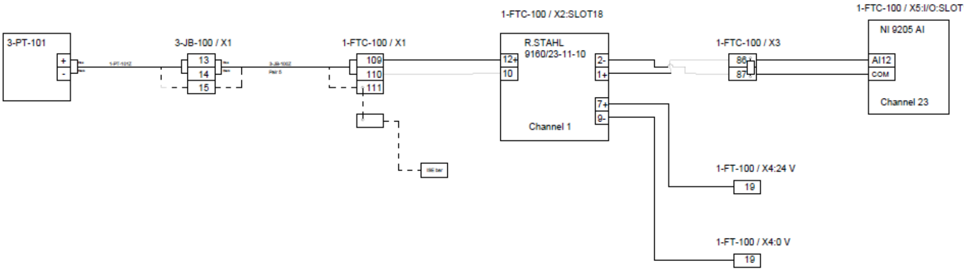


Figure 4.31: Electrical loop diagram for a pressure transmitter in Phase 2.

The figure presents a circuit diagram for a pressure transmitter in Phase 2. It shows the circuit from the transmitter to the communication devices in the 1-FTC-Marshalling Cabinet. IS circuits requires that the current is small enough to not cause ignition when broken. The function of the modules in X2 is to work as energy restricting barriers. The selected barriers are galvanic isolators, which are easy to install, requires no connection to ground and will generate power to supply the IS circuits via an external source [42].

From the barriers, circuits go through fuse terminals in X3 before looping through the I/O module and back again. X4 represents the 4 V and 24 V supply, used for the barriers to be functional and feeding the IS circuits. The I/O modules can communicate with a computer either using Ethernet- or a Universal Serial Bus (USB)-cable. The Ethernet cable has a possible length of 90 m compared to the maximum length of 5 m for a USB cable and is selected as the preferable method during the control of Phase 1. Loop diagrams for all components can be found in Appendix F.

4.5.5 Electrical system

The galvanic isolators and I/O modules require 24 VDC to be operational. This is not readily available in the workshop, resulting in a AC/DC rectifier being implemented in the Marshalling cabinet to convert 230 VAC from the main power supply of the workshop to 24 VDC. As presented in [42], the selected rectifier is the NI PS-15. Its power supply can deliver 120 W, where 60.4 W is estimated to be used during Phase 1 operation. An estimation of the implemented rectifier, and wether it can supply both Phase 1 and 2 is presented in Tab. 4.10. The estimated power consumption is 99 W, resulting in the selected rectifier being suitable for both Phase 1 and 2 operation.

Table 4.10: Estimation of power consumption for Phase 1 and 2 [42].

Equipment	**Quantity**	**Power Consumption [W]**
Phase 1 total	1	60.4
Phase 2 - Flowmeters	6	18
Phase 2 - STAHL 9165/26-11-11	2	6.6
Phase 2 - STAHL 9165/23-11-10	8	24
Available power from rectifier		**120**
Total power consumption		**99**
Reserve Power		**21**

The 24 VDC distribution system with modular fuses in the terminal block is located in section X4 in the marshalling cabinet [42]. It is intended that Phase 2 will be connected to the already existing 24 V distribution system. Similar to Phase 1, 2 A fuses is selected for the galvanic isolators, based on recommendations from the supplier. An updated 24 V distribution diagram can be found in Appendix G.

Chapter 5

Procurement of equipment

The final design of Phase 2 presented in Chapter 4 requires a wide range of equipment and components. The function and purpose of the different equipment have all been covered in Chapters 2, 3 and 4.

Procurement of equipment is an important task to any engineering project, as it affects the final system performance and cost. To find the preferred equipment and vendors for Phase 2, the Phase 1 project team have been consulted. Recommendations from industry contacts have also been taken in consideration. Delivery time for different equipment varies from 1 to 10 weeks. To manage the procurement process, each equipment has been given a status of procurement. Tab. 5.1 list the hierarchy of procurement status.

Table 5.1: Equipment procurement status.

Status	**Description**
Ready to order – general	The equipment is standard stock inventory at the supplier and is ready for ordering. Suppliers has been contacted for data sheet and quote. Cost information have been added in budget.
Ready to order – custom	The equipment is customized, with calculations based on the process data for the specific application. Custom offer has been retrieved from the supplier and submitted to Mr. Holden.
Not ready to order – revision required	The equipment selection, final model or calculations are not completed. Further discussion with supplier, system configuration must be accomplished first.

As several of the equipment offers are confidential, no information regarding cost and application calculation can be listed. Chapter 7 describes the overall budget for the CSL project. Detailed budget, application calculations and data sheets are provided to Mr. Holden at the submission of the thesis. Appendix I holds contact information for every supplier used for the CSL Phase 2. The equipment for Phase 2 is listed in the following subsections in alphabetical order.

5.1 CFU

The objectives in Chapter 1.4 states the arrangement of CFU manufacturing is one of the objectives for this master's thesis. The design of the CFU is a result of the work conducted in this thesis, hence, the CFU will be custom build. The arrangement of CFU manufacturing is described in Chapter 6.1.

5.2 Construction steel

5.2.1 Main frame

Construction steel for the Phase 2 main frame will be bought locally from Smith Staal. The selected steel profiles are hollow squared profiles with dimensions 40 mm x 40 mm x 4 mm of S355J2H steel. The S355J2H steel has good mechanical properties and is suitable for welding. The steel profiles are delivered in lengths of 6 m. By inspecting the CAD model in Section 4.2 the main frame requires 74 m of steel.

Table 5.2: Steel for main frame.

Status	**Ready to order – general**
Supplier	Smith Staal
Material	S355JH2H steel
Profile dimensions	40 mm x 40 mm x 4 mm
Weight	4.3 kg/m
Meters required	74 m
Nr. of steel lengths	13

5.2.2 Gas holding cage

Construction steel for the gas holding cage will be bought together with the steel for the main frame from Smith Staal. The steel profiles for the holding cage will have a squared shape constructed with S355JH2H steel. The profile dimensions are 30 mm x 30 mm x 3 mm. By inspection of the CAD model, 25 m of steel is required.

Table 5.3: Steel for holding cage and pipe support.

Status	**Ready to order – general**
Supplier	Smith Staal
Material	S355JH2H steel
Profile dimensions	30 mm x 30 mm x 3 mm
Weight	2.41 kg/m
Meters required	30 m
Nr. of steel lengths	5

5.3 Electrical

5.3.1 Barriers

STAHL 9165/26-11-10 for AI and 9165/26-11-11 for AO are galvanic isolators, which will be implemented to the existing marshalling cabinet to restrict high currents and supply the IS circuits, described in Section 4.5. There are 15 AI signals and 5 AO signals required, meaning 8 STAHL 9165/26-11-10 and 3 STAHL 9165/26-11-11 electrical barriers are required.

Table 5.4: Sthal-Syberg energy restricting barriers.

Status	**Ready to order – general**
Model	9165/26-11-10 9165/26-11-11
Supplier	Stahl-Syberg AS
input signal	0–4 mA
Output signal	20 mA
Supply voltage	24 VDC
EX certified Zone 1	No

5.3.2 I/O module

Phase 2 requires 15 AI signals to be connected to I/O modules and are intended to be connected to the spare slots in the existing modules implemented in Phase 1. Phase 2 have a total of five automatic flow control valves, that all require automatic output signals. The existing NI 9265 AO module installed in the marshalling cabinet has one port available for usage. To facilitate operation of Phase 2, one additional I/O module is required. The NI9265 module is suitable for the required ports for Phase 2, as described in Section 4.5.

Table 5.5: I/O module.

Status	**Ready to order – general**
Model	NI9265
Supplier	National Instrument
Output signal	0–20 mA
External supply voltage	9–36 VDC

5.3.3 Junction Box

The Ex-e (i) 8146/2083-3A junction box is delivered by Stahl-Syberg AS and used as a connection point for Phase 2 transmission lines to the marshalling cabinet. The junction box should only contain ignition free and no-heat emitting equipment. The junction box will be located at the Phase 2 frame in a non-corrosive area, which enables a junction box manufactured in reinforced polyester. Polyester is very cost-efficient relative to metal, and allows easy access to transmission lines.

Table 5.6: Stahl-Syberg Ex-e junction box.

Status	**Ready to order – general**
Model	Ex e (i) 8146/2083-3A junction box
Supplier	Stahl-Syberg AS
Material	Polyester
EX certified Zone 1	Yes

5.3.4 Cables

The instrumentation process for Phase 2 is described in Sections 4.4 and 4.5. The necessary cables are electronic connections from valves and transmitters to the junction box, 2 multicores and cables from the junction box to the Marshalling Cabinet, +/- cables from X1 to X5 inside the cabinet and cables for each connection to earth via the ISE bar.

Specifications regarding exact cable types and length of the given equipment is to be decided by the students constructing Phase 2. During construction of Phase 1, spare electronic equipment is available. This equipment is to be revised before contacting Stahl-Syberg AS to acquire the needed equipment.

5.4 GLCC

The objectives in Section 1.4 states the arrangement of GLCC manufacturing as one of the objectives for the thesis. The GLCC will be custom build at the NTNU Finmekanisk workshop according to the design and specifications in Section 3.2.6. The arrangement of GLCC manufacturing is described in Section 6.2.

5.5 Flexible hose system

5.5.1 Cam-Lock couplings

Cam-Lock couplings will be used for easy connection and de-connection between the flexible hose lengths. The CAM-SF-E is a female coupling to connect to the CAM-SF-C male coupling by two spring loaded clamps. The PARI PC252060070 clamp is used to install the Cam-Lock couplings to the flexible hose and pipe ends. The couplings are manufactured in several materials. The GLCC will only operate with water and air, hence, aluminum couplings are selected due to the low price and satisfying properties. For future possible experiments with oil and natural gas, couplings in 316L must be considered. The hose lengths described in Section 4.1.6.1 will require a total of six Cam-Lock couplings (CAM-AL-E and CAM-AL-C) and twelve PARI clamps.

Table 5.7: Cam-lock connections.

Status	**Ready to order – general**
Model	CAM-SF-E 2″ CAM-SF-C 2″
Supplier	Hydroscand
Material	316L
Pressure rating	PN16
Additional equipment	PARI PC252060070 Clamp SF

5.5.2 Flexible hose

Vacupress Cristial is manufactured by Merlett and supplied by Hydroscand. The hose is manufactured in transparent PVC material with a S235JRG2 galvanized steel spiral to ensure flexibility and durability. The hose will be cut in specific length intervals described in Section 4.1.6.1, and installed in 3-FH-100. The 170 mm bending radius of the hose make it easy to wrap the hose inside the Phase 1 and 2 bottom frame deck. Cam-Lock couplings will be used to connect the different hose intervals. The hose is delivered in drums of 30 m, and since Phase 2 requires 60 m, two drums must be bought.

Table 5.8: Vacupress Cristal flexible hose.

Status	**Ready to order – general**
Model	Vacupress Cristal 2″
Supplier	Hydroscand
Dimension	OD = 63 mm ID = 50 mm
Material	Transparent PVC S235JRG2 steel
Pressure rating	PN40
Temperature range	−5 to 65 °C
Weight	1.6 kg/m
Bending radius	170 mm

5.6 Flow meter

5.6.1 Coriolis flow meter for water outlet

The Micro Motion Elite Coriolis CMFS075MA28N2 flow meter is manufactured by Micro Motion and delivered by Emerson Process management. The flow meter will be installed in 3-FT-201, at the joint water outlet for the CFU water outlet and the GLCC liquid outlet. In addition to mass flow, the flow meter measures the flow density which can be used to calculate oil-, and gas content in the liquid flow.

Table 5.9: Coriolis mass flow meter for water outlet.

Status	**Ready to order – custom**
Model	Micro Motion Elite Coriolis CMFS075MA28N2
Supplier	Emerson Process Management
Material	316L
Mass flow accuracy	± 0.1 %
Density accuracy	0.5 kg/m^3
Pressure drop	0.447 bar
Process connection	DN50 ASME 150 flange
Output signal	4–20 mA
EX certified Zone 1	Yes
Additional equipment	Micro Motion 2700 flow and density transmitter

5.6.2 Coriolis flow meter for CFU multiphase reject

The Micro Motion Elite Coriolis CMFS075MA28N2 flow meter is manufactured by Micro Motion and delivered by Emerson Process management. The flow meter will measure the multiphase flow at the CFU oil reject in 3-FT-204. The process data of the multiphase flow is difficult to calculate, and is indicated on the basis of various literature cases and industry feedback in Chapter 2 and from [V]. Because of the composition range of the multiphase flow, Emerson Process Management have expressed concern for the functionality and accuracy of 3-FT-204. If the process data cannot be estimated with higher accuracy, Emerson have suggested a *try&buy* solution, where the flow meter is delivered and commissioned for a trial period of 60 days without any economic cost. If the results are positive, the flow meter is billed and formally bought, otherwise the flow meter is returned to Emerson. The data provided in Tab. 5.10 is calculated on the basis of the estimated process data.

Table 5.10: Coriolis mass flow meter for oil reject.

Status	**Ready to order – custom**
Model	Micro Motion Elite Coriolis CMFS025M313N2
Supplier	Emerson Process Management
Material	316L
Mass flow accuracy	±0.1 %
Density accuracy	±0.5
Pressure drop	0.186 bar
Process connection	DN25 ASME 150 flange
Output signal	4–20 mA
EX certified Zone 1	Yes
Additional equipment	Micro Motion 2700 flow and density transmitter

5.6.3 Ex-flow control

Bronkhorst Ex-flow is a mass flow controller manufactured by Bronkhorst and delivered by Flow Teknikk AS. The flow controller utilizes a mass flow meter and an electrically actuated control valve for flow control. An electric module with galvanic barriers is located in the safe zone for valve control and process data. The flow controller will be installed in 3-FV-101/3-FT-101 to control pressurized air flow to the GLCC and in 3-FV-102/3-FT-102 to control nitrogen gas flow to the CFU. The different units will be calibrated to handle different flow values, and connected to the same electric module in the junction box.

Table 5.11: Bronkhorst Ex-flow control unit.

Status	**Ready to order – custom**
Model	Bronkhorst Ex-flow F-202AX-XC-HEE-55-V
Supplier	Flow-Teknikk AS
Material	316L
Mass flow accuracy	±1 %
Process connection	G1/2″ fitting
Output signal	4–20 mA
EX certified Zone 1	Yes
Additional equipment	Electric dual module E-7100-04-22-22-EDD

5.6.4 Magnetic Flow meter

The Rosemount 8705 magnetic flow meter is manufactured by Rosemount and delivered by Emerson Process Management. The flow meter will be installed in 3-FT-203 to measure the liquid flow downstream the scrubber.

Table 5.12: Rosemount magnetic mass flow meter.

Status	**Ready to order – custom**
Model	Rosemount 8705 magnetic flow meter
Supplier	Emerson Process Management
Material	316L
Mass flow accuracy	±1 %
Process connection	DN50 ASME 150 flange
Output signal	4–20 mA
EX certified Zone 1	Yes
Additional equipment	Rosemount 8732E transmitter

5.6.5 Vortex gas flow meter

The Heinrichs DVH-P-255S-LL2S3-H vortex flow meter is manufactured by Heinrichs and delivered by Flow Teknikk AS. The flow meter will be installed in 3-FT-202 to measure the air separated by the scrubber vessel. Because the scrubber is open to air, the pressure will theoretically be 1 atm. At this pressure, no flow will occur. In practice, the pressure from the GLCC operation will propagate from the outlet pipe and create an over-pressure of air in the scrubber, which causes mass flow thought the flow meter. The flow meter is delivered with DN25 process connections, and will require reducers to fit the DN80 air outlet from the scrubber vessel.

Table 5.13: Vortex gas flow meter.

Status	**Ready to order – custom**
Model	Heinrichs DVH-P-255S-LL2S3-H vortex flow
Supplier	Flow-Teknikk AS
Material	316L
Mass flow accuracy	±1 %
Process connection	DN25 ASME 150 flange
Output signal	4–20 mA
EX certified Zone 1	Yes

5.7 Nitrogen gas

5.7.1 Nitrogen gas bottles

The nitrogen gas reservoir described in Section 4.1.8 is designed to hold four gas bottles of nitrogen gas. The bottles have a volume of 50 liter pressurized to 200 bar. By applying the ideal gas law, the volume equals 11.7 kg of nitrogen gas. The nitrogen gas is accumulated and pressurized by AGA and delivered by Würth Norge. For nitrogen bottles procurement, a rental agreement for bottles must be established.

Each bottle is rented by a daily fee, in addition to the fixed cost of the nitrogen gas. The rental agreement can be terminated at any given time.

Table 5.14: Nitrogen gas bottles.

Status	**Ready to order – general**
Gas purity	> 99.6 %
Bottle volume	9.72 am^3 | 50 liter
Bottle pressure	200 bar | 15 °C
Regulator connection	DIN10 W 24.32 x 1-1/4″ BSP threads
Bottle dimensions	d = 230 mm h = 1775 mm
Total weight incl. gas	81 kg

5.7.2 Nitrogen gas regulator

The AGA Pro200 regulator is manufactured by AGA and delivered by Würth Norway. The regulator is specifically constructed for nitrogen gas and will only connect to nitrogen gas bottles. The regulator outlet can deliver the gas at a pressure from 0–40 bar. Two manometers indicates bottle pressure and outlet pressure from the regulator. The status of the gas regulator deviates from the status hierarchy listed in Table. 5.1 as it was ordered and delivered to use for pressure testing of Phase 1 by the Phase 1 project team.

Table 5.15: AGA nitrogen gas regulator.

Status	**Delivered**
Model	AGA Pro 200/40 bar N_2
Supplier	Würth Norge
Inlet pressure	$<$200 bar
Output pressure	$<$40 bar

5.7.3 Static mixer

The Primix PMS32 static mixer is manufactured by Primix and delivered by Christian Berner. The static mixer is one of the gas injection solution for CFU nitrogen injection, described in Section 2.3.1. The mixer will have eight helical elements to mix oily water and nitrogen gas. The mixer body is manufactured in transparent PVC, while the mixer elements is manufactured in 316L. The mixer connects with DN32 flange connections, hence, pipe reducers are required. The gas inlet is connected by DN40 bsp threads, and will require an adapter.

Table 5.16: Primix static mixer.

Status	**Ready to order – custom**
Model	Primix PMS32-8-PVC/SS
Supplier	Christian Berner
Pressure rating	PN16
Pressure drop	0.3 bar
Process connection	DN32 flange liquid DN40 BSP treaded connection gas
Material	PVC body 316L mixer elements

5.7.4 Liquid jet ejector

Transvac is a leading manufacturer and supplier of liquid jet compressor ejectors for gas injections to liquid flow. The liquid ejector is an alternative CFU nitrogen gas injection method described in Section 2.3.1. The ejector is custom built to the specific application process data. The ejector is only available for rental at a monthly fee. The ejector technology provides improved pressure and bubble size control relative to the static mixer, but at a higher cost.

Table 5.17: Transvac LJC ejector.

Status	**Ready to order – custom**
Model	Liquid jet ejector custom build Q23284
Supplier	Transvac AS
Pressure rating	PN16
Pressure drop	2 bar
Process connection	DN40 flange liquid DN25 flange gas
Material	316L
Estimated bubble size	160 μm

5.8 Process lines

5.8.1 Piping and miscellaneous

The steel pipes of Phase 2 will be pre-fabricated by Trondheim Staal as described in Section 4.3, except the process lines connecting Phase 1 and Phase 2 where pipes will be bough at standard lengths and welded together. The steel pipes for Phase 1 and 2 process connection is bought locally from Ahlsell AS, including required flanges, tee-connection, elbows and reducers. Tab. 5.18 presents the general dimensions and material properties of the pipes. Pre-fabrication specifications and estimated lengths and quantities are provided to Mr. Holden at the completion of this thesis.

Table 5.18: Pipelines.

Status	**Not ready for order - revision required**
Dimensions	DN80 Sch10s DN50 Sch10s DN25 Sch10s Miscellaneous
Supplier	Trondheim Staal Ahlsell AS
Material	316L
Pressure rating	PN40

5.8.2 Tubing and miscellaneous

12 mm tubing lines will be used to connect pressure,- and temperature sensors and gas injection, while 6 mm tubing will be used for sampling points. All tubing are bought in standard lengths from Hoke and Ahlsell. Standard G1/2″ and G1/4″ fittings will be used for connection. Tab. 5.19 presents the general dimensions and material properties of the tubes and fittings. Estimated lengths and quantities are provided to Mr. Holden at the completion of this master's thesis.

Table 5.19: Tubing and miscellaneous.

Status	**Ready to order – general**
Model	12 mm tubing 6 mm tubing G1/4″ fittings G1/2 fitting Miscellaneous
Supplier	Hoke Ahlsell AS
Material	316L
Pressure rating	PN40

5.9 Sample cylinder

The 4HDY300 sampling cylinder is manufactured by Hoke and delivered by MRS Global. The cylinders will be installed in SP4 and SP5 for extraction of liquid samples for laboratory examination and verification of the OiW sensor accuracy. Double ended cylinders have been selected for the possibility to isolate and extract sample without removing the cylinder itself.

Table 5.20: Sample cylinders.

Status	**Ready to order – general**
Model	Formed sampling cylinder 4HDY300
Supplier	MRC Global
Cylinder volume	300 ml
Material	316L
Pressure rating	PN80

5.10 Scrubber

5.10.1 Pipe and heads

The manufacturing arrangement of the scrubber vessel is described in Section 6.3. The scrubber vessel will be constructed and assembled at the MTP workshop and at the NTNU Finmekanisk workshop. The main cylinder pipe and cover plates are acquired by Astrup, whereas inlet, outlets and ribs are constructed by NTNU Finmekanisk workshop. Tension rods, bolts, washers and flanges are bough locally from Ahlsell.

Table 5.21: Astrup Acryl pipe and aluminium cover plates.

Status	**Ready to order – custom**
Acryl pipe	OD = 350 mm ID = 320 mm Length = 2100 mm
Cover plate	Dimensions = 400 mm x 400 mm x 15 mm EN AW-1050-H14/H24 aluminum

5.10.2 Mesh pad

The mesh pad is an important unit of the scrubber assembly, which allows mist to be trapped in the wire mesh and allows dry gas to flow through the gas outlet. Koch-Glitsch is a leading manufacturer of demisters, and Christian Berner is the Norwegian supplier.

Table 5.22: Koch-Glitsch demister.

Status	**Ready to order–specific**
Model	Koch-Glitsch demister
Supplier	Christian Berner
Material	316L
Dimension	d = 318 mm

5.11 Transmitters

5.11.1 Absolute pressure transmitter

The Apliens PCE-28 absolute pressure transmitter is manufactured by Apliens and delivered by OEM Automatics. The transmitter utilizes a piezo resistive sensor to measure the pressure. The range of the transmitter is from 0 to 1000 bar, and can be calibrated within this range for improved accuracy. The accuracy is given at ±0.02 % of the calibrated range. The transmitter will be installed in 3-PT-102, 3-PT-103, 3-PT-201 and 3-PT-202.

Table 5.23: Apliens absolute pressure transmitter.

Status	**Ready to order – general**
Model	Apliens PCE-28
Supplier	OEM Automatics
Process connection	G1/2″
Pressure range	0–70 bar
Accuracy	±0.075
Output signal	4–20 mA
Supply voltage	12–55 VDC
EX certified Zone 1	Yes

5.11.2 Differential pressure transmitter

The Apliens APR2000ALW differential pressure transmitter is manufactured by Apliens and delivered by OEM Automatics. The transmitter utilizes a piezo resistive sensor to measure differential pressure from two points. The range of the transmitter is from 0 to 70 bar, and can be calibrated within this range for improved accuracy. The accuracy is given at 0.075 % of the calibrated range. The transmitter will be installed in 3-PDT-101.

Table 5.24: Apliens differential pressure transmitter.

Status	**Ready to order – general**
Model	Apliens APR2000ALW
Supplier	OEM Automatics
Process connection	G1/2″
Pressure range	0–70 bar
Accuracy	±0.075
Output signal	4–20 mA
Supply voltage	12–55 VDC
EX certified Zone 1	Yes

5.11.3 Temperature transmitter

The Apliens GB-0050050T Ex temperature transmitter is manufactured by Apliens and delivered by OEM Automatics. The transmitter utilize RDT measurement principle by a Pt100 element. The range of the transmitter is from −50 to 150 °C, but with calibration, the range is specified from 20 to 70 °C for improved accuracy. The transmitter will be installed in 3-TT-101, 3-TT-201 and 3-TT-202.

Table 5.25: Apliens temperature transmitter.

Status	**Ready to order – general**
Model	Apliens GB-0050050T
Supplier	OEM Automatics
Process connection	G1/2″
Temperature	−50 to 150 °C
Output signal	4–20 mA
Supply voltage	8–30 VDC
EX certified Zone 1	Yes

5.12 Valves

5.12.1 Control valves

The control valve Samson 3241 belongs to a general class of control valves manufactured by Samson and delivered by Matek. Phase 2 will require a total of three control valves at 3-FV-201, 3-FV-202 and 3-FV-203 for flow control at the joint water outlet, at the GLCC gas outlet and at the CFU oil reject respectively. Parameters for each valve are calculated based on the specific process data for each application.

Samson 3241 2″CL150RF will be installed at 3-FV-201, Samson 3241 4″CL150RF will be installed at 3-FV-202 and Samson 3241 1″CL150RF will be installed at 3-FV-203. All three valves are operated by pneumatic actuators. The valve body is manufactured in 1.0619 cast steel, while the the plug and seat is manufactured in 316L. Flange connections will be used to connect the valve in the process lines. 3-FV-202 is connected in a DN80 process lines, but manufactured with DN100 process connections in order to handle the flow velocity. Hence, reducers must be installed upstream and downstream of the valve.

Table 5.26: Matek 3241 control valves.

Status	**Ready to order – custom**
Model	Samson 3241 2″CL150 Samson 3241 4″CL150RF Samson 3241 1″CL150RFRF
Supplier	Matek
Process connection	DN150 ASME 150 flange DN100 ASME 150 flange DN25 ASME 150 flange
Max pressure	PN40
Material	Cast steel 1.0619
Output signal	4–20 mA
EX certified Zone 1	Yes
Additional equipment	Pneumatic actuator EX- certified positioner

5.12.2 Manual ball valve with flange connections

The FA4379050 manual ball valve is manufactured by Fagerberg and delivered by Sigum Fagerberg. The valve is delivered with flange connections for easy installation. FA43790-50 will be installed in 3-MV-101, 3-MV-102, 3-MV-201, 3-MV-202 and 3-MV-204

Table 5.27: Fagerberg manual ball valve flange connection.

Status	**Ready to order – general**
Model	FA4379050
Supplier	Sigum Fagerberg
Process connection	DN50 ASME 150 flange
Material	316L
Pressure rating	PN40

5.12.3 Manual ball valve with welding connections

The FA4391-50/25 manual ball valve is manufactured by Fagerberg and delivered by Sigum Fagerberg. The FA43910-50/25 is delivered with welding ends, and the last two digits of the model number indicates the dimension. FA4391-50 will be installed in 3-MV-001, 3-MV-002, and 3-MV-003. FA4391-25 will be installed in 3-MV-004.

Table 5.28: Fagerberg manual ball valve welding connection.

Status	**Ready to order – general**
Model	FA4391-50 FA4391-25
Supplier	Sigum Fagerberg
Process connection	DN50 welding ends DN25 welding ends
Material	316L
Pressure rating	PN64

5.12.4 Manual globe valve

The Ari-Stobu 55.006 manual globe valve is manufactured by Armaturen and delivered by Prosessventiler. The valve is delivered with flange connections for easy installation. Ari-Stobu 55.006 will be installed in 3-MV-103 and 3-MV-203 for gas - liquid mixing to GLCC inlet and maintain scrubber liquid level at NLL respectively.

Table 5.29: Ari-Stobu manual globe valve.

Status	**Ready to order – general**
Model	Ari-Stobu 55.006
Supplier	Prosessventiler
Process connection	DN50 ASME 150 flange
Material	316L
Pressure rating	PN40

5.12.5 Pressure safety valve

The Tosaca 1216 pressure relief valve is manufactured by Tosaca and delivered by Sigum Fagerberg. The valve uses a spring mechanism that open at a pre-determined pressure to bleed down the system pressure. The valve will be installed as 3-PSV-101 and function as a safety barrier to avoid dangerous situations with over-pressure in the CFU vessel.

Table 5.30: Tosaca pressure relief valve.

Status	**Ready to order – general**
Model	1216
Supplier	Sigum Fagerberg
Process connection	Upstream DN15 Downstream DN25
Pressure rating	PN40
Material	316L
Pressure rating	PN40

5.12.6 Needle valve

Needle valves will be used to isolate sampling points in SP4 and SP5, and for the two drain points located at the CFU and GLCC outlet. Each sampling point requires a total of three valves to isolate the sample from process pipe, ventilation of the sampling system, upstream the sampling cylinders and downstream the sampling cylinders. In total the Phase 2 sampling systems will require eight needle valves.

Table 5.31: Hoke needle valve.

Status	**Ready to order – general**
Model	1711M4Y needle valve
Supplier	Hoke
Process connection	NPT 1/4″ male
Manometer range	0–25 bar
Material	316L
Pressure rating	PN400

Chapter 6

Construction arrangements

This chapter describes the arrangements made for construction of the CFU, GLCC and scrubber vessels. By following these arrangements the construction can start as soon as Mr. Holden approves the design and initiates the construction phase. Further instructions for construction of the complete CSL Phase 2 is described in Section 8.3.

6.1 CFU construction

The manufacturing of the CFU vessel has been outsourced to RadøyGruppen Engineering to ensure the quality and integrity of the vessel. RadøyGruppen Engineering have long experience with custom projects of pressurized vessels, both steel and plastic materials. Rune Skarpenes [VI] is the contact person at RadøyGruppen and will manage the manufacturing process. Mr. Skarpenes have provided valuable input regarding the design of the CFU vessel, hence, the authors feel confident about RadøyGruppens capability of constructing quality products.

The CFU vessel will be manufactured according to the design presented in Section 3.1.7. The vessel has a PN16 pressure rating and is governed by the PED regulations for a pressurized vessels. Safety and integrity concerns is one of the main reasons for outsourcing the CFU manufacturing process to RadøyGruppen Engineering, who will perform pressure tests and certification.

The CFU vessel is arranged to be constructed and assembled by RadøyGruppen Engineering, such that the vessel can be installed in CSL Phase 2 by connecting the process lines by flange connections. The cost for the CFU manufacturing is not listed in this thesis due to the confidentiality of RadøyGruppens offer confidentiality. The complete manufacturing drawings for the CFU can be found in Appendix D.

6.2 GLCC Construction

The GLCC vessel is arranged to be manufactured in-house by Øystein Hagemo [VII] at NTNU Finmekanisk workshop. The design of the GLCC is presented in Section 3.2.6, and manufacturing drawings are included in Appendix E. The complex geometry of the GLCCs main inlet cylinder requires a high level of precision and manufacturing expertise. Mr. Hagemo and his crew at the NTNU Finmekanisk workshop have long experience with high precision manufacturing and are recognized as a quality manufacturer within the discipline.

The shape of the GLCC is recognized as a pipe, not a vessel. This classification is important for PED regulations and simplifies the construction of the vessel.

The GLCC manufacturing process will be divided into three phases: manufacturing phase, assembly phase and final installation phase. The manufacturing phase includes manufacturing of the GLCCs main inlet cylinder section and flanges.

The main inlet section will be manufactured from one single block of material. The single block manufacturing eliminates the use of adhesives between the inlet and the main pipe, which previously was a concern with regards to integrity and leakage. Mr. Hagemo will handle procurement of necessary materials for the GLCC vessel.

The assembly phase includes attaching all the manufactured flanges to the pipe sections and install O-rings. A special PVC material adhesive is utilized to ensure the integrity of the assemblies. It is important that flanges are assembled correctly with respect to each other since the GLCC inlet and outlet pipes have different angles. An illustration of the manufactured and partially assembled GLCC sections is presented in Fig. 6.1.

Figure 6.1: Illustration of GLCC sections after manufacturing and partial assembly. The background is retrieved from Keyshot 6 software.

The installation phase for the GLCC vessel includes assembling all sections together, and connect the GLCC to the Phase 2 process lines. This procedure can be preformed either by Mr. Hagemo or by the project team responsible for the construction of Phase 2. When the GLCC is installed, a leakage and pressure test must be conducted. If the tests are conducted successfully the GLCC is ready for commissioning.

6.3 Scrubber construction

The scrubber vessel is arranged to be manufactured in-house in collaboration with Arild Sæther [XI] at the MTP Workshop and Øystein Hagemo [VII] at the NTNU Finmekanisk workshop. The design of the scrubber have been presented in Section 3.3.4, and manufacturing drawings is included are Appendix F.

The materials for construction of the scrubber will be procured from Astrup and the mesh pad is supplied by Christian Berner, as described in Section 5.10. Since the scrubber vessel is open to atmosphere, it is considered as a holding tank rather than a pressurized tank. Hence, the scrubber vessel is not governed by PED regulations, which simplifies the construction.

The steel manufacturing for the scrubber vessel will be conducted by Mr. Sæther and his crew. This includes cutting the cover plates to the correct dimensions, including grooves for the main pipe and holes for the tension rods. The vertical gas and liquid outlets will be welded to the two cover plates including flanges. Tension rods are manufactured to correct length, including threads for bolt assembly.

The transparent PMMA main pipe will be delivered to Mr. Hagemo at NTNU Finmekanisk for manufacturing of the inlet pipe and the ribs for the mesh pad to be rested upon. The mesh pad ribs, inlet pipe and inlet flange will be manufactured from PMMA and attached to the main pipe by special PMMA adhesive. An illustration of the manufactured and partially assembled Scrubber sections is presented in Fig. 6.2.

When the main pipe, cover plates and tension rods are manufactured, the scrubber vessel can be installed. The installation process is fairly easy and can be conducted by the project team responsible for the construction of Phase 2. The installation will only require a wrench to fasten the bolts of the tension rods. It is recommended to add a layer of sanitary silicone sealant between the main cylinder and bottom cover plate, to eliminate the possibility for leakage. After the installation is completed a leakage test must be performed, and if the test is conducted successfully the scrubber is ready for commissioning.

Figure 6.2: Illustration of scrubber sections after manufacturing. The background is retrieved from Keyshot 6 software.

Chapter 7

Budget

Managing project economy is an essential part of any project, independent of whether the project focuses on research or business activity. Failure to manage economy can result in shut down for a research project before completion.

During the development of the CSL Phase 2, the budget has been continuously updated with new offers and equipment solutions. To protect themselves in the market, most industry suppliers have confidentiality regulations when providing equipment offers. To respect the confidentiality regulations, a detailed budget is not presented in this master's thesis. Instead, the budget have been summarized in six main disciplines to present the estimated budget for Phase 2.

The detailed budget, and the list of contact information for all equipment suppliers are delivered to Mr. Holden with at the submission of this master's thesis. All costs includes shipping and are listed in Norwegian kroner (NOK).

7.1 Phase 2 budget

The budget overview for Phase 2 is divided into the following six disciplines:

Process separators	Total cost for material and construction for the CFU, GLCC and scrubber vessels.
Piping	All process pipes required for Phase 2 construction.
Valves	All valves implemented in the Phase 2 process layout.
Instrumentation	Flow meters, transmitters and sampling bombs.
Automation	Cables, junction box, fuses, I/O module and miscellaneous.
Unforeseen expenses	Unforeseen expenses in equipment or services the authors have not accounted for in the design.

The estimated budget for Phase 2 of the CSL is listed in Tab. 7.2. Each discipline contains the total estimated cost for Phase 2 expenses within their respective discipline.

Table 7.2: Budget overview Phase 2.

Discipline	**Cost (no VAT)**	**VAT**	**Total cost**
Process separators	124,000	31,000	155,000
Piping	84,800	21,200	106,000
Valves	120,000	30,000	150,000
Instrumentation	330,000	82,500	412,500
Electrical	36,000	9,000	45,000
Unforeseen expenses	-	-	50,000
Total cost Phase 2			**NOK 918,500**

The initial budget for the CSL Phase 2 conducted by [64] estimates the total cost of Phase 2 to 228,399 NOK. The new budget for Phase 2 presented in Tab. 7.2, estimates the total cost to 918,500 NOK, equal to an increase of over 400 %. The increase in estimated cost is a consequence of the low level of detail in the initial budget and the recent expansion of the CSL Phase 2.

The initial budget does not contain realistic costs for the main components, especially CFU vessel, control valves and instrumentation. The proposed design of Phase 2 by [64] is only superficial, and does not perform research on the actual costs of obtaining a CFU vessel. The initial control valves have been replaced by new Samson-Matek control valves for improved performance, which caused an increase in cost.

The initial budget lacks important instrumentation including flow meters, electrical components and additional cost. The sum of these costs have increased the estimated cost considerably relative to the initial budget.

The tentative design of the gas reservoir, presented in [64] contains a large pressurized vessel and two compressors. The new design does not use this solution in favor of pressurized gas bottles. The new design of the gas reservoir has a lower estimated cost relative to the tank and compressors in the initial budget, which decreases the total estimated cost.

At the start up of the thesis, in January 2017, it was decided to extend Phase 2 of the CSL to also include a GLCC and scrubber. The GLCC vessel was intended to be placed in parallel with the CFU to enable operation of both separators with the same process equipment. During the development of the design, the initial plan of utilizing the same process equipment was partially abandoned due to differences in CFU and GLCC process data. Hence, the additional process equipment including a control valve and two flow meters contributes highly to the increase in estimated cost. In addition, the cost for the GLCC vessel itself and the required scrubber vessel increases the total estimated cost of Phase 2.

7.2 Overall CSL budget

The CSL project has been allocated a total of 3,000,000 NOK, funded by SUBPRO. At the time of submission for this thesis, the total expenses for the CSL project is the sum of the Phase 1 construction costs and the Würth nitrogen gas regulator.

The gas regulator is a part of the Phase 2 process equipment, but was bought in advance to be utilized in pressure tests of Phase 1 by the Phase 1 project team. Tab. 7.3 lists the available funds and expenses at the time of submission for this thesis.

Table 7.3: Remaining funds for the CSL project.

Discipline	**Total cost**
Available funds	3,000,000
Phase 1 construction expenses	1,040,000
Remaining funds	**1,960,000**

The estimated budget presented in [64] allocate the available funds among the CSL Phase 1, Phase 2 and Phase 3. Operation of Phase 1 and Phase 2 depends on the pump and reservoir system implemented in Phase 3. In addition, the Phase 3 design will implement a phase-splitter and a de-liquidizer to the CSL. The phase-splitter and de-liquidizer have been assumed sponsored to the CSL project [64], and does not represent a significant expense to the total Phase 3 budget. The total cost of Phase 3 is estimated to be NOK 743,018 [64].

The budget for Phase 1 includes procurement of two OiW sensors to analyze the oil content in the separated water online. The OiW sensors have a high cost, which exceeds the NTNU boundary for a tender offer (all expenses above 100,000 NOK, without VAT). This causes the procurement of the OiW sensors to be announced as a tender offer. The estimated cost of the OiW sensors are based on consultation from different OiW sensor suppliers performed by [64]. The overal CSL project economy is listed in Tab. 7.4. For orderly reasons, the Phase 1 expenses and estimated cost of the OiW sensors are divided in two different rows.

Table 7.4: Overall CSL project economy.

Discipline	**Total cost**
Phase 1 expenses	1,040,000
Phase 2 estimate	918,500
Phase 3 estimate	750,000
OiW sensor estimate	1,000,000
Total cost	**3,708,500**

The economy of the overall CSL project is difficult to estimate accurately, as actual expenses often deviate from the estimated cost. In particular, the cost of the OiW sensors cannot be estimated accurate due to the tender offer requirement. The estimated cost of Phase 3 is based on the design in [64] and will most likely change when the final design is presented. Some equipment is bought from international suppliers and thereby also affected by currency changes. The overall project balance is listed in Tab. 7.5.

Table 7.5: Overall CSL project economy balance.

Discipline	**Total cost**
Available funds	3,000,000
Total estimated cost of the project	3,708,500
Economical balance	**−708,500**
Economical safety margin	**−28.6 %**

The economical balance of the CSL project have bad health as the total estimated cost exceeds the available funds by 708,500 NOK. The authors reflections and recommendations regarding the CSL project economy is described in Section 8.1.

Chapter 8

Conclusion

This is the final chapter of this master's thesis. In Section 8.1, the authors discusses the quality of the work conducted in this thesis. Several subjects regarding design limitations, design decisions and economy are discussed. Section 8.2 presents the conclusion for this master's thesis. In Section 8.3 the recommendations for further work regarding the CSL Phase 2 is described.

8.1 Discussion

CFU technology requires a high level of knowledge in hydrodynamics, gas-liquid interference and flotation, which often requires years of study and experience to obtain. The CFU design presented in Sectionc 3.1.7 is based on available literature described in Chapter 2, input and recommendations from industry contacts and the best knowledge of the authors.

More extensive results can be provided regarding gas and liquid behaviour during flow simulation if a more extensive software is used. Due to the lack of knowledge regarding such programs, a more basic software is used for flow simulation.

During this thesis, Solidworks Flow Simulation^{TM} is selected due to its intuitive implementation with Solidworks 3D software described in Section 4.1.3. Solidworks Flow Simulation^{TM} can only simulate a single-phase flow and is used to provide a quantitative representation of the rotational flow field inside the vessel. The numerical results presented are not valid, as the mesh generation of the CFU is simplistic, but indicates satisfactory results with regards to the varying flow ranges in the different separation zones.

Innovative CFU design solutions such as the Cameron TST CFU MS3 represent a next generation of CFU vessels, with complex design and improved performance. Independent from the next generation of CFUs, the CFU design developed in this master's thesis still represents a basic CFU capable of facilitating the development of advanced novel control algorithms. The CFU vessel design presented will increase the scientific value of conducting experiments, as performance depends heavily on the control of outlet- and injection flow control valves. The design has been facilitated for possible future modification, where the inlet pipe, vortex breaker, suspended reject pipe and inner cylinder can be replaced. The CFU is connected to the main process system via flange connections and can be replaced if a more advanced model is desired for experimental purposes. This can be done as a test to see if the developed control algorithms are applicable for a commercial CFU, constructed for industrial operation.

The GLCC operation described in Section 3.2.2 will utilize water and air at a operational pressure below 10 bar. Separation of water and air occurs naturally at low pressure levels, as intended for the Phase 2 GLCC. The scientific value is low is the conducting GLCC experiments if the separation occurs without being affected by the control parameters.

The first design iteration of the GLCC, described in Section 3.2.4, reduces the overall GLCC dimensions, hence the design differs from the normal design models. This reduction enables a wider range of experiments and the GLCC performance may vary depending on the control variables, thereby increasing the scientific value. This argument can also be applied to increase the interest of re-locating the CSL to SINTEFs Tiller Facility for experiments with real hydrocarbons.

The placement of the CFU and GLCC in parallel without the possibility for simultaneous operation allows the use of joint process equipment. The similarity of the flow values from the CFU water outlet and the GLCC liquid outlet enables a joint outlet and same control valve, mass flow meter and instrumentation.

Even though the process data is similar, it will not be identical. The CFU water outlet will contain oil particles and nitrogen gas, while the outlet of the GLCC will have a higher operational pressure. The joint connection also forces the control valve to be located at a greater distance from the two outlets, extending the distance between the processes and the control parameter.

For a system with unilateral focus on performance, the two vessels should be designed completely separate from each other, including process equipment. However, process equipment is by far the highest cost for Phase 2, hence, a joint water outlet is preferred due to economical limitations.

During the development of the Phase 2 design, the estimated cost has increased significantly relative to the initial budget presented in [64]. Section 7.1 presents the new budget for Phase 2 and describes the two main reasons for the cost increase. All design decisions regarding equipment, suppliers and manufacturing arrangements have been done to the best the authors ability, balancing between functionality and cost.

It is possible to reduce the total cost of the Phase 2 design. One possibility is reducing the number of measurements, especially mass flow measurements which represents a large factor of the total cost. By reducing the number of mass flow measurements, the available process data is reduced, which furthermore reduces the available data used to optimize performance and develop advanced novel control algorithms. This compromises the Phase 2 functionality, which is undesirable.

The designed scrubber vessel is based on the worst case liquid flow rate from the GLCC gas outlet. This estimate is relatively conservative, and could possibly be scaled down. A lower liquid flow rate will result in a smaller scrubber vessel and thereby reduce cost. Reducing the scrubber vessel volume will increase the possibility of flooding the vessel, which also is undesirable.

The overall economy of the CSL project is described in Section 7.2, with a total balance of $-708{,}500$ NOK where Phase 1, 2, 3 and OiW sensors are included. Phase 1 has been constructed, with a total cost of 1,040,000 NOK.

The overall economy is a problem, since the available funds will only cover two out of the three remaining investments (Phase 2, Phase 3 and OiW sensors). The CSL cannot be operated without a pump and feeding system,which is planned to be implemented in Phase 3. This simple fact alone is sufficient to prioritize Phase 3 as the next investment in the project. Furthermore the OiW sensors are the key to measure the separation performance for both the Phase 1 hydrocyclones and the Phase 2 CFU vessel. Operation without the OiW sensors would require manual sampling, which is highly inconvenient and will only provide median results of the oil concentration. The OiW sensor will generate real-time and dynamic concentration values during operation.

One obvious solution to reduce cost is to only invest in one OiW sensor. The two sensors utilize the same monitor and processing unit, which must be bought either way. The cost reduction of only investing in one OiW sensor is therefore not sufficient to fund both Phase 2 and Phase 3.

Another possibility to the economical situation is to increase the available funds, which requires an application to SUBPRO or individual SUBPRO partners. If scientific results produced by CSL experiments are presented, the magnitude of an application would be increased. To produce results the CSL must be operative, which implies to invest in Phase 3 before Phase 2.

It is worth mentioning that the Phase 2 automation design described in Section 4.5 is based on the assumption of Phase 2 as the next investment, considering the available terminals in the marshalling cabinet. Depending on the extent of the automation system for Phase 3, the available ports in the marshalling cabinet occupied during Phase 2 automation design may not be available. If the remaining space is not sufficient, the need for a new or extended marshalling cabinet and revision of the Phase 2 automation design is necessary.

8.2 Conclusion of the thesis

This master's thesis is aimed towards developing a finalized design for Phase 2 of the CSL, including a CFU and a GLCC vessel. Its purpose is to facilitate research and development of advanced novel control algorithms for compact separators.

The CSL project contains three Phases. Phase 1 focuses on produced water treatment by three hydrocyclone liners configured in series, and has been constructed during the fall semester of 2016. Phase 2 implements a CFU and a GLCC to the system. Phase 3 consist of a pump and reservoir systems to feed Phase 1 and 2 with oil and water for separation. The CSL project is funded by SUBPRO with a total budget of 3,000,000 NOK.

The Phase 2 CFU and GLCC vessels are configured in parallel without the possibility for simultaneous operation. This enables the vessels to be partially operated by the same process equipment, which decreases the total cost. The P&ID for Phase 2 is illustrated in Fig. 4.1 and described in Tab. 4.1. Fig. 4.3 illustrates the complete Phase 2 process equipment including the steel frame and the gas reservoir. Both the

CFU and the GLCC are designed to be manufactured in transparent PVC material so the separation process can be visualized during operation.

The CFU is a water treatment vessel designed to separate oil particles from water by utilizing injected gas for flotation. The design process for the CFU vessel is described in Section 3.1, where Section 3.1.7 presents the final design. The manufacturing of the CFU vessel is outsourced to RadøyGruppen Engineering, as described in Section 6.1. To provide the CFU with nitrogen gas, a gas reservoir with a capacity of four nitrogen gas bottles has been designed.

The GLCC is a liquid-gas separator designed to separate water and air. The design process for the GLCC vessel is described in Section 3.2, where Section 3.2.6 presents the final design. The GLCC vessel is arranged to be manufactured in-house by the NTNU Finmekanisk workshop, as described in Section 6.2.

The air is injected to the GLCC water feed by a tee-connection. A seat valve will apply shear forces and a pressure drop to mix the water and air. A interchangeable transparent flexible hose system is designed to be implemented between the air injection and the GLCC inlet, for researching on different flow times between the air injection and the GLCC inlet. The transparent hose also enables study of multiphase flow patterns.

The separated air from the GLCC will contain liquid droplets as a result of LCO, one of two phenomena responsible for GLCC performance. To be able to measure the amount of liquid droplets, a scrubber vessel with a mesh pad has been designed and implemented in the Phase 2 design.

Phase 2 has been designed for an operational pressure of 10 bar. A pressure rating of PN16 is used to abide the general NTNU safety factor of 1.6. The pressure rating has been an important factor for the overall design, equipment selection, material selection and pipe dimensions.

The future Phase 3 pump and reservoir system will be capable of producing a combined water and Exxsol D140 model oil flow, totaling 5 m^3/h and provide a pressure of 25 bar. The Phase 1 hydrocyclones and Phase 2 CFU vessel focuses on produced water treatment with oil contents of 1 to 5 % (10,000–50,000 ppm), with the objective of separating the oil content in the water to below 30ppm.

At a later stage, it will be of interest to relocate the CSL to SINTEFs Tiller facility to conduct experiments with oil representative of real hydrocarbons. To facilitate the re-location, the Phase 2 process equipment is designed to be installed in a modular steel frame. SINTEFs Tiller facility requires all equipment to have an Ex Zone 1 certificate, hence, all electric equipment for Phase 2 are designed with Ex Zone 1 certification in mind. The CFU vessel is defined as a pressurized vessel, hence, it is governed by PED regulations. The arranged construction of the CFU fulfills these requirements.

A estimated budget for Phase 2 is presented in Section 7.1 where all expenses have been summarized in five disciplines. The Phase 2 expenses are estimated to 918,500 NOK.

The budget presented in this thesis increases the estimated cost of Phase 2 by 400 % relative to the initial budget. The main reason for this increase is the low level of detail in the initial budget, and the expansion of Phase 2.

The authors are confident that the objectives presented in Section. 1.4 are conducted in a satisfactory degree.

8.3 Recommendations for further work

With the submission of this thesis, the final design and construction arrangements for the CSL Phase 2 are handed over to Mr. Holden. The review of this thesis will determine if the design of Phase 2 fulfills the requirements of quality, functionality and economy set by Mr. Holden. In addition to the evaluation of the Phase 2 design, the economical issues regarding the CSL project described in Section 7.2 and discussed in Section 8.1 must be reviewed.

If the circumstances above are determined to be in favour of Phase 2, the construction of Phase 2 can be initiated. By the opinion of the authors, recommendations for further work are described as follows:

1. *Familiarize:* Fully understand the design of Phase 2 by reading this master's thesis. It is recommended to read Chapter 2 to understand the principles and technology of the processes and equipment of Phase 2, but not mandatory for conducting the construction of Phase 2. Chapter 3 to Chapter 6, including the appendices and equipment offers delivered to Mr. Holden with submission, provides all necessary information for construction of the Phase 2.
2. *Equipment procurement:*
    a) Finalize the pre-fabrication procedure of all process pipes in collaboration with Trondheim Staal, as described in Section 5.8.1.
    b) Order to all the process equipment listed in Chapter 5. Note that delivery time can vary from 1 to 10 weeks. Nitrogen gas bottles are rented at a daily fee. The LJC ejector is rented at a monthly fee, but has a delivery time of 6 weeks. Hence, detailed planning is required to not waste economical resources and time.
    c) Initiate the CFU, the GLCC and the scrubber manufacturing. The arrangements for construction are described in Chapter 6.
3. *Construction:* Weld the steel frame for Phase 2 and the holding cage for the gas reservoir. Welding equipment can be borrowed at the MTP workshop. A motorized steel saw can be used to cut the steel profiles to correct lengths and angles.
4. *Installation:*
    a) Install the pre-fabricated process pipes, separator vessels and process equipment by flange connections. Necessary bolts, nuts and washers remains from Phase 1 construction.
    b) Hire external contractor to weld the process pipes connecting Phase 1 and Phase 2, and fittings for pressure, temperature and drain points. An external contractor must also provide and install pipe supports to the process pipes.

   c) Install remaining instrumentation and equipment. This includes transmission lines, pneumatic system, junction box, cable trays, electric power cables and automation.

5. *Expand software control system:* Expand the existing control system in LabView for the CSL to include the following:
   a) Phase 2 process layout
   b) Automatic data logging system.
   c) Alarm and monitoring system, including connection to the emergency shutdown system.
6. *Commissioning:* Perform pressure test and leakage test to ensure the integrity of Phase 2. HSE precautions must be taken seriously as this is the first time pressure is applied to the Phase 2 process lines and equipment.
7. *Delivery:* The construction of Phase 2 is finalized, commissioned and ready for scientific experiments by Mr. Holden, Mr. Ohrem and Mr. Kristoffersen. Well done!

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Oral references

The following persons have made great contributions to this thesis by sharing their knowledge and opinions for the development of the CSL Phase 2 design.

I Holden, Christian [Associate Professor and Supervisor, NTNU Faculty of Engineering Science]

II Ohrem, Sveinung Johan [PhD Candidate, NTNU Faculty of Engineering Science]

III Kristoffersen, Torstein Thode [PhD Candidate, NTNU Faculty of Engineering Science]

IV Kristiansen, Olav [Principal Engineer, Statoil ASA]

V Hannisdal, Andreas [Director Separation and Produced Water Treatment, Fjords Processing]

VI Skarpenes, Rune [Mechanical Engineer, Radøygruppen Engineerng]

VII Hagemo, Øystein Gjervan [Staff Engineer, NTNU Faculty of Natural Science]

VIII Short, Gary [Design & Innovation Director, Transvac Systems]

IX Kaasboell, Edgard Inge [Engineer, NTNU Building Management Section]

X Langelie, Øystein [Senior Engineer, Technical Management Section, NTNU Technical Management Section]

XI Stanko, Milan [Associate Professor, NTNU Faculty of Engineering Science]

XII Rawlins, Hank [Director, eProcess Technologies]

XIII Uander, Tor Erling [Research Manager, SINTEF]

XIV Sæther, Arild [Department Engineer, MTP Workshop]

Appendices

A: Laboratory Engineering Numbering System

1 Main Equipment Tag Format

Tag number format for main equipment is shown in Figure 1 (AutoCAD P&ID, 2010).

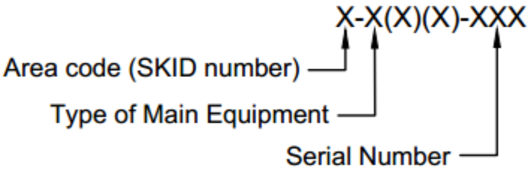


Figure 1: Tag number format for main equipment

An example tag can be 2-HC-100, which gives the area code, type of equipment and the serial number. Table 1 shows some example of typical main equipment for the laboratory (AutoCAD P&ID, 2010).

Component	**Type of Main Equipment**
Hydrocyclone	HC
Compact Flotation Unit	CFU
Pump	P
Tank	T

Table 1: Example of typical main equipment

2 Electrical and Instrumentation Tag Format

Tag number format for electrical and instrumentation is shown equipment Figure 2 (AutoCAD P&ID, 2010).

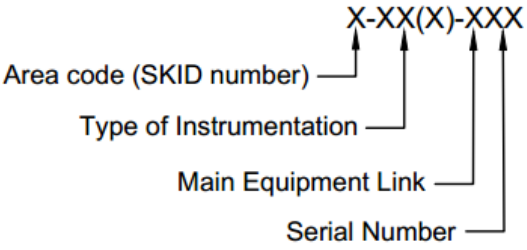


Figure 2: Tag number format for electrical equipment

An example tag can be 2-TT-102. Table 2 shows some example of typical instrumentation for the laboratory (AutoCAD P&ID, 2010).

Component	**Type of Instrumentation**
Temperature Transmitter	TT
Pressure Transmitter	PT
Pressure indicator	PI
Pressure differential transmitter	PDT
Flow meter	FT
Pressure Switch	PS
Oil in water measurement	OIW
Safety valve	SV
Flow Control Valve	FV
Choke Valve	CH
Manual Valve	MV
Junction Box	JB
Sampling point	SP

Table 2: Example of instrumentation equipment

3 Cable Tag Format

Tag number format for cables is shown in Figure 3. The cable tag format is almost identical to the instrumentation format, except for cable type. Table 3 shows some example of cable type for the laboratory.

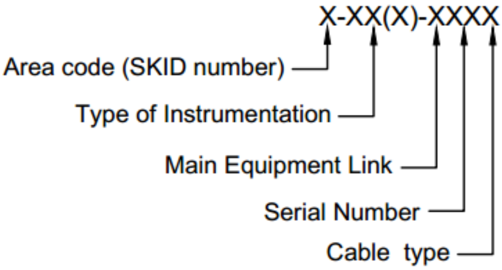


Figure 3: Tag number format for cables

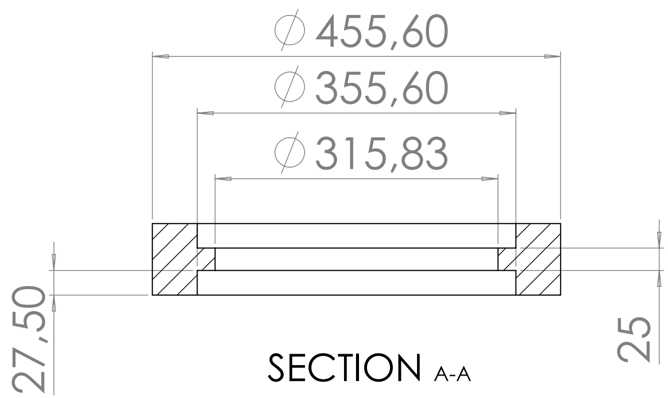
Cable	Cable type
Intrinsically Safe	Z
Non Intrinsically Safe	K
Low power	EL
High power	EH

Table 3: Examples of cable types

B: Compact Separation Laboratory Phase 1 Tag Description

Tag	Description
1-FT-101	Coriolis Flow and Density input to HC100
1-TT-101	Temperature input to HC100
1-CH-101	Choke Vale on Emergency Line
2-PT-101	Absolute Pressure Inlet HC100
2-PDT-101	Differential Pressure Inlet and oil outlet HC100
2-PDT-102	Differential Pressure Inlet and water outlet HC100
2-TT-102	Temperature Transmitter water outlet HC100
2-FV-101	Flow Control Valve with positioner converter oil outlet HC100
2-FV-102	Flow Control Valve with positioner converter water outlet HC100
2-FT-102	Electromagnetic Flowmeter water outlet HC100
2-OIW-101	Oil in Water Measurement water outlet HC100
2-PDT-201	Differential Pressure Inlet and oil outlet HC200
2-PDT-202	Differential Pressure Inlet and water outlet HC200
2-TT-202	Temperature Transmitter water outlet HC200
2-FV-201	Flow Control Valve with positioner oil outlet HC200
1-FV-202	Flow Control Valve with positioner converter water outlet HC200
2-FT-202	Electromagnetic Flowmeter water outlet HC200
1-PDT-301	Differential Pressure Inlet and oil outlet HC300
1-PDT-302	Differential Pressure Inlet and water outlet HC300
1-TT-302	Temperature Transmitter water outlet HC200
1-FV-301	Flow Control Valve with positioner converter oil outlet HC300
1-FV-302	Flow Control Valve with positioner converter water outlet HC300
1-OIW-301	Oil in Water Measurement water outlet HC100
1-PT-301	Absolute Pressure Oil outlet HC300
1-PS-101	Safety System Pressure Switch
1-SV-101	Safety System Ball Valve w/Pneumatic Actuator
1-MV-201	Manual valve routing past HC300
1-MV-201	Routing inlet HC300
SP1	Sampling point inlet HC100
SP2	Sampling point inlet HC200
SP3	Sampling point outlet HC200/HC300

C: CFU Construction Drawings



SECTION A-A

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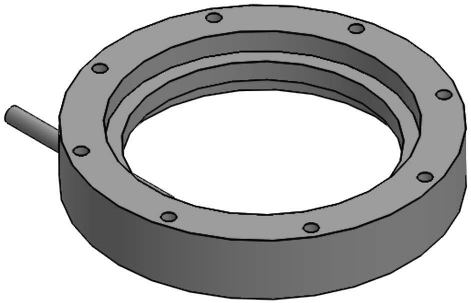

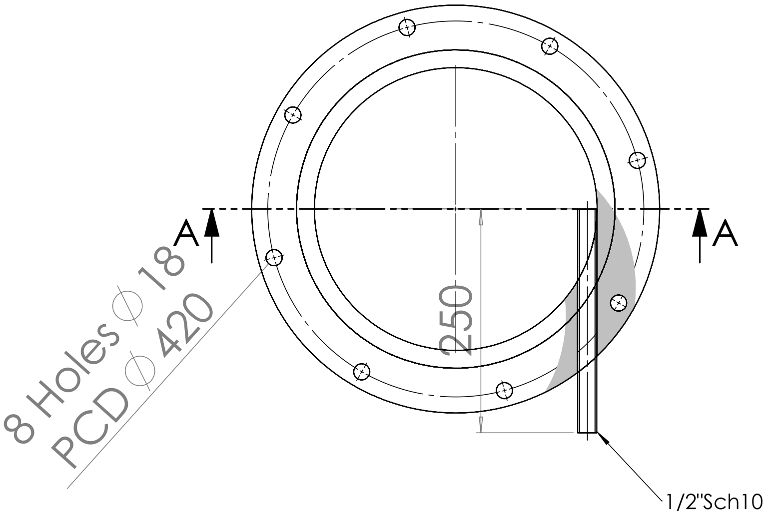

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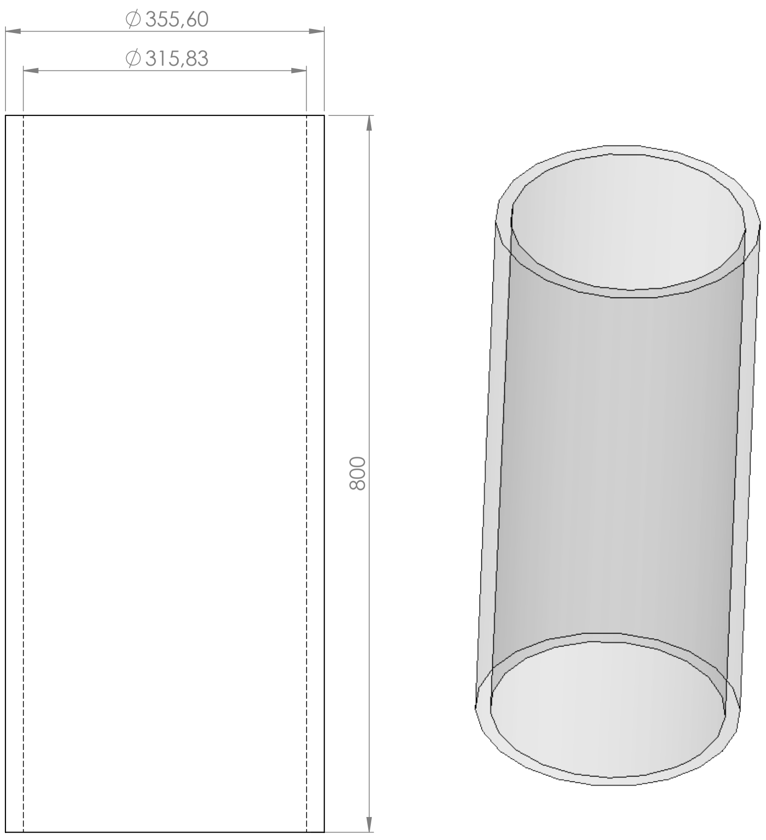
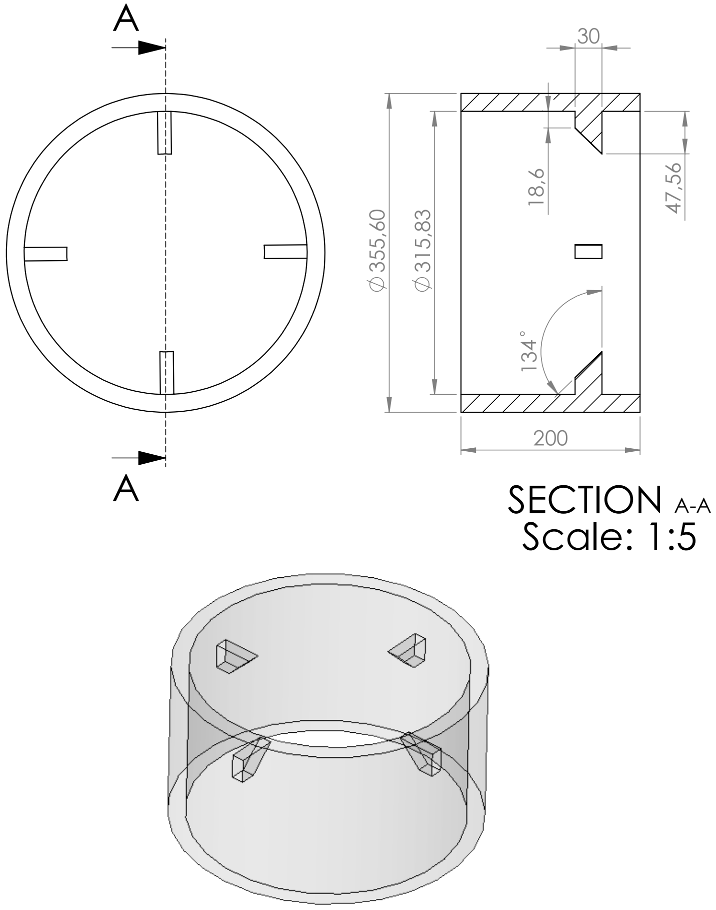
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Daniel Hjørnevik		25.05			CFU vessel	
CHK'D	Sindre Fotland		27.05				
APPV'D							
MFG							
Q.A				MATERIAL: 316L SS		DWG NO. Metalbelt Rev. 3	A3
				WEIGHT:		SCALE:1:10	SHEET 1 OF 1





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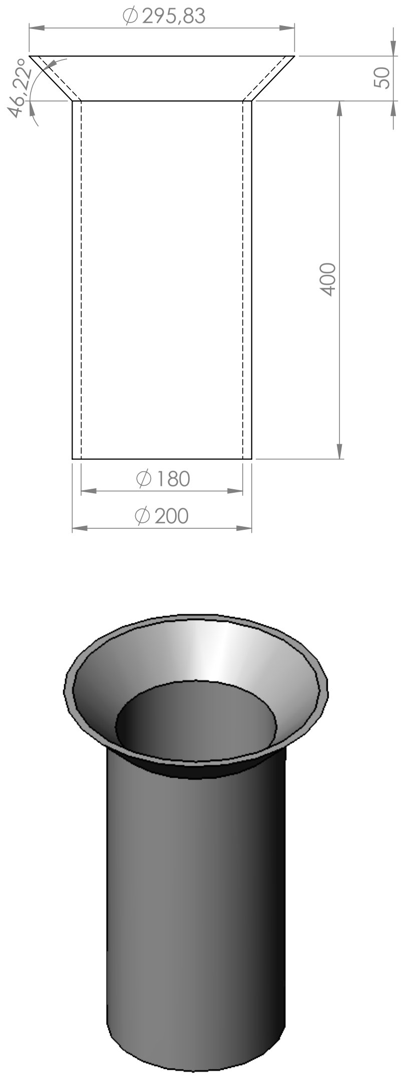
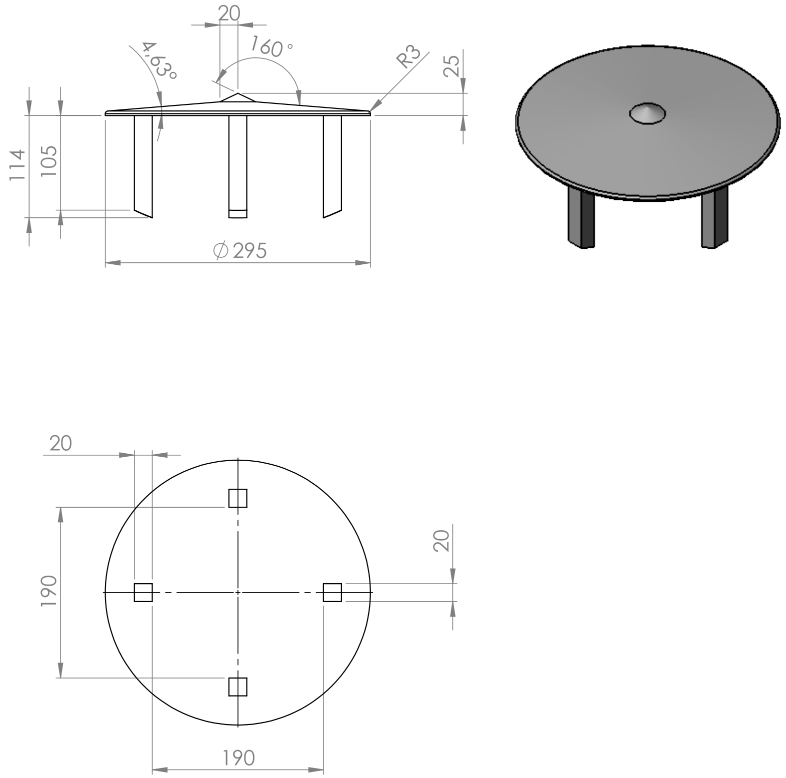
DRAWN	Sindre Fotland		20.05.		
CHK'D	Daniel Hjørnevik		20.05.		
APPV'D					
MFG					
Q.A			MATERIAL: Transparent PVC	DWG NO. UpperMain, LowerMain	A3
			WEIGHT:	SCALE:1:5	SHEET 1 OF 1





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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sindre Fotland		19.05.
CHK'D	Daniel Hjørnevik		19.05.
APPV'D			
MFG			
Q.A			

TITLE:

CFU vessel

MATERIAL:
IC: Transparent PVC
VB: 316L SS

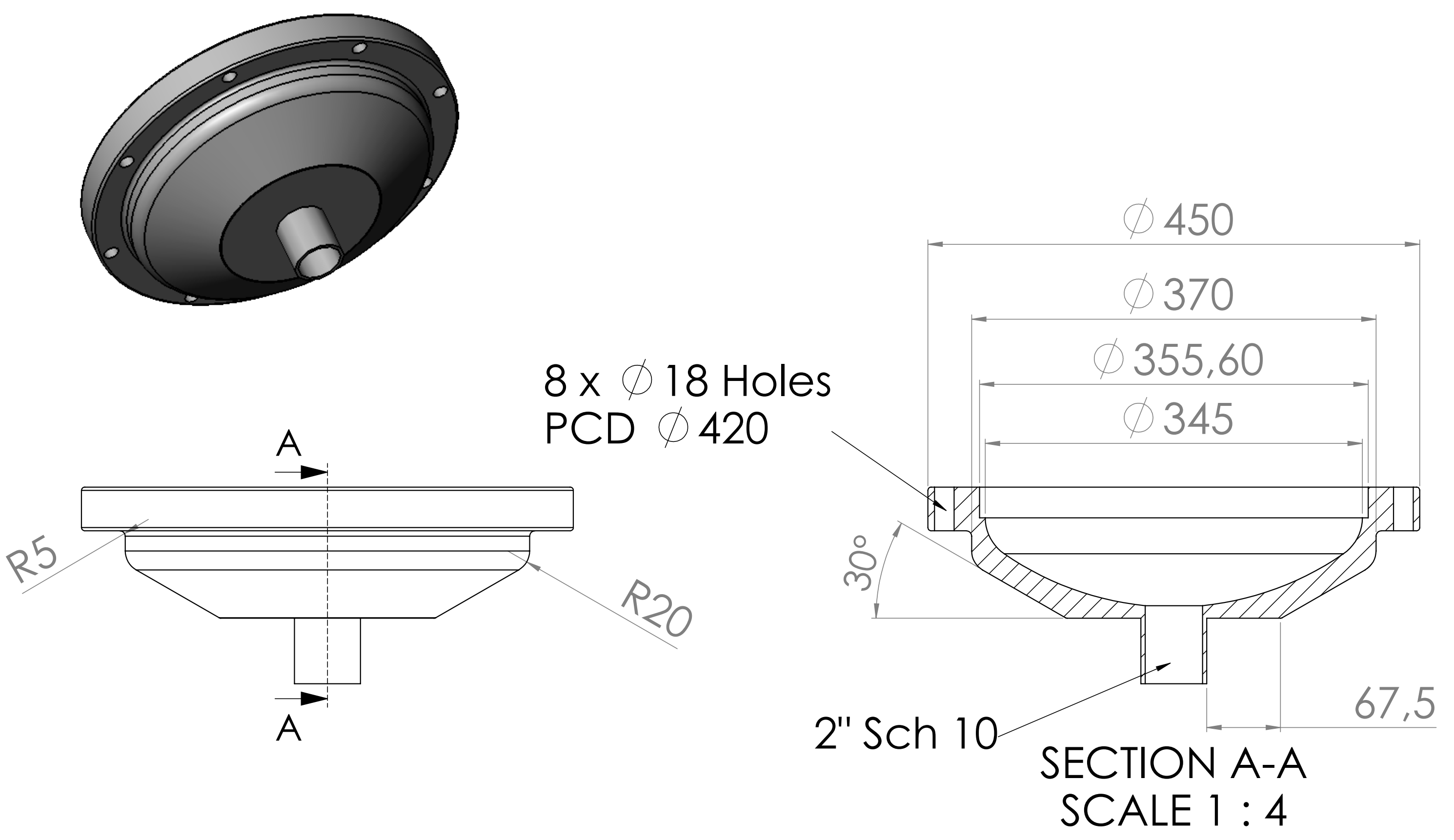
WEIGHT:

DWG NO.
InnerCylinder,
VortexBreaker

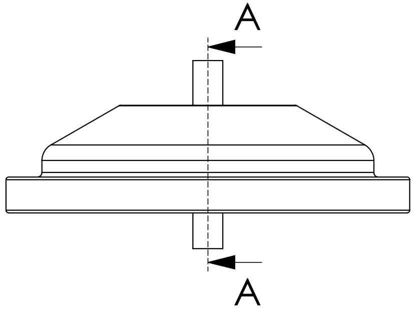
A3

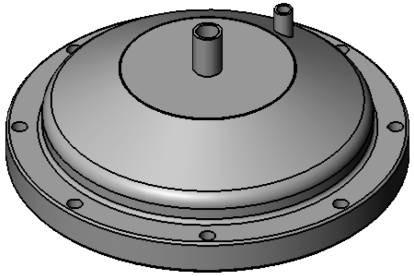
SCALE:1:5

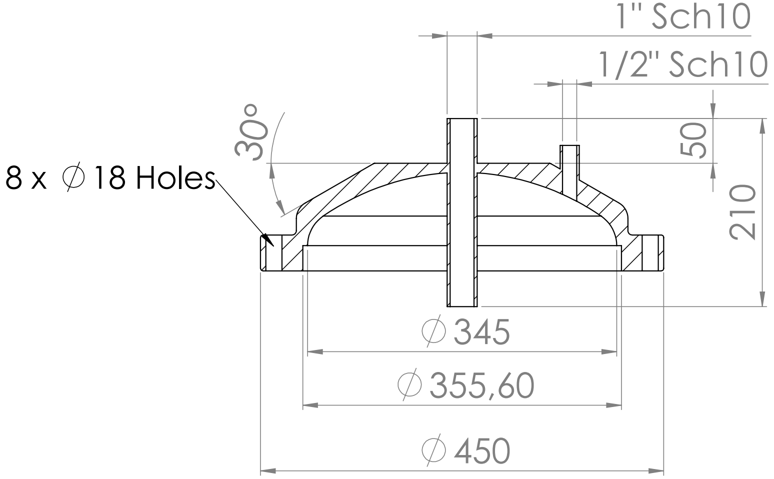
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Sindre Fotland		12.05.	CFU vessel	
CHK'D	Daniel Hjørnevik		12.05.		
APPV'D					
MFG					
Q.A			MATERIAL: 316 L SS	DWG NO. PVH_bottom	A3
			WEIGHT:	SCALE: 1:4	SHEET 1 OF 1







SECTION A-A
SCALE 1 : 5

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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sindre Fotland		20.05.
CHK'D	Daniel Hjørnevik		20.05.
APPV'D			
MFG			
Q.A			

TITLE: CFU vessel

MATERIAL: 316L SS

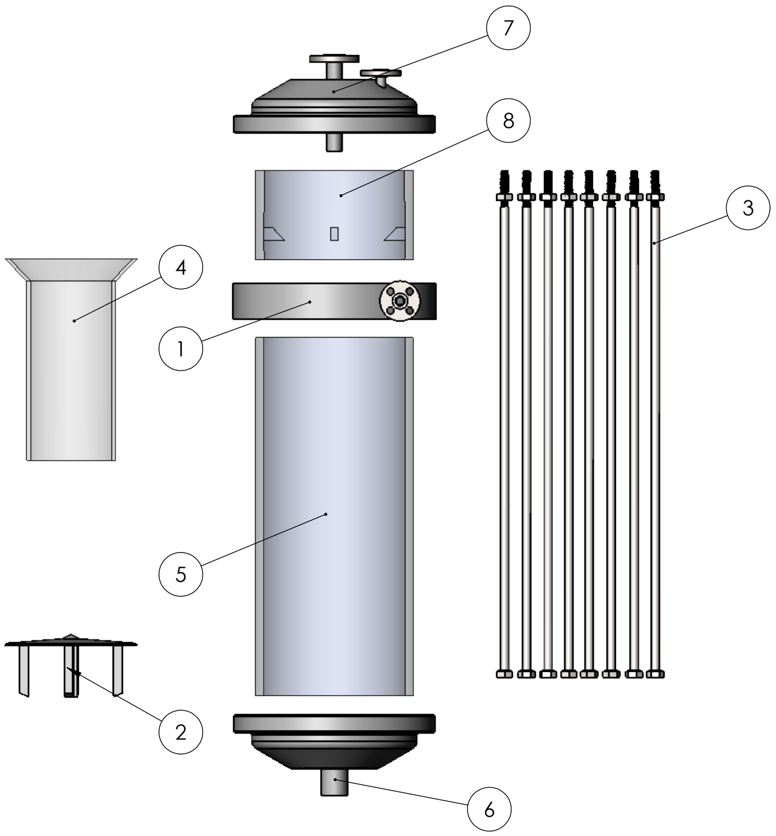
DWG NO. PVH top

A3

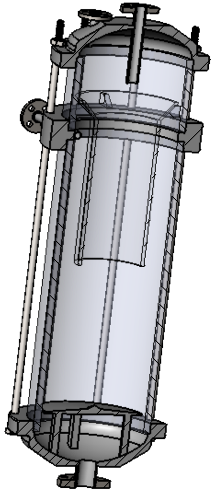
WEIGHT:

SCALE: 1:5

SHEET 1 OF 1



Item no.	PART NUMBER	DESCRIPTION	QTY.
1	MetalBelt	Metal belt for inserting tangential inlet pipe	1
2	VortexBreaker	Vortex breaker with support legs	1
3	CFUTension	Cfu tension rod with boltet connections, 316 L SS	8
4	InnerCylinder	Inner cylinder	1
5	LowerMain	Lower part of main cylinder	1
6	PVH bottom	Bottom pressure vessel head	1
7	PVH top	Top pressure vessel head	1
8	Uppermain	Upper part of main cylinder	1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sindre Fotland		26.05.
CHK'D	Daniel Hjørnevik		26.05.
APPV'D			
MFG			
Q.A			

MATERIAL:
Specified in part drawings

WEIGHT:

TITLE:
CFU vessel

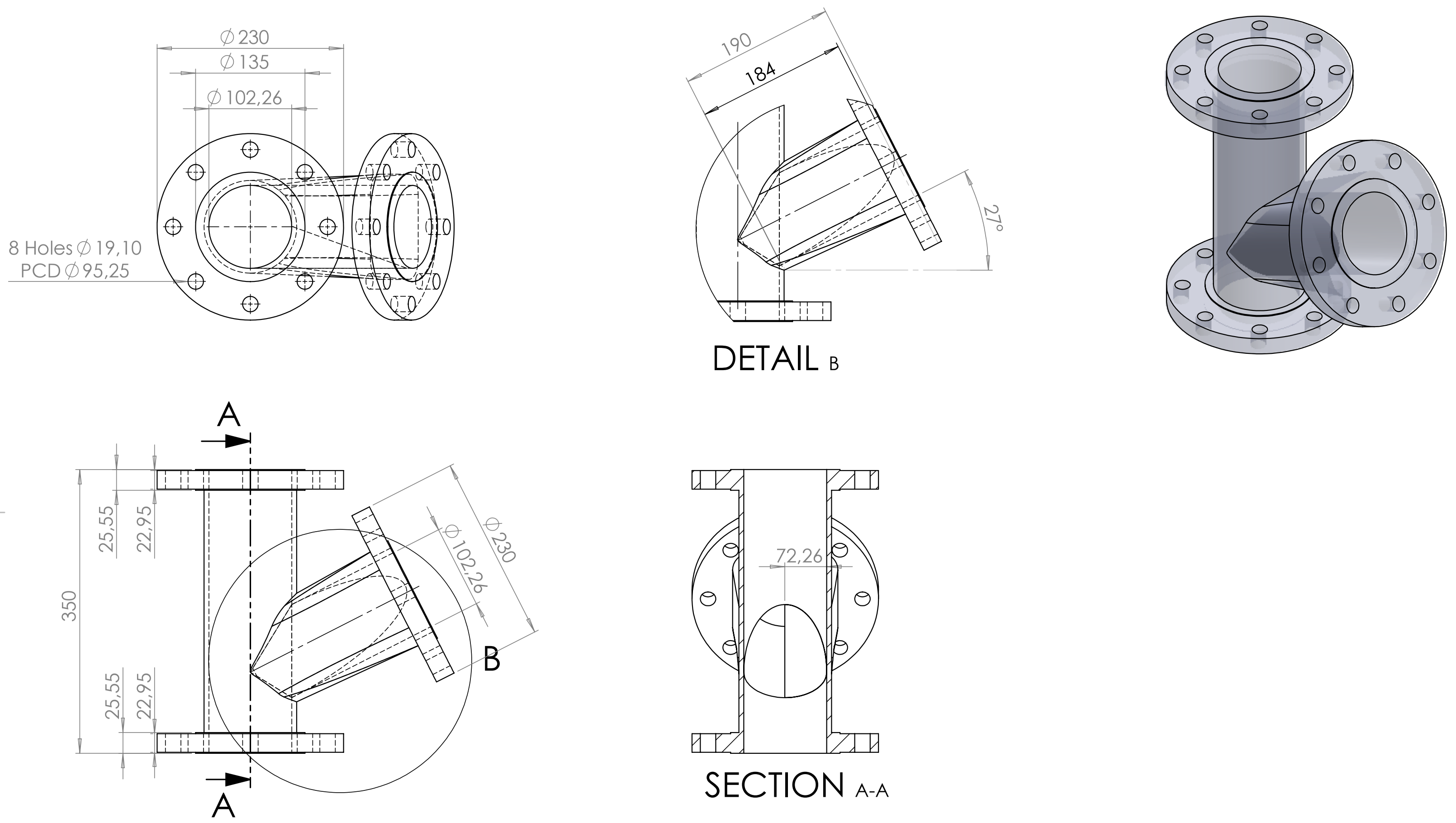
DWG NO.
CFUasm

A3

SCALE:1:20

SHEET 1 OF 1

D: GLCC Construction Drawings



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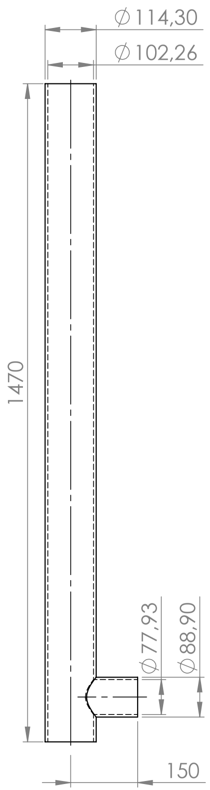
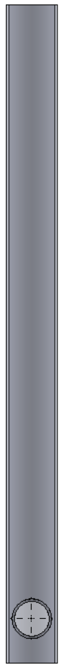
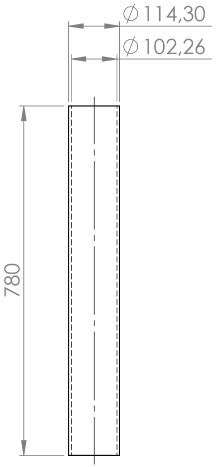
	NAME	SIGNATURE	DATE		REVISION
DRAWN	Daniel Hjørnevik		26.05.17		TITLE: GLCC vessel
CHK'D	Sindre Fotland		26.05.17		
APPV'D					
MFG					
Q.A				MATERIAL: Transparent PVC	DWG NO. Inlet-main pipe A3
				WEIGHT:	SCALE:1:5 SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Daniel Hjørnevik		19.03.
CHK'D	Sindre Fotland		21.03
APPV'D			
MFG			
Q.A			

TITLE:
GLCC vessel

MATERIAL:
Transparent PVC

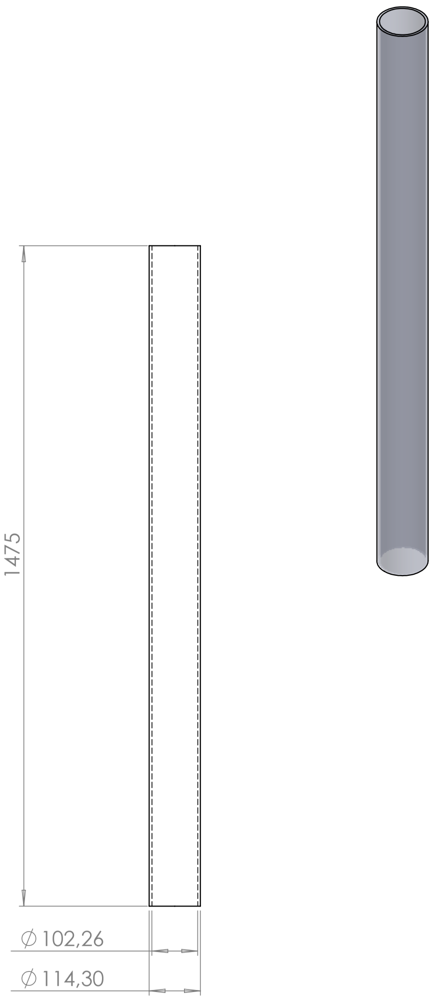
DWG NO.
GLCCbottom | GLCCtop

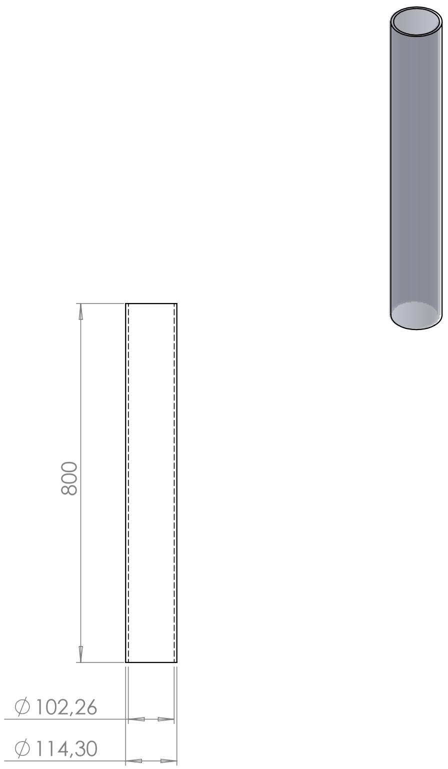
A3

WEIGHT:

SCALE:1:20

SHEET 1 OF 1





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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Daniel Hjørnevik		26.05.17
CHK'D	Sindre Fotland		26.05.17
APPV'D			
MFG			
Q.A			

TITLE:

GLCC vessel

MATERIAL:
Transparent PVC

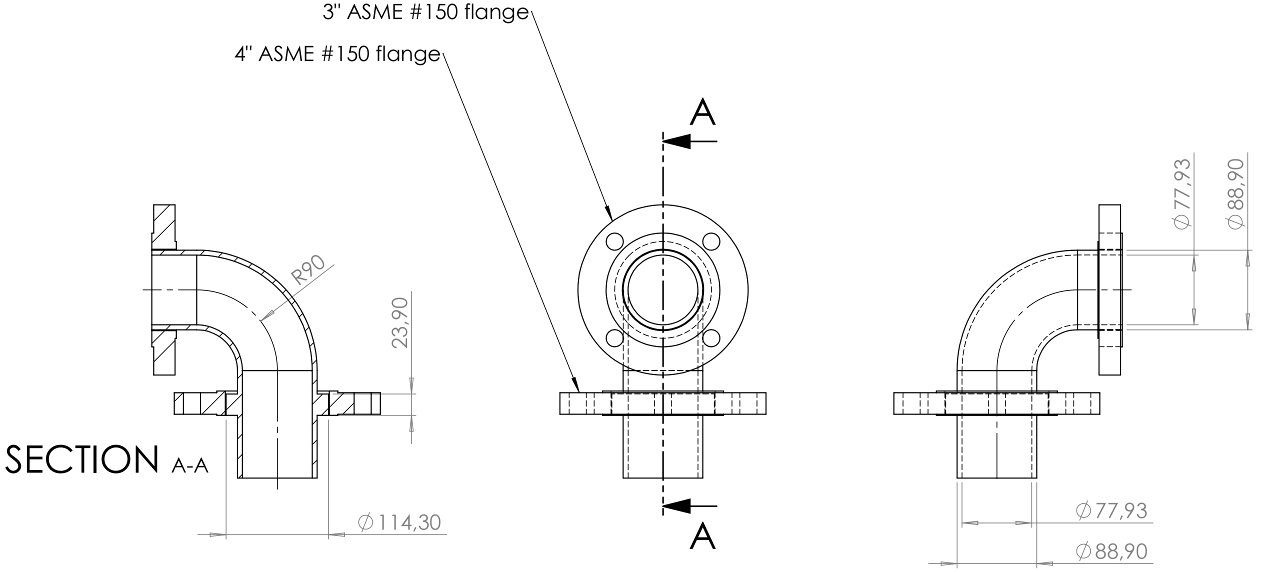
DWG NO.
CFC pipe | inlet pipe

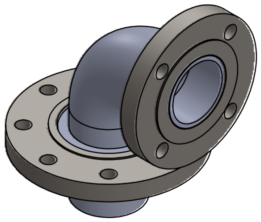
A3

WEIGHT:

SCALE:1:10

SHEET 1 OF 1





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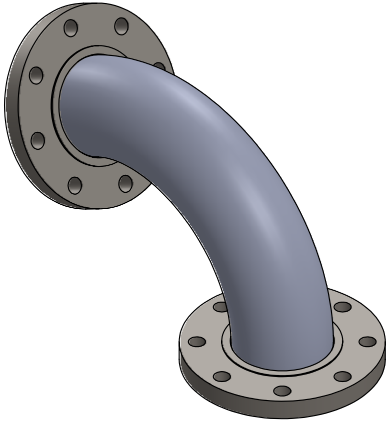
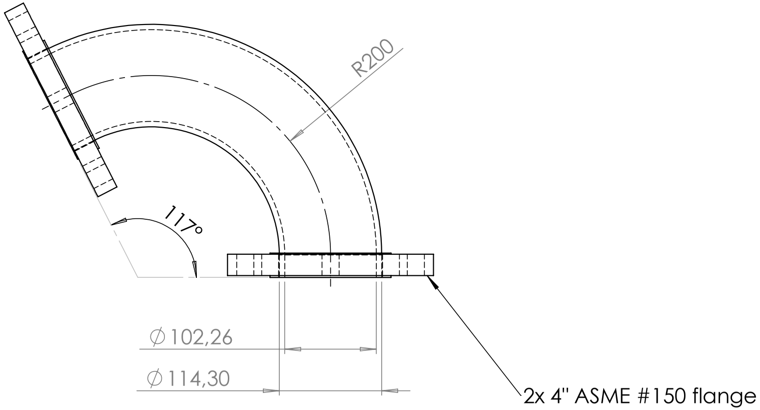
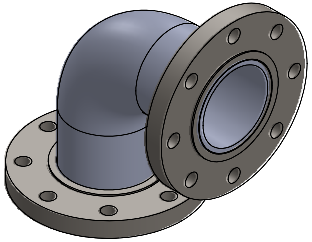
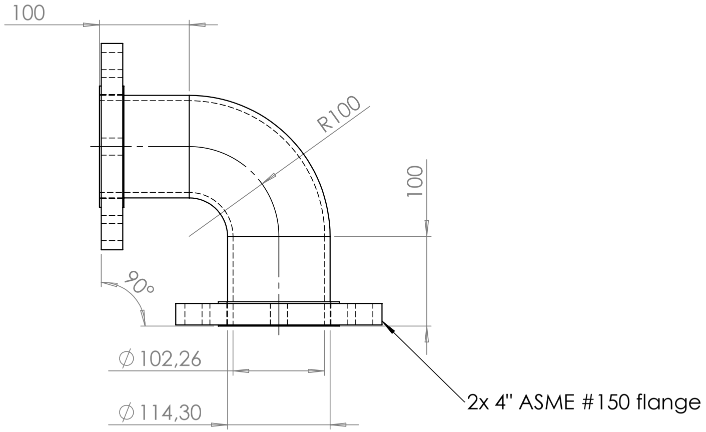
	NAME	SIGNATURE	DATE			TITLE: GLCC vessel	
DRAWN	Daniel Hjørnevik		26.05.17				
CHK'D	Sindre Fotland		26.05.17				
APPV'D							
MFG							
Q.A				MATERIAL: 316L SS		DWG NO. Top cap	A3
				WEIGHT:		SCALE:1:5	SHEET 1 OF 1

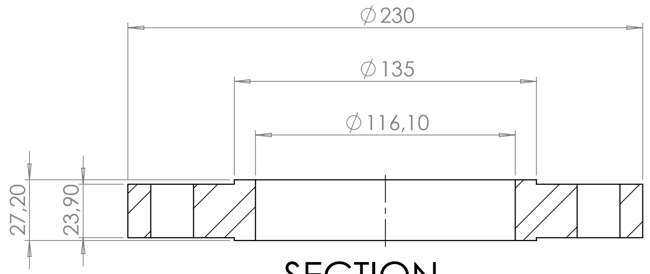




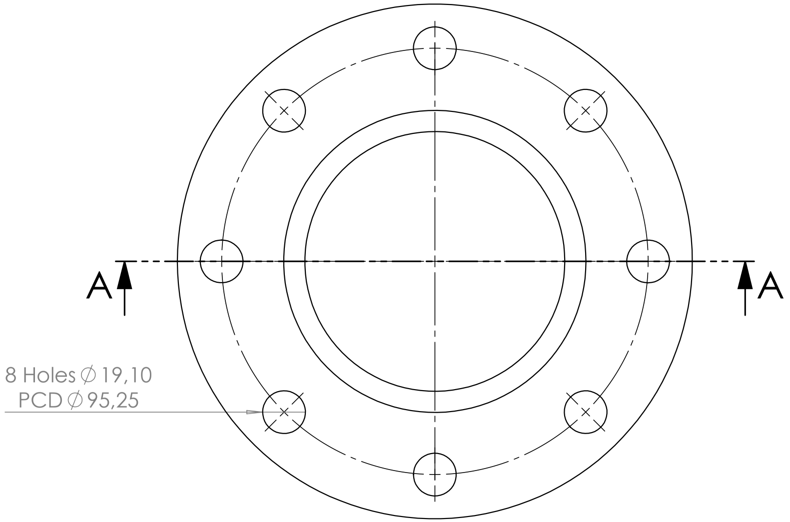


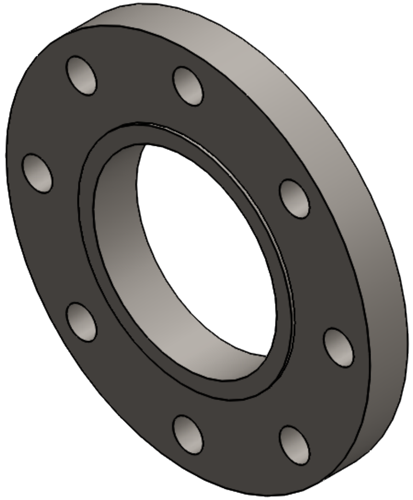


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:	GLCC vessel
DRAWN	Daniel Hjørnevik		26.05.17		
CHK'D	Sindre Fotland		26.05.17		
APPV'D					
MFG					
Q.A			MATERIAL: 316L SS	DWG NO. CFC-inlet bend | CFC bend	A3
			WEIGHT:	SCALE:1:5	SHEET 1 OF 1



SECTION A-A





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Daniel Hjørnevik		26.05.17
CHK'D	Sindre Fotland		26.05.17
APPV'D			
MFG			
Q.A			

TITLE:
GLCC vessel

MATERIAL:
Transparent PVC

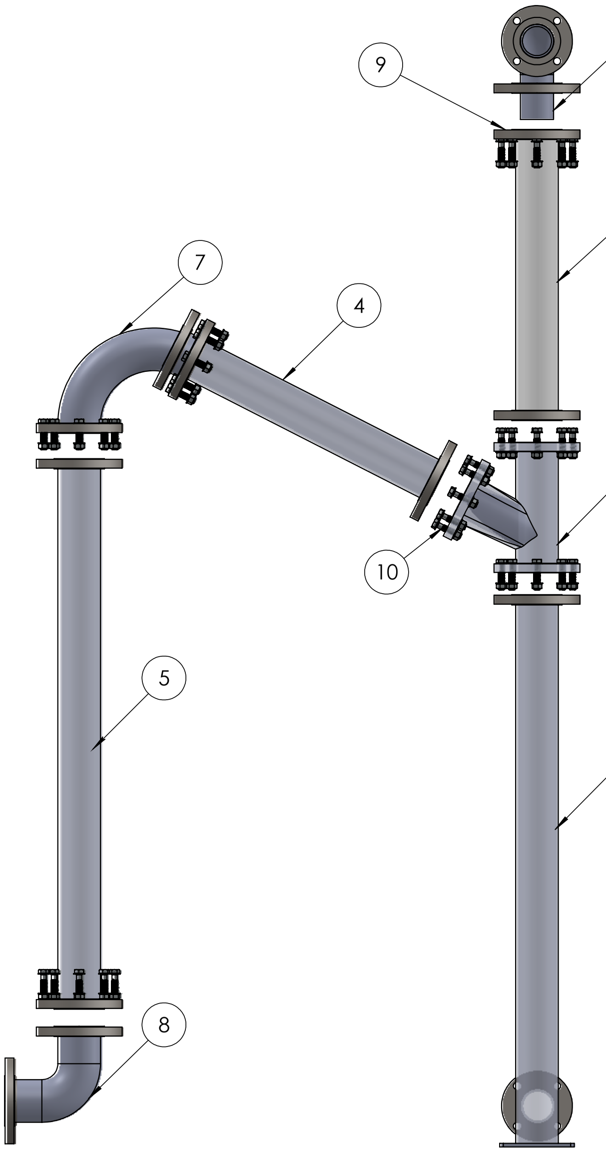
DWG NO.
4" ASME#150 flange

A3

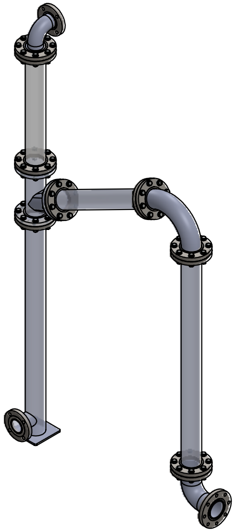
WEIGHT:

SCALE:1:2

SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Inlet-main pipe	Main section with inlet and diverter plate	1
2	Bottom main pipe	Bottom main pipe with liquid outlet	1
3	Top main pipe	Top main pipe	1
4	Inlet pipe	Declined inlet pipe	1
5	CFC pipe	CFC pipe for pre-separation	1
6	Top cap	Top cap with submerged pipe	1
7	CFC - inlet bend	Pipe bend for CFC - inlet	1
8	CFC bend	Pipe bend for CFC	1
9	4" flange	4" ASME #150 flange	7
10	M20 bolt	M20 bolt, 1.2 mm washer and nut for assembly	56



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Daniel Hjørnevik		20.03
CHK'D	Sindre Fotland		21.03.
APPV'D			
MFG			
Q.A			

TITLE:

GLCC vessel

MATERIAL:

Specified in part drawings

DWG NO.

GLCC asm

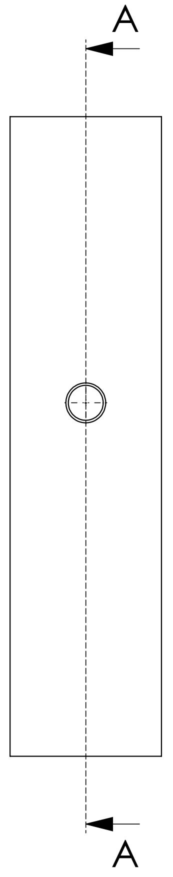
A3

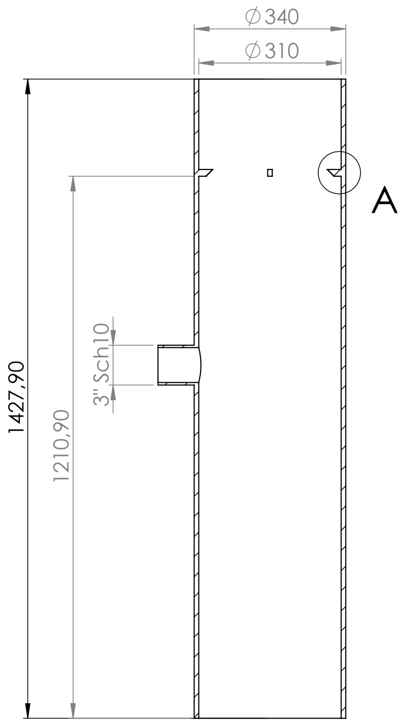
WEIGHT:

SCALE:1:10

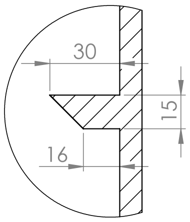
SHEET 1 OF 1

E. Scrubber Construction Drawings

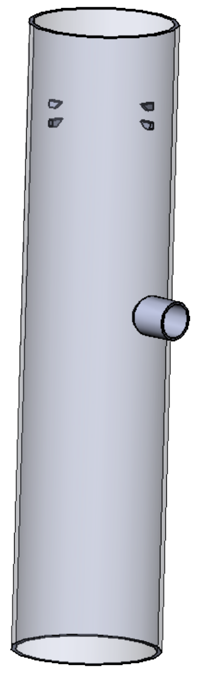




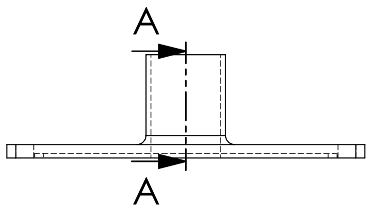
SECTION A-A
SCALE 1 : 10

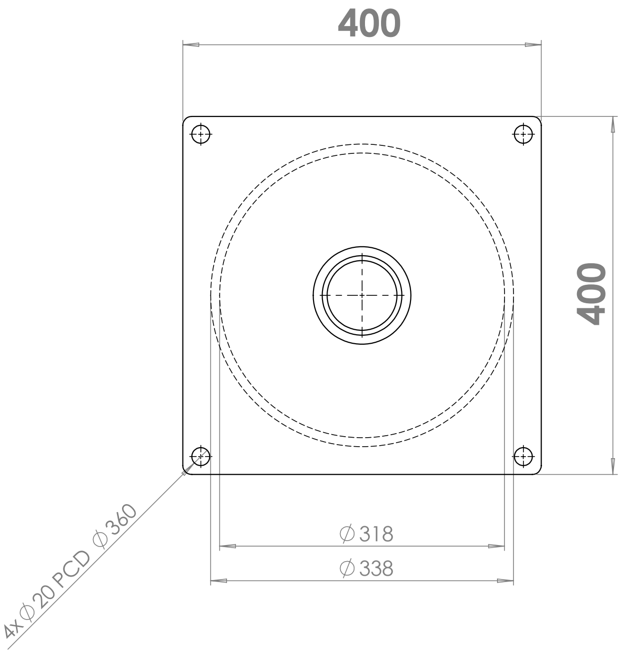


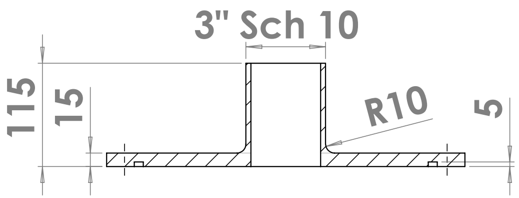
DETAIL A
SCALE 1 : 2

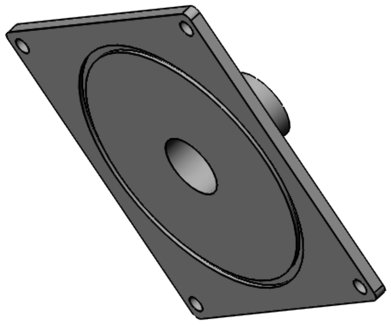


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Scrubber vessel	
DRAWN	Sindre Fotland		22.04.				
CHK'D	Daniel Hjørnevik		22.04.				
APPV'D							
MFG							
Q.A				MATERIAL: Transparent Acryl		DWG NO. MainCylinder	A3
				WEIGHT:		SCALE:1:10	SHEET 1 OF 1









UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sindre Fotland		25.04.
CHK'D	Daniel Hjørnevik		25.04.
APPV'D			
MFG			
Q.A			

TITLE:
Scrubber vessel

MATERIAL:
EN 6028 Aluminium

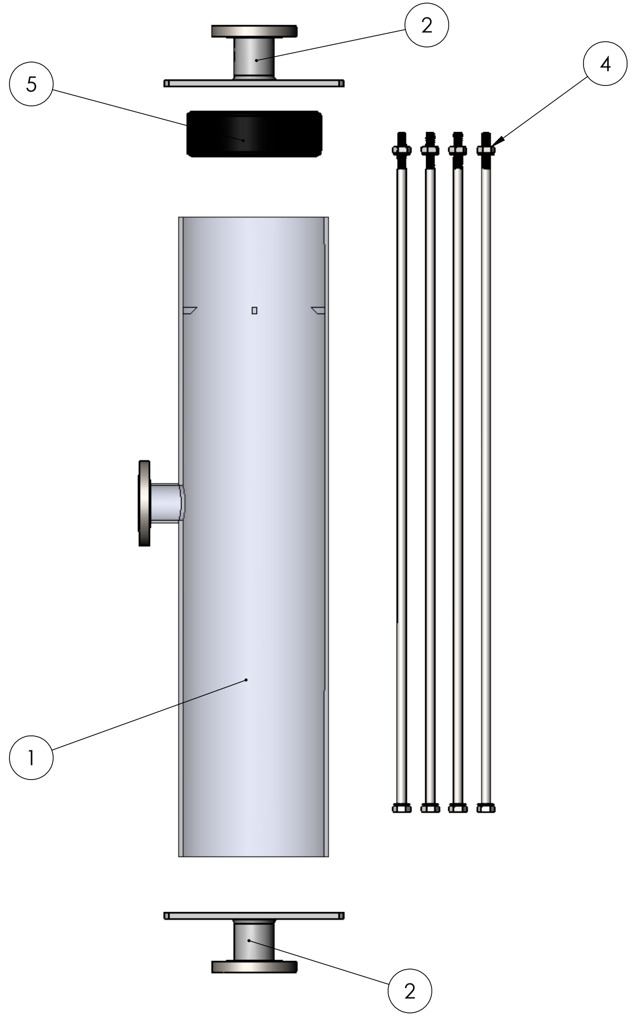
DWG NO.
CoverPlate

A3

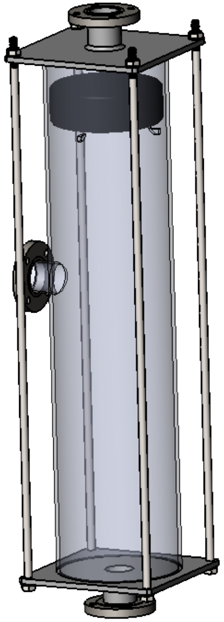
WEIGHT:

SCALE:1:5

SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	MainCylinder	Main cylinder with inlet pipe and ribs for mesh pad implementation	1
2	CoverPlate	Plates with flanged connection at outlet pipe	2
3	Meshpad	Mesh Pad	1
4	Scrubber tension rod	Tension rods with bolted connections, 316L SS	4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sindre Fotland		26.04.
CHK'D	Daniel Hjørnevik		26.04.
APPV'D			
MFG			
Q.A			

TITLE:
Scrubber Vessel

MATERIAL:
See component drawings

WEIGHT:

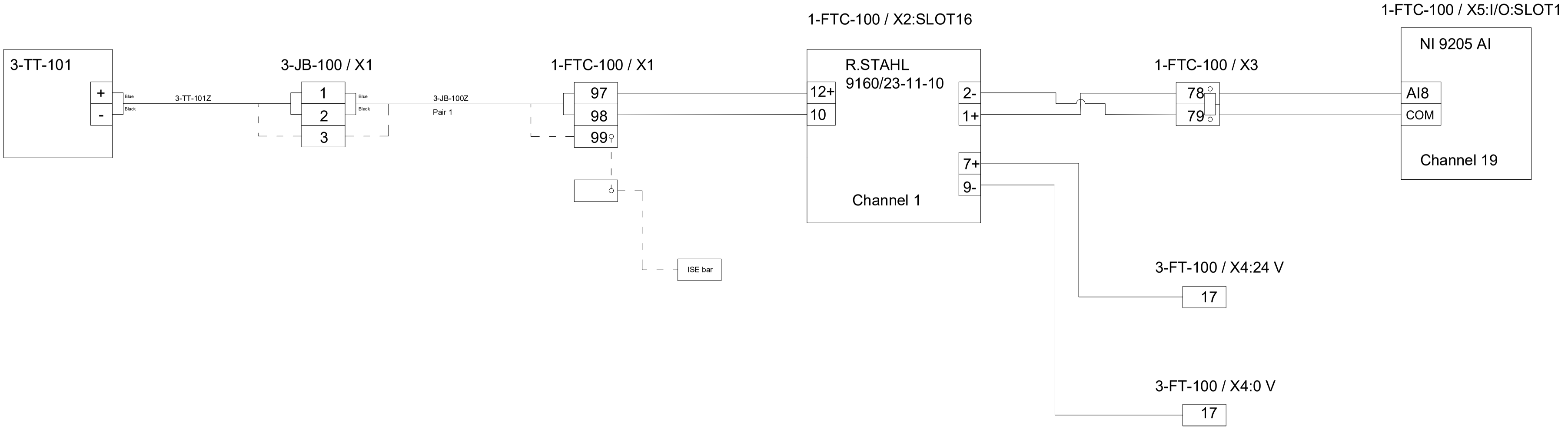
DWG NO.
Scrubberasm

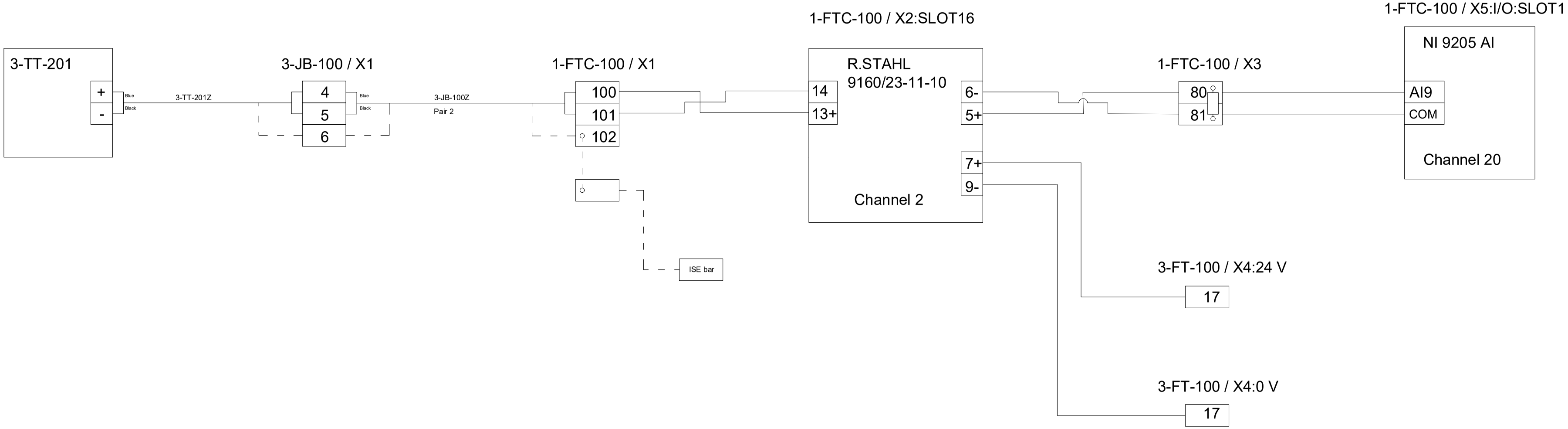
A3

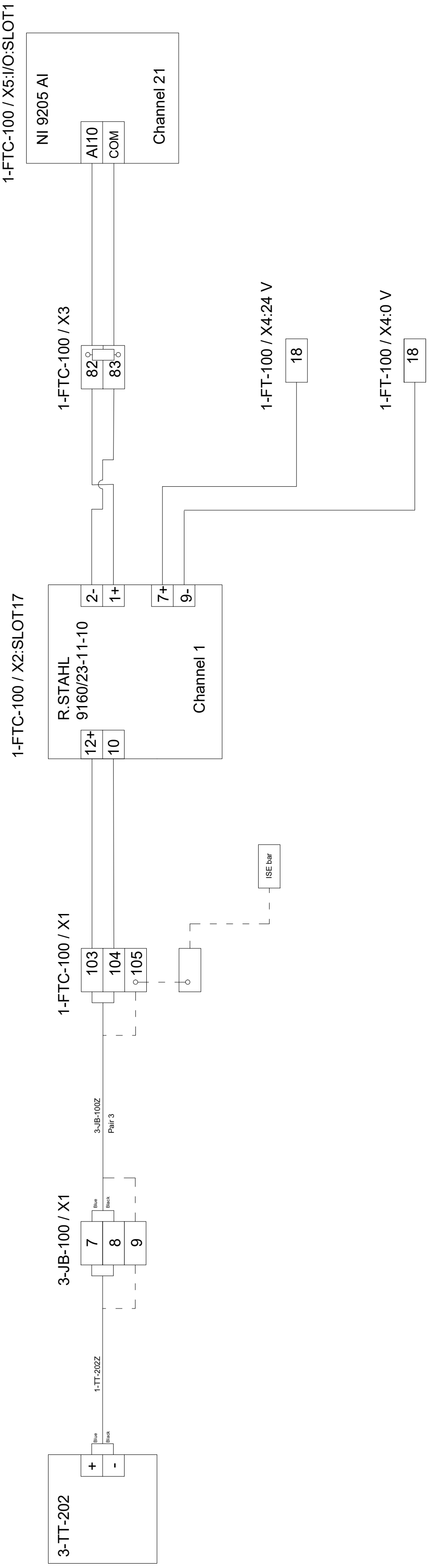
SCALE:1:10

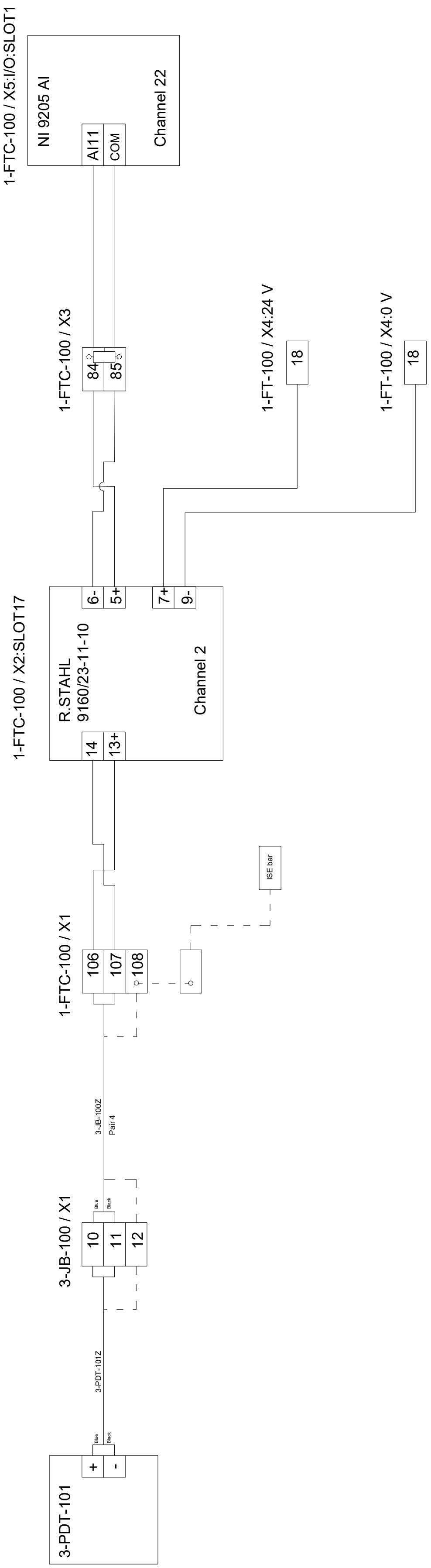
SHEET 1 OF 1

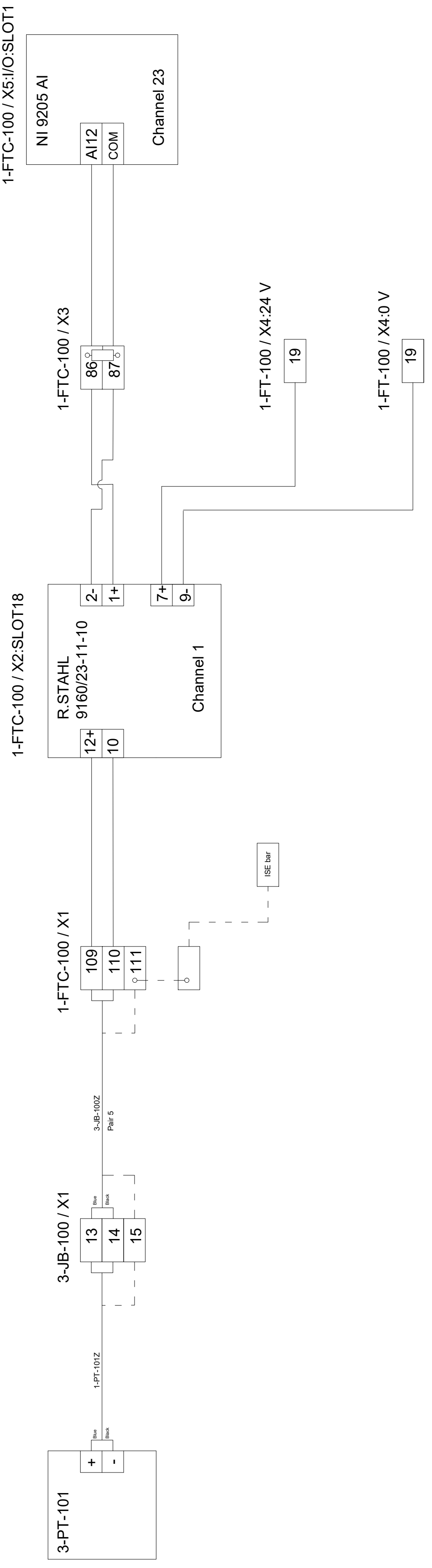
F. Electrical Loop Diagrams

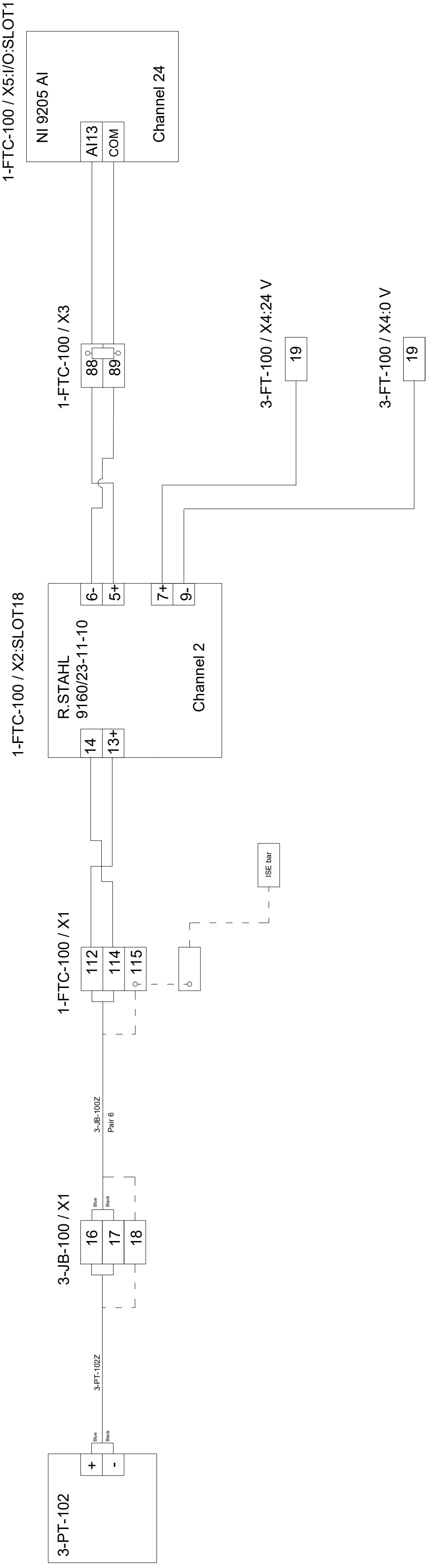

3-TT-101
+
-
Blue
Black
3-TT-101Z
3-JB-100 / X1
1
2
3
Blue
Black
3-JB-100Z
Pair 1
1-FTC-100 / X1
97
98
99
ISE bar
1-FTC-100 / X2:SLOT16
R.STAHL
9160/23-11-10
12+
10
2-
1+
7+
9-
Channel 1
1-FTC-100 / X3
78
79
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI8
COM
Channel 19
3-FT-100 / X4:24 V
17
3-FT-100 / X4:0 V
17

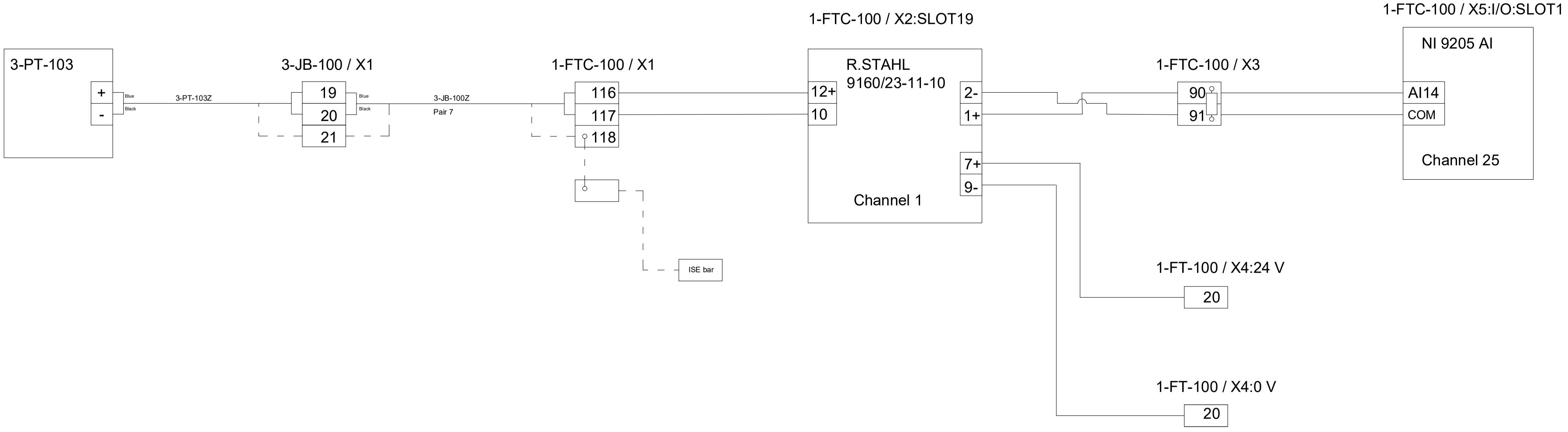

3-TT-201
+
-
Blue
Black
3-TT-201Z
3-JB-100 / X1
4
5
6
Blue
Black
3-JB-100Z
Pair 2
1-FTC-100 / X1
100
101
102
ISE bar
1-FTC-100 / X2:SLOT16
R.STAHL
9160/23-11-10
14
13+
6-
5+
7+
9-
Channel 2
1-FTC-100 / X3
80
81
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI9
COM
Channel 20
3-FT-100 / X4:24 V
17
3-FT-100 / X4:0 V
17

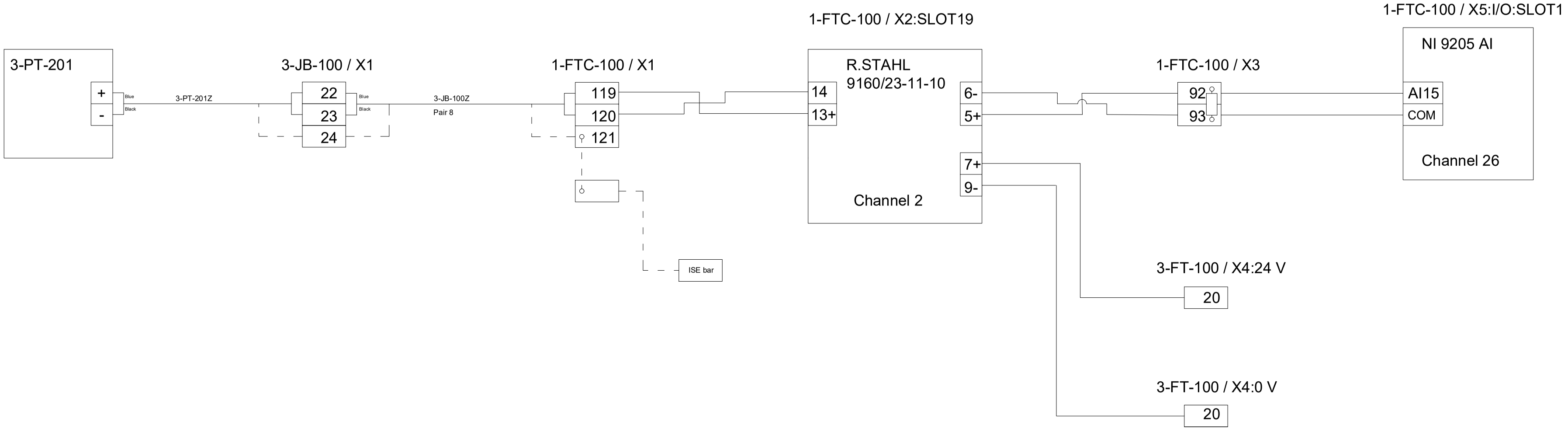

1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI10
COM
Channel 21
1-FTC-100 / X3
82
83
1-FT-100 / X4:24 V
18
1-FT-100 / X4:0 V
18
1-FTC-100 / X2:SLOT17
R.STAHL
9160/23-11-10
Channel 1
2-
1+
7+
9-
12+
10
ISE bar
1-FTC-100 / X1
103
104
105
3-JB-100Z
Pair 3
3-JB-100 / X1
Blue
Black
7
8
9
1-TT-202Z
Blue
Black
+
-
3-TT-202

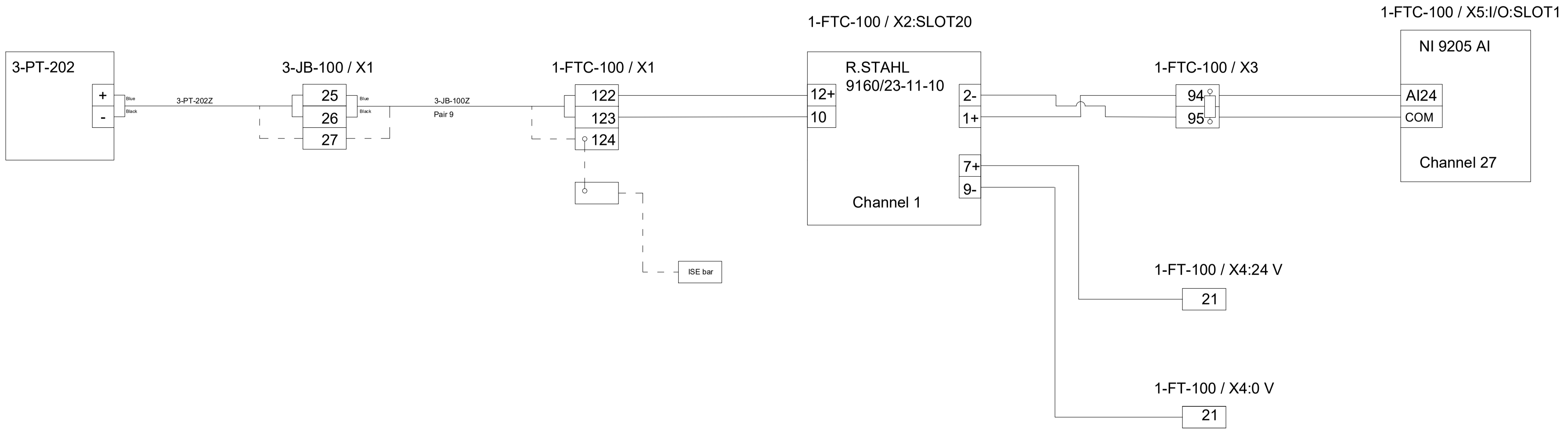

1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI11
COM
Channel 22
1-FTC-100 / X3
84
85
1-FT-100 / X4:24 V
18
1-FT-100 / X4:0 V
18
1-FTC-100 / X2:SLOT17
R.STAHL
9160/23-11-10
Channel 2
6-
5+
7+
9-
14
13+
ISE bar
1-FTC-100 / X1
106
107
108
3-JB-100Z
Pair 4
3-JB-100 / X1
Blue
Black
10
11
12
3-PDT-101Z
Blue
Black
+
-
3-PDT-101

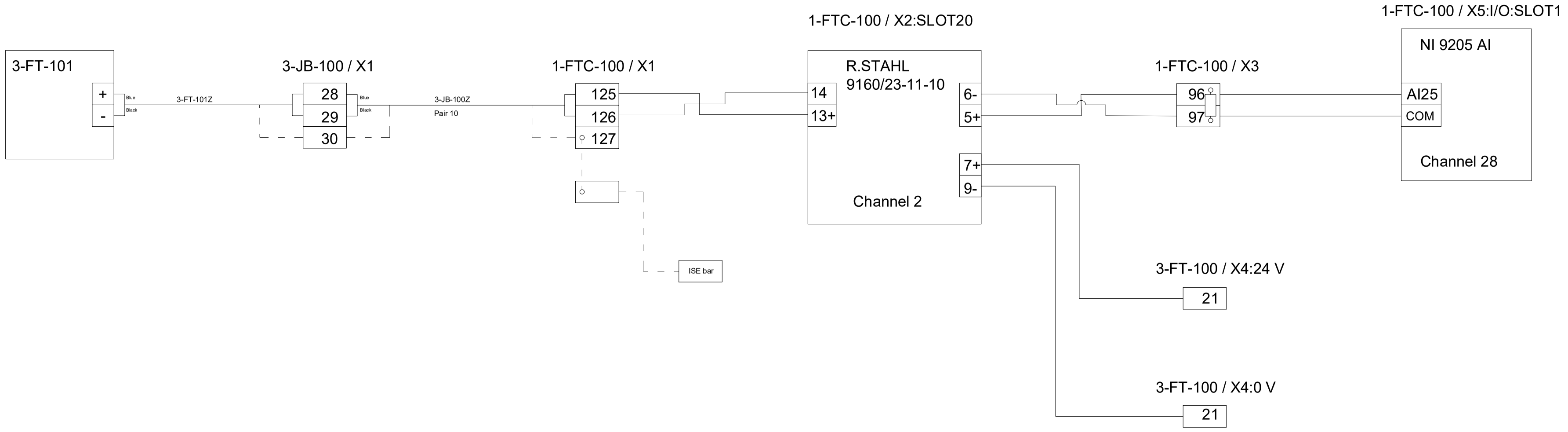

1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI12
COM
Channel 23
1-FTC-100 / X3
86
87
1-FT-100 / X4:24 V
19
1-FT-100 / X4:0 V
19
1-FTC-100 / X2:SLOT18
R.STAHL
9160/23-11-10
Channel 1
2-
1+
7+
9-
12+
10
ISE bar
1-FTC-100 / X1
109
110
111
3-JB-100Z
Pair 5
3-JB-100 / X1
Blue
Black
13
14
15
1-PT-101Z
Blue
Black
+
-
3-PT-101

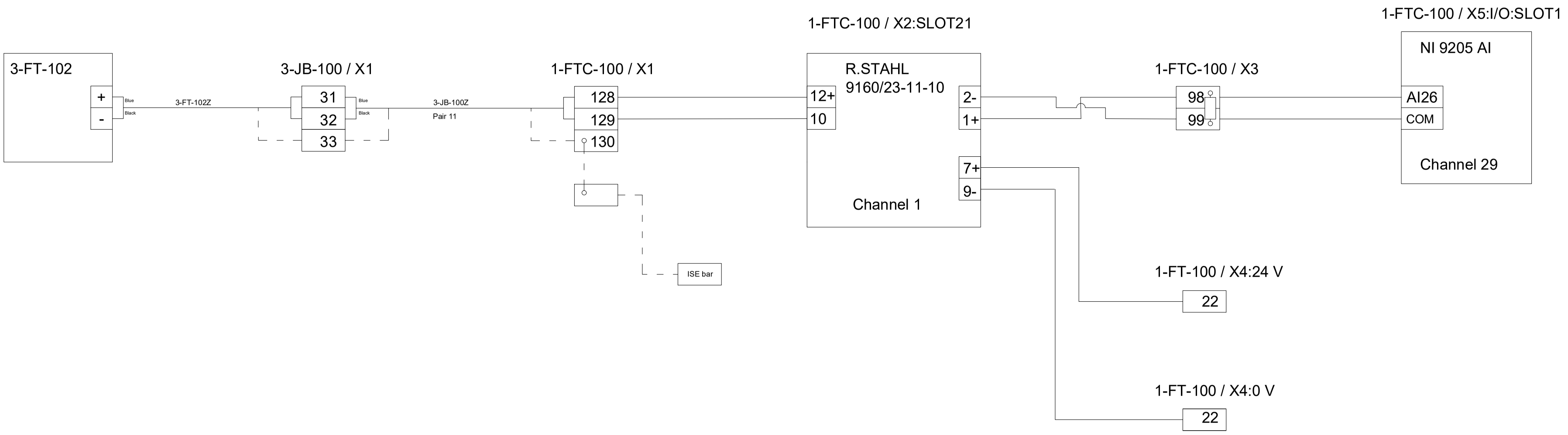

1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI13
COM
Channel 24
1-FTC-100 / X3
88
89
3-FT-100 / X4:24 V
19
3-FT-100 / X4:0 V
19
1-FTC-100 / X2:SLOT18
R.STAHL
9160/23-11-10
Channel 2
6-
5+
7+
9-
14
13+
ISE bar
1-FTC-100 / X1
112
114
115
3-JB-100Z
Pair 6
3-JB-100 / X1
Blue
Black
16
17
18
3-PT-102Z
Blue
Black
+
-
3-PT-102

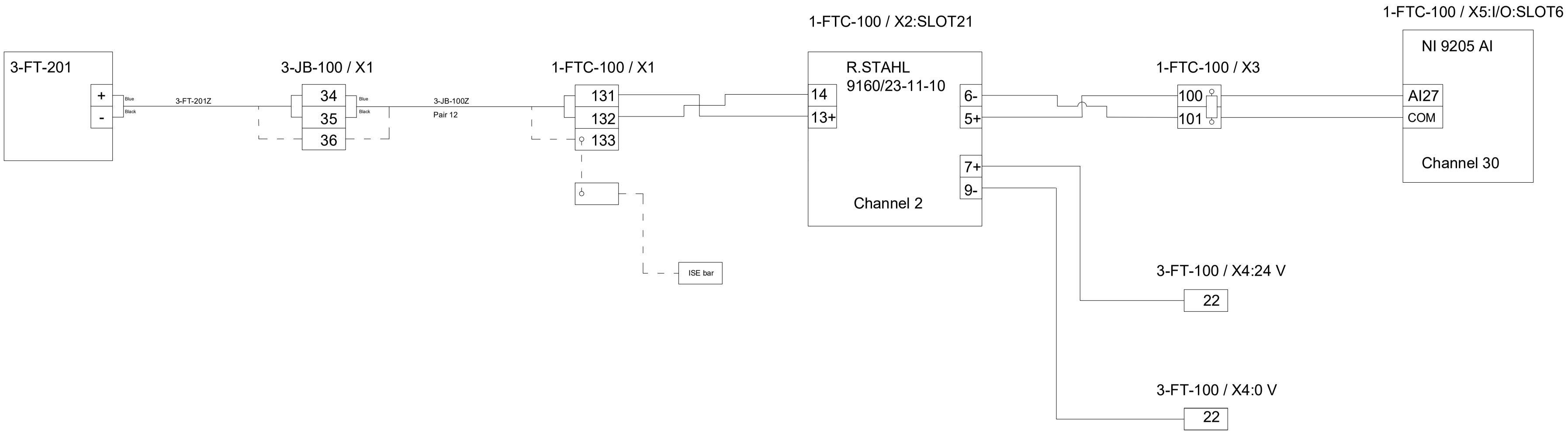

3-PT-103
+
-
Blue
Black
3-PT-103Z
3-JB-100 / X1
19
20
21
Blue
Black
3-JB-100Z
Pair 7
1-FTC-100 / X1
116
117
118
ISE bar
1-FTC-100 / X2:SLOT19
R.STAHL
9160/23-11-10
12+
10
2-
1+
7+
9-
Channel 1
1-FTC-100 / X3
90
91
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI14
COM
Channel 25
1-FT-100 / X4:24 V
20
1-FT-100 / X4:0 V
20

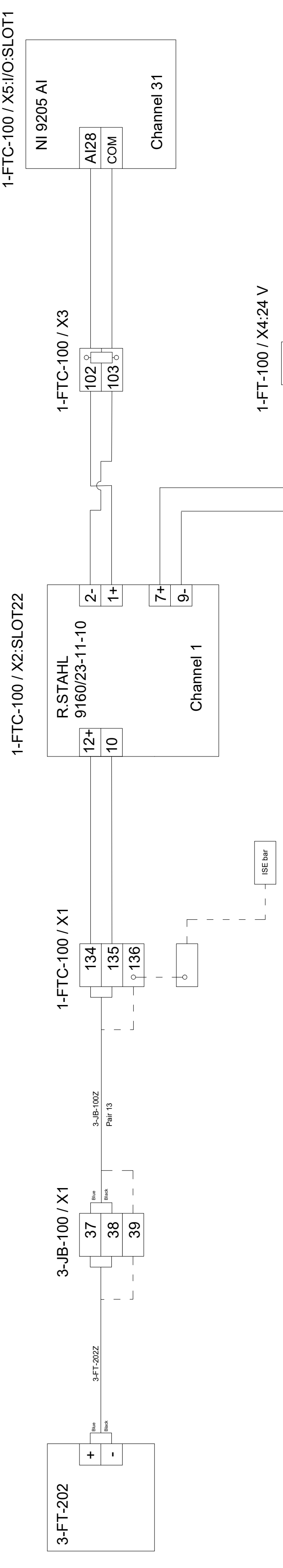

3-PT-201
+
-
Blue
Black
3-PT-201Z
3-JB-100 / X1
22
23
24
Blue
Black
3-JB-100Z
Pair 8
1-FTC-100 / X1
119
120
121
ISE bar
1-FTC-100 / X2:SLOT19
R.STAHL
9160/23-11-10
14
13+
6-
5+
7+
9-
Channel 2
1-FTC-100 / X3
92
93
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI15
COM
Channel 26
3-FT-100 / X4:24 V
20
3-FT-100 / X4:0 V
20

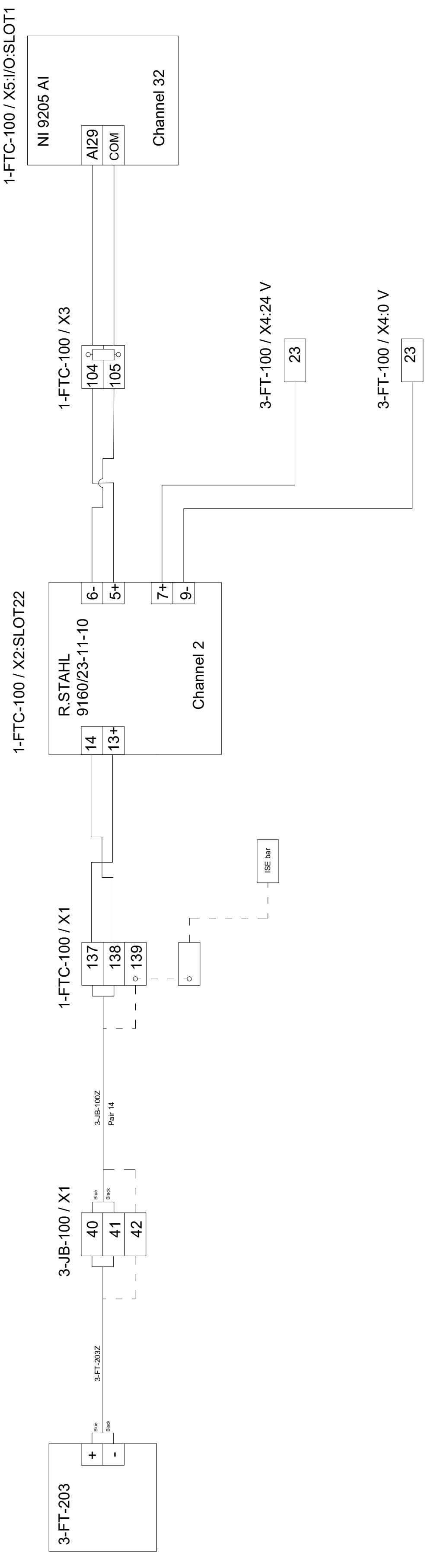

3-PT-202
+
-
Blue
Black
3-PT-202Z
3-JB-100 / X1
25
26
27
Blue
Black
3-JB-100Z
Pair 9
1-FTC-100 / X1
122
123
124
ISE bar
1-FTC-100 / X2:SLOT20
R.STAHL
9160/23-11-10
12+
10
2-
1+
7+
9-
Channel 1
1-FTC-100 / X3
94
95
1-FT-100 / X4:24 V
21
1-FT-100 / X4:0 V
21
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI24
COM
Channel 27

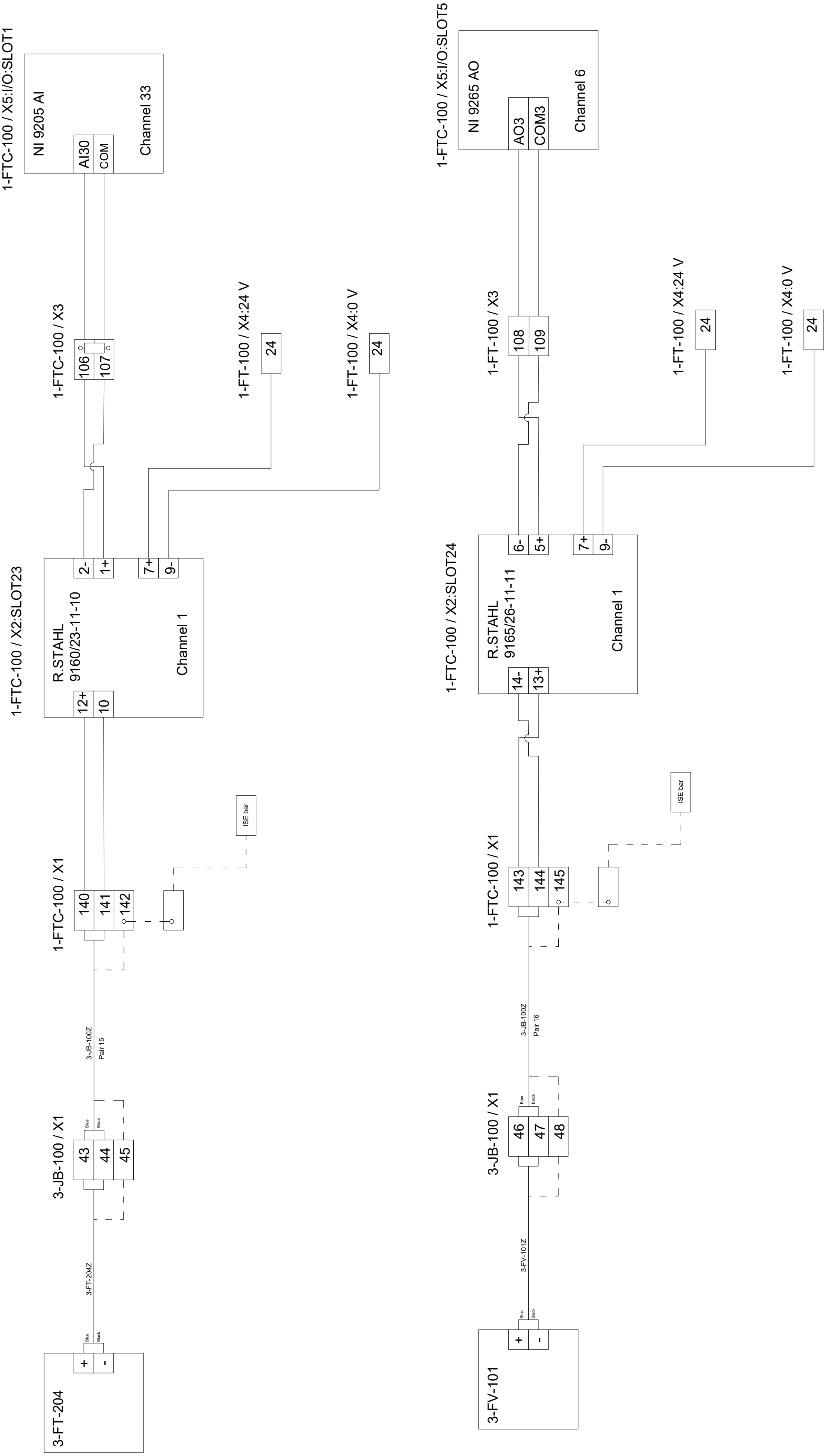

3-FT-101
+
-
Blue
Black
3-FT-101Z
3-JB-100 / X1
28
29
30
Blue
Black
3-JB-100Z
Pair 10
1-FTC-100 / X1
125
126
127
ISE bar
1-FTC-100 / X2:SLOT20
R.STAHL
9160/23-11-10
14
13+
6-
5+
7+
9-
Channel 2
1-FTC-100 / X3
96
97
3-FT-100 / X4:24 V
21
3-FT-100 / X4:0 V
21
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI25
COM
Channel 28

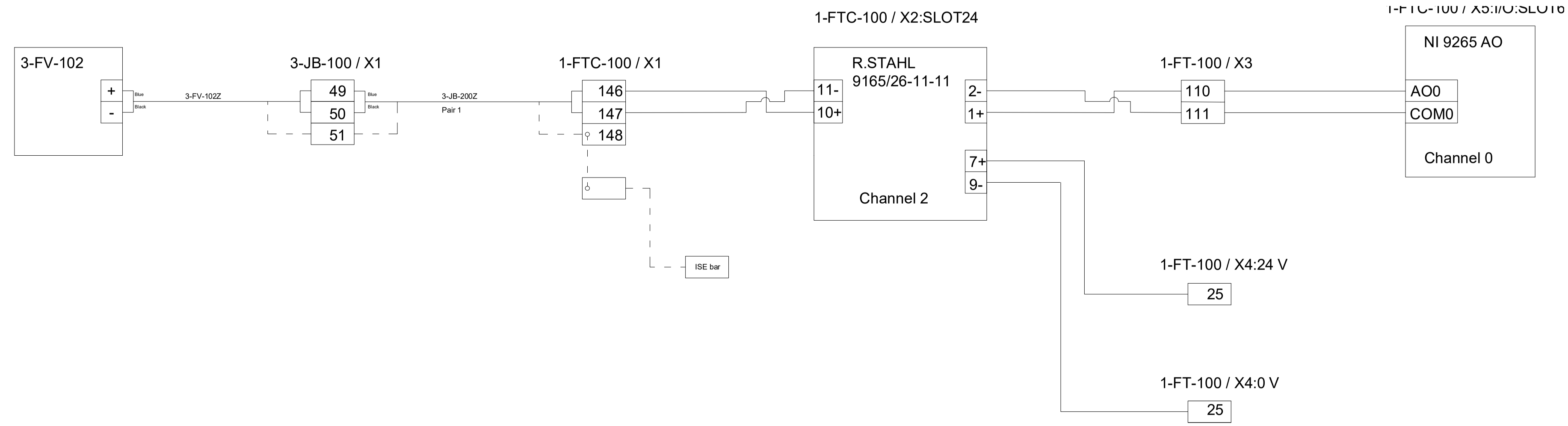

3-FT-102
+
-
Blue
Black
3-FT-102Z
3-JB-100 / X1
31
32
33
Blue
Black
3-JB-100Z
Pair 11
1-FTC-100 / X1
128
129
130
ISE bar
1-FTC-100 / X2:SLOT21
R.STAHL
9160/23-11-10
12+
10
2-
1+
7+
9-
Channel 1
1-FTC-100 / X3
98
99
1-FT-100 / X4:24 V
22
1-FT-100 / X4:0 V
22
1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI26
COM
Channel 29

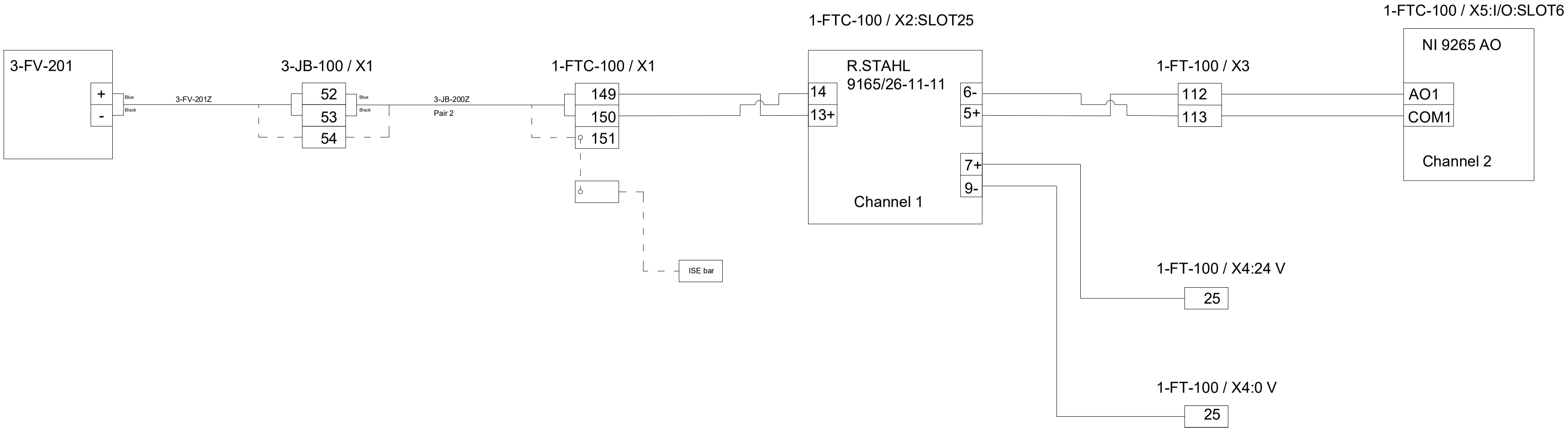

3-FT-201
+
-
Blue
Black
3-FT-201Z
3-JB-100 / X1
34
35
36
Blue
Black
3-JB-100Z
Pair 12
1-FTC-100 / X1
131
132
133
ISE bar
1-FTC-100 / X2:SLOT21
R.STAHL
9160/23-11-10
14
13+
6-
5+
7+
9-
Channel 2
1-FTC-100 / X3
100
101
3-FT-100 / X4:24 V
22
3-FT-100 / X4:0 V
22
1-FTC-100 / X5:I/O:SLOT6
NI 9205 AI
AI27
COM
Channel 30

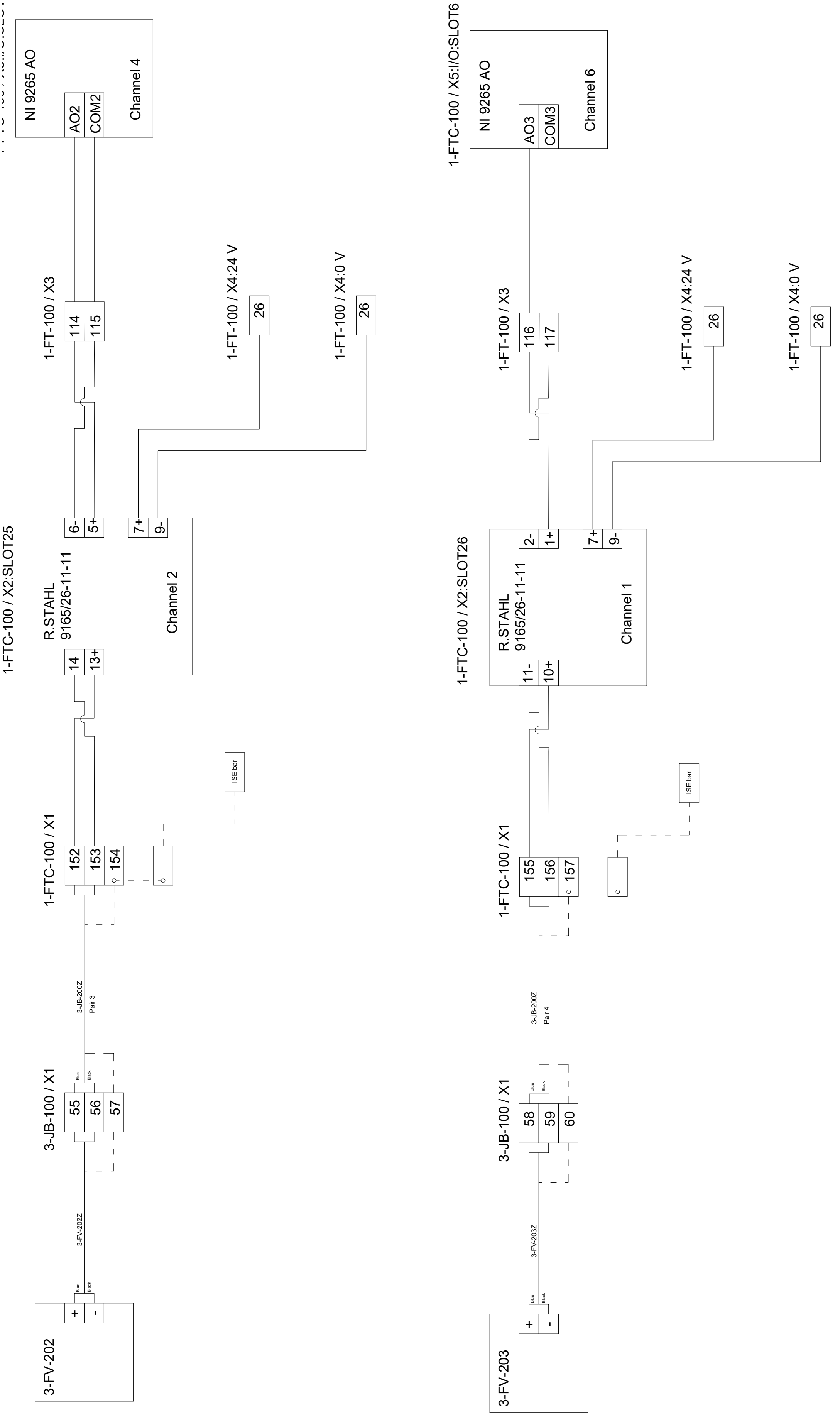

1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI28
COM
Channel 31
1-FTC-100 / X3
102
103
1-FT-100 / X4:24 V
23
1-FT-100 / X4:0 V
23
1-FTC-100 / X2:SLOT22
R.STAHL
9160/23-11-10
2-
1+
7+
9-
12+
10
Channel 1
ISE bar
1-FTC-100 / X1
134
135
136
3-JB-100Z
Pair 13
3-JB-100 / X1
Blue
Black
37
38
39
3-FT-202Z
Blue
Black
+
-
3-FT-202


1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI29
COM
Channel 32
1-FTC-100 / X3
104
105
3-FT-100 / X4:24 V
23
3-FT-100 / X4:0 V
23
1-FTC-100 / X2:SLOT22
R.STAHL
9160/23-11-10
6-
5+
7+
9-
14
13+
Channel 2
ISE bar
1-FTC-100 / X1
137
138
139
3-JB-100Z
Pair 14
3-JB-100 / X1
Blue
Black
40
41
42
3-FT-203Z
Blue
Black
+
-
3-FT-203

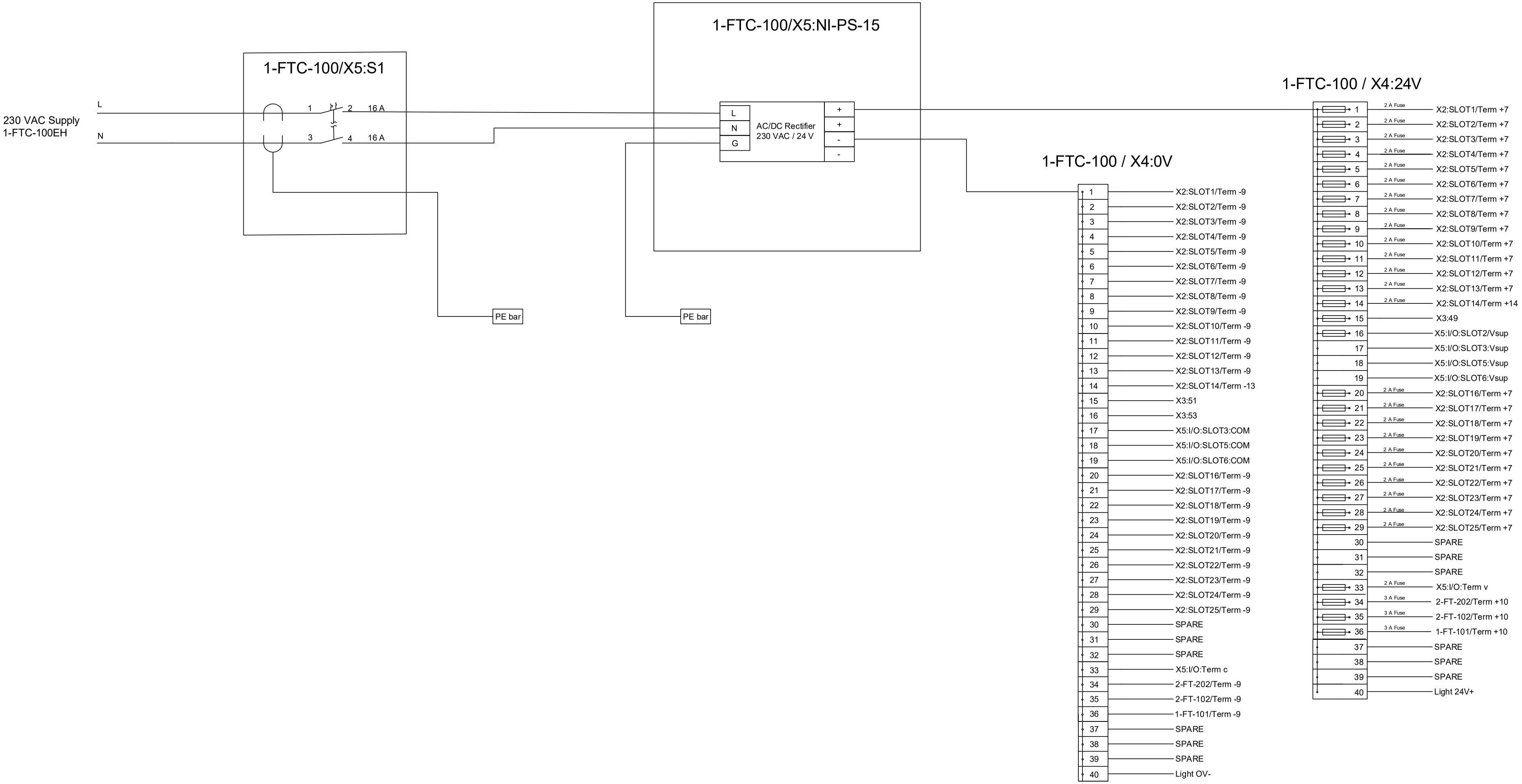

1-FTC-100 / X5:I/O:SLOT1
NI 9205 AI
AI30
COM
Channel 33
1-FTC-100 / X3
106
107
1-FT-100 / X4:24 V
24
1-FT-100 / X4:0 V
24
1-FTC-100 / X2:SLOT23
R.STAHL
9160/23-11-10
Channel 1
2-
1+
7+
9-
12+
10
1-FTC-100 / X1
140
141
142
ISE bar
3-JB-100Z
Pair 15
3-JB-100 / X1
Blue
Black
43
44
45
3-FT-204Z
3-FT-204
+
-
1-FTC-100 / X5:I/O:SLOT5
NI 9265 AO
AO3
COM3
Channel 6
1-FT-100 / X3
108
109
1-FT-100 / X4:24 V
24
1-FT-100 / X4:0 V
24
1-FTC-100 / X2:SLOT24
R.STAHL
9165/26-11-11
Channel 1
6-
5+
7+
9-
14-
13+
1-FTC-100 / X1
143
144
145
ISE bar
3-JB-100Z
Pair 16
3-JB-100 / X1
Blue
Black
46
47
48
3-FV-101Z
3-FV-101
+
-


1-FTC-100 / X5:I/O:SLOT6
NI 9265 AO
AO0
COM0
Channel 0
1-FTC-100 / X2:SLOT24
R.STAHL
9165/26-11-11
11-
10+
2-
1+
7+
9-
Channel 2
1-FT-100 / X3
110
111
1-FT-100 / X4:24 V
25
1-FT-100 / X4:0 V
25
3-FV-102
+
-
Blue
Black
3-FV-102Z
3-JB-100 / X1
49
50
51
Blue
Black
3-JB-200Z
Pair 1
1-FTC-100 / X1
146
147
148
ISE bar


1-FTC-100 / X5:I/O:SLOT6
NI 9265 AO
AO1
COM1
Channel 2
1-FTC-100 / X2:SLOT25
R.STAHL
9165/26-11-11
14
13+
6-
5+
7+
9-
Channel 1
1-FT-100 / X3
112
113
1-FT-100 / X4:24 V
25
1-FT-100 / X4:0 V
25
3-FV-201
+
-
Blue
Black
3-FV-201Z
3-JB-100 / X1
52
53
54
Blue
Black
3-JB-200Z
Pair 2
1-FTC-100 / X1
149
150
151
ISE bar


NI 9265 AO
AO2
COM2
Channel 4
1-FT-100 / X3
114
115
1-FT-100 / X4:24 V
26
1-FT-100 / X4:0 V
26
1-FTC-100 / X2:SLOT25
R.STAHL
9165/26-11-11
Channel 2
6-
5+
7+
9-
14
13+
1-FTC-100 / X1
152
153
154
ISE bar
3-JB-200Z
Pair 3
3-JB-100 / X1
Blue
Black
55
56
57
3-FV-202Z
Blue
Black
+
-
3-FV-202
1-FTC-100 / X5:I/O:SLOT6
NI 9265 AO
AO3
COM3
Channel 6
1-FT-100 / X3
116
117
1-FT-100 / X4:24 V
26
1-FT-100 / X4:0 V
26
1-FTC-100 / X2:SLOT26
R.STAHL
9165/26-11-11
Channel 1
2-
1+
7+
9-
11-
10+
1-FTC-100 / X1
155
156
157
ISE bar
3-JB-200Z
Pair 4
3-JB-100 / X1
Blue
Black
58
59
60
3-FV-203Z
Blue
Black
+
-
3-FV-203

G. 24 V Distribution Diagram


230 VAC Supply
1-FTC-100EH
L
N
1-FTC-100/X5:S1
1
2
3
4
16 A
16 A
PE bar
1-FTC-100/X5:NI-PS-15
L
N
G
AC/DC Rectifier
230 VAC / 24 V
+
+
-
-
PE bar
1-FTC-100 / X4:0V
1 X2:SLOT1/Term -9
2 X2:SLOT2/Term -9
3 X2:SLOT3/Term -9
4 X2:SLOT4/Term -9
5 X2:SLOT5/Term -9
6 X2:SLOT6/Term -9
7 X2:SLOT7/Term -9
8 X2:SLOT8/Term -9
9 X2:SLOT9/Term -9
10 X2:SLOT10/Term -9
11 X2:SLOT11/Term -9
12 X2:SLOT12/Term -9
13 X2:SLOT13/Term -9
14 X2:SLOT14/Term -13
15 X3:51
16 X3:53
17 X5:I/O:SLOT3:COM
18 X5:I/O:SLOT5:COM
19 X5:I/O:SLOT6:COM
20 X2:SLOT16/Term -9
21 X2:SLOT17/Term -9
22 X2:SLOT18/Term -9
23 X2:SLOT19/Term -9
24 X2:SLOT20/Term -9
25 X2:SLOT21/Term -9
26 X2:SLOT22/Term -9
27 X2:SLOT23/Term -9
28 X2:SLOT24/Term -9
29 X2:SLOT25/Term -9
30 SPARE
31 SPARE
32 SPARE
33 X5:I/O:Term c
34 2-FT-202/Term -9
35 2-FT-102/Term -9
36 1-FT-101/Term -9
37 SPARE
38 SPARE
39 SPARE
40 Light OV-
1-FTC-100 / X4:24V
1 2 A Fuse X2:SLOT1/Term +7
2 2 A Fuse X2:SLOT2/Term +7
3 2 A Fuse X2:SLOT3/Term +7
4 2 A Fuse X2:SLOT4/Term +7
5 2 A Fuse X2:SLOT5/Term +7
6 2 A Fuse X2:SLOT6/Term +7
7 2 A Fuse X2:SLOT7/Term +7
8 2 A Fuse X2:SLOT8/Term +7
9 2 A Fuse X2:SLOT9/Term +7
10 2 A Fuse X2:SLOT10/Term +7
11 2 A Fuse X2:SLOT11/Term +7
12 2 A Fuse X2:SLOT12/Term +7
13 2 A Fuse X2:SLOT13/Term +7
14 2 A Fuse X2:SLOT14/Term +14
15 X3:49
16 X5:I/O:SLOT2/Vsup
17 X5:I/O:SLOT3:Vsup
18 X5:I/O:SLOT5:Vsup
19 X5:I/O:SLOT6:Vsup
20 2 A Fuse X2:SLOT16/Term +7
21 2 A Fuse X2:SLOT17/Term +7
22 2 A Fuse X2:SLOT18/Term +7
23 2 A Fuse X2:SLOT19/Term +7
24 2 A Fuse X2:SLOT20/Term +7
25 2 A Fuse X2:SLOT21/Term +7
26 2 A Fuse X2:SLOT22/Term +7
27 2 A Fuse X2:SLOT23/Term +7
28 2 A Fuse X2:SLOT24/Term +7
29 2 A Fuse X2:SLOT25/Term +7
30 SPARE
31 SPARE
32 SPARE
33 2 A Fuse X5:I/O:Term v
34 3 A Fuse 2-FT-202/Term +10
35 3 A Fuse 2-FT-102/Term +10
36 3 A Fuse 1-FT-101/Term +10
37 SPARE
38 SPARE
39 SPARE
40 Light 24V+

H. Electronic appendices list

The following electronic appendices are included with the submission of this thesis:

- **EA-1:** Phase 2 3D model
- **EA-2:** Construction of Compact Separation Laboratory. Specialization project thesis. NTNU, 2016. J. Djupvik and M. Hellem.
- **EA-3:** Flow simulation specifications for first and final iteration of the CFU