AAUE Produced Water Treatment Pilot-Plant

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Abstract

C:/Program Files/Inkscape/This document describes the capabilities of the PWT emulation platform constructed in cooperation with the PDPWAC-project, SWTS-project, and DHRTC at AAU Esbjerg. The platform contains six sections; reservoir, pipeline-riser, separator, hydrocyclone, heating, and membrane filtration. Note that the membrane filtration sections will not be described in this document! This manual will provide knowledge which is needed to control the oil-rig emulator setup.

Requirements for host computer: $MATLAB > 2016b$, MATLAB compatible compiler (see supported compilers on MathWorks), PC with ethernet card, and Microsoft Access.

Contents

Chapter 1

Introduction & Process System

Offshore oil and gas production is facing an increasing challenge as the water fraction from the production wells rises over time. It is not uncommon that the extracted mixture contains a water cut of more than 90%, which renders the separation process a key factor as production must comply with the local environmental regulations. The common oil and gas separation process uses multi-phase separator tanks that utilizes gravity to separate different composites by density. Normally gas being lightest fills the top of the tank and oil will approach and settle above the water surface. In order to achieve better separation of oil, hydrocyclones are used to further separate the remaining oil from the separator tank's water outlet by using vortex based flow to expose the fluid to large centrifugal forces, forcing the water to the wall of the cyclone and causing the lighter oil droplets to migrate to the center. An overview of the produced water treatment can be seen in figure 1.1.

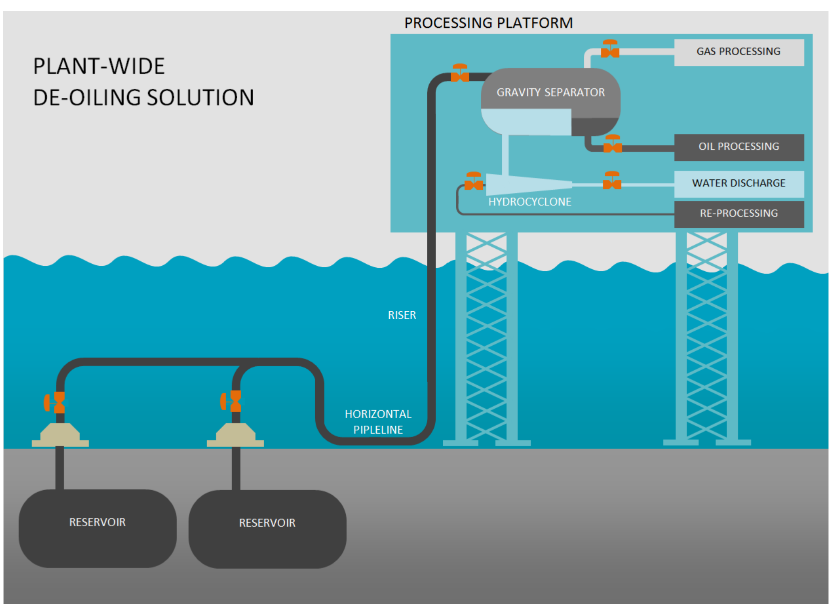


Figure 1.1: Illustration of plant-wide produced water treatment.

The current North Sea discharge legislation states that the dispersed hydrocarbon concentration in water must be less than 30 parts per million (ppm), therefore the discharged liquid is sampled 2-3 times per day and analyzed using the OSPAR recommended GC-FID method. However, the variations of Oil-in-Water (OiW) concentration between sampling time points are unknown and could exceed the regulatory limits. If the discharge limit is exceeded, the produced water must be barreled. The cost for barreling produced water is taken directly from the contribution of the oil production and it is therefore a goal to reach a separation level that meets OSPAR recommendation.

This oilrig plant test setup described in this documentation is located at AAUE Energy Laboratory (C2.025). The setup is mainly used for applying various modeling principles and performance analysis to emulate the main parts of an offshore deoiling process to validate potential performance improvements of different applied control strategies. Furthermore, the performance of various equipment can be mapped with chosen operating conditions. An overview of the main process parts is shown in figure reffig:SubsystemParameter1.

Firstly, the sub-surface reservoir is emulated using a combination of tanks and pumps to create 3-phase pressurized flow. All flows are measured separately before mixing to ensure a desired ratio.

Secondly, a horizontal pipeline and vertical riser emulate transport of the reservoir product from a remote production to the processing platform; this is allows for emulation of transport related issues such as terrain and riser slugging. In addition the riser is fitted with a gas-lift assist system which allows emulation of casing-head severe slugging.

Thirdly, oil-water-gas separation is emulated using two commercial methods; a gravity separator is used as the first stage separation; hydrocyclones are used as the second stage oil-water separation.

Throughout the system, sensors are mounted to monitor the system status, exceeding the sensing solutions that is commonly used offshore. As an example, the pipeline pressure is monitored at several positions along the pipe; where normally the pressure is only monitored at inlet and outlet, and there is a multi-phase Coriolis flow meter at the outlet before the first-stage separator. The oilrig plant setup is controlled by an assigned computer running real-time windows target in Simulink. The Matlab Simulink-software gives different inputs to the valves, pumps and reads the outputs from all sensors and actuators.

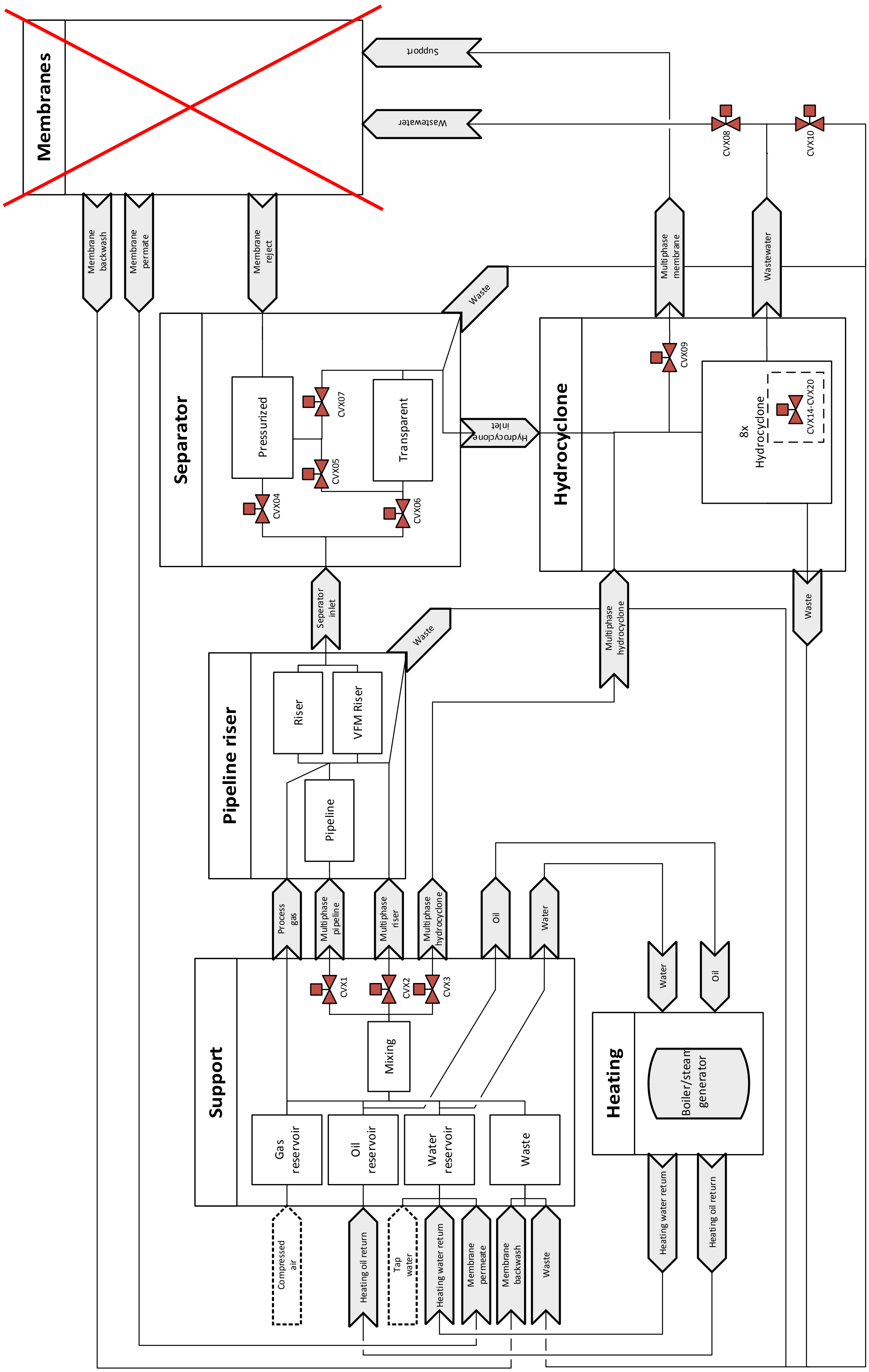


Figure 1.2: The main plant subsystem parameter-window.

1.1 Subsystems

The overview P&ID can be seen in figure reffig:SubsystemParameter1, The setup can be divided into five main segments, without the membrane filtration segment:

- Support
- Pipeline-riser
- Separator Tank
- Hydrocyclones
- Heating

To read the P&IDs (E.G. figure 1.3), the tags of the components must be found in chapter 6, where manufacturer type for each specific tag is described. The specifications of the specific component's manufacturer type is described in apendix 7. The pipe materials and diameters are color coded in the P&IDs as explained in section 1.3.

Support Subsystem

Waste- and supply-tanks are described in this subsystem. Note that the tanks are physically built together sharing an exterior surface.

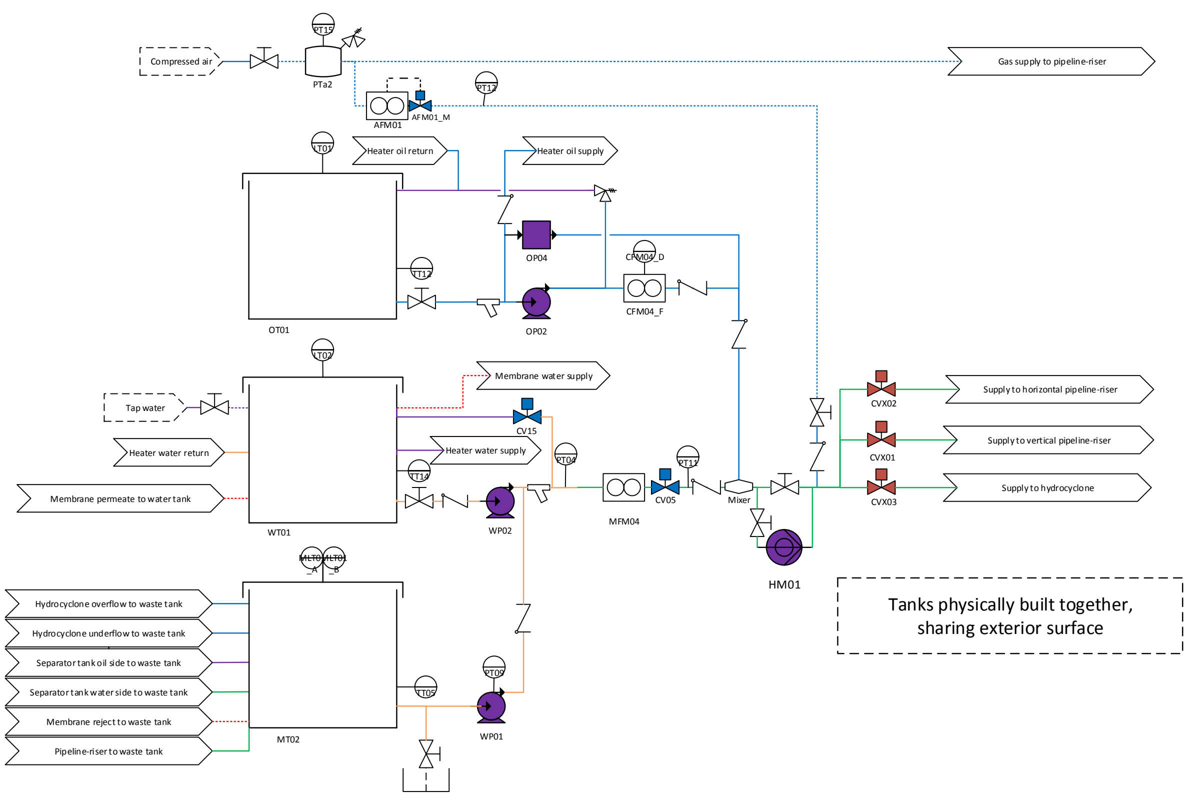


Figure 1.3: Support subsystem.

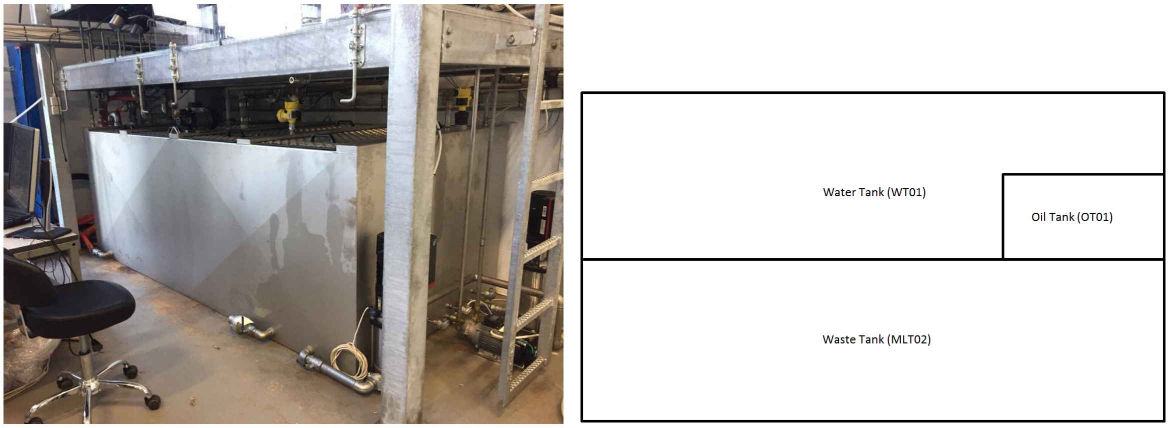
A temperature transmitter TT14 and a level sensor LT02 are mounted on the water tank WT01, LT02 provides the distance information from top of the tank to the liquid surface. A hand control valve is mounted right after the water tank to be able to isolate the water tank. The water pump WP02 serves as the main pump. As a part of the pump setup, the pressure of the inner backflow loop is provided with PT04. Right after the pump, a filter is mounted to catch solid particles. To enable tests with either constant pressure or flow rate, a backflow pipeline with a control valve CV15 leading flow back to the water tank is installed. After the backflow T-junction a magnetic flow meter MFM04 is mounted to measure the flow rate of water into the setup. The flow rate continuing into the setup will be the flow rate through the pump subtracted with the backflow. A control valve CV05, which can be used to control the water flow rate, is mounted after the magnetic flow meter. A pressure transmitter PT11 is mounted after the control valve to provide the pressure of the water before mixing with oil.

The oil supply has a similar structure as the water supply. A temperature transmitter TT12 and a level sensor LT01 is mounted on the oil tank OT01, the LT01 provides the distance information from top of the tank to the liquid surface. A hand control valve is mounted right after the oil tank to manually be able to isolate the oil tank. A filter is mounted to catch solid particles. The oil can be injected into the system with either an dosing pump OP04 or a rotary vane pump OP02. After the OP02 pump an Coriolis flow meter CFM04 is mounted to measure the flow rate and density of oil into the setup. The water and oil enters in a T-junction where it either can be mixed directly with air by bypassing the homogenizer HM01 with hand control valves, or led through the homogenizer before mixing with air.

The compressed air is given from an external supply, which can be connected or disconnected from the pressure tank PTa2 by the hand control valve. The pressure transmitter PT15 provides the tank pressure. A combined air flow meter with a controlled air valve AFM01 is mounted to control the gas injected into the system. A pressure transmitter PT12 is mounted after the air control valve to provide the pressure of the air at the mixer inlet. To prevent any liquid to flow back into the gas system, a direction valve is mounted.

The waste water is led down to the waste tank MT02 where it either can be recycled by the pump WP01 or be further separated by the membrane setup. A pressure transmitter PT09 is mounted on the pump WP01. A temperature transmitter TT05 and a multi-level transmitter MLT01 is mounted on the waste tank. The hand control valve connected right after the water tank can be used to acquire manual samples for offline tests or to empty the waste tank.

As mentioned in the beginning of this section, the tanks are physically built together sharing an exterior surface which can be seen in figure 1.4a and 1.4b.



(a) The tanks sharing an exterior surface.

(b) Topview of the tanks sharing surface.

Figure 1.4: A graphical description of the tanks sharing surface.

Size of the supply tank can be seen in figure 1.5.

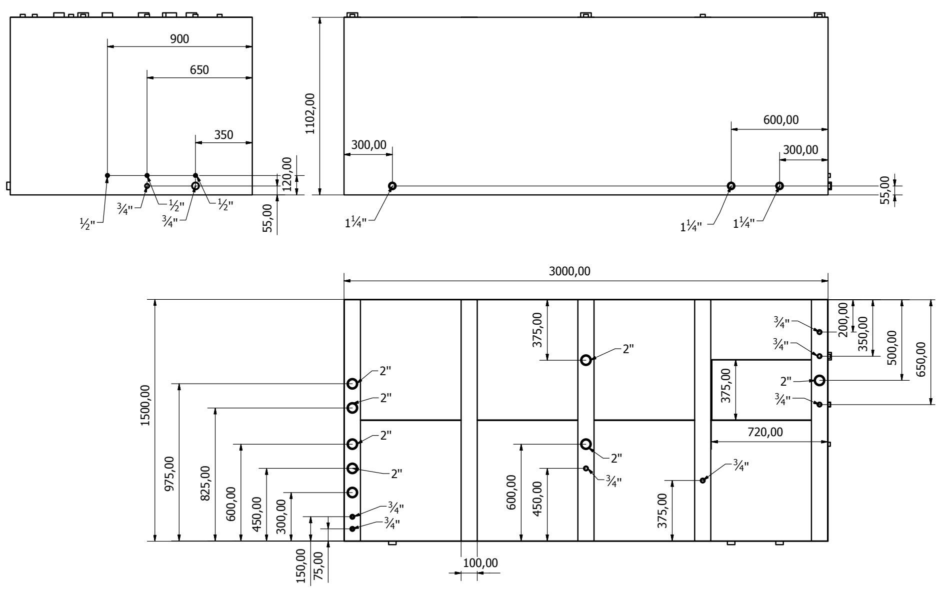


Figure 1.5: Supply tank schematic.

Pipeline-Riser Subsystem

The pipeline-riser subsystem consists of the horizontal pipeline and two vertical risers. There is the possibility to use gas-lifting by injecting air into the bottom of the riser. The pipeline-riser subsystem is illustrated in figure 1.6 and the segments of the pipeline are as follows:

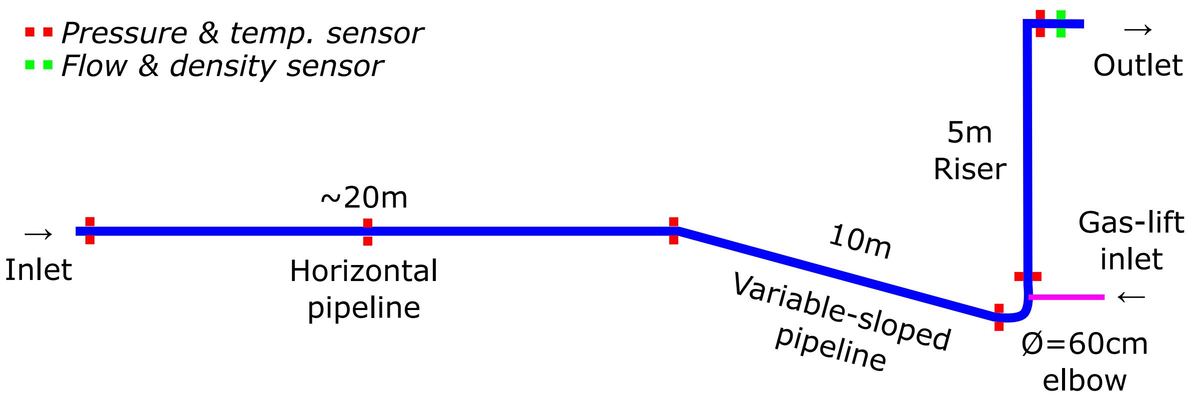


Figure 1.6: Pipeline-riser schematic.

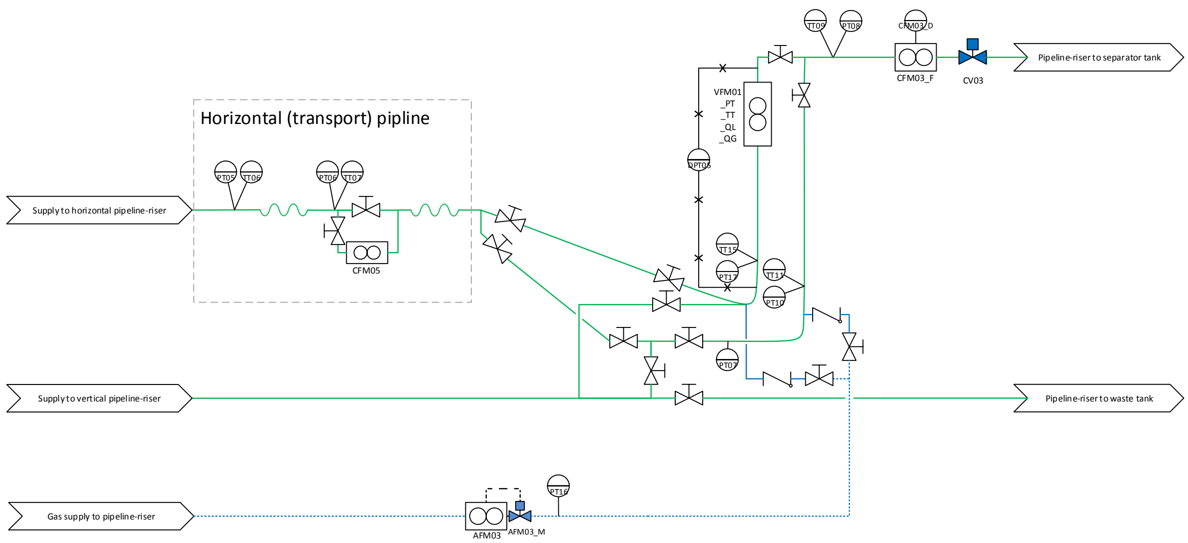


Figure 1.7: Pipeline-riser subsystem.

Pressure and temperature sensors are mounted at several locations along the transport system, including the inlet and top and bottom of riser. A pressure transmitter PT05 and temperature transmitter TT06 are mounted in the beginning of the horizontal pipeline and half of the way on the horizontal pipeline another pressure transmitter PT06 and temperature transmitter TT07 are mounted. In addition a Coriolis flow meter CFM05 is mounted right after PT06 and TT07 to measure the flow and density, the Coriolis flow meter can be bypassed by hand control valve if necessary. There are two different flow patttens after the horizontal pipeline, you can either select vertical pipeline with the virtual flow meter VFM01 or the transparent vertical pipeline without VFM01 by manually manipulating the different hand control valves.

Vertical pipeline with VFM01: A pressure transmitter PT17 and temperature transmitter TT15 are mounted in the bottom of the pipeline and also a difference pressure transmitter DPT05 is mounted to measure the pressure over the entire vertical pipeline.

Transparent vertical pipeline without VFM01: A pressure transmitter PT10 and temperature transmitter TT11 are mounted in the bottom of the pipeline and an addition pressure transmitter PT07 before them.

At the top of the riser another set of pressure transmitter PT08 and temperature transmitter TT09 are mounted just before a Coriolis flow meter CFM03. The control valve CV03 is used for controlling the slugging flow into the separator. The use of gas-lift injection can be selected by turn the hand valve to the specific configuration.

A highlighted flow path is shown in figure 1.8, this flow path is the most commonly used for produced water treatment. This path includes horizontal, inclined and vertical pipe line. CV08 is a often used valve for anti-slug control research and development. The highlighted path does not include gas lifting.

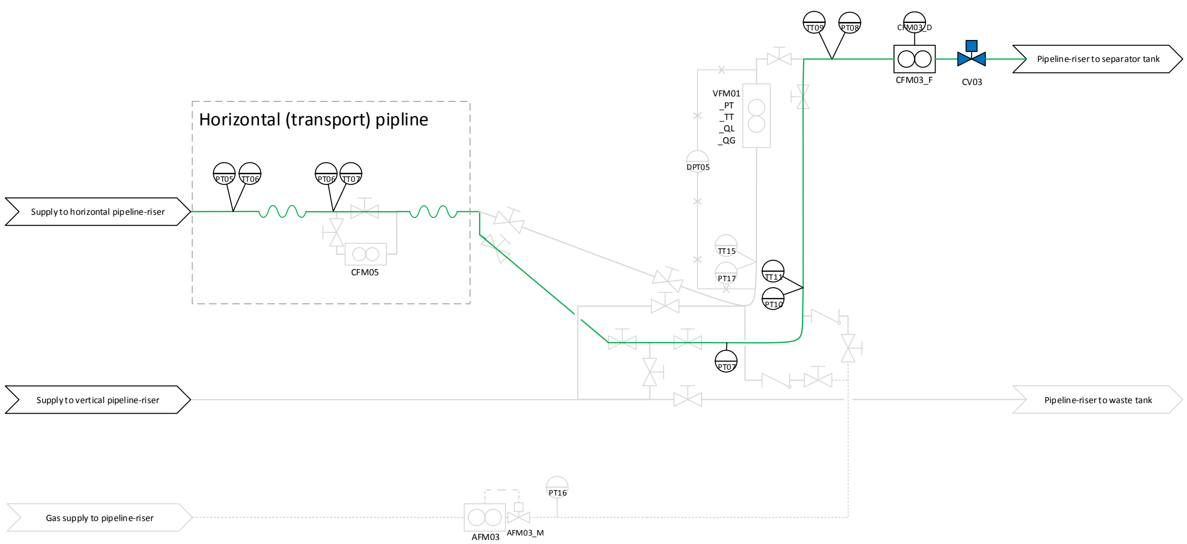


Figure 1.8: Highlighted pipeline-riser subsystem.

Gravity Separator Subsystem

A first-stage three-phase separator tank that utilizes gravity to separate different composites by different densities initially separates the produced fluid from the production wells. Gas, being lightest, fills the top of the tank and oil will approach and settle above the water surface. The separation tank has three outlets; gas, oil, and water.

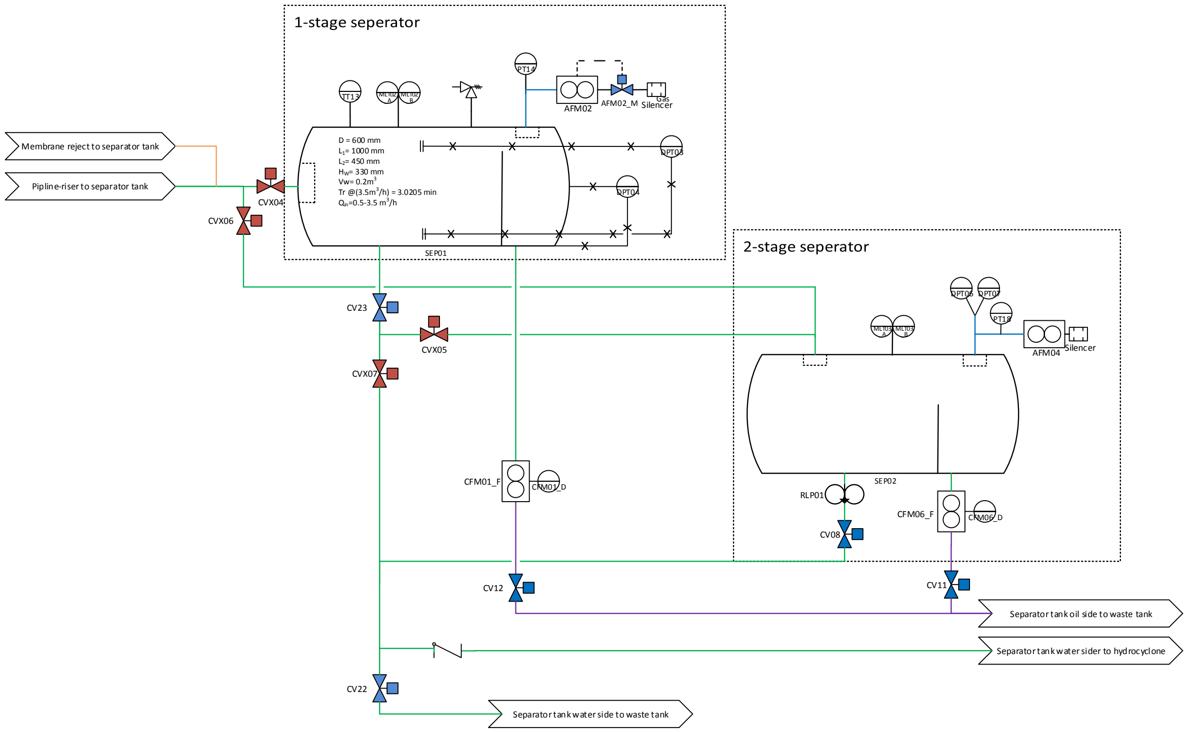
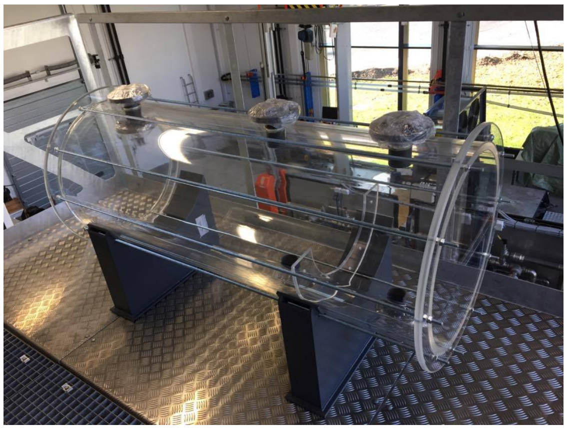


Figure 1.9: Separator subsystem.

The separator tank SEP01 is equipped with a temperature sensor TT13 and pressure transmitter PT14 as well as a multilevel transmitter MLT02 that provides the level of oil and water interface in the tank. SEP01 is pressurizable and is able to withstand a pressure of 10bar. The pressure difference is measured both before and after the oil-separating weir with DPT03 and DPT04, for an additional method to provide the water and oil levels within the separator tank. The weir inside the separator tank is changeable. The weir can be changed by opening the separator tank and switching the weir manually. A pressure relieve valve ensures that the pressure within the separator tank is maintained below the critical pressure of 10BarG. A combined air flow meter with a controlled air valve (AFM02 and ACV02) is mounted to control the gas leaving the separator tank. A gas silencer is mounted at the end of the gas outlet to reduce the gas discharge noise. At the oil outlet, a Coriolis flow meter CFM01 is mounted to provide the flow rate of oil leaving the separator tank. On the same pipeline, a control valve CV12 is mounted to control the oil flow from the separator tank. The oil outlet of the separator tank is directly discharged into the waste tank. The water outlet from the separator tank can either be discharged directly to the waste tank or continue into the hydrocyclone system by controlling the the control valve CV22 and CV07 respectively, see figure 1.13 for CV07.

The acrylic separator tank SEP02 can only withstand atmospheric pressure, therefore the acrylic separator tank is only used for visual inspection of the flow phenomenons inside the chamber. SEP02 is equipped with a pressure transmitter PT18 and air flow meter AFM04 for safety, as well as two pressure difference transmitter DPT05 and DPT06, which provides the level of oil and water interface in the tank. At the oil outlet, a Coriolis flow meter CFM06

is mounted to provide the flow rate of oil leaving the separator tank. On the same pipeline, a control valve CV11 is mounted to control the oil flow from the separator tank. The oil outlet of SEP02 is directly discharged into the waste tank. The water outlet from the separator tank can either be discharged directly to the waste tank or continue into the hydrocyclone system by controlling the the control valve CV08 and CV22 respectively. For boosting the flow rate from SEP02 a rotary lobe pump RLP01 is connected right after the water outlet.
A picture of the two custom-made separator tanks can be seen in figure 1.10a and 1.10b.



(a) Acrylic separator tank.

(b) Steel vessel separator tank.

Figure 1.10: Separator tanks that can be used in the setup.

The custom-made three phase gravity separator was designed with a residence time of approximately 3 minutes, following industrial guidelines. The residence time can be changed by altering the height of the interchangeable weir. The acrylic separator tank has same dimension as the pressurized steel vessel separator tank, except the curved edges. The dimensions can be seen in figure **??**.

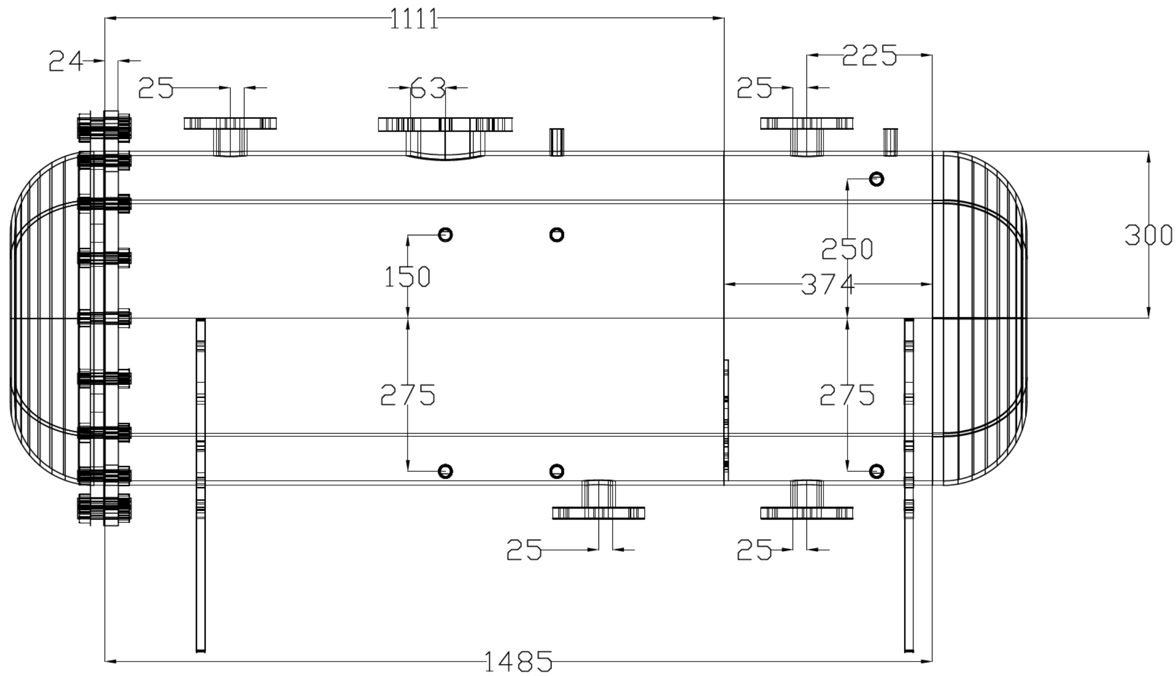


Figure 1.11: Separator tank dimensions.

A highlighted flow path is shown in figure 1.12, this flow path is the most commonly used for produced water treatment. This path includes the steel three phase separator; Oil outlet goes to waste tank, water outlet goes to the hydrocyclone subsystem, and air is discharged to room. AFM02_M is used to control the pressure inside the separator. CV12 is often fully opened. Note that the water level in the separator is often controlled by the underflow valve in the hydrocyclone subsystem. The highlighted path does not include the acrylic separator.

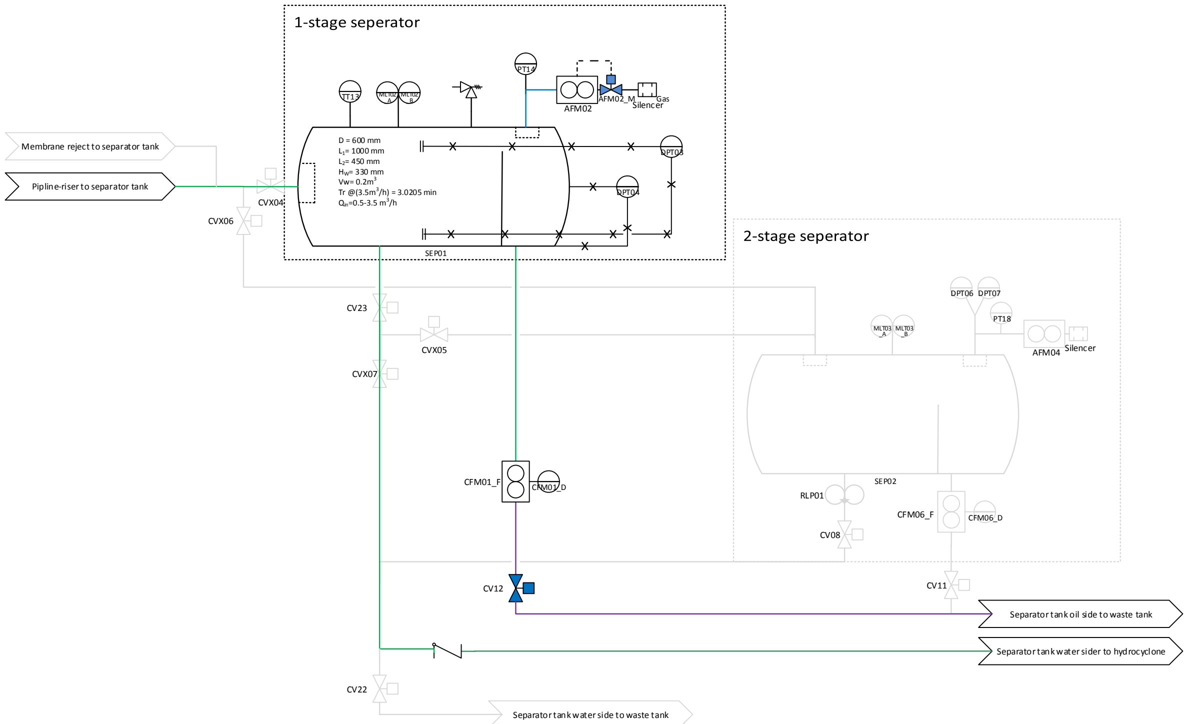


Figure 1.12: Highlighted separator subsystem.

Hydrocyclone Subsystem

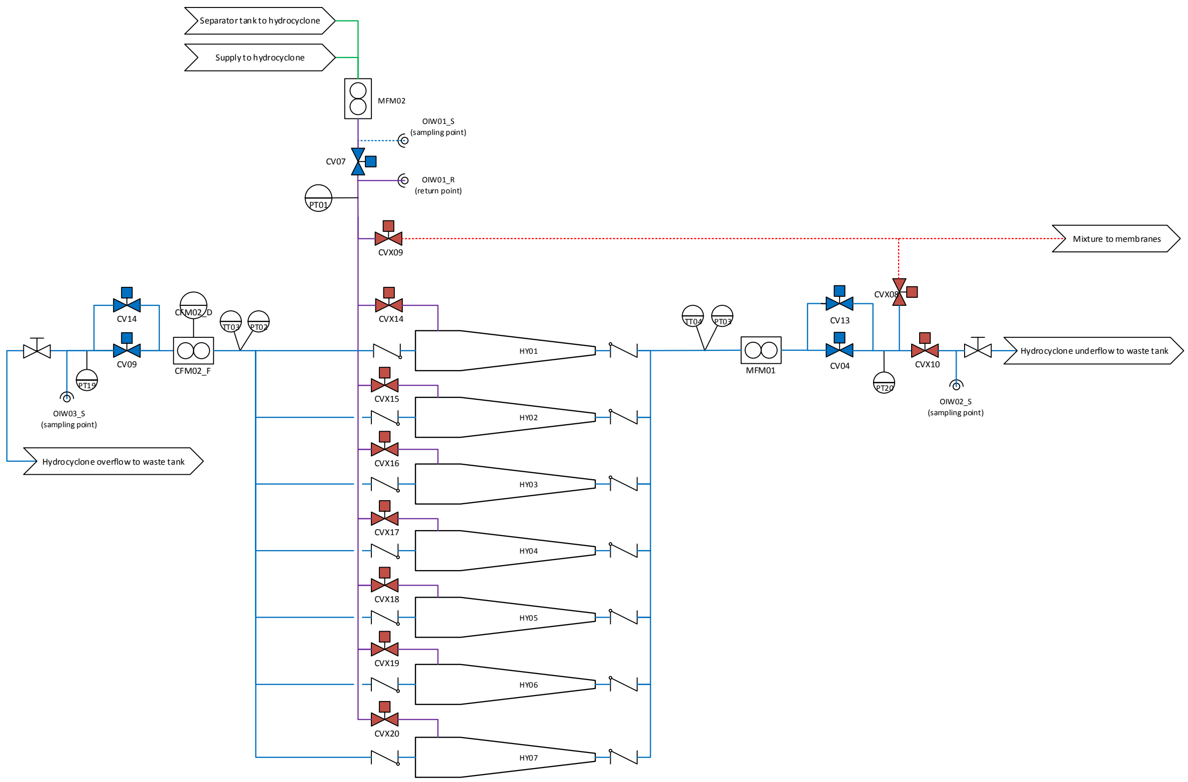
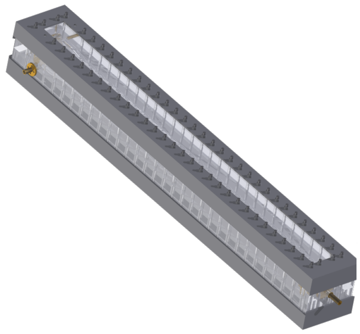


Figure 1.13: Hydrocyclone subsystem.

Two magentic flow meters (MFM02 and MFM01) are mounted at the inlet and underflow respectively, where as a Coriolis flow meter CFM02 is mounted at the overflow. Inlet, underflow, and overflow pressures are measured by PT01, PT03, and PT02 respectively. They can be used to generate PDR. At the underflow CV04 and at the overflow CV09 a control valve is mounted to allow various valve-opening tests. CV13 and CV14 are mounted to give a higher openness degree if necessary. The pressure transmitters PT19 and PT20 measure the back-pressure of the overflow outlet and underflow outlet respectively. The waste from the underflow leads to the waste tank and the waste from overflow can either be conserved or directed to the waste tank. the control valve CV07 is used to generate a pressure drop when the oil-in-water monitors are used on sidestream. The hydrocyclones (HY01-HY07) includes several parallel-connected hydrocyclones. Isolation valves CVX14-CVX20 before and after each hydrocyclone determine if the individual hydrocyclones are connected to the setup. It is possible to use more than one hydrocyclone at a time. The hydrocyclone subsystem include one transparent acrylic hydrocyclone HY07, two offshore hydrocyclones HY05-HY06, and four customized scaled-down hydrocyclones HY01-HY04 as seen in figures 1.14a, 1.14b, and 1.14c respectively.



(a) Acrylic hydrocyclone.

(b) Single offshore hydrocyclone.

(c) Mini hydrocyclones.

Figure 1.14: Hydrocyclones that can be used in the setup.

The industrial Vortoil 35mm liners are designed to be placed inside a pressure vessel with 40-50 in parallel, which are defined as a hydrocyclone. The hydrocyclone has been scaled for the pilot-plant, where one hydrocyclone consists of one industrial liner in one individual pressure vessel, see figure 1.15.

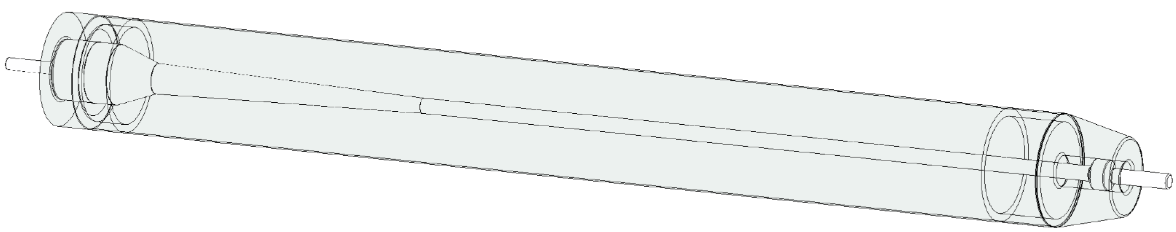
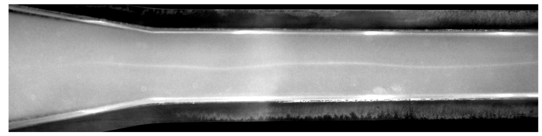


Figure 1.15: Vortoil 35mm liner.

The acrylic hydrocyclone dimensions are slightly larger than a usual offshore hydrocyclone and can ONLY withstand a pressure of 6bar, therefore the acrylic hydrocyclone is only used for visual inspection of the flow characteristics inside the cyclone chamber, as well as documentation of flow patterns using video recordings and photos. An example of the recordings can be seen in figure 1.16a and 1.16b. Note that both pictures of recordings is part of Petar's PhD dissertation.

(a) The air-core developed inside the in-house designed transparent hydrocyclone. The experiment was operated at low flow rates as separation of water and air does not require large centrifugal/centripetal forces due to the large density difference.



(b) The oil-core developed inside the in-house designed transparent hydrocyclone. The experiment was operated using large quantities of oil such that the oil-core became visible to the naked eye

The acrylic hydrocyclone is made of PMMA and has the following dimensions; $D_i = 8.75mm$, $D = 50mm$, $D_n = 25mm$, $D_o = 2.50mm$, $D_u = 12.50mm$, $L_1 = 50mm$, and $L_3 = 800mm$. The acrylic hydrocyclone can be seen in figure 1.17 and 1.18. Note that figure 1.17 is the dimensions of the acrylic part and steel piping is inserted into the connections.

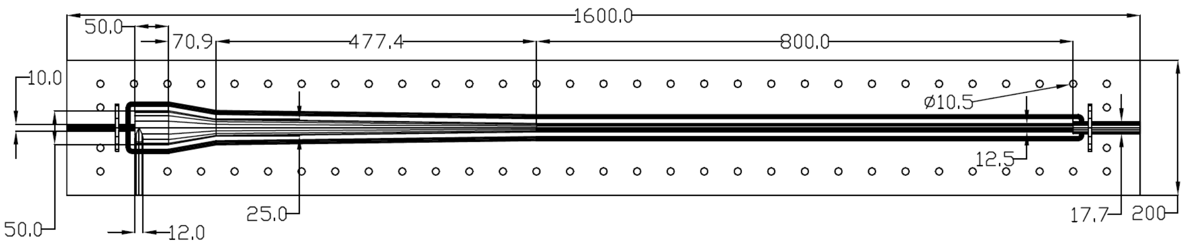


Figure 1.17: Acrylic hydrocyclone dimensions.

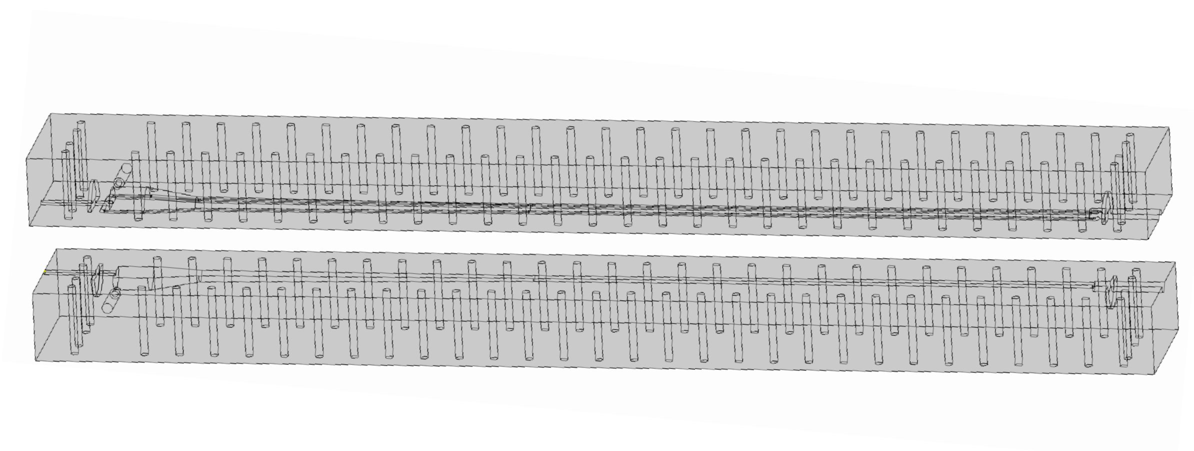


Figure 1.18: Acrylic hydrocyclone 3D.

The small scale hydrocyclones have the following dimensions; $D_i = 4.9mm$, $D = 28mm$, $D_n = 14mm$, $D_o = 1.4mm$, $D_u = 7mm$, $L_1 = 28mm$, and $L_3 = 420mm$. Figure 1.19 illustrates the common hydrocyclone dimension notation.

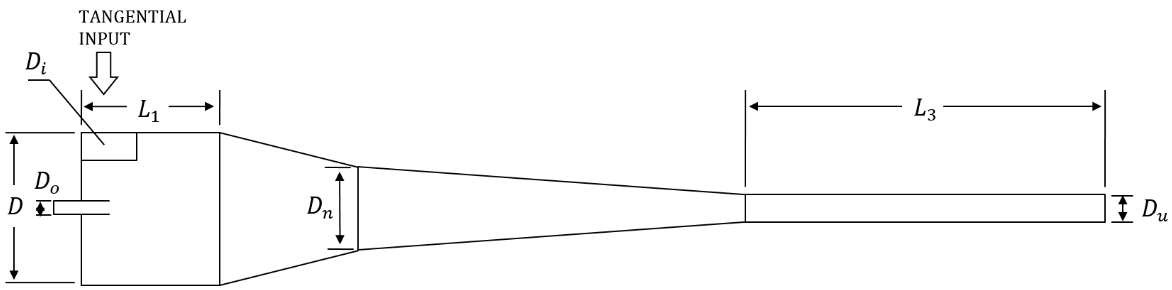


Figure 1.19: Hydrocyclone Dimensions

A highlighted flow path is shown in figure 1.20, this flow path is the most commonly used for produced water treatment. This path includes a single offshore hydrocyclone; Both overflow (oily water) and underflow (cleaned water) goes to waste tank. The pressures used for common offshore hydrocyclone control solutions are:

- Inlet pressure (P_i) PT01.
- Overflow pressure (P_o) PT02.
- Underflow pressure (P_u) PT03.

The overflow valve (V_o) CV09 is often used for PDR, flow split, or separation efficiency control. The underflow valve (V_u) CV04 is often used for controlling the water level in the upstream separator tank. This flow path often uses real time OiW monitors to measure the inlet and underflow OiW concentration.

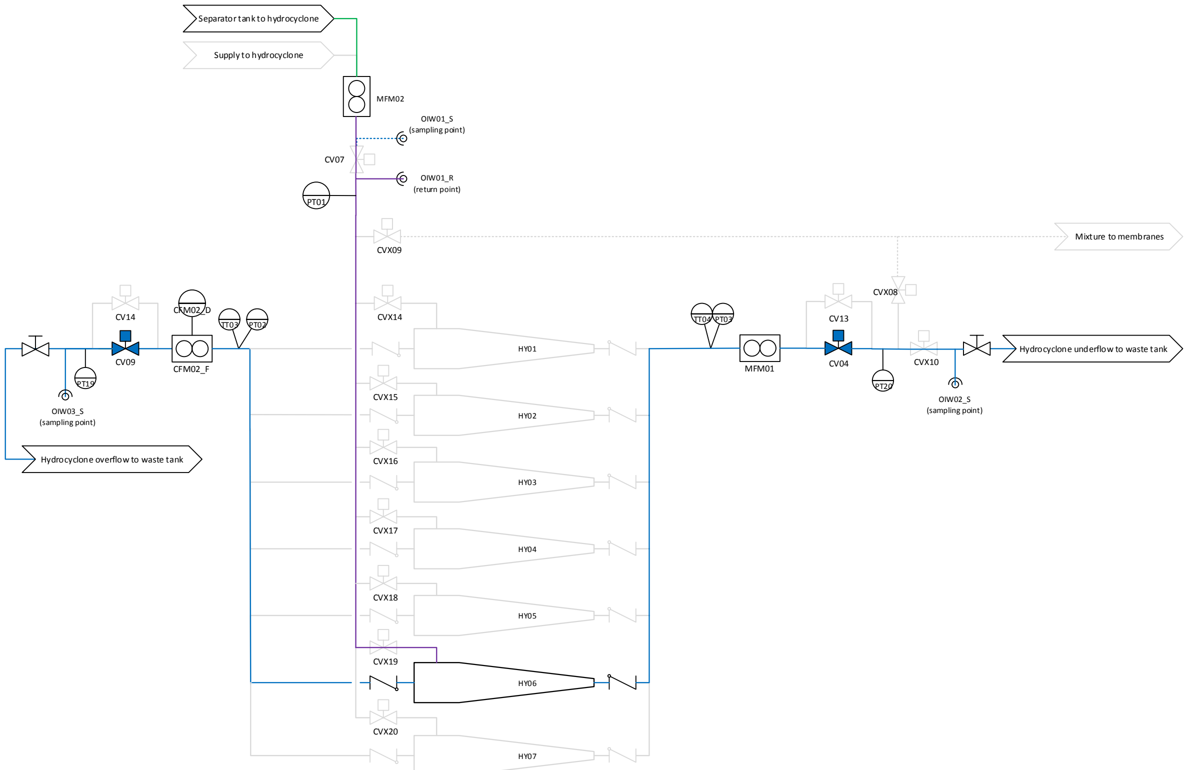


Figure 1.20: Highlighted hydrocyclone subsystem.

Heat subsystem

It is possible to heating up the oil and water separately to investigate the influence of temperature changes. OP06 pumping the oil from the oil tank through a heat exchanger HE02 and back to the oil tank. The same procedure for heating the water, where WP05 pumping the water from the water tank through a heat exchanger HE01 and back to the water tank. The steam generator supply the heat exchangers with hot steam/water in order to transfer heat energy to both the oil and the water tank. The steam generator can also be used hot water supply to the membrane setup by manipulating the isolation valves CVX11, CVX12, and CVX13 respectively.

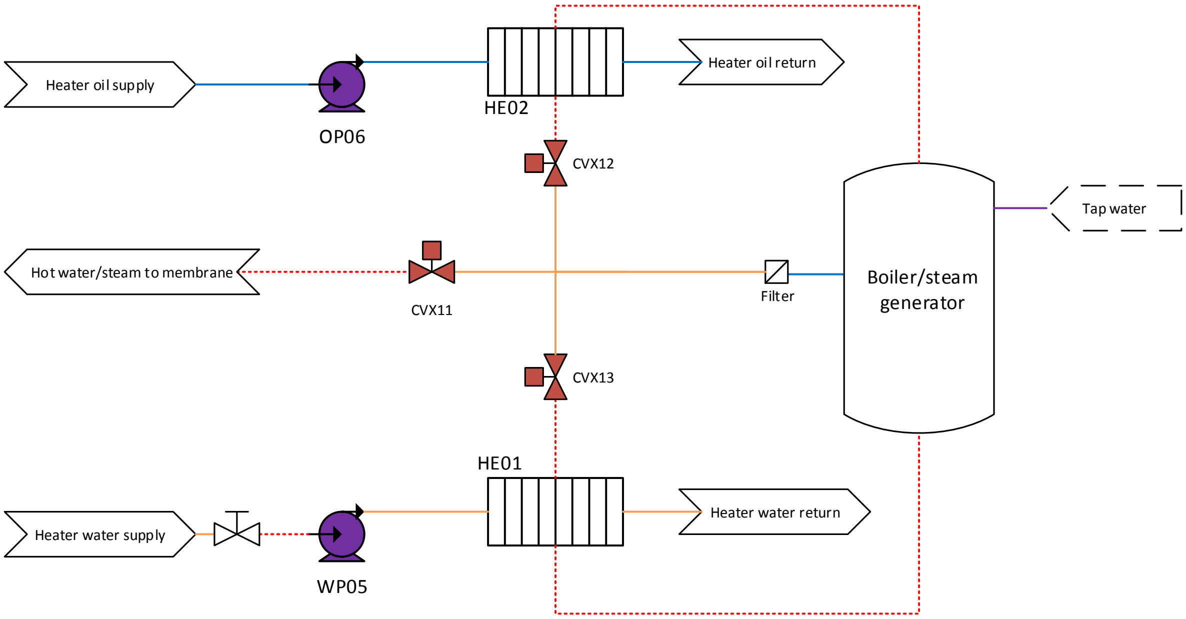


Figure 1.21: Heat subsystem.

Interconnection

The interconnection is the connection between membrane setup and pilot plant. The membrane setup is illustrated as block for simplification, if any information needed from the membrane setup contact the research group. There are two inlets and two outlets from the membrane setup. The membrane can either be supplied with a oil/water-mixture before the hydrocyclone(s) or with clean water from the water tank by WP04. The discharge from the membrane either be led directly to the waste tank by or rejected to the separator tank subsystem by WP03. The three isolation valves CVX502, CVX503, and CVX510 are used for isolating different flow pattens if necessary. CV501 is used for controlling the membrane back-pressure.

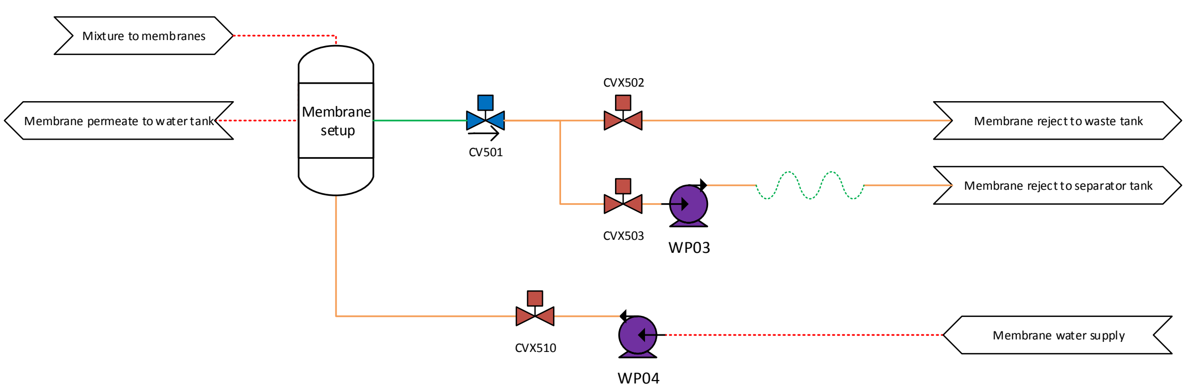


Figure 1.22: interconnection between membrane setup and pilot plant.

1.2 Bypass Configurations

The system has the possibility to test different configurations and separating conditions. The flow can be delivered to different parts of the system using the isolation-valves and hand valves, therefore it must be taken into consideration which subsystems that are relevant for your experiment before testing. After the supply subsystem there are tree configurations; direct the flow directly from the supply subsystem to the hydrocyclones, direct the flow directly from the supply subsystem to vertical pipeline-riser, or direct the flow through the horizontal pipeline-riser subsystem. In the hydrocyclone subsystem it is possible to bypass different hydrocyclones by isolation valves CVX14-CVX20, according to your specific experiment. The different configurations can be seen in table 1.1 and 1.2 where $\odot$ means open and $\otimes$ means closed.

Flowpath	CVX1	CVX2	CVX3
To the vertical pipeline-riser subsystem	$\odot$	$\otimes$	$\otimes$
To the horizontal pipeline-riser subsystem	$\otimes$	$\odot$	$\otimes$
To the hydrocyclone subsystem	$\otimes$	$\otimes$	$\odot$

Table 1.1: Flow path configurations from supply subsystem.

For the Pipeline-Riser subsystem there are four possible configurations; completely bypass the pipeline-riser and led directly to the waste tank or through the hydrocyclones. Bypass the horizontal transport pipeline and lead the flow directly through one of the vertical pipeline to the separator tank. The last two configuration uses the horizontal transport pipeline were it either can be led through the separator tank or directly down to the waste tank. Note, there is several hand valves that must be configured in the right position for each specific experiment.

For the separator subsystem there are several possible configurations; either direct the flow through separator tank (SEP01), through the acrylic separator tank (SEP02), or lead the flow through both separator tanks. Afterwards, two different pattens can be selected; either to the waste tank or to the hydrocyclone sub-system. The different configurations can be seen in table 1.2.

Flowpath	CVX4	CVX06	CVX05	CVX07	CV22
Through SEP01 to the hydrocyclones bypassing SEP02	$\odot$	$\otimes$	$\otimes$	$\odot$	$\otimes$
Through SEP02 to the hydrocyclones bypassing SEP01	$\otimes$	$\odot$	$\otimes$	$\otimes$	$\otimes$
Through SEP01 to the waste tank bypassing SEP02	$\odot$	$\otimes$	$\otimes$	$\odot$	$\odot$
Through SEP02 to the waste tank bypassing SEP01	$\otimes$	$\odot$	$\otimes$	$\otimes$	$\odot$
Through SEP01, then SEP02, then hydrocyclones	$\odot$	$\otimes$	$\odot$	$\otimes$	$\otimes$
Through SEP01, then SEP02, then to waste tank	$\odot$	$\otimes$	$\odot$	$\otimes$	$\odot$

Table 1.2: Separator tank subsystem configurations.

The underflow of the hydrocyclones can either be directed to the waste tank or to the membrane filtration system. If the underflow should go to waste tank then CVX10 must be open and CVX08 must be closed, and the other way around for flow to the membranes as shown in figure 1.13.

1.3 Pipe Material and Sizing

To indicate the pipe size in the P&ID the pipes are color coded as in table 1.3.

Pipe diameter	Color code
1/2"	Blue
3/4"	Purple
1"	Red
1 1/4"	Orange
2"	Green

Table 1.3: Pipe diameter color code.

In the P&ID the full lined pipes are stainless steel and the dotted lines are bendable hose-piping.

316 380C 10.3bar (150PSI) 150

The various bendable hose-piping used is shown in table 1.4 for each pipe diameter.

Pipe diameter	Type	Max. pressure (20°C)	Temperature range
1/2" (12.5mm)	Prima-tex 12053-63	11bar	-20°C to 60°C
3/4" (19mm)	Prima-tex 12080-63	13bar	-20°C to 60°C
1" (25mm)	Prima-tex 12095-63	10bar	-20°C to 60°C
2" (50mm)	Prima-tex 12115-63	4bar	-20°C to 60°C
1" (25mm)	IVG Steam Victoria 1186280	18bar	-40°C to 210°C
2" (51mm)	IVG Steam Victoria 1221566	18bar	-40°C to 210°C

Table 1.4: Hose types.

The Prima-tex pipes are cross-reinforced hose and Steam Victoria pipes have inner tube of smooth EPDM rubber, inserts of steel wire for reinforcement and smooth (wrapped finish) temperature resistant EPDM rubber. Note that two hose types are used for 1" diameter. As the Prima-tex 1" has a lower maximum temperature, it is only utilized few places such as before WP05. Prima-tex 3/4" hose are used to transport tab water to the water tank. Prima-tex 3/4" and 2" hoses are used for short junctions to connect pipes to the waste tank.

Transparent PVC-U, DIN 8062, Series 5, 63 x 4,7 mm, SDR 13,5/PN 16, RTPVCU063047T05, pipes are used in the pipeline-riser subsystem. PVC-U pipe systems should never be used for temperatures above 60°C. Table 1.5 gives a rough guide to the temperature/pressure relationship of PVC-U PN16 following DIN 8062 pipework systems.

Temperature	20°C	30°C	40°C	50°C	60°C
Pressure	16.0bar	12.8bar	9.2bar	6.2bar	3.5bar

Table 1.5: Metric ratings for RTPVCU063047T05

Chapter 2

Setup of Computer

This guideline will help different individual user through the setup of their computers, making Matlab compatible with the connected Real-Time Target Machine from Speedgoat (xPC). First step through the guideline shows how to set up a data source and connect to your MicrosoftR AccessTM database. This tutorial uses the Microsoft Access Driver (*.mdb, *accdb) to connect to the Microsoft Access 2010 database by use of Open Database Connectivity (ODBC).

1. Click Start, and then click Control Panel.

2. In the Control Panel, double-click Administrative Tools.

3. In the Administrative Tools dialog box, right-click on Data Sources (ODBC) and select: "run as administrator". NOTE: It is very important that you use "run as administrator", if not you will probably experience difficulties to install the data source to the right driver in ODBC!

4. The ODBC pop-up window will appear as in figure 2.1.

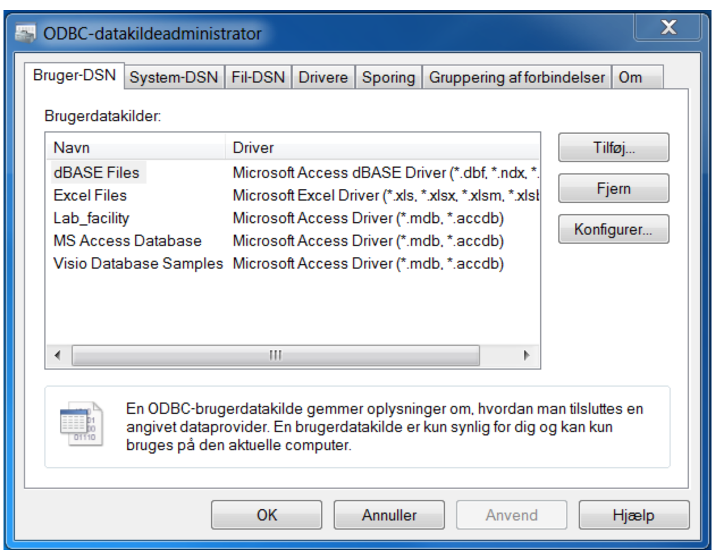


Figure 2.1: ODBC pop-up window 1.

5. Click ”add”-button to create new connections, see figure 2.2.

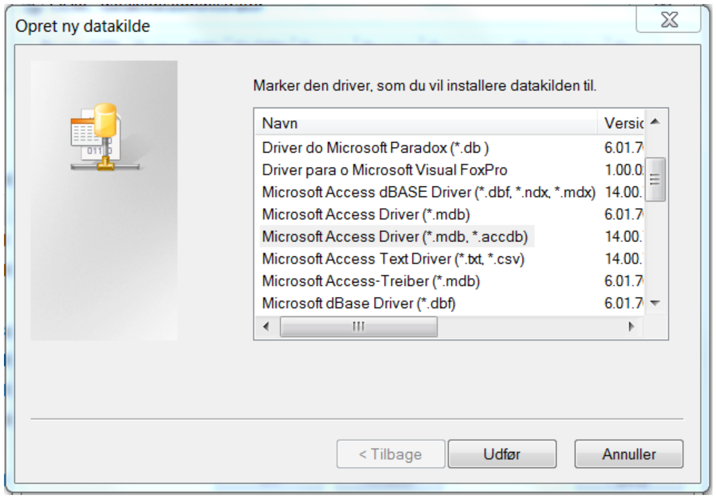


Figure 2.2: ODBC pop-up window 2.

6. Select the MicrosoftAccess Driver (*.mdb. *.accdb) and click OK, see figure 2.3.

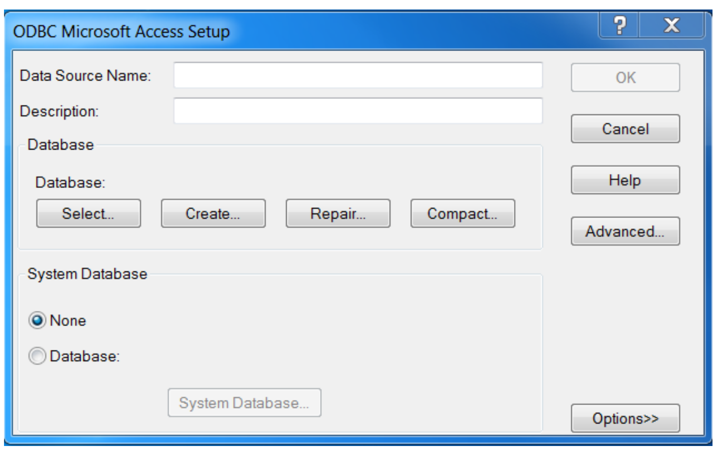


Figure 2.3: ODBC Microsoft Access Setup 1.

7. Write ”Lab_facility” under Data Source name. Afterwards, click on ”select” under Database, see figure 2.4

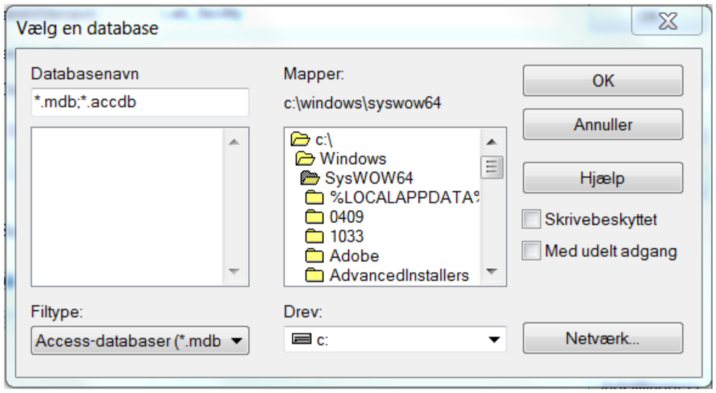


Figure 2.4: Access Database Path.

8. Select the path were the Access connection sheet is saved and click OK, see figure 2.5.

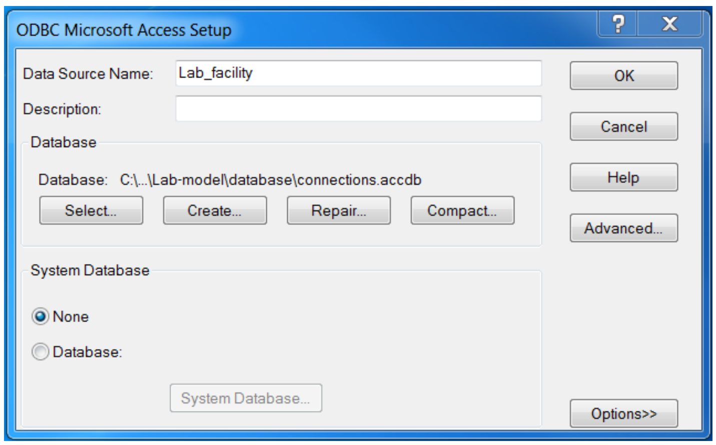


Figure 2.5: ODBC Microsoft Access Setup 2.

9. Click OK.

The data source should now successfully be connected to the MicrosoftR AccessTM database. If not, there is some typical mistakes that maybe can be fixed. The guideline would advise you to take one solution of a time and then go back the step one, starting from solution a).

(a) If you did not choose "run as administrator", probably you would have experienced that MicrosoftAccess Driver (*.mdb. *.accdb) is not a possible driver to select, see figure 2.6. Try again by "run as administrator".

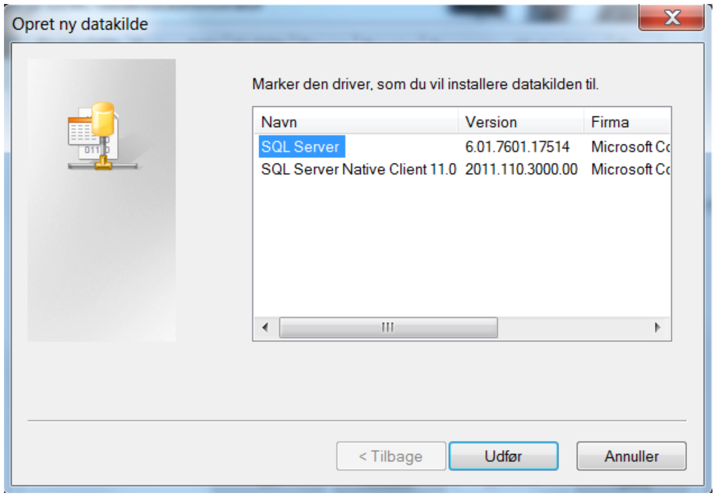


Figure 2.6: ODBC Not working.

(b) Download "Microsoft Access Database Engine 2010 Redistributable" from: `https://www.microsoft.com/en-us/download/details.aspx?id=13255` and install. This download will install a set of components that can be used to facilitate transfer of data between 2010 Microsoft Office System files and non-Microsoft Office applications.

(c) Repair your Microsoft Office program by: 1. click Start then Control Panel then Remove Programs. 2. Right-click on your Microsoft Office program, select repair and follow the steps.

(d) Last solution that some have experienced is to update the Microsoft Office program to Microsoft Office 2016.

Second step, test if you Matlab can find any supported compiler on your computer. Different compilers that Matlab is compatible with can be seen in figure 2.7.

MATLAB Product Family – Release 2016b											
Compiler	MATLAB	MATLAB Compiler	MATLAB Compiler SDK				MATLAB Coder	SimBiology	Fixed Point Designer	HDL C oder	HDL Verifier
	For MEX-file compilation, **`loadlibrary`**, *and external usage of MATLAB Engine and MAT-file APIs*	*Excel add-in for desktop*	*C/C++ & COM*	*.NET*	*Java*	*Excel add-in for MPS*	*For all features*	*For accelerated computation*	*For accelerated computation*	*For accelerated testbench simulation*	*For DPI and TLM component generation*
MinGW 4.9.2 C/C++ (Distributor: TDM-GCC) Available at no charge	✓						✓ [6]	✓	✓	✓	✓
Microsoft Visual C++ 2015 Professional	✓	✓	✓	✓ [4]			✓	✓	✓	✓	✓
Microsoft Visual C++ 2013 Professional	✓	✓	✓	✓ [4]			✓	✓	✓	✓	✓
Microsoft Visual C++ 2012 Professional	✓	✓	✓	✓ [4]			✓	✓	✓	✓	✓
Microsoft Windows SDK 7.1 Available at no charge; requires .NET Framework 4.0	✓	✓	✓				✓ [6]	✓	✓	✓	✓
Intel Parallel Studio XE 2016 for C/C++ [3]	✓										
Intel Parallel Studio XE 2015 for C/C++ [3]	✓										
Intel C++ Composer XE 2013 [3]	✓										
Intel Parallel Studio XE 2016 for Fortran [3]	✓										
Intel Parallel Studio XE 2015 for Fortran [3]	✓										
Intel Visual Fortran Composer XE 2013 [3]	✓										
Microsoft .NET Framework SDK 2.0, 3.0, 3.5, 4.0, 4.5, 4.6 Available at no charge	✓			✓ [4,5]		✓ [10]					
Java Development Kit (JDK) 1.7 Available at no charge					✓						
lcc-win64 Included with products that support it							✓ [6]	✓	✓	✓	

Figure 2.7: Matlab compilers.

Write; "mex -setup" in the Matlab Command Window, if Matlab find a compiler on your computer it will give you the response seen in figure 2.8:

```
>> mex -setup
MEX configured to use 'Microsoft Visual C++ 2013 Professional (C)' for C language compilation.
Warning: The MATLAB C and Fortran API has changed to support MATLAB
     variables with more than 2^32-1 elements. In the near future
     you will be required to update your code to utilize the
     new API. You can find more information about this at:
     http://www.mathworks.com/help/matlab/matlab_external/upgrading-mex-files-to-use-64-bit-api.html.

To choose a different language, select one from the following:
 mex -setup C++
 mex -setup FORTRAN
```

Figure 2.8: Mex -Setup working.

If not, the response in figure 2.9 will appear.

```
>> mex -setup
Error using mex
No supported compiler or SDK was found. You can install the freely available MinGW-w64 C/C++
compiler; see Install MinGW-w64 Compiler. For more options, visit
http://www.mathworks.com/support/compilers/R2016b/win64.html.
```

Figure 2.9: Mex -Setup not working.

Then you must install a compiler or a new compiler if you already have one. The guideline will recommend Microsoft Visual C++ 2013 Professional (C). Afterwards, try again to type in; "mex -setup" in the Matlab Command Window.

Third step, download and Speedgoat Setup Package from: `https://www.speedgoat.ch/downloads/sglib/speedgoat_8.zip` (if the link is expired contact one of the administrator of the oilrig setup). After downloading, do as following in Matlab:

1. Find the current folder where the p-file (speedgoat_setup.p) is saved in Matlab. (do not work if the path to the current folder of the p-file is not found in Matlabs' Current Folder Window).

2. Write speedgoat_setup in the Matlab Command Window and press "y" to update or install speedgoat tools and drivers.

Fourth step, Setup your Host-to-Target communication, go to:

1. Click Start, and then click Control Panel.

2. In the Control Panel, click on Network Connections.

3. Right-click on LAN-connection and select properties, see figure 2.10

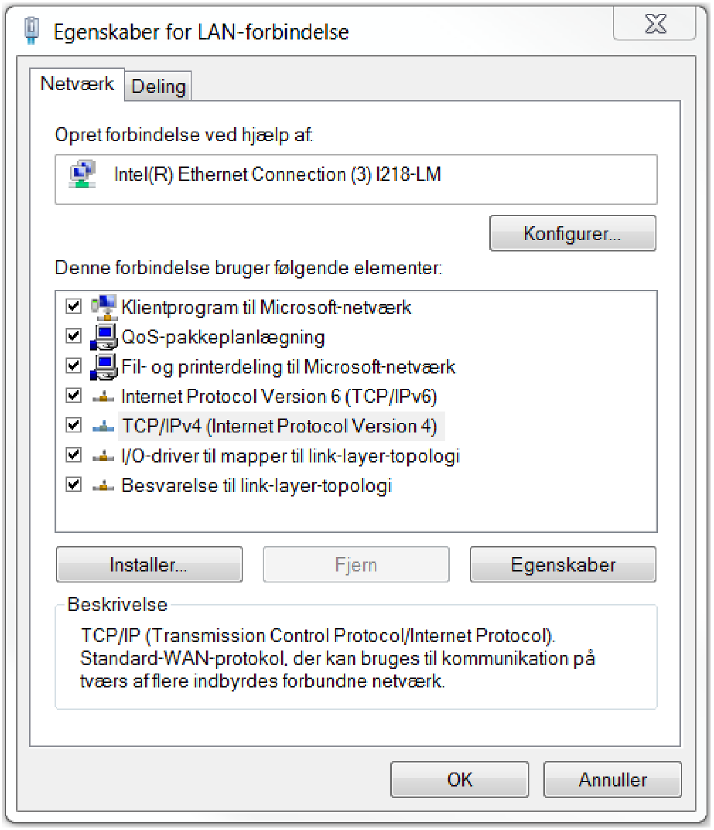


Figure 2.10: Ethernet Connection

4. Double-click on TCP/IPv4 (Internal Protocol), see figure 2.11.

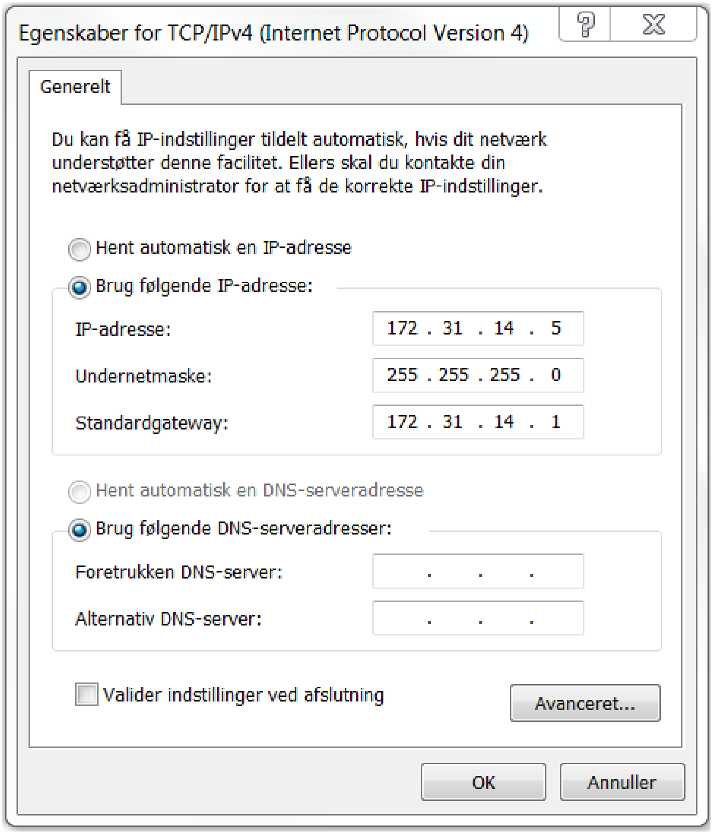


Figure 2.11: Internal Protocol

5. Write the following numbers in the IP-address as seen figure 2.11, press OK.
6. Go back to Matlab Command Window and type: ”xpcexplr” and the the window in figure 2.12 will appear:

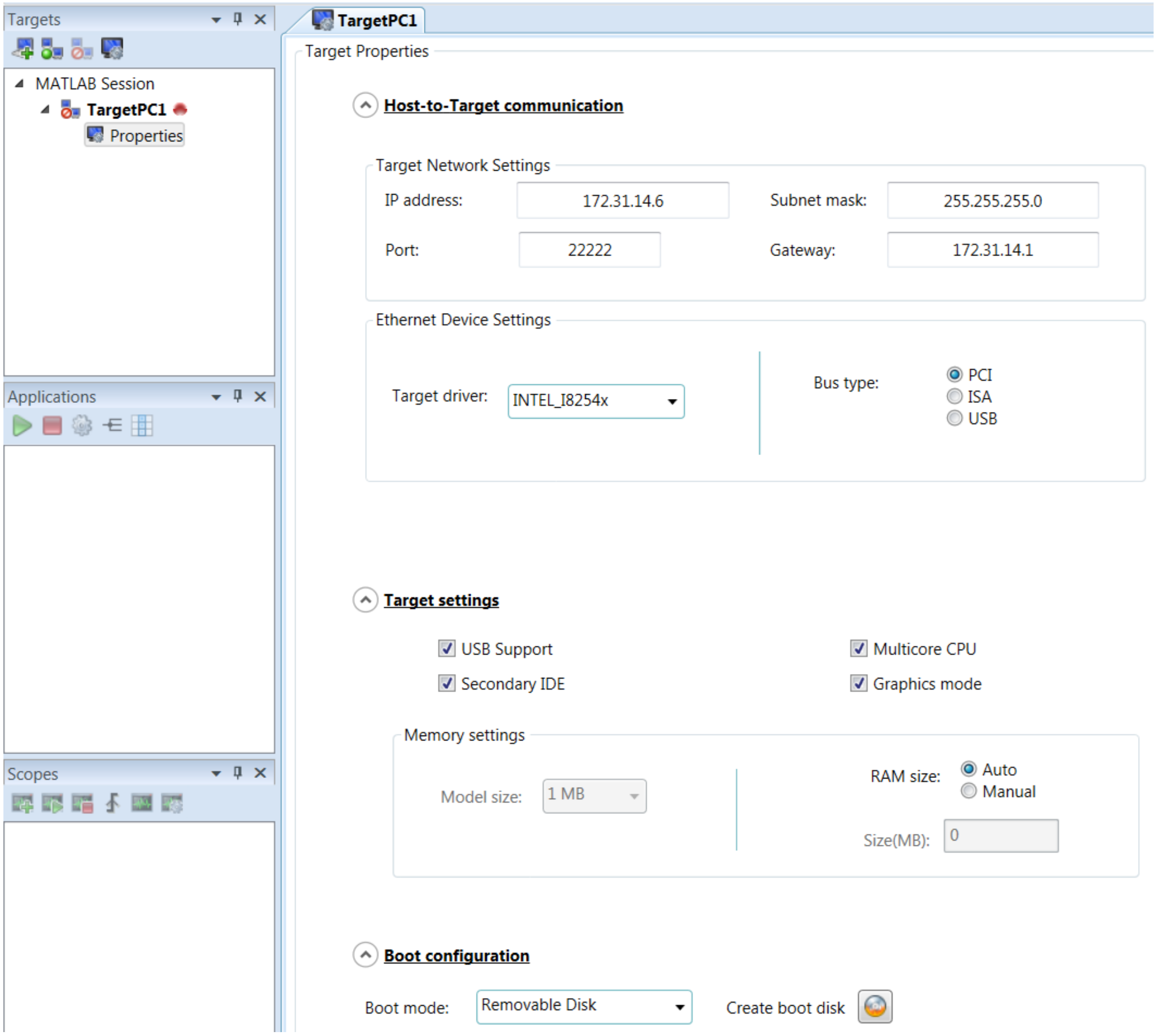


Figure 2.12: TagetPC1

7. Type, checkmark, and select the exact same as seen in figure 2.12 and press save.

Now the Matlab setup should compatible with the connected xPC.

Chapter 3

Data Acquisition and Control

All data acquisition and control is performed using a custom-build Speedgoat real-time machine (xPC).

3.1 Simulink-realtime target PC

The PC itself is a custom-build Speedgoat real-time machine, and is located inside the membrane control cabinet. Four NI data acquisition and output PCI-cards are situated in separate box inside the plant control cabinet and connected over a 1X PCI-express link using a DVI-cable and adapter. All sensors and actuators of the pilot-plant system are connected to these four cards using breakout boards and screw terminals.

! → *The DVI cable MUST NOT be connected to a video port, graphics card or display*

The target PC is used to run data capture and control experiments. It runs the "Simulink real-time target" operating system compatible with MATLAB 2014a and later. Models can be uploaded through a direct Ethernet connection using the following target configuration:

When running realtime-models, control of PC can be gained using the wireless keyboard and mouse connected to onboard USB 2.0 ports (USB 3.0 ports are disabled for compatibility)

Figure 3.1: Wireless keyboard and mouse

Some of the commands that can be executed by the wireless keyboard on the target PC are list below:

- start
- stop
- reboot
- stoptime
- sampletime
- setpar
- getpar

When the following command is tabbed then press ENTER. Otherwise, it is also possible to executed the command on the host PC by writing: ex. "stop(slrt)" in the Matlab command window.

Additional information can be found in the the Simulink Real-time (xPC) manual: `https://se.mathworks.com/help/pdf_doc/sldrt/sldrt_target_ug.pdf`

3.2 Simulink reference model

As the entire setup includes multiple inputs and outputs for logging, a connection sheet has been created to link what I/O PCI-card pin correspond to input and output of the setup. As this sheet is in Access format it enables quick future updating and revisions. The Microsoft Access file is described in chapter 6. The Simulink connections are named after the P&ID schematic for consistency. A simple test-model in Simulink is illustrated in figure 3.2.

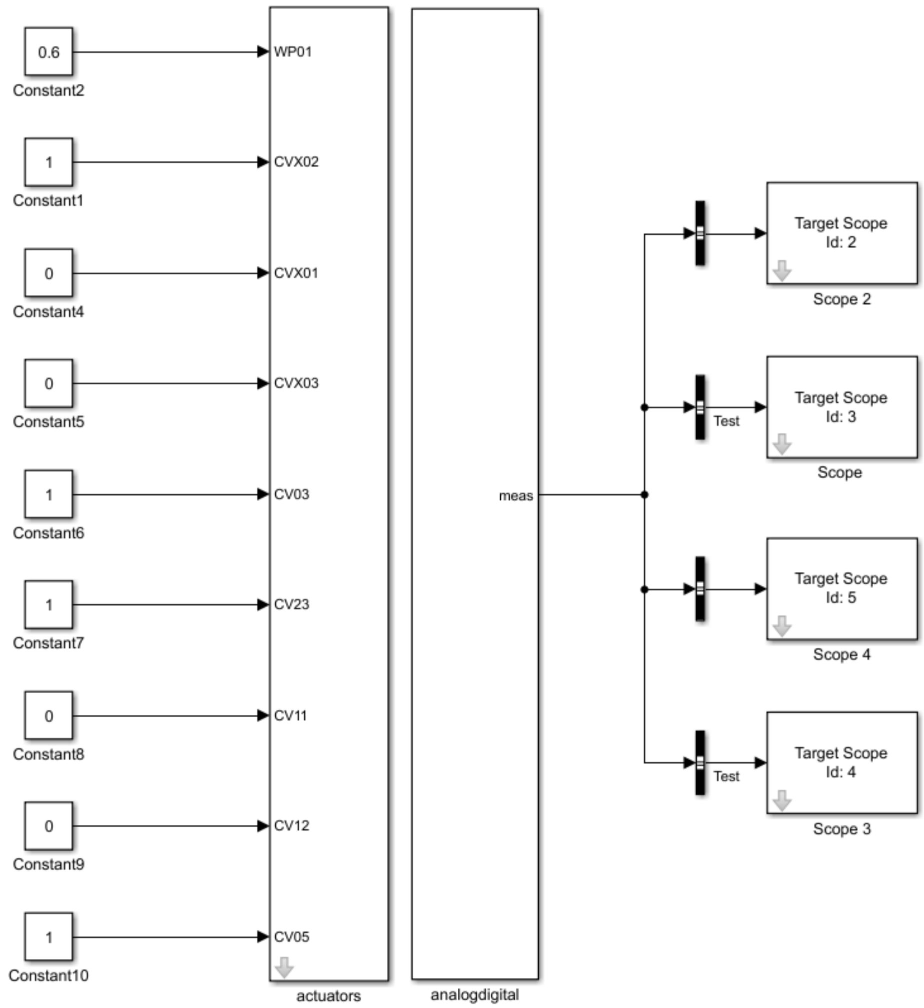


Figure 3.2: Simple test-model in Simulink:"`feedback_plant`"

This simple Simulink test-model is called "`feedback_plant`" and is found on the Lab-computer: `C:\...\Desktop\Lab_facility\Lab-model\plant\feedback_plant.slx`

For running the Simulink model some important steps have to be fulfilled:

1. Open Matlab.
2. Run the project file "`Labmodel.prj`" found in the **Current folder**.
3. Then go to the Command Window and write:
   `Capture_run('Simulink file name / Name of the data',sample time in seconds).`
   - As an example; for running the simple Simulink test-model "`feedback_plant`" in 1000s the capture_run-script will be:
     `Capture_run('feedback_plant/Test',1000)` and press ENTER.

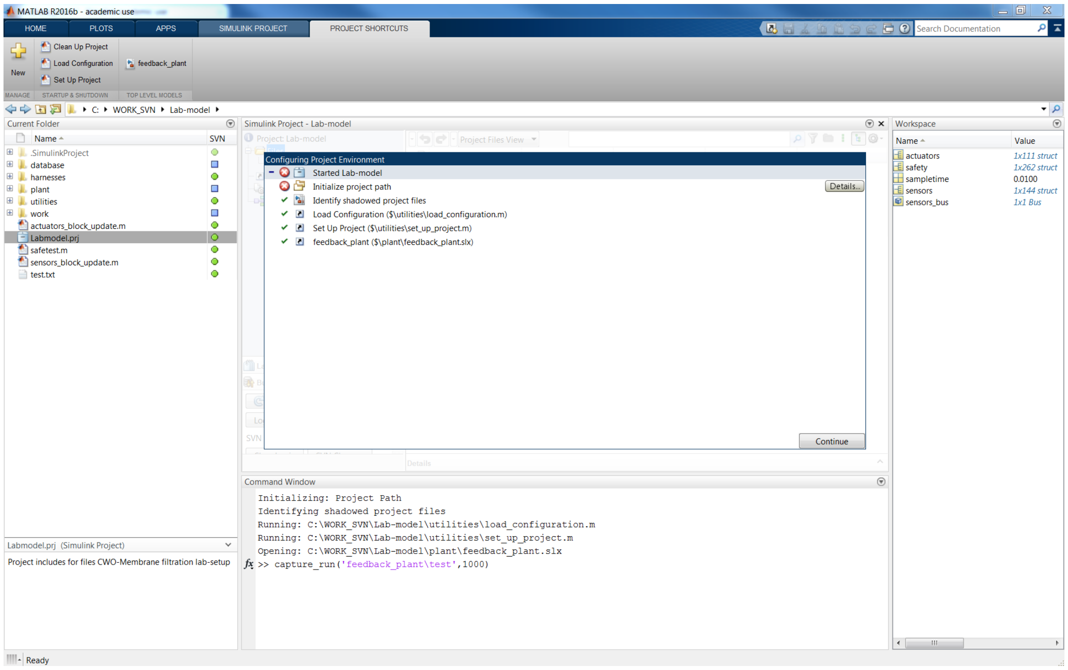


Figure 3.3: Matlab's command window

4. Matlab will start compiling the Simulink model, this can take some time, approximately 1-2 minutes.

5. When the compiling succeed, the system will start with the specification given from the Simulink model and the different scopes in the Simulink model will be displayed at the xPC, as seen in figure 3.4.

Figure 3.4: xPC display of different scopes in Simulink.

6. The test is done after the given test duration in the capture_run-script and the data-file can be found at: `C:\...\Desktop\Lab_facility\Lab-model\....`

The data is returned in a Matlab structure format, which includes the sensor data, actuator signals, experiment name, date and time and creating user. The sensor and actuator data are saved as a timeseries collection with the names corrosponding to the global sensor name list which respects the P&ID schematic. In addition the data is saved to disk for future analysis and statistics.

The individual sensors can be extracted like this:

```
exp_struct.Data.PT01 //Access pressure sensor PT01
exp_struct.Exc.WP02  //Access water pump WP02
exp_struct.Name      //Access experiment name
```

The timeseries can be directly plotted in matlab using plot command for quick viewing

```
plot(exp_struct.Data.PT01) //Plot pressure sensor PT01
title(exp_struct.Name)      //Label with experiment name
```

This will result in an image such as shown in figure 3.5:

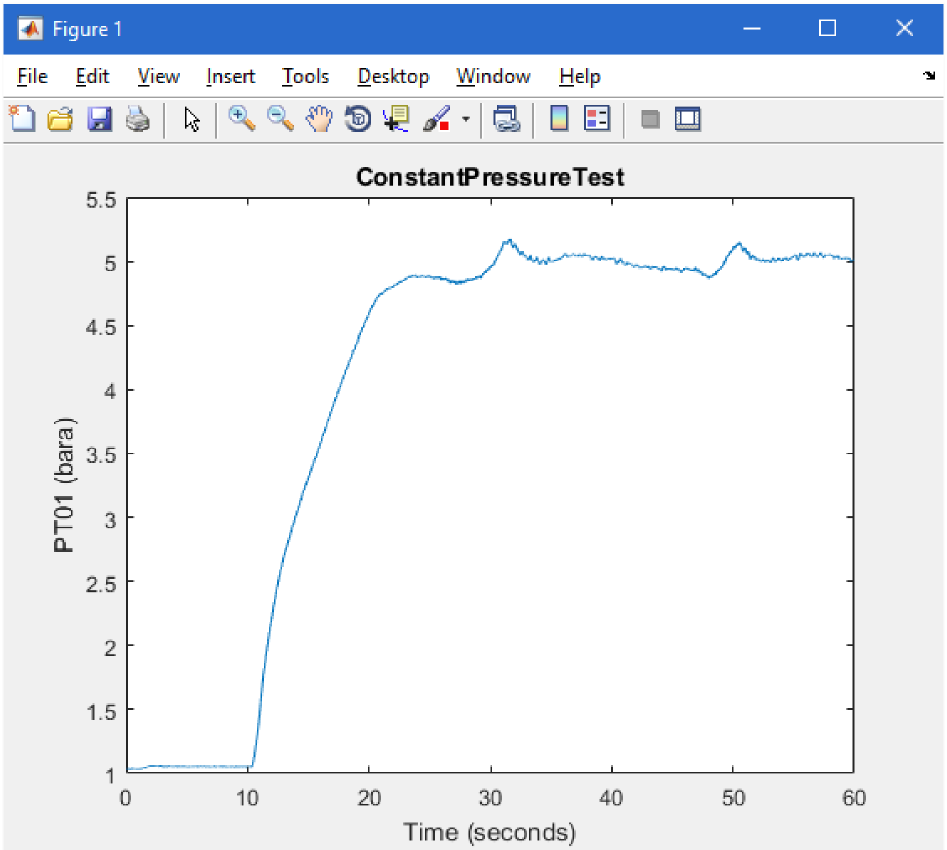


Figure 3.5: Example of plotting the acquired data

The main plant subsystem blocks

The main plant subsystem blocks can be seen in figure **??**. The main plant subsystem blocks contains a specific amount of signals from the main window, as seen in figure 3.2. Specific reference conditions outputs a signal to actuators and pumps to a wanted position or speed within the safety limitation predefined in the connection sheet.

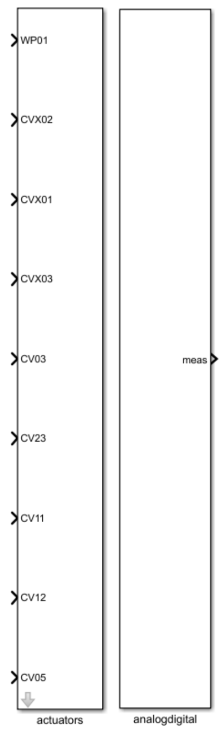


Figure 3.6: The main plant subsystem blocks.

If you want to open up the subsystem, click on the gray arrow down in the left corner. Nothing inside this main plant subsystem blocks should be changed by means of connecting or disconnecting signals, as doing so could lead to fatal damage of the software and hardware. For safety measures contact the oilrig plant setup staff if some changes should be done inside the main plant subsystem blocks.

By double-clicking on the subsystem a parameter window will appear as seen in figure 3.7.

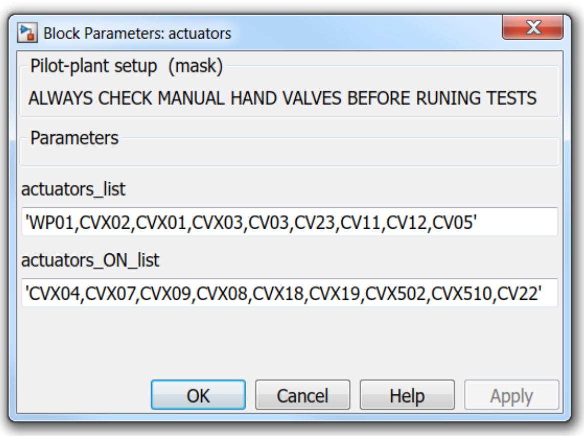


Figure 3.7: The main plant subsystem parameter-window.

- In the **Actuator list** select the different actuators you want to control from the P&ID

schematic.

- All actuators are default closed/OFF, under the **actuators_ON-list** select which actuators should be open/ON.
- Note the "ALWAYS CHECK MANUAL VALVES BEFORE RUNNING TEST" message. It is very important that the manual valves are configured correctly before running, as it can cause blocked flow paths and thereby high pressure built ups, which may lead to hardware damage!

Real-Time Target Scope Block

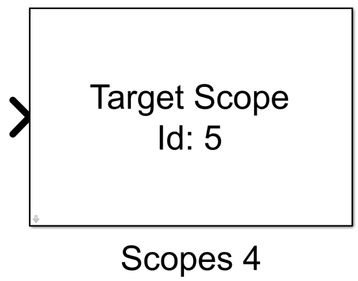


Figure 3.8: The main plant subsystem parameter-window.

Real-Time Target Scope Blocks can be configured to display signal and time data on the target computer monitor by adding Real-Time Target Scope Blocks and select in the **Scope type** list: *Target*, and configure the other parameters as described in the following procedure in figure 3.9.

Simulink Real-Time Scope block is NOT the same as a standard Simulink Scope block. Standard Simulink Scope block CAN NOT be used in the setup as a scope!

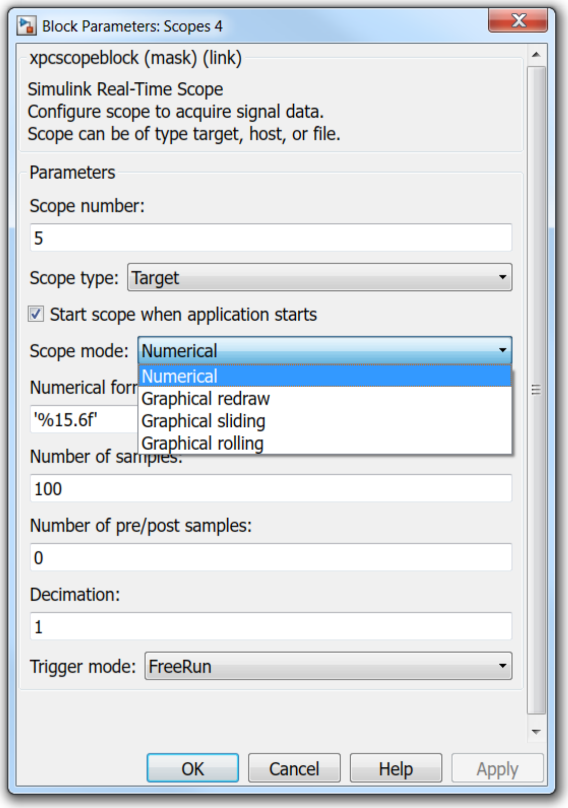


Figure 3.9: Real-Time Target Scope Block parameter window.

- The **Scope number** box is the scope number.
- From the **Scope type** list, select *Target* if it is not already selected.
- The **Scope mode** list makes it possible to select the display mode off your scope: *Numerical, Graphical redraw, Graphical sliding, or Graphical rolling.*
  - If you choose numerical scope mode and do not choose to complete the **Numerical format** box, the Simulink Real-Time software displays the signal using the default format of $\%15.6f$. This format is a floating-point format without a label.
- Enter the number of values in **Number of samples** box that you want displayed before updating the scope frame.
  - If you select a **Scope mode** of *Graphical*, the display redraws the graph every Number of samples.
  - If you select a **Scope mode** of *Numerical*, the block updates the output every number of samples.
- Select the default value 0 in **Number of pre/post samples** box.
- In the **Decimation** box select 1, means that the data is collected each sample time.

More information about the Real-Time Target Scope Block can be found on the webpage:
`http://se.mathworks.com/help/xpc/ug/trace-signals-with-xpc-target-target-scopes.html`

Bus Selector

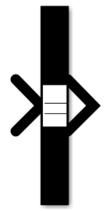


Figure 3.10: Bus selector block.

The Bus Selector block outputs a specified subset of the elements of the bus at its input. The block can output the specified elements as separate signals or as a new bus. When the block outputs separate elements, it outputs each element from a separate port from top to bottom of the block.

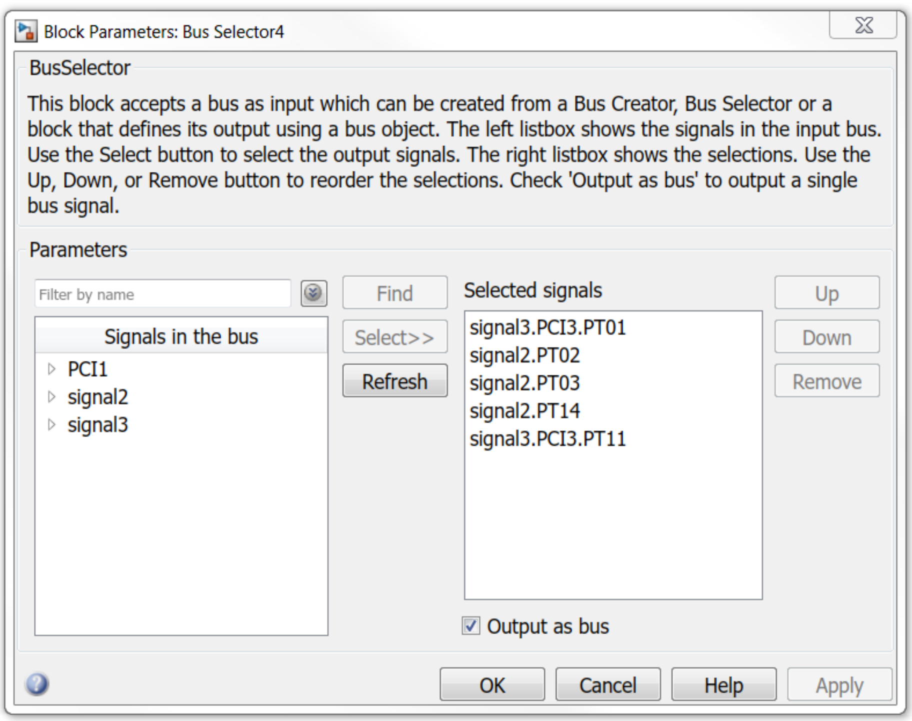


Figure 3.11: Bus selector parameter window.

This block accepts a bus as input which can be created from a Bus Selector that defines its output using a bus object. The left list-box show the **signals in the input bus**.

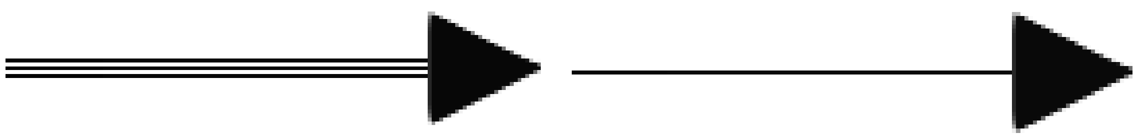
- **Filter by name** edit box make it easy to search for different equipment signals you want to select, and click on the **Select**≫-button, or manual select the different signals in the **Signals in the bus** edit.
- The right list-box shows the **selected signals**. Use the *Remove*-, *Down*-, or *Up*-button to reorder the selections.

The Output as bus checkbox determines if you want the outputs as bus signal or as single signals.

More information about the Bus Selector can be found on the webpage:
`https://se.mathworks.com/help/simulink/slref/busselector.html`

Signals

Just a small explanation about the difference between a **Bus Signal** and a normal **Scalar Signal**.



(a) Bus signal. (b) Scalar signal.

Figure 3.12: Different signals

Virtual Bus signals graphically combines two or more scalar signals into one signal line. A Simulink Bus Signal does not combine signals in any functional sense: it exists only virtually, and its only purpose is to simplify the visual appearance of a model. Using a series of scalar signals as a Bus Signal does not have an effect on simulation or generated code.

- Be aware that sometimes the Bus Signals in Simulink are NOT visually represented correct and graphically appears as a normal Scalar Signals.

The Bus Signal can always be split into single scalar signals by adding a Bus Selector and uncheck the checkbox output as bus, as shown in figure 3.13:

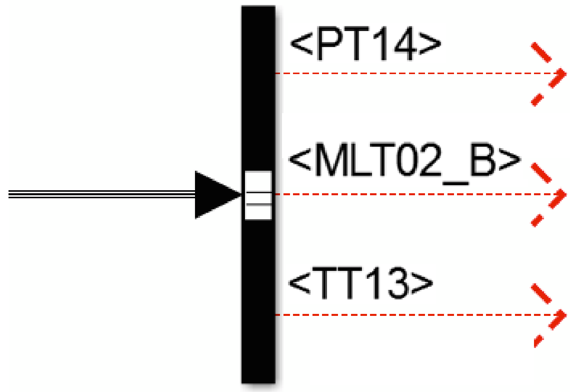


Figure 3.13: Split a bus signal into single scalar signals by adding a bus selector.

More and other information about different signals can be found on the webpage: `https://se.mathworks.com/help/simulink/ug/signal-basics.html`

Chapter 4

Quick start guide

4.1 Starting the system

1. Make an health check of the system including the following

   a) No major leaks

   b) Water tank (WT01) level not empty

   c) ~~Oil tank (OT01) level not empty~~

   d) Waste (MT02) level not full

2. Turn on main power on the rotating switch on the left of the cabinet
   Main switch

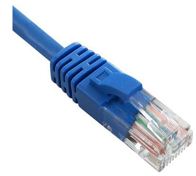
3. Make sure the correct version bootloader USB is inserted into the PC (corrosponding to your MATLAB version)

4. Turn on the control PC

4.2 Running experiments

1. see also **??**heck that valves are configured for the experiment

2. see also Section 3.1onnect your PC to the setup



a) Connect the blue ethernet cable to your PC (laptop)
   Ethernet cable

b) Use the script *network_setup.m* to set your network card to the same range as given on the screen of the control PC screen

c) Use the script *connect.m* to configure your MATLAB for the connection

3. see also Section 3.2mplement your experiment in the main model

   a) Put your design model inside the subsystem marked *controller*, overwriting the default actuator signals using bus assignment block

4. Run the experiment using the script (or manually)

5. If the experiment script was used, the data is returned as timeseries collections and saved to disk

4.3 Shutting down the system

1. Turn off the control PC

2. Turn off main power on the rotating switch on the left of the cabinet

3. Return valves to default positions

Chapter 5

Troubleshooting

Below are the solutions to various error conditions might occur. Some errors are caused by the real-time target PC, others by the host PC, and others are related to the process system

5.1 Real-time target PC

PCI card not found/present Verify that the PCI-expansion box inside the cabinet is powered, then reboot the PC.

Could not find target Verify that the network cable is connected, and that the host PC TCP/IP settings are in the right range.

Invalid version of Simulink Verify that the correct USB stick version has been inserted into the PC, then restart it.

5.2 MATLAB error

Could not build Verify that the PCI objects (PCI34, PCI35, PCI36, PCI37) are in the MATLAB workspace, if not, close and reopen model.

Could not build Remove the slprt and rtw named folders in the current folder, then try again

oilrig_setup not loaded Verify that the main model is open and properly loaded

5.3 Process errors

PT15 too high The buffer air pressure is too high, reduce the inlet pressure at the wall mounted regulator (to below 5 bar)

WT1 too high There is too much water in the waste tank, verify that it is being emptied automatically, and that the pumps are turned on

WT2 too high There is too much water in the supply tank, verify that automatic filling is not malfunctioning

Chapter 6

Access file

The Microsoft Access file is generated to create a broad overview of the oilrig setup multiple components, connections, lower- and upper-safety limits, datasheets, and etc. The Access file serves as an all-in-one package for more user-friendly interface, so individual users do not have to search for multiple documents. Figure 6.1 shows part of the information that can be found in the Access file. The table can be used for; debug inappropriate shutdowns, cross-connect with the P&ID schematic, check connections, find data sheets for specific components, etc. The Access file can be found on the assigned oilrig setup computer at `C:\...\Desktop\Lab-facility\Lab-model\Database\connections.accdb`.

Actuator List with all Specs | Devices | DeviceTypes | InterfacePins | Interfaces

Tag	Manufacturer type	Actuator terminal	Subsystem	Lower safe	Upper safe	Card type	Breakout	Physical pin	Type	Slot	Offset	Gain	Unit
AFM01	Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508	X2.2.7.2	Supply	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
AFM01_M	Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508	X2.2.8.2	Supply	0	1	PCI6229 A	1	19	DO	[6,5]	0	10	one
AFM02	Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508	X2.2.9.2	Seperator	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
AFM02_M	Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508	X2.2.10.2	Seperator	0	1	PCI6229 A	1	51	DO	[6,5]	0	10	one
AFM03	Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508	X2.2.11.2	Pipelineriser	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
AFM03_M	Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508	X2.2.12.2	Pipelineriser	0	1	PCI6229 A	1	16	DO	[6,5]	0	10	one
CV03	Bürkert 8692 + Bürkert 2301 item no.: 00214039	X2.12.2.2	Pipelineriser	0	1	PCI6229 C	1	22	AO	[6,7]	0	10	one
CV04	Bürkert 8692 + Bürkert 2301 item no.: 00205010	X2.5.5.2	Hydrocyclone	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
CV05	Bürkert 8692 + Bürkert 2301 item no.: 00205019	X2.5.9.2	Supply	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
CV07	Bürkert 8692 + Bürkert 2301 item no.: 00205012	X2.5.3.2	Hydrocyclone	0	1	PCI6229 A	1	21	AO	[6,5]	0	10	one
CV08	Bürkert 8692 + Bürkert 2301 item no.: 00205019	X2.11.2.2	Seperator	0	1	PCI6229 B	0	22	AO	[6,6]	0	10	one
CV09	Bürkert 8692 + Bürkert 2301 item no.: 00210529	X2.5.7.2	Hydrocyclone	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
CV101	Bürkert 8692 + Bürkert 2301	1W3.1.03	Membrane1	0	1	IO110 A	0	3	AO	[2,4]	0	10	one
CV102	Bürkert 8692 + Bürkert 2301	1W3.1.04	Membrane1	0	1	IO110 A	0	4	AO	[2,4]	0	10	one
CV11	Bürkert 8692 + Bürkert 2301 item no.: 00205012	X2.11.3.2	Seperator	0	1	PCI6229 B	0	21	AO	[6,6]	0	10	one
CV111	Bürkert 8692 + Bürkert 2301	1W3.1.05	Membrane1	0	1	IO110 A	0	5	AO	[2,4]	0	10	one
CV112	Bürkert 8692 + Bürkert 2301	1W3.1.06	Membrane1	0	1	IO110 A	0	6	AO	[2,4]	0	10	one
CV12	Bürkert 8692 + Bürkert 2301 item no.: 00205012	X2.5.13.2	Seperator	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
CV121	Bürkert 8692 + Bürkert 2301	1W3.1.07	Membrane1	0	1	IO110 A	0	7	AO	[2,4]	0	10	one
CV122	Bürkert 8692 + Bürkert 2301	1W3.1.08	Membrane1	0	1	IO110 A	0	8	AO	[2,4]	0	10	one
CV13	Bürkert 8692 + Bürkert 2301 item no.: 00205010	X2.4.3.2	Hydrocyclone	0	1	PCI6229 C	0	21	AO	[6,7]	0	10	one
CV14	Bürkert 8692 + Bürkert 2301 item no.: 00210529	X2.4.2.2	Hydrocyclone	0	1	PCI6229 C	0	22	AO	[6,7]	0	10	one
CV15	Bürkert 8692 + Bürkert 2301 item no.: 00205012	X2.5.19.2	Supply	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
CV201	Bürkert 8692 + Bürkert 2301	2W3.1.11	Membrane2	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV202	Bürkert 8692 + Bürkert 2301	2W3.1.12	Membrane2	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV211	Bürkert 8692 + Bürkert 2301	2W3.1.13	Membrane2	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV212	Bürkert 8692 + Bürkert 2301	2W3.1.14	Membrane2	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV22	Bürkert 8692 + Bürkert 2301 item no.: 00205019	X2.5.17.2	Seperator	0	1	PCI6704	0	0	AO	[6,4]	0	10	one
CV221	Bürkert 8692 + Bürkert 2301	2W3.1.15	Membrane2	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV222	Bürkert 8692 + Bürkert 2301	2W3.1.16	Membrane2	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV23	Bürkert 8692 + Bürkert 2301 item no.: 00205019	X2.12.3.2	Seperator	0	1	PCI6229 C	1	21	AO	[6,7]	0	10	one
CV301	Bürkert 8692 + Bürkert 2301	3W3.1.19	Membrane3	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
CV302	Bürkert 8692 + Bürkert 2301	3W3.1.20	Membrane3	0	1	IO110 A	0	10	AO	[2,4]	0	10	one
[illegible]	Bürker[illegible]692 + Bü[illegible]rt 2301	[illegible].21	[illegible]brane3	[illegible]	1	IO110 A	0	10	AO	[2,4]	0	10	one
[illegible]	Bür[illegible]2 + B[illegible]t 2301	[illegible]	[illegible]e3	[illegible]	[illegible]	IO110 A	[illegible]	[illegible]	[illegible]	[2,4]	0	[illegible]	[illegible]

Figure 6.1: Example from Access: Actuators.

In addition to the columns shown in table 6.1 other relevant information, that could be useful, can be found in the Access file. The list below will provide a brief explanation of all columns found in the Access file.

1. The **Tag** column can be used to cross-check each specific component's manufacture type, connections, and etc. with the P&ID schematic.
2. The **Manufacturer type** column is a list of all components full manufacturer names.
3. Each sensor and/or actuator connections are listed in **Sensor terminal**- and **Actuator terminal** columns.
4. The **Subsystem** column is what subsystem the component can be found in.
5. The **Lower safety** and **Upper safety** columns are determined safety values. If one of the safety limits is exceeded under an experiment the system will shut down.
6. The **Shutdown** check-boxes are used to checkmark each specific component that should detect its lower and upper safety limit and shut down. If no checkmark, the system will not shut down even though it had exceeded its limitations.
7. The **Card type** is what I/O-card the component is connected to.
8. The **Breakout** column shows what breakout board the component is connected to.
9. The **Physical pin** column shows what physical pin on the I/O-card the component is connected to.
10. The **Type** column shows if the component is analog or digital and input or output.
11. The **Slot** column shows the card type of the I/O-card and the breakout board.
12. The **Offset** column shows the offset calculation factor of the components signal to I/O-card connection.
13. The **Gain** column shows the gain calculation factor of the components signal to I/O-card connection.
14. The **Unit** column indicates the unit of each specific component.
15. The **Datasheet** column contains PDF-files of all components' data sheets.

Chapter 7

Device description

This chapter describes all components used in the oilrig test setup. Detailed information about specific components can be found in the components data sheet respectively.

7.1 Valves

There exist variety of different valve types used in industrial applications, each with its pros and cons. Therefore, it is essential to choose the right type of valves, which fulfills the requirements for that specific setup they are implemented in. Some of the more common types of valves are: ball valve, butterfly valve and globe valve. All control valves have an inherent flow characteristic that defines the relationship between valve openings and flow rates under constant pressure conditions. Figure 7.1 shows different characteristic curves for different valve types.

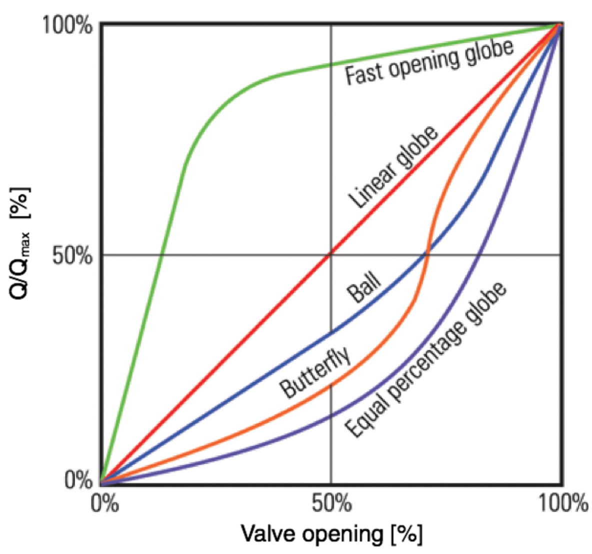


Figure 7.1: Inherent flow characteristic curves of typical valves.

However, when valves are installed with pumps, piping, and other process equipments, the pressure drop across the valve will vary as the plug moves. This will give a different flow rate with same valve opening percentage, compared with its inherent characteristic curve, which is defined as an installed characteristic curve. The installation effect of a valve often results in the inherent characteristic curve of a linear globe valve will resemble a quick opening characteristic curve, and an equal percentage globe valve characteristic curve will in general resemble a linear curve.

Bürkert 2301 globe control valve with Bürkert 8692 position controller

The oilrig test setup uses Bürkert 2301 pneumatically operated 2-way globe control valve incorporated with Bürkert 8692 electro-pneumatic position controller. The combination of Bürkert positioner type 8692 and valve type 2301 is used as a valve-set for all controllable valves in the entire oilrig test setup. The Bürkert valve-set is seen in figure 7.2.

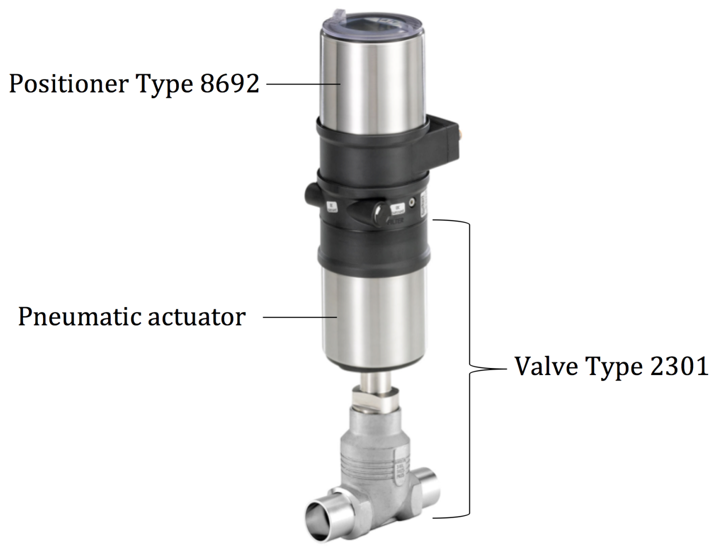


Figure 7.2: Complete valve-set of Bürkert positioner type 8692 and Bürkert valve type 2301.

The inherent characteristic curve of Bürkert globe valve type 2301 is an equal percentage flow curve, which can be seen in figure 7.3.

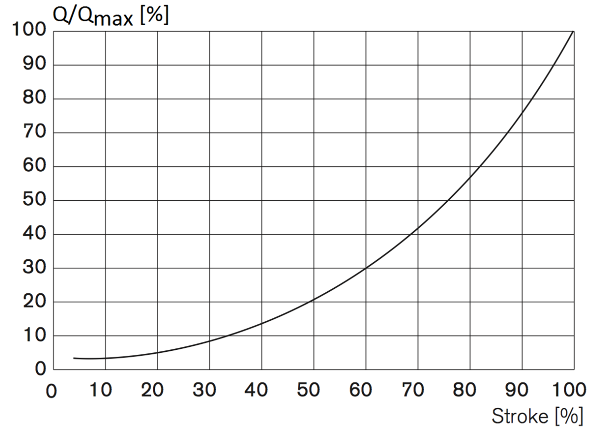


Figure 7.3: Equal percentage inherent characteristic flow curve of Bürkert 2301 globe control valve.

The stroke is the opening percentage of the valve and Q/Q_{max} is the flow ratio seen in figure 7.3. Q is the flow rate at different strokes and Q_{max} is the maximum flow rate value through the valve. This gives an idea that Bürkert 2301 globe valve should operate as a linear curve of flow rate as a function opening percentage, in an installed setup. The operating time for the entire stroke, from fully open to fully closed, is a range from 1-60s, which can be adjusted on the position controller under the X.TIME settings. In the oilrig test setup all Bürkert valves' operating time is set to 1s. The pneumatic actuator is the reason for this relative fast response time. The pneumatic actuator has a chamber in which regular air is contained and allowed to expand. As the air expands, a pressure difference between the inside of the chamber and the natural atmospheric pressure causes the air to build up energy. The air is then allowed to leave the chamber in a controlled manner so that the position of the valve is at the desired opening percentage. The Bürkert 8692 position controller secures that the valve is at the desired opening percentage, its function diagram is illustrated in figure 7.4.

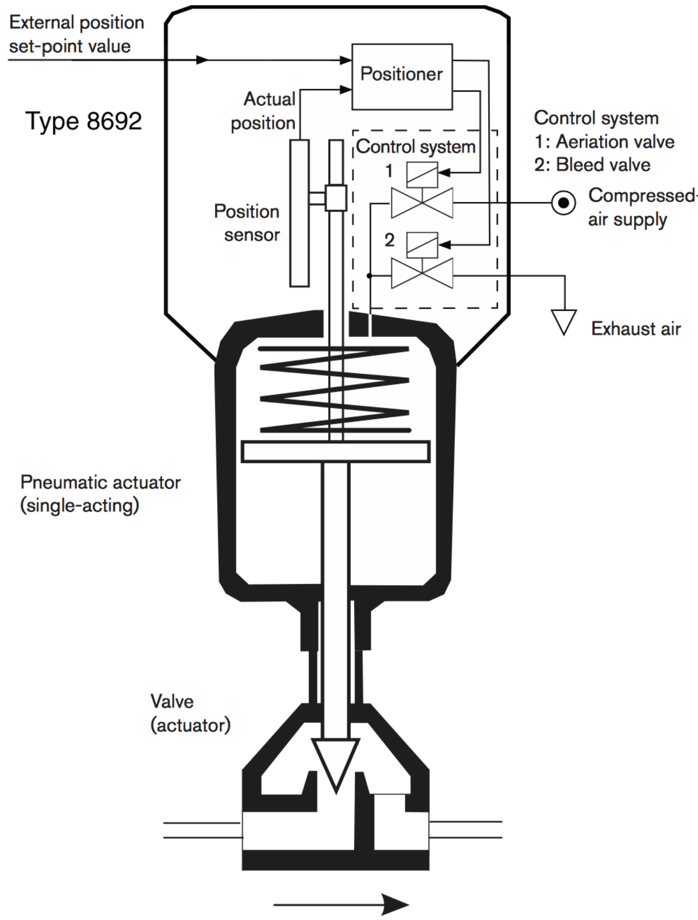


Figure 7.4: Function diagram of Bürkert positioner controller 8692.

When a set-point value is given to the controller, the controllers' positioner compares this actual position value with the set-point value (CMD), which is specified as a standard signal. The position sensor records the current position (POS) of the pneumatic actuator, which gives the actual position feedback to the positioner. The positioner gives two outputs, if there is a positive control difference in single-acting actuators, the air inlet is controlled via aeration valve, as seen in figure 7.4, or as output B1 in figure 7.5. If the control difference is negative, the exhaust air is controlled via bleed valve, as seen in figure 7.4, or as output E1 in figure 7.5. In this way the position of the actuator is changed until control difference is equal to zero. Z1 represents a disturbance variable.

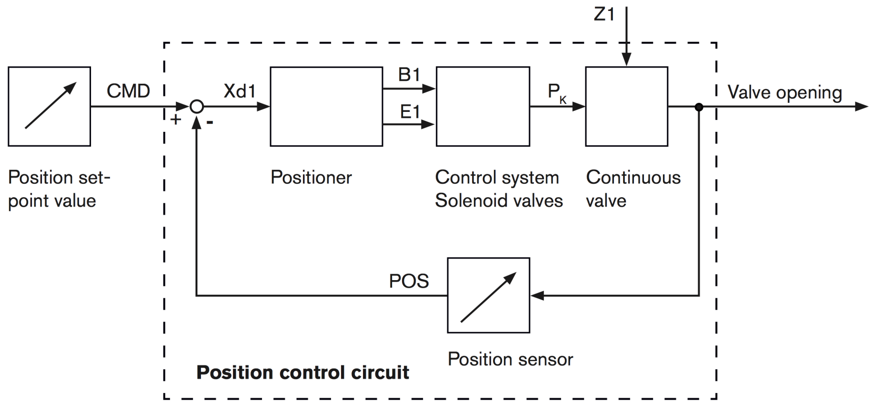


Figure 7.5: Circuit diagram of Bürkert positioner controller 8692.

Table 7.1 shows the common specifications for the Bürket 8692 + 2301 and table 7.2 shows the different subtype specifications.

Specification	Rating
Air supply pressure	5.5-7Bar
Air supply temperature	$-10°C$ to $55°C$
Medium temperature	$-10°C$ to $185°C$
Hysteresis	1%
Supply voltage	24V DC
Input signal	4-20mA
Operating time	1s

Table 7.1: Bürket 8692 + 2301 control valves specifications

Subtype	Port size	Kvs	Operation pressure	Seat Size
00210529	1/2"	0.5	16Bar	4mm
00205010	1/2"	4.3	16Bar	15mm
00205012	3/4"	7.1	16Bar	20mm
00205019	2"	28	7Bar	50mm
00214039	2"	37	16Bar	50mm

Table 7.2: Bürket 8692 + 2301 control valves subtype specifications

Belimo R2050-S4 + SR24A-SR Isolation Valves

The isolation-valves (on/off-valves) are Belimo two-way ball valves of the type R2050-S4. To control the ball valves a Belimo SR24A-SR actuator is mounted. These valves can only be in an open- or close-state and have a operating time of 90s, see figure 7.6. This valve has an equal percentage characteristic (VDI/VDE 2178) and optimized in the opening range.

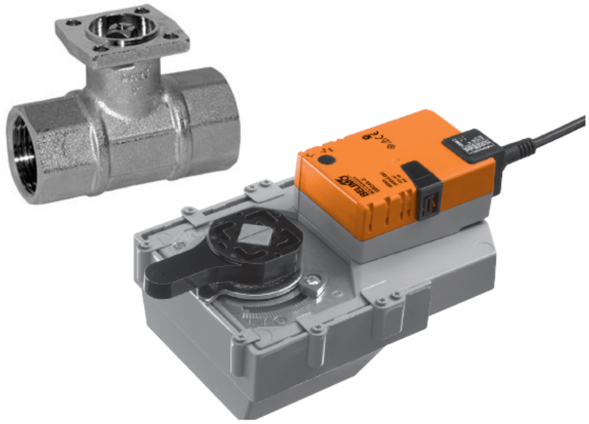


Figure 7.6: Belimo SR24A-SR actuator and Balimo R2050-S4 two-way ball valve.

Table 7.3 shows the specification of the Belimo SR24A-SR actuator and Balimo R2050-S4 two-way ball valve. Note that Kvs-value is the unit of measurement for water flow rate in m^3/h flowing through the fully opened valve with a pressure difference over the valve of 1Bar.

Specification	Rating
Liquid temperature range	$-10°C$ to $120°C$
Max. operating pressure	6.9Bar (100psi)
Rated pressure ps	16Bar
Closing pressure Δps	14Bar
Deferential pressure Δpsmax	3.5Bar
Accuracy	±5%
Kvs-value	25 or $40m^3/h$
Input signal	2-10V
Pipe connection	2”
Ambient temperature	$-30°C$ to $50°C$
Response/running time	90s

Table 7.3: Belimo isolation valves specifications

Bürkert 2051 + 6519 Isolation Valves

Table 7.4 shows the specification of the Bürkert 2051 + 6519.

Specification	Rating
Liquid temperature range	$-10°C$ to $50°C$
Operating pressure	2-8Bar
Ambient temperature	$-25°C$ to $55°C$
Qnm value air	900L/min
Opening time	20 or 75ms
Closing time	40 or 115ms

Table 7.4: Bürket 2051 + 6519 isolation valves specifications

7.2 Pressure Transmitters

The setup contains Siemens SITRANS P200 7MF1565 pressure sensors. The pressure sensor measures the absolute pressure and have a measuring range of either 0-6barA, 0-10barA, or 0-16barA, which are placed strategically in their respective areas, cross-check the P&ID schematic with the Access file to find each specific pressure transmitters' measuring range. Figure 7.7 shows the pressure sensor.

Figure 7.7: Siemens SITRANS P200 7MF1565 pressure sensor.

The pressure sensor has a typical 0.25% deviation from the characteristic curve with hysteresis and a maximum of 0.5% measuring inaccuracy.

7.3 Differential Pressure Transmitter

ASK 800 Contrans P is a differential pressure transmitter, which can be used for different kind of measurements; liquid-, gas-, vapor-, and level measurement. ASK 800 Contrans P can be seen in figure 7.8.

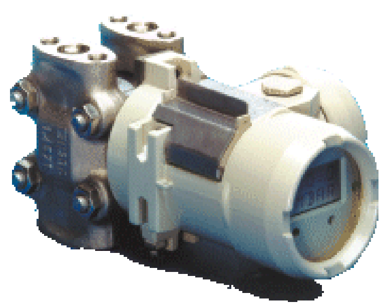


Figure 7.8: Differential pressure transmitter ASK 800 Contrans P.

The differential pressure transmitters are in this setup used for level measurement inside the separator tank on both produced waterside and oil side. In the separator tank the gas pressure acts on the liquid and at the same time via the connected differential pressure pipe, on the other side of the differential pressure transmitter see figure 7.9.

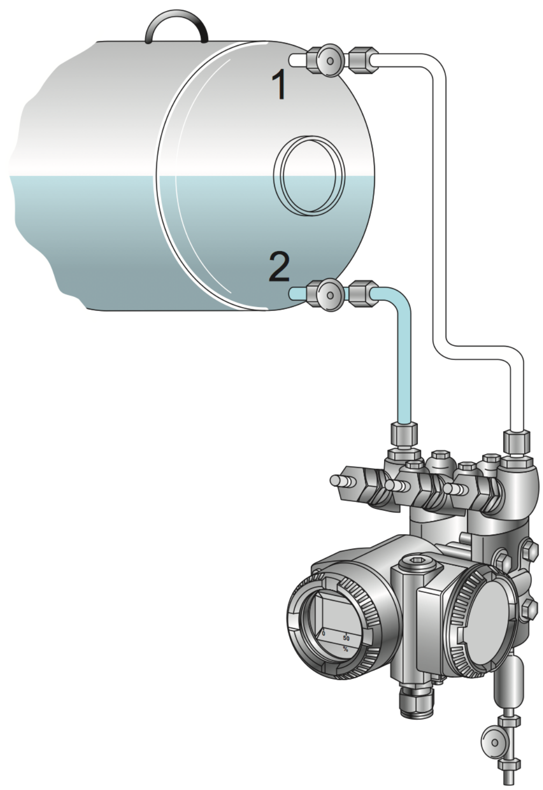


Figure 7.9: Differential pressure transmitter with a dry leg installation.

As the gas pressure acts on both sides simultaneously, it cancels out. The output signal of the transmitter is therefore proportional to the level of the separator tank. The transmitter must be installed beneath or as same height as the outlet. The outlet must be installed at the side of the tank. The height of the transmitter is decisive for the lower range value. To calibrate the level measurement of the differential pressure transmitters to the given current, 4-20mA, you have to take some part into consideration.

Do to the density of the gas is significantly lower than the fluid, the gas will fill the top of the tank. Thereby the gas is transmitted to the low-pressure side of the differential pressure transmitter. This type of pressure connection is known as a dry leg. In situations where the gas tends to condense at certain temperatures, the reference leg can't be kept dry. Therefore, both leg must be filled with liquid to produce a wet reference leg. Or situation where the interface level should be measured of two different liquids.

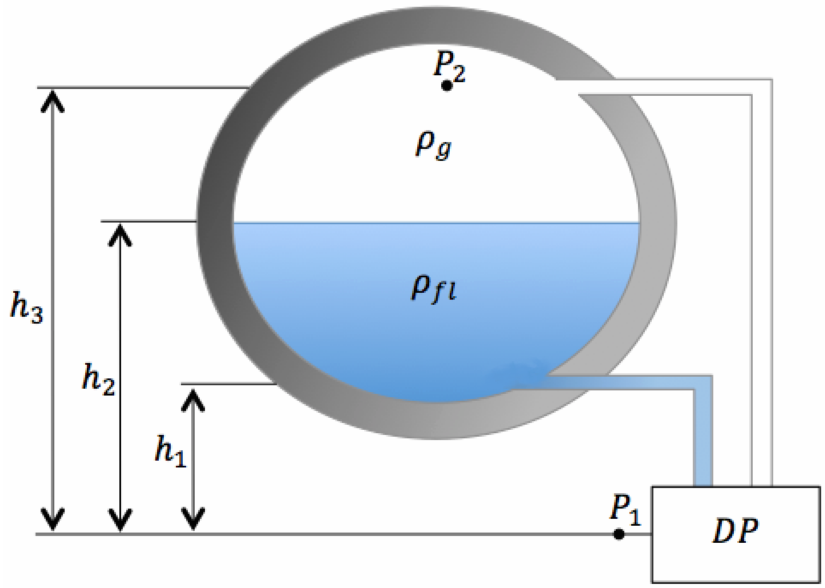


Figure 7.10: Calibration of differential pressure transmitters with a dry leg installation.

In the oilrig setup we are dealing with two phases, fluid and gas, which means we have a dry leg condition, as seen in figure 7.10. The following calibration of the level with the differential pressure transmitters can be calculated as equation 7.1 to 7.3. Where ΔP_{min} corresponds to 4mA, ΔP_{max} corresponds to 20mA, and ΔP is the level in between.

$$\Delta P_{min} = \rho_g g(h_3 - h_1) + p_{fl} g h_1 \tag{7.1}$$

$$\Delta P_{max} = \rho_{fl} g h_3 \tag{7.2}$$

$$\Delta P = \rho_g g(h_3 - h_2) + \rho_{fl} g h_2 \tag{7.3}$$

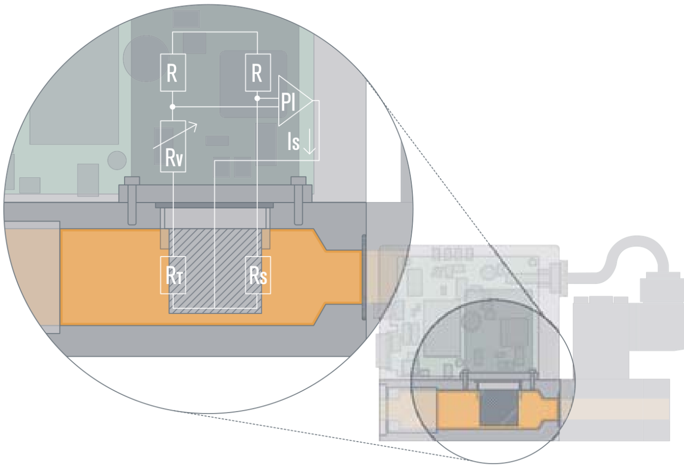
If there are significant temperature changes, the amount of error will vary widely. Also if small diameter diaphragms are installed on seals, the differential pressure transmitter is more sensitive to temperature changes. Larger diameter diaphragms help to minimize the errors. Slugging flow in the separator tank will also affect the measurement of the level.

7.4 Air Flow Meter

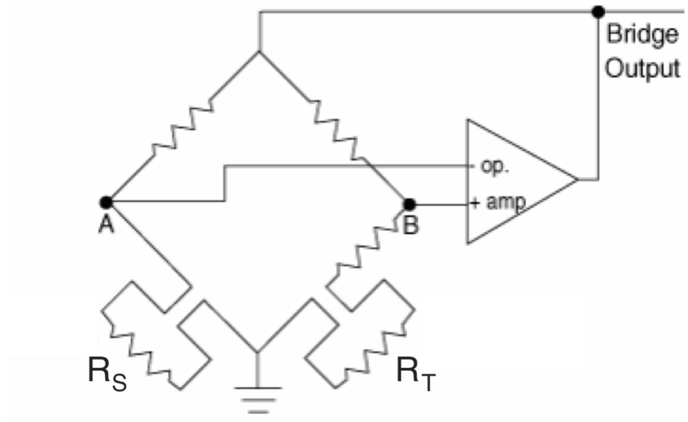
An air flow meter, measure the air is flowing through a pipeline. It does not measure the volume of the air passing through the pipeline, but instead the mass. The oilrig setup uses Bürkert 8626 Air flow meters which can be seen in figure 7.11.

Figure 7.11: Bürkert 8626 air flow meter.

The mass flow controller (MFC) type 8626 is suited for regulating the mass flow of high gas flows. The thermal inline sensor is located directly in the gas stream and therefore reaches very fast response times. The air flow meter has a nominal flow range of 20 to $1500L/min$ and a maximum operating pressure of 10bar. The nominal flow range is for air, which is the gas used in the oilrig setup, however the nominal flow range will of course change if another gas was used. The gas temperature must not be lower than $-10°C$ or above $70°C$. The air flow meter transmitter works with use of a hot-film CTA anemometer (Constant Temperature Anemometer). It consists of two thermistor resistors, which working as sensors: The first resistor (R_T) measures the fluid temperature, while the second resistor (R_s) is heated to maintained at a fixed predefined over-temperature with respect to the fluid temperature. R_T then senses the surrounding air temperature and forces the R_s to stay at a constant "overheat" temperature.



(a) Datasheet's illustration of the Wheatstone bridge.



(b) Wheatstone bridge diagram.

Figure 7.12: Measuring principle of the air flow meter.

The circuit forces the voltage at points A and B to be equal by means of an operational amplifier. Air flowing past R_s tends to cool the resistor and thereby driving down its resistance. The operational amplifier responds by immediately delivering more power to the top of the bridge to maintain voltage equilibrium at points A and B. As more air flows passes through the resistor, more power is required to maintain a balanced bridge. This means that the power going into the top of the bridge is related to the velocity of the air flowing past the resistor.

Table 7.5 shows the specification of the Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508.

Specification	Rating
Max. operating pressure	10Bar
Gas temperature	$-10°C$ to $70°C$
Accuracy	$\pm0.3\%F.S$
Repeatability	$\pm0.1\%F.S$
Qnm value air	900L/min
Control valve	Normally closed
Valve orifice	0.8 to 12mm
Kvs	0.02 to $2.8m^3/h$
Supply Voltage	24V DC
Input Signal	0-10V
Port Connection	G1/4

Table 7.5: Bürkert MFC8626 + Bürkert 2833 + Bürkert 2508

With atmospheric air the min. and max. nominal I_N/min are 20 and 1500 respectively.

7.5 Temperature Transmitter

AMETEK 1XPt100 temperature transmitters are used to measure the temperature in pipes and tanks. They have an operating range up to 600°C, maximum 60bar, and a maximum flow velocity of 25m/s. the temperature transmitter can be seen in figure 7.13.

Figure 7.13: AMETEK 1XPt100 temperature sensor.

7.6 Multilevel Sensors

Multilevel sensors Vegaflex 81 are used to measure the level of all types of liquids in the waste tank and separator tank. The Vegaflex 81 transmits high frequency microwave pulses to measure the level. Some of the pulses are reflected at the surface and the remaining unknowns travels on and is reflected at the interface. The distance or level is proportional to the time it takes to send and receive pulses at the product layers. Vegaflex 81 has a measuring range up to 6m (rod probe). It can detect temperatures from -40°C to 200°C, process pressure from -1bar to 40bar and has an accuracy of ±2mm. To measure the oil settling above the water, a minimum of 1cm height is required.

Figure 7.14: Multilevel sensor Vegaflex 81.

7.7 Level Sensors

The ultrasonic level sensor Vegason 62 is mounted on the oil tank and water tank. The transducer of the ultrasonic sensor transmits small ultrasonic pulses, to measure the level. The pulses are reflected by the surface of the liquid and received as echoes by the transducer. The distance or level is proportional to the time it takes to send and receive pulses.

Figure 7.15: Ultrasonic level sensor Vegason 62.

7.8 Coriolis Flow Meters

The coriolis flow meter method is normally based on one or two tubes inside, where an exciter causes the tubes to oscillate constantly. If there is no flow the measuring tubes oscillates uniformly, sensors are located at the inlet and outlet of the coriolis flow meter, and do a precise registration of the oscillation. As soon as the fluids starts to flow in the measuring tubes, an additional twisting is applied on the oscillation as a results of the liquids inertia, which is the fluids resistance to change in its state of motion. Do to the coriolis effect, the inlet and outlet chapter of the tubes oscillates in different directions at the same time. The highly sensitive sensors pick up this twisting oscillation, known as the phase shift. The phase shift is the time difference between the waves and is directly proportional to the mass flow rate of liquid, or gases, flowing through, which can be seen in figure 7.16. Simultaneously it can measure the density of the liquids or gases, this is done by measuring the oscillation frequency.

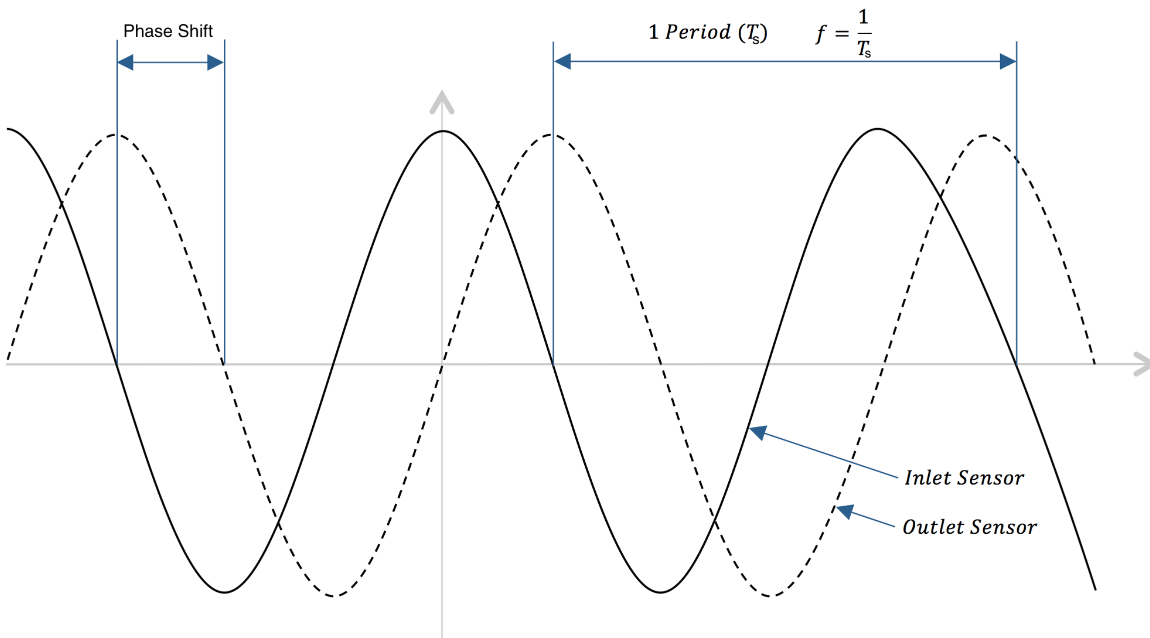


Figure 7.16: Coriolies flow meter wave illustration.

Although temperature measurement is not necessary to determine mass flow rate, most coriolis flow meters include temperature sensor to compensate for small temperature changes, which has an influence on the tubes stiffness, Young's Modulus of Elasticity. Therefore, temperature is typically offered as a third output variable, along with mass flow rate and density. The Coriolis flow meters there are used in the oilrig test setup are Micro Motion ELITE coriolis flow meters of the type CMFS010M and CMFS015M and can be mounted on vertical, horizontal, or inclined pipelines. The Micro Motion ELITE coriolis flow meter can be seen in figure 7.17, where the only design difference between type CMFS010M and CMFS015M is the nominal diameter.

Figure 7.17: Micro Motion ELITE coriolis flow meter type CMFS010M and CMFS015M.

Micro Motion ELITE coriolis flow meter can measure the three outputs simultaneously; mass flow rate, density, and temperature. It gives an accuracy and repeatability performance offset value for the three outputs, seen in table 7.6.

Performance Specification	Standard
Mass/volume flow accuracy	$\pm 0.10\%$ rate
Mass/volume, flow repeatability	$\pm 0.05\%$ rate
Density ,accuracy	$\pm 0.0005\ g/cm^3$
Density, repeatability	$\pm 0.0002\ g/cm^3$
Temperature, accuracy	$\pm 1°C$ $\pm 0.5°C$ of reading
Temperature, repeatability	$\pm 0.2°C$

Table 7.6: Accuracy and repeatability on liquids with Micro Motion ELITE coriolis flow meters.

Where the operating conditions for the offset standard values are determined under the following conditions:

- Water at 20-25$°C$ and 1-2 barG
- A density range up to 5 g/cm^3
- The accuracy is based in industry leading accredited to International Organization for Standardization calibration and testing laboratories, ISO 17025.

One of the difficulties for all flow meters is accurate measurement in two-phase flow. The fluid dynamic characteristics of a liquid and gas mixture are extremely complex, that measurement of such an unpredictable flow stream is a challenge with all types of flow meters, including Coriolis.The Micro Motion Coriolis flow meters distinguish between the compositions by using Gas Void Fraction (GVF) as seen in equation 7.4.

$$GVF = \frac{Q_{gas}}{Q_{gas} + Q_{liquid1} + Q_{liquid2} + \cdots} \tag{7.4}$$

where Q is the mass flow rate and GVF is a ratio of 0-1. Note that there is a difference between gas volume fraction and gas void fraction. For example, 50% gas void fraction could be 75% gas volume fraction as the gas usually travels at higher velocity than liquid. Micro Motion ELITE Coriolis Flow meter series do not give any information of how accurate they are to handle two-phase flows.

All installed Coriolis flow meters in the setup have accuracy and repeatability on liquids stated in table 7.7 and on gasses in table 7.8. Note that table 7.8 is divided in two model types.

Performance	Standard
Mass flow accuracy	±0.10% of rate
Mass flow repeatability	±0.05% of rate
Density accuracy	$\pm 0.5 kg/m^3$
Density repeatability	$\pm 0.2 kg/m^3$
Temperature accuracy	$\pm 1°C \pm 0.5\%$ of reading
Temperature repeatability	$\pm 0.2°C$

Table 7.7: Accuracy and repeatability on liquid

Performance	CMF models	CMFS models
Mass flow accuracy	±0.35% of rate	±0.25% of rate
Mass flow repeatability	±0.20% of rate	
Temperature accuracy	$\pm 1°C \pm 0.5\%$ of reading	
Temperature repeatability	$\pm 0.2°C$	

Table 7.8: Accuracy and repeatability on gases

Table 7.9 shows specifications on each Coriolis flow meter type used in the setup.

Model	Nominal line size	Nominal kg/h	Max. kg/h	Gas kg/h	Sensor	Case
CMFS010	1/10”	$97.0 kg/h$	$110 kg/h$	$30 kg/h$	125BarG	105BarG
CMFS015	1/6”	$310 kg/h$	$330 kg/h$	$76 kg/h$	125BarG	105BarG
CMFS040	3/8”	$2320 kg/h$	$4640 kg/h$	$540 kg/h$	103BarG	39BarG
CMFS075	3/4”	$6270 kg/h$	$12500 kg/h$	$1400 kg/h$	103BarG	27BarG
CMF200	2”	$47900 kg/h$	$87100 kg/h$	$10000 kg/h$	109BarG	38BarG

Table 7.9: CMF series Coriolis flow meters

7.9 Magnetic Flow Meters

To determine the flow of liquids, magnetic flow meters use Faraday's law of electromagnetic induction, where a magnetic field is generated and channels through the pipe. Following Faraday's law, liquid that are conductive will cause a voltage signal to be sensed by the electrodes located on the flow pipe walls. The generated voltage is proportional to the flow rate. The sensor is based on flow changing the magnetic field, as oil is not conductive these flow meters are placed strategically in the setup.

There are two magnetic flow meters in the setup of the type Bailey Fischer Porter (ABB instrumentation) 10DX4311C that can be seen in figure 7.18.

Figure 7.18: Bailey Fischer Porter 10DX4311C magnetic flow meter.

Another magnetic flow meter used in the setup is the Rosemount 8732, which is mounted and configured the same way as the Bailey Fischer Porter. The flow meter can be seen in figure 7.19.

Figure 7.19: Rosemount 8732 magnetic flow meter.

7.10 Pumps

Grundfos Centrifugal Pumps

One of the pump types used in the setup is a vertical multistage centrifugal pump with a sealed top mounted frequency controlled motor, with incorporated PI-controller in the motor terminal box. The typical vertical multistage centrifugal pump used in the setup can be seen in figure 7.20.

Figure 7.20: Centrifugal pump of the type Grundfoss CRNE3-17-A-P-G-V-HQQV.

By increasing the pump speed the pump curve will increase. The pump performance curve with the example nominal operation point is illustrated in figure 7.21. The pumps come with an integrated pressure sensor, which allows measuring the pressure over the pumps.

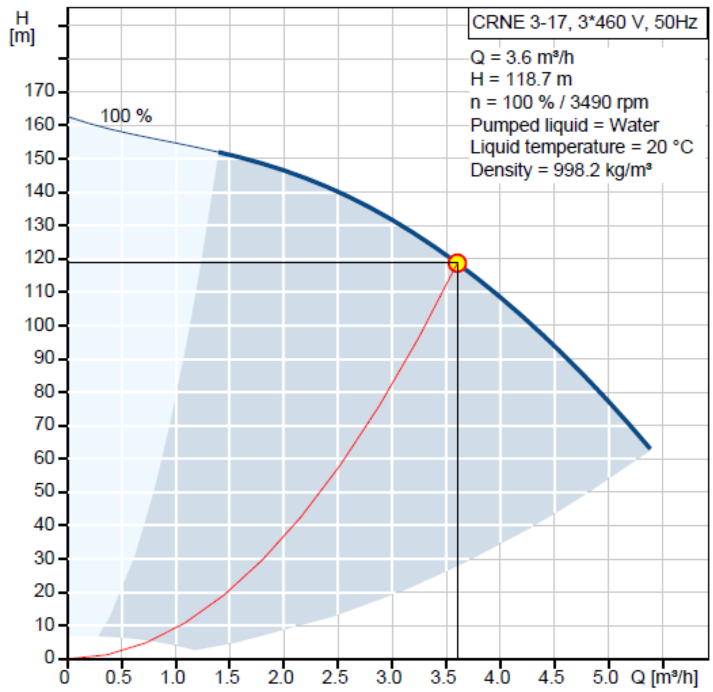


Figure 7.21: The pump performance curve of Grundfoss CRNE3-17-A-P-G-V-HQQV.

Types of Centrifugal Pumps

Each installed centrifugal pump consist of a combination of a pump and a motor. Table 7.10 shows the designed flow rate Q_{design}, the number of impellsers, maximum head H_{max}, maximum efficiency $\mu_m ax$, flow rate at maximum efficiency Q_{eff}, and head at maximum efficiency H_{eff}. All of the pump types must operate below maximum ambient temperature of 50°C. The transported medium must be within the temperature range -20°C to 90°C and below 25bar.

Pump & motor types	CRNE5-9 A-P-G-V-HQQV MGE90LD 2-FT115-IA	CRNE3-17 A-P-G-V-HQQV MGE90LD 2-FT115-IA	CRNE1-9 A-P-G-V-HQQV MGE80A 2-FT100-IA	CRNE5-2 A-P-G-V-HQQV MGE71A 2-FT85-IA	CRNE1-4 A-P-G-V-HQQV MGE71A 2-FT85-IA	CRNE10-02 A-P-G-V-HQQV MGE90SC 2-FT115-IA	CRNE3-5 A-P-G-V-HQQV MGE80A 2-FT100-IA
Q_{design}	$5m^3/h$	$3m^3/h$	$1m^3/h$	$5m^3/h$	$1m^3/h$	$10m^3/h$	$3m^3/h$
Speed	3501rpm	3501rpm	3474rpm	3447rpm	3447rpm	3501rpm	3474rpm
Impellers	9	17	9	2	4	02	5
Stages	9	17	9	2	4	2	5
H_{max}	93.3m	162.7m	80.8m	20.6m	36.3m	29.4m	47.7m
μ_{max}	61.9%	57.6%	49.8%	54.5%	45.6%	60.0%	59.2%
Q_{eff}	$6.9m^3/h$	$3.5m^3/h$	$2.2m^3/h$	$6.9m^3/h$	$2.2m^3/h$	$12.1m^3/h$	$3.5m^3/h$
H_{eff}	68m	122m	61.2m	12.9m	28.2m	22.9m	35.6m
Flange for motor	FT115	FT115	FT100	FT85	FT85	FT115	FT100
Motor type	90LD	90LD	80A	71A	71A	90SC	80A
Frame size	90mm	90mm	80mm	71mm	71mm	90mm	80mm
Rated power-P2	$2.2kW$	$2.2kW$	$0.75kW$	$0.55kW$	$0.37kW$	$1.5kW$	$0.75kW$
Rated current	4.15-3.40A	4.15-3.40A	1.70-1.60A	1.35-1.30A	1.05-1.00A	2.90-2.40A	1.70-1.60A
Pipe connection	42.4mm	42.4mm	42.4mm	42.4mm	42.4mm	60.1mm	42.4mm

Table 7.10: Centrifugal pump types

Common for all the pump types are the following:

- (E) Integrated frequency converter
- (A) Pump version: Basic version
- (P) Pipe connection: PJE coupling
- (G) Materials: Wetted parts EN 1.4401/AISI 316
- (V) Rubber parts in pump: FKM (Viton)
- (H) Balanced cartridge seal with O-ring
- (Q) Rotating seal face material: Silicon carbide
- (Q) Stationary seal face material: Silicon carbide
- (V) Secondary seal material (rubber parts): FKM (Viton)

Common for all the motor types are the following:

- (MGE) Motor Grundfos electrical control

- (2-) Number of poles: 2
- (FT) Flange version: Tapped holes
- (IA) Model designation
- Rated speed: 360-4000rpm
- Rated voltage: 3x380-500V

CRNE5-9 A-P-G-V-HQQV

The pump curve of CRNE5-9 A-P-G-V-HQQV can be seen in figure 7.22. The original pump performance curves are available at:
https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14920015081880196325375555567848&pumpsystemid=200559883&qcid=214167555

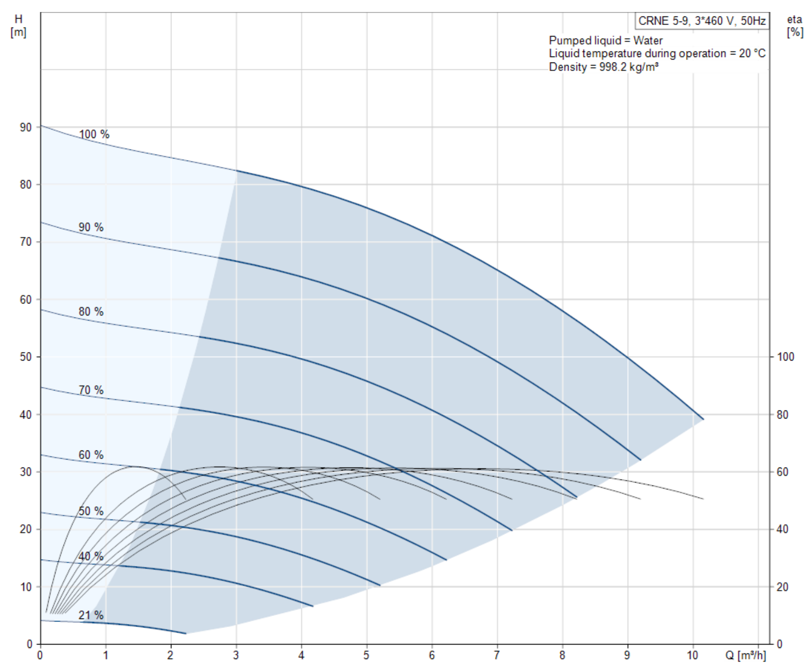


Figure 7.22: CRNE5-9 A-P-G-V-HQQV pump curve.

CRNE3-17 A-P-G-V-HQQV

The pump curve of CRNE3-17 A-P-G-V-HQQV can be seen in figure 7.23. The original pump performance curves are available at:
https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14920009316950419809516862205368&pumpsystemid=205296937&qcid=214164709

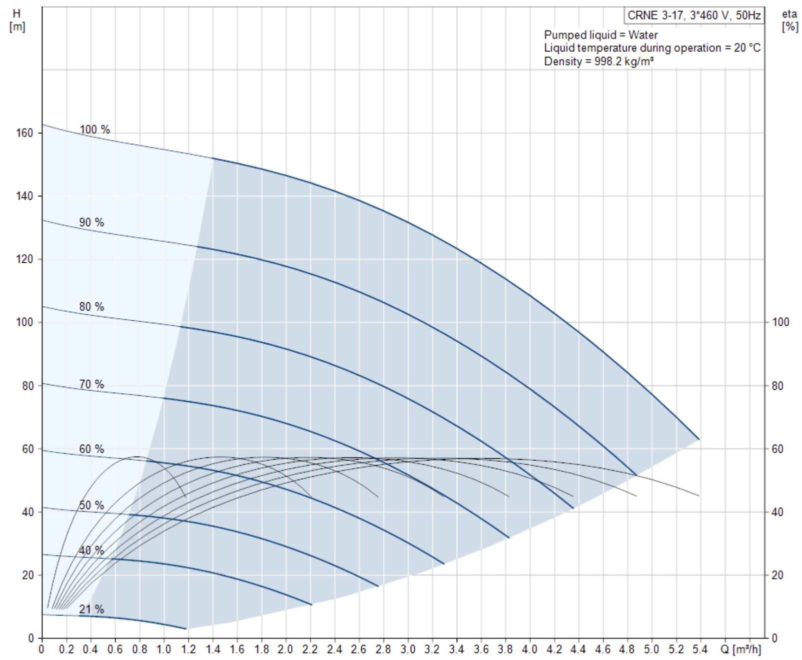


Figure 7.23: CRNE3-17 A-P-G-V-HQQV pump curve.

CRNE1-9 A-P-G-V-HQQV

The pump curve of CRNE1-9 A-P-G-V-HQQV can be seen in figure 7.24. The original pump performance curves are available at:
`https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14920021549820268840191190624868&pumpsystemid=205444781&qcid=214174008`

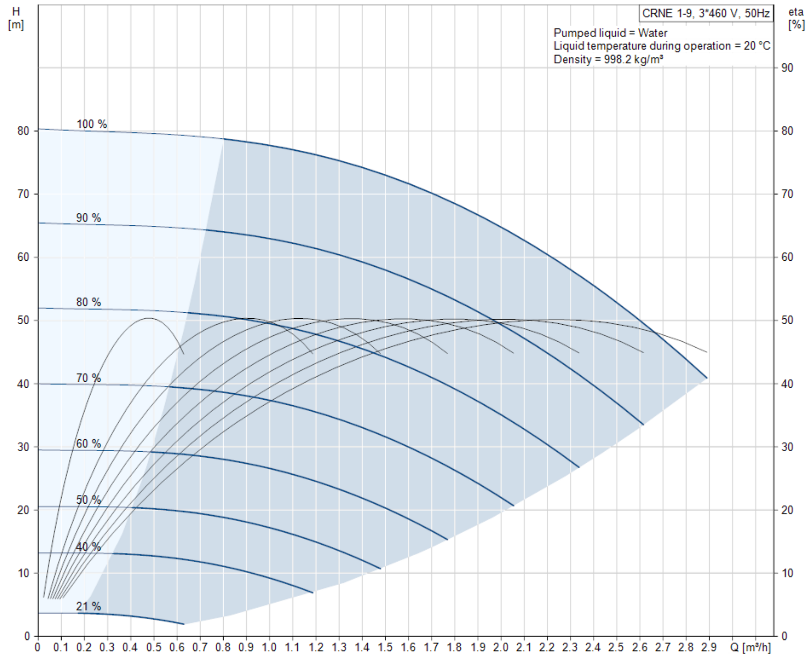


Figure 7.24: CRNE1-9 A-P-G-V-HQQV pump curve.

CRNE5-2 A-P-G-V-HQQV

The pump curve of CRNE5-2 A-P-G-V-HQQV can be seen in figure 7.25. The original pump performance curves are available at:
`https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14920026143040372906524957143O5&pumpsystemid=201007099&qcid=214158793`

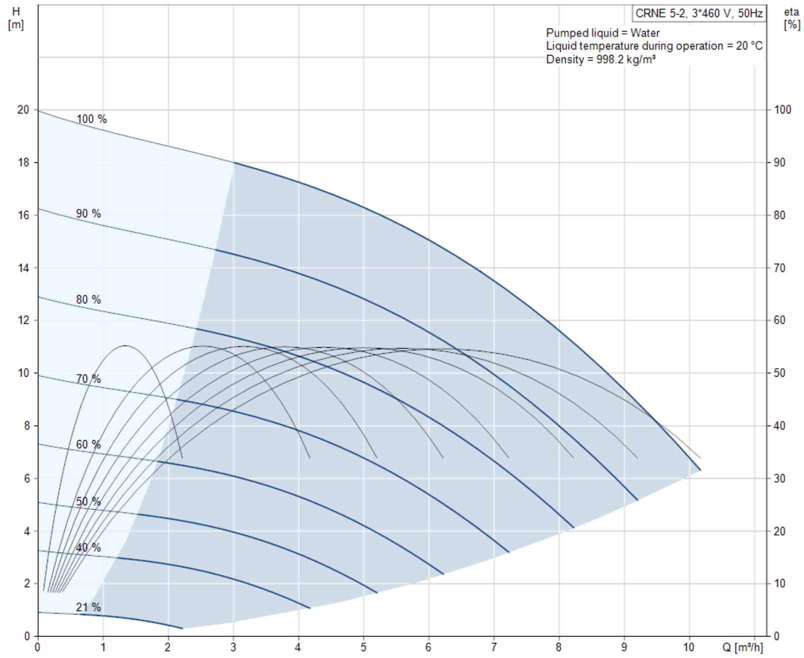


Figure 7.25: CRNE5-2 A-P-G-V-HQQV pump curve.

CRNE1-4 A-P-G-V-HQQV

The pump curve of CRNE1-4 A-P-G-V-HQQV can be seen in figure 7.26. The original pump performance curves are available at:
`https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14920023830270803423027079658 3&pumpsystemid=214175775&qcid=214176495`

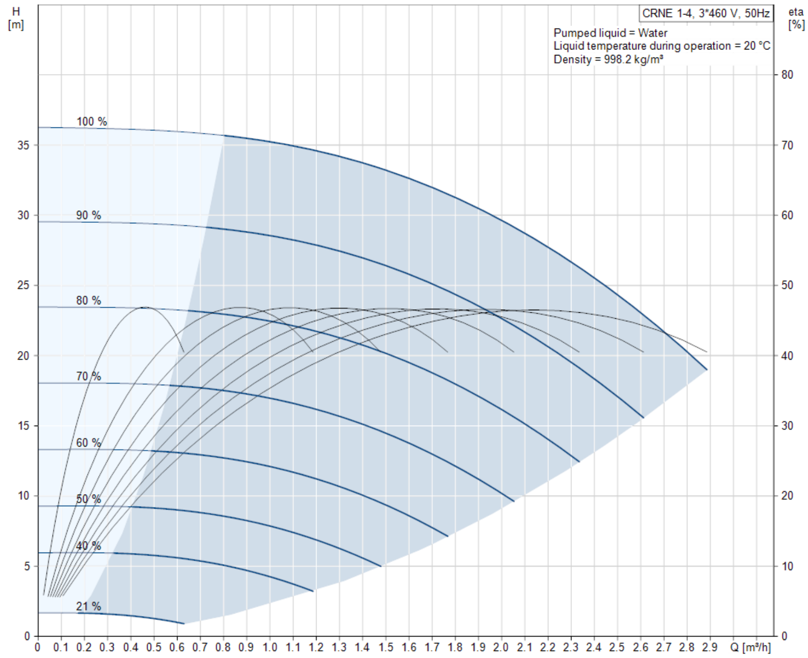


Figure 7.26: CRNE1-4 A-P-G-V-HQQV pump curve.

CRNE10-02 A-P-G-V-HQQV

The pump curve of CRNE10-02 A-P-G-V-HQQV can be seen in figure 7.27. The original pump performance curves are available at:
`https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14920029157240788003519750474 9&pumpsystemid=203240315&qcid=214181752`

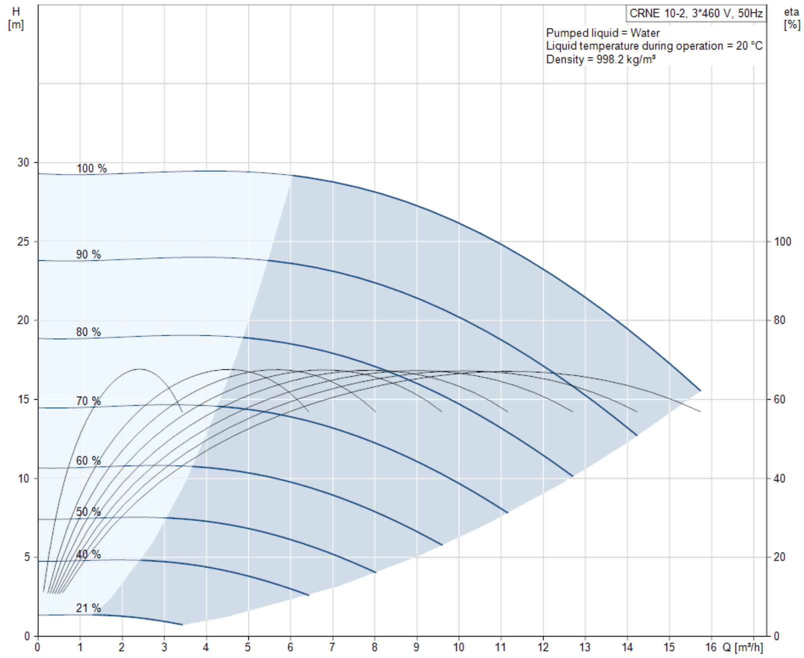


Figure 7.27: CRNE10-02 A-P-G-V-HQQV pump curve.

CRNE3-5 A-P-G-V-HQQV

The pump curve of CRNE3-5 A-P-G-V-HQQV can be seen in figure 7.28. The original pump performance curves are available at:
`https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=149200232454808080029219080942&pumpsystemid=209036485&qcid=149022984`

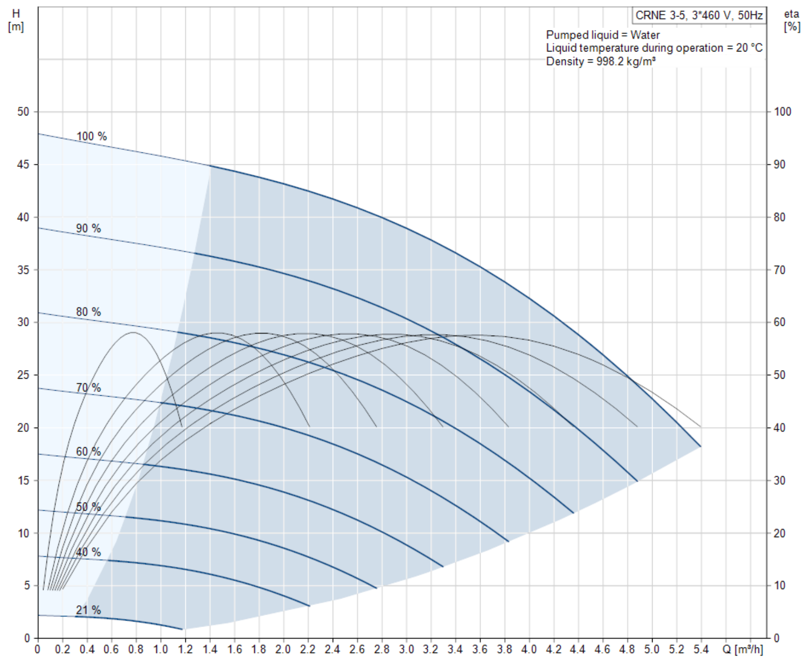


Figure 7.28: CRNE3-5 A-P-G-V-HQQV pump curve.

Dosing Pumps

Another pump type used in the setup is a Grundfos DDA 7.5-16 FCM-PV/T/C-F-31U2U2FG SMART Digital dosing pump with a user friendly display and intelligent flow control, as illustrated in figure 7.29.

Figure 7.29: Grundfos DDA 7.5-16 FCM-PV/T/C-F-31U2U2FG SMART Digital dosing pump.

The flow control function is used to monitor the dosing process. Even though the pump is running, various factors influence the functionality, such as air bubbles, which can reduce the flow or even stop the dosing process. With the enabled "FlowControl"-function it detects the following errors; overpressure, air in the dosing chamber, and discharge valve-leakage $> 70\%$. The sensor in the dosing head measures the current pressure and continuously sends the measured value to the pumps' microprocessor. Specifications of the Grundfos DDA 7.5-16 FCM-PV/T/C-F-31U2U2FG SMART Digital dosing pump are:

- Flow range: 2.5 mL/h - 7.5 L/h
- Medium temperature range: -10°C to 45°C
- Maximum operation pressure: 16bar
- Repeatability accuracy: 1%
- Input signal: 4-20mA

The pump curve of this dosing pump can be seen in figure 7.30. The original pump performance curves are available at:
`https://product-selection.grundfos.com/product-detail.product-detail.html?from_suid=14925150294070672433172913 81&pumpsystemid=215551810&qcid=148386052`

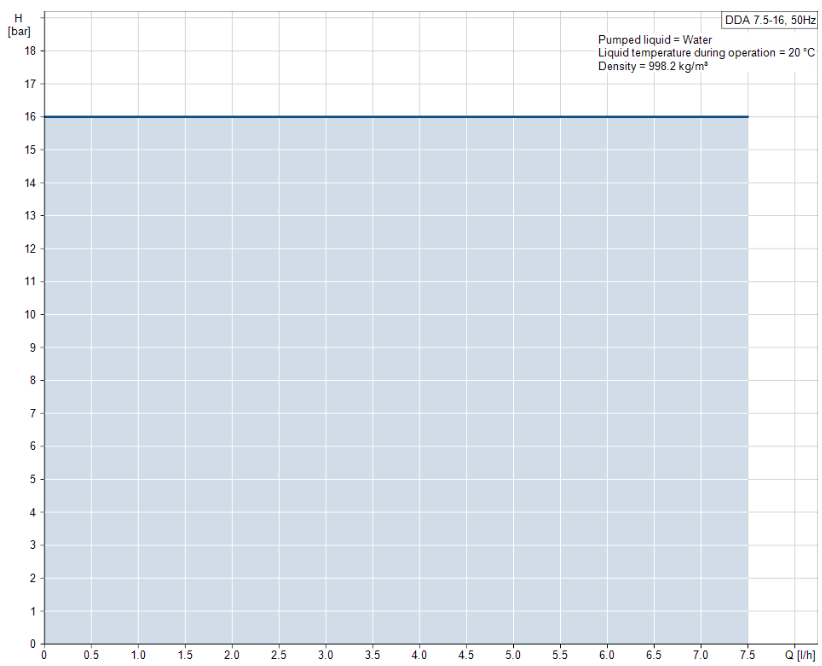


Figure 7.30: Grundfos DDA 7.5-16 FCM-PV/T/C-F-31U2U2FG SMART Digital dosing pump curve.

Vane Pumps

The vane pump type used in the setup is a Piusi S.P.A Viscomat 350/2 and 90T rotary vane pumps. To control the pump's power with 0-10V, a Vacon0100 AC-driver is connected to the pump. The AC-driver receives an analog signal from the PCI card and transforms the analogue voltage signal to frequency. This enables the pump to be controlled by an analog signal in the range 0-10V. Figure 7.31a, 7.31b and 7.31c shows the 350/2, 90T and AC-driver respectively.

(a) Viscomat 350/2. (b) Viscomat 90T. (c) AC-driver.

Figure 7.31: Piusi S.P.A Viscomat 350/2, Piusi S.P.A Viscomat 90T and Vacon0100 driver.

Table 7.11 shows the specifications of the vane pumps.

Vane pump	Viscomat 350/2	Viscomat 90T
Q_{Design}	$0.54m^3/h$ $(9L/min)$	$3m^3/h$ $(50L/min)$
Max. pressure	25Bar	5Bar
Power	750W	2000W
Pipe connection	1”	1”
rpm	1450	1450

Table 7.11: Vane pump specifications.

Figure 7.32 and 7.33 show the pump curve of the Piusi S.P.A Viscomat 350/2 and 90T respectively.

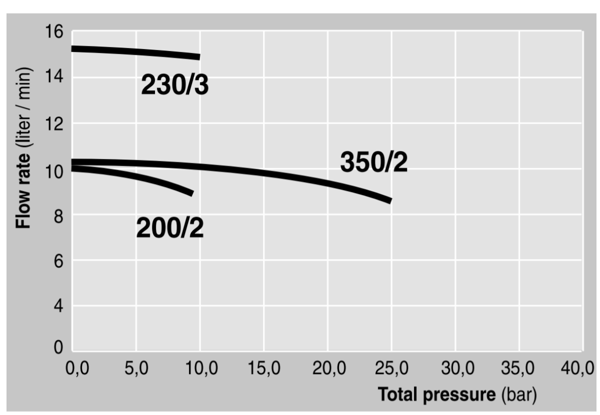


Figure 7.32: Piusi S.P.A Viscomat 350/2 pump curve.

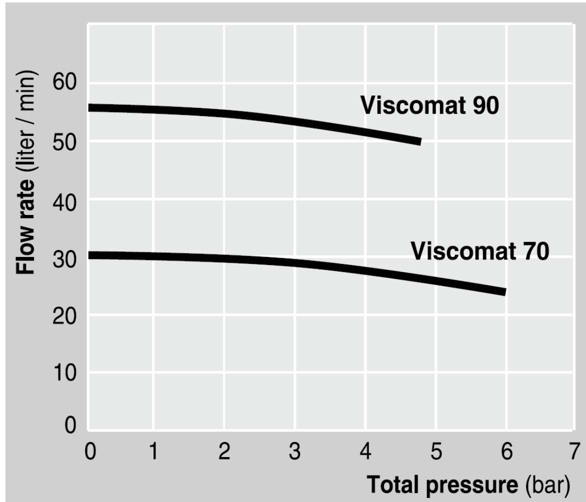


Figure 7.33: Piusi S.P.A Viscomat 90T pump curve.

7.11 Homogenizer

Homogenization is a process, which has the aim to homogenize a polar and non-polar liquid into a uniform size distribution. This is often used in the dairy industry to prevent the fat in milk to settle on the surface. Since fat particles have a size range from $1\mu m$ to $10\mu m$ in diameter, they migrate towards the milk's surface due to having lower density than the milk. By homogenizing the milk, the fat particle size is reduced.

Standard Silverson Multi-Purpose In-Line Mixer is used in the oilrig setup for producing difference sizes of uniform oil droplet distributions. Silverson homogenizer can be seen in figure 7.34.

Figure 7.34: Silverson Multi-Purpose In-Line Mixer.

The multi-toothed rotor in Multistage In-Line Mixer consists of two concentric sets of blades and teeth running against two separate WorkHeads. The WorkHeads can be shifted depending on what size particles you want.The Silverson homogenizer have three operation stages as seen in figure 7.35.

1. The high-speed rotation of the rotor blades makes the liquid and/or solid materials drawn into the rotor assembly.
2. Centrifugal force then drives the materials toward the periphery of the workhead where they are subjected to a grinding operation.
3. Forceful hydraulic shear occurs as the material is forced, at high velocity, out through the holes in the workhead, through the mixers' outlet, and into the pipeline.

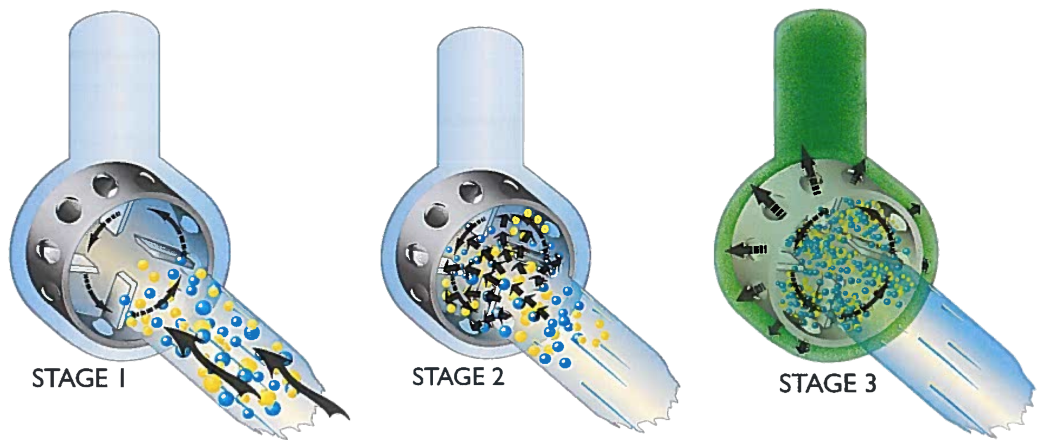


Figure 7.35: The three operation stages of the Silverson homogenizer.

The different Workheads can be seen in figure 7.36, where:

- **General Purpose Disintegrating Head** is used for a wide variety of applications. The workhead provides the highest capacity. Suitable for mixing liquids with varying viscosities.
- **Square Hole High Shear Screen** provides exceptionally high shear rates ideal for fast size reduction of granular solids. It is also suitable for the preparation of emulsions.
- **Positive Cut Slotted Disintegrating Head** and **Slotted Disintegrating Head** are used for the dissolution of the fibrous materials, such as organic tissues, as well as solubilization of materials like polymers.
- The last two workheads are called **Emulsor Monitors**. These workheads are useful in the liquid/liquid compositions, and are especially useful for the preparation of emulsions.

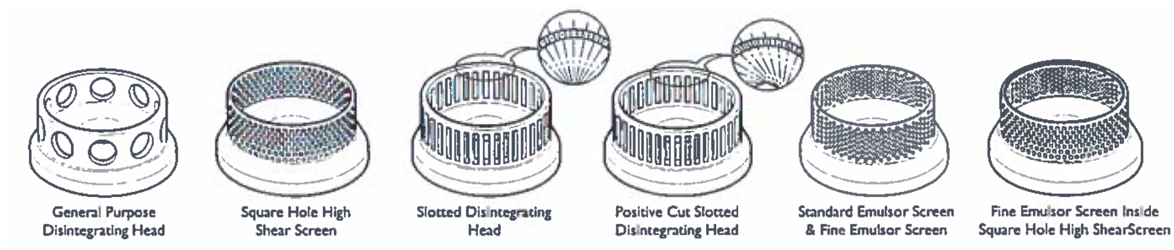


Figure 7.36: Different workheads for the homogenizer.

The produced droplet sizes distributions will vary greatly depending on the materials and fluids. Therefore, Silverson have not given a fixed size distribution of the different workheads. Also, the homogenizer is not suitable for exceeding pressures above 6.85Bar (100psi) and the homogenizer should not be exposed to temperatures below $-50°C$ or above $120°C$. lastly the homogenizer must always be filled with fluid, otherwise it can result in mechanical damage. On the setup the homogenizer receives a frequency signal as input, from a Proxidrive IP66/NEMA 4x.

7.12 Turner TD-4100XDC

The Turner TD-4100XDC online monitor detects the oil content of aromatic hydrocarbons in water using fluorometry in combination with a proprietary flow cell. The fluorescence technology makes Turner TD-4100XDC resistant to interference from turbid water, which would affect the online UV-absorption, IR-absorption or light scatter instruments. The Turner TD-4100XDC has an air chamber so that the produced water will not be in contact with any surfaces to prevent the optical windows from becoming dirty. The air chamber system also keeps the optical windows fog-free in hot water applications.

Turner Design claims that Turner TD-4100XDC can detect down to 1ppb diesel fuel in water free of interfering compounds.

Figure 7.37: Turner TD-4100XDC online OiW monitor.

Operating

Turner TD-4100XDC measures the level of hydrocarbon sample by fluorescence analysis. Fluorescence occurs when a molecule, in this case a hydrocarbon molecule, relaxes to its ground state after being electronically excited. Fluorescent hydrocarbon absorbs light at wavelengths within its absorption band, and then instantaneously emits light at longer wavelengths within its emission band. The emitted light is filtered and translated to a voltage response, which corresponds to the concentration of fluorescent hydrocarbons in the sample.

The Turner TD-4100XDC contains five main components illustrated in figure 7.38:

1. Light source.
2. Excitation filter.
3. Sample cell.
4. Emission filter.
5. Light detector.

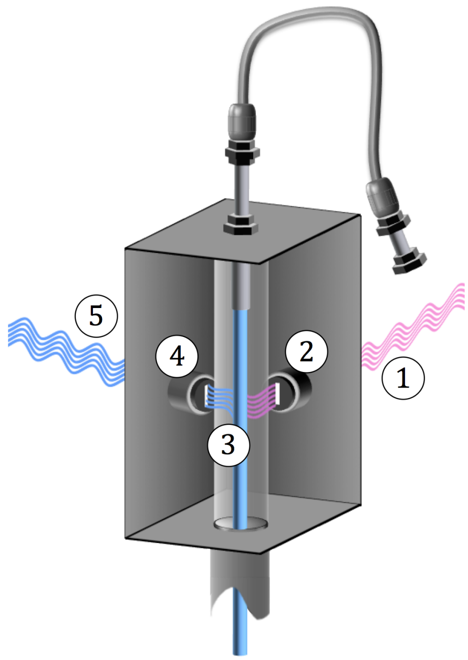


Figure 7.38: Illustration of the main components inside Turner TD-4100XDC.

Most common fluorescence instruments are based on optical filters. A typical system has three basic filters: an excitation filter, a beam splitter, and an emission filter, which is also the case for Turner TD-4100XDC. The excitation filter is typically a band-pass filter, which limits the wavelength to a specific range. The beam splitter is an oblique angle of 45 degrees filter, which reflect the light onto the sample cell and transmit the light back through the emission filter. The emission filter leaves only the desired wavelengths and blocks all unwanted light outside this band. The last step in the process is the light detector also known as photomultiplier. The light detector detects when a photon reaches and amplify the photon. This will produce an electrical pulse, which Turner TD-4100XDC uses to determine the concentration in the water flowing through the flow cell.

Concentration

The calibration part is an essential process to find a relationship between fluorescence and OiW concentration. To calibrate the Turner TD-4100XDC known concentration samples are made to generate a set of data.

By following the calibration chapter from Turner TD-4100XDC datasheet, it suggest preparing two types of calibration:

- 0-20ppm calibration.
- 20-200ppm calibration.

For producing different concentration samples between 0-20ppm, or 20-200ppm, a stock solution is made. To prepare 0-20ppm samples a 1000ppm stock solution is produced by diluting 100μL of ARDECA SAE30 oil into 100mL total volume of 99% purity isopropanol.

Similar for the 20-200ppm samples, but with a 10000ppm stock solution by diluting 1000 μL of ARDECA SAE30 oil into 100mL total volume of 99% purity isopropanol. The two stock solutions are used to prepare a calibration standard in respect to 0-20ppm and 20-200ppm. This is done by diluting the following volumes of stock solution into 100 mL of isopropanol using a second clean 100mL volumetric flask at different concentrations as listed in table 7.12 and 7.13.

High Cal. Std.	100ppb	500ppb	1ppm	5ppm	10ppm	15ppm	20ppm
1000ppm stock	10μL	50μL	100μL	500μL	1mL	1.5mL	2mL

Table 7.12: 0-20ppm calibration.

High Cal. Std.	20ppm	25ppm	50ppm	75ppm	100ppm	150ppm	200ppm
10000ppm stock	200μL	250μL	500μL	750μL	1mL	1.5mL	2mL

Table 7.13: 20-200ppm calibration.

The Turner TD-4100XDC generates a relative fluorescence unit (RFU). This means that samples, which contain higher concentration, will have higher corresponding RFU values.

For any injection of 100mL, concentration values are added in the software with the measured RFU. The software windows can be seen in figure 7.39.

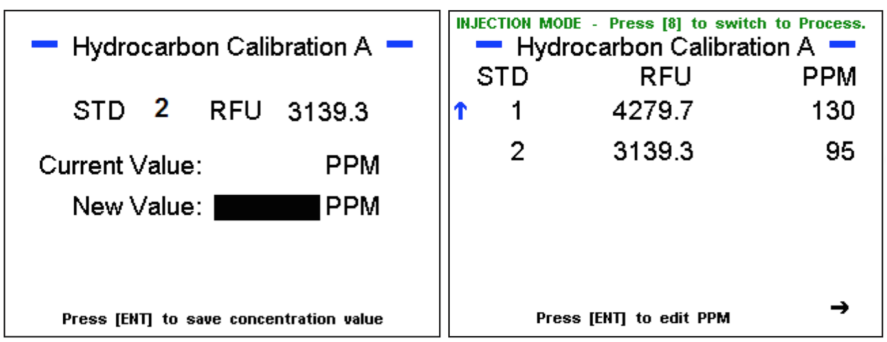


Figure 7.39: Graphical user interface of the Turner TD-4100XDC.

After injection, a 10 second average of RFU is made before the steady state RFU value can be determined with the given ppm concentration. When a series of ppm measurements has been saved into the Turner TD-4100XDC memory, an equation describing the RFU as function of ppm can be generated.

7.13 Jorin ViPA B HiFlo

Jorin Visual Process Analysis (ViPA) B HiFlo analyzer is an online instrument for monitoring complex multiphase systems and handle any mixture of particles, droplets, and bubbles.

Figure 7.40: Jorin ViPA B HiFlo analyzer.

ViPA uses video microscopy to capture images of the particles in a flow. The image analysis techniques are used to distinguish between different species by analyzing captured objects, such as oil droplets and solids, by measuring shape factor and optical density. The image data for each particle is independently sent to the computer, which analyzes the data using ViPA software. This makes ViPA essential to measure droplets size distribution and concentrations of oil droplets and solids in produced water.

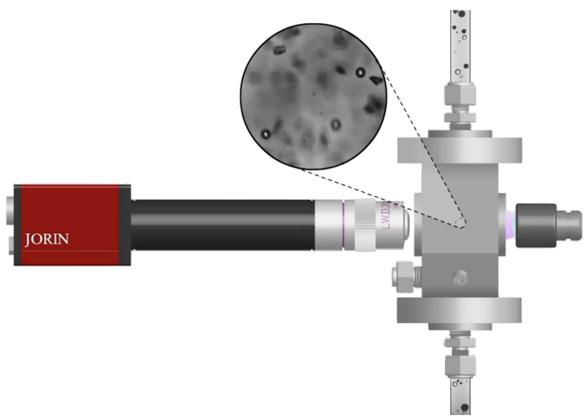


Figure 7.41: ViPA video microscope and cell module with a scope still image example.

The video microscope consists of a high speed video camera, lens, and a light source for examining the contents of the liquid. The produced water flows between a pair of transparent windows in the ViPA flow cell. The camera captures the emitted light that has passed through the flow cell from the light source, as seen in figure 7.41. This enables the ViPA software to determine solid particles, droplets of oil or gas bubbles. ViPA works by taking a still image of a single frame and analyzing the present objects. The still image is also used to calibrate the ViPA.

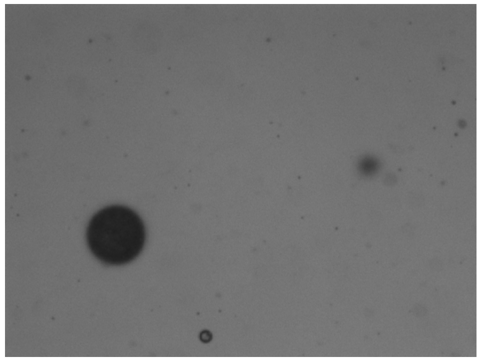


Figure 7.42: Typical ViPA still image.

Figure 7.42 shows a typical still image from ViPA with solution of oil droplets in water, where ViPA uses three parameters for each object; size, shape factor, and concentration, to determine the (average) size and (average) concentration of oil droplets and solids.

Size

Feret diameter of an object is the distance between two parallel planes, which is the boundary of the object perpendicular to the direction, that defines the surface of the object being measured. For non-circular objects, the Feret diameter will differ according to the axis of measurement. The advantage of using Feret diameter is that it can project a 3D object on a 2D plane. The ViPA measures Feret diameters of all 3D objects in 2D plane produced by the video camera from four fixed angles; 0°, 45°, 90°and 135°, and takes the average of these diameters to define the size of the object, which can be seen in figure 7.43.

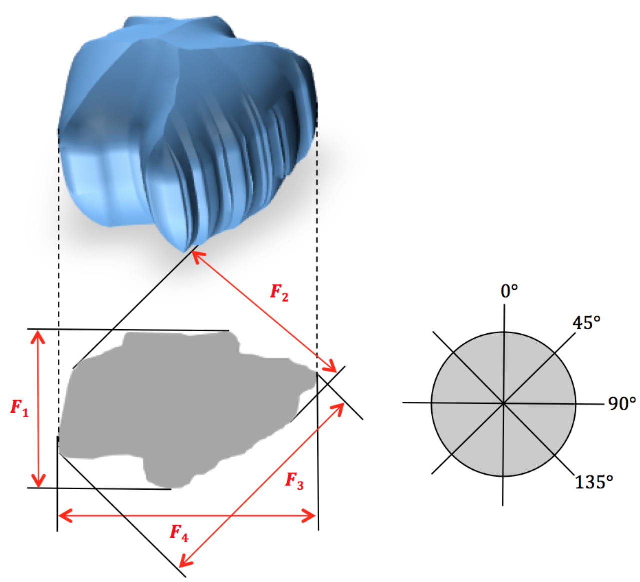


Figure 7.43: Example of a 3D object projected to 2D plane and averaging the four axes of Feret Diameter.

Shape Factor

ViPA uses the shape factor as one of the tools to distinguish between certain classes of objects in a sample. The mathematical equation used to calculate the shape factor can be seen in equation 7.5.

$$ShapeFactor = \frac{4\pi Area}{Perimeter^2} \tag{7.5}$$

Where the shape factor of a perfect circle will always be one. The shape factor ratio decreases rapidly when the objects perimeter is to the power of two in the denominator of equation 7.5. Some different shapes and their corresponding shape factors are seen in table 7.44, to give an idea of the shapes' influence of its shape factor. The shape factor algorithm is embedded in the software and can not be changed by the user.

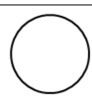
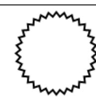
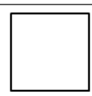
Shape	Shape Factor	Shape	Shape Factor
	1.0		0.19
	0.79		0.00061

Figure 7.44: Various shapes and their corresponding shape factors.

Concentration

The ViPA measures concentration as visible ppm. The visible concentration is calculated in each frame volume of the amount of particles and droplet size. At the end of each analysis cycle, the software sums all objects in each frame together, which enables ViPA to generate an average concentration for each cycle. Only the objects detected is measured and included in the calculation. Objects passing through the cell that are not in focus, are not detected and are thereby not measured. This could be a problem in order to determine the correct concentration to pass through the ViPA. However, by a good calibration, it should be possible to give a reasonable estimation of what the average ppm concentration of oil droplets in produced water is and an average size distribution.

Calibration

When calibrating ViPA some experiments needs to be conducted, where a set of predefined steps needs to be followed. The experimental setup is illustrated in figure 7.45.

Figure 7.45: ViPA calibration experiment setup.

Once launched if the video image is dirty, the flow cell needs to be cleaned. A beaker with a known OiW stock solution is mixed. The hose pump controls the flow through the ViPA. The image background of ViPA must be calibrated before use, this is acquired by taking 100 frames from the camera. For particle validation calibration the ViPA uses a still image that has an oil droplet in focus by toggling the live/still image feed manually. When a proper still image, with a droplet in focus, is acquired the threshold value can be manually adjusted until the oil droplet is colored white. As the threshold value increases, fewer objects are colored white and as the value is decreases, more objects are colored white. The goal is to the get the oil droplet marked with a white ring/halo around it, as illustrated in figure 7.46. Other particles than oil should be colored entirely white.

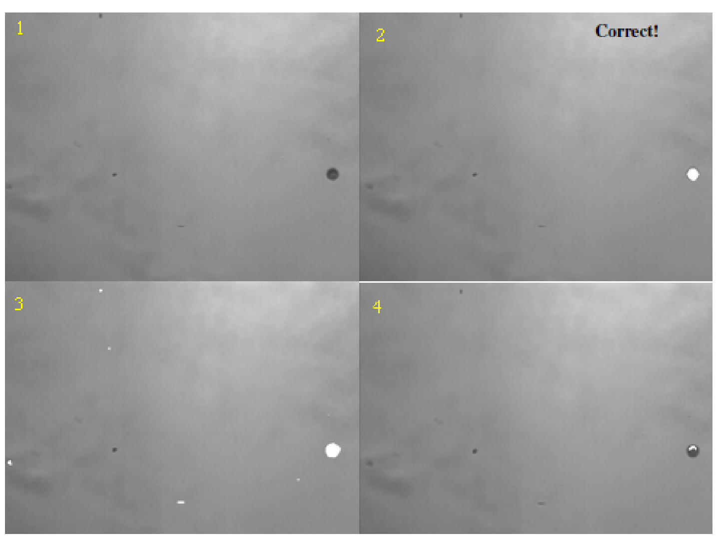


Figure 7.46: ViPA threshold examples.

Figure 7.46 illustrates four different pictures in one, where different threshold values are chosen. Picture 1 shows an oil droplet where no threshold value was chosen, while picture 2 is the correct threshold setting for the oil droplet. Picture 4 illustrates a high threshold value where the oil droplet is barely colored white, while picture 3 has a low threshold value where too many objects are colored white. It can therefore be difficult to define what is a proper threshold value and what influence an invalid threshold setting has on the output.

Chapter 8

Box Connections

Figure 8.1 shows that top and bottom syntax for table 8.1, 8.2, 8.3, 8.4, 8.5, and 8.6.

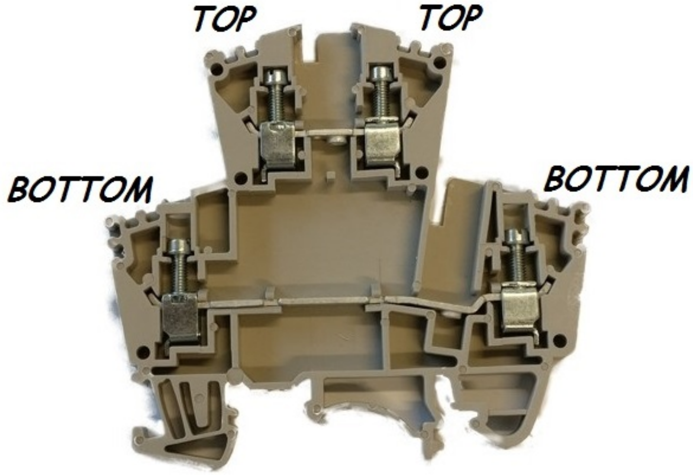


Figure 8.1: Illustration of top and bottom connections.

Box 1

Component	Conductor signal & color		Terminal	Multi-conductor signal & color		Multi-conductor label name
	Top:	**Bottom:**		**Top:**	**Bottom:**	
PT12	Blue: -	Brown: +	1	Green/Black	Brown/Black*	MCC 1.1
PT16	Blue: -	Brown: +	2	Black/Green	Brown/Black*	MCC 1.1
TT06	Blue: -	Brown: +	3	Blue/Black	Brown/Black*	MCC 1.1
PT05	Blue: -	Brown: +	4	Black/Blue	Brown/Black*	MCC 1.1
PT07	Blue: -	Brown: +	5	Orange/Black	Brown/Black*	MCC 1.1
PT10	Blue: -	Brown: +	6	Black/Orange	Brown/Black*	MCC 1.1
TT11	Blue: -	Brown: +	7	Gray/Black	Brown/Black*	MCC 1.1
PT20	Blue: -	Brown: +	8	Black/Gray	Brown/Black*	MCC 1.1
TT03	Blue: -	Brown: +	9	Green/Blue	Brown/Black*	MCC 1.1
PT15	Blue: -	Brown: +	10	Blue/Green	Brown/Black*	MCC 1.1
PT02	Blue: -	Brown: +	11	Orange/Blue	Brown/Black*	MCC 1.1
PT19	Blue: -	Brown: +	12	Blue/Orange	Brown/Black*	MCC 1.1
			13	White/Blue	Brown/Black*	MCC 1.1
PT03	Blue: -	Brown: +	14	Blue/White	Brown/Black*	MCC 1.1
TT04	Blue: -	Brown: +	15	Black/Brown	Brown/Black*	MCC 1.1

Table 8.1: Wiring of box 1.

Box 2

Component	Conductor signal & color		Terminal	Multi-conductor signal & color		Multi-conductor label name
	Top:	**Bottom:**		**Top:**	**Bottom:**	
MLT01	White: CH A -		1	Green/Black		MCC 2.1
	Green: CH B -	Brown: +	2	Black/Green	Brown/black*	
LT02	Blue: -	Brown: +	3	Blue/Black	Brown/black*	MCC 2.1
TT05	Blue: -	Brown: +	4	Black/Blue	Brown/black*	MCC 2.1
LT01	Blue: -	Brown: +	5	Orange/Black	Brown/black*	MCC 2.1
TT14	Blue: -	Brown: +	6	Black/Orange	Brown/black*	MCC 2.1
PT09	Blue: -	Brown: +	7	Gray/Black	Brown/black*	MCC 2.1
TT12	Blue: -	Brown: +	8	Black/Gray	Brown/black*	MCC 2.1
PT11	Blue: -	Brown: +	9	Green/Blue	Brown/black*	MCC 2.1
PT04	Blue: -	Brown: +	10	Blue/Green	Brown/black*	MCC 2.1
PT01	Blue: -	Brown: +	11	Orange/Blue	Brown/black*	MCC 2.1
MFM04	Blue: -	Brown: +	12	Blue/Orange	Brown/black*	MCC 2.1
–			13	White/Blue	Brown/black*	MCC 2.1
			14	Blue/white	Brown/black*	MCC 2.1
CFM02	Blue: -	Brown: +	15	Black/Brown	Brown/Black**	MCC 2.2
CFM04	Blue: -	Brown: +	16	Green/Black	Brown/Black**	MCC 2.2
CFM01	Blue: -	Brown: +	17	Black/Green	Brown/Black**	MCC 2.2
CFM02	Black: FO -	Gray: FO +	18	Blue/Black***	Black/Blue	MCC 2.2
CFM04	Black: FO -	Gray: FO +	19	Blue/Black***	Orange/Black	MCC 2.2
CFM01	Black: FO -	Gray: FO +	20	Blue/Black***	Black/Orange	MCC 2.2
MFM02	Blue: -	Brown: +	21			MCC 2.2
MFM01	Blue: -	Brown: +	22			MCC 2.2

Table 8.2: Wiring of box 2.

Box 3

Component	Conductor signal & color		Terminal	Multi-conductor signal & color		Multi-conductor label name
	Top:	**Bottom:**		**Top:**	**Bottom:**	
CVX09	White: +	Brown: -	1	Red	Blue*	MCC 3.1
CVX14	White: +	Brown: -	2	Green	Blue*	MCC 3.1
CVX15	White: +	Brown: -	3	Black	Blue*	MCC 3.1
CVX16	White: +	Brown: -	4	Yellow	Blue*	MCC 3.1
CVX17	White: +	Brown: -	5	Red/Blue	Blue*	MCC 3.1
CVX18	White: +	Brown: -	6	Gray/Pink	Blue*	MCC 3.1
CVX19	White: +	Brown: -	7	Purple	Blue*	MCC 3.1
CVX20	White: +	Brown: -	8	White	Blue*	MCC 3.1
CVX08	White: +	Brown: -	9	Pink	Blue*	MCC 3.1
CVX10	White: +	Brown: -	10	Brown	Blue*	MCC 3.1
CV14	Brown: 24V	Blue: GND	11	Brown**	Blue***	MCC 3.2
	Gray: setpoint +	Black: ASR +	12	Black	Gray	
CV13	Brown: 24V	Blue: GND	13	Brown**	Blue***	MCC 3.2
	Gray: setpoint +	Black: ASR +	14	White	Pink	
DPT05	Brown: +	Blue: -	15	Brown**	Purple	MCC 3.2
PT17	Brown: +	Blue: -	16	Brown**	Red/Blue	MCC 3.2
TT15	Brown: +	Blue: -	17	Brown**	Gray/Pink	MCC 3.2

Table 8.3: Wiring of box 3.

Box 4

Component	Conductor signal & color		Terminal	Multi-conductor signal & color		Multi-conductor label name
	Top:	**Bottom:**		**Top:**	**Bottom:**	
CV08	Brown: 24V	Blue: GND	1	Pink*	Blue**	MCC 4.1
	Gray: setpoint +	Black: ASR +	2	Gray	Green/White	
CV11	Brown: 24V	Blue: GND	3	Pink*	Blue**	MCC 4.1
	Gray: setpoint +	Black: ASR +	4	Brown	Yellow/Brown	
CFM06 supply	Brown: +	Blue: -	5	Pink*	Blue**	MCC 4.1
CFM06 CHA	Brown: +	Blue: -	6	White	Yellow/White	MCC 4.1
CFM06 CHB	Gray: +	Black: -	7	Yellow	Gray/Pink	MCC 4.1
DPT07	Brown: +	Blue: -	8	Pink*	Black	MCC 4.1
DPT06	Brown: +	Blue: -	9	Pink*	Red	MCC 4.1
PT18	Brown: +	Blue: -	10	Pink*	Green	MCC 4.1
AFM04	Brown: meas. +	Blue: meas. GND	11	Red/Blue	Blue**	MCC 4.1
AFM04 supply	Brown: 24v	Blue: GND	12	Pink*	Blue**	MCC 4.1
MLT03	Brown: +	White: CH A -	13	Pink*	Green/Brown	MCC 4.1
		Green: CH B -	14		Purple	

Table 8.4: Wiring of box 4.

Box 5

Component	Conductor signal & color		Terminal	Multi-conductor signal & color		Multi-conductor label name
	Top:	**Bottom:**		**Top:**	**Bottom:**	
CV03	Brown: 24V	Blue: GND	1	Blue*	Brown/Yellow**	MCC 5.1
	Gray: setpoint +	Black: ASR +	2	Pink	White/Yellow	
CV23	Brown: 24V	Blue: GND	3	Blue*	Brown/Yellow**	MCC 5.1
	Gray: setpoint +	Black: ASR +	4	Red	Red/Blue	
PT14	Brown: +	Blue: -	5	Yellow	Brown/Yellow**	MCC 5.1
DPT04	Brown: +	Blue: -	6	Green	Brown/Yellow**	MCC 5.1
TT13	Brown: +	Blue: -	7	Black	Brown/Yellow**	MCC 5.1

Table 8.5: Wiring of box 5.

Box 6

Component	Conductor signal & color		Terminal	Multi-conductor signal & color		Multi-conductor label name
	Top:	**Bottom:**		**Top:**	**Bottom:**	
PT08	Blue: -	Brown: +	1	Green/Black	Brown/Black*	MCC 6.1
TT09	Blue: -	Brown: +	2	Black/Green	Brown/Black*	MCC 6.1
MLT02	White: CH A -		3	Black/Orange	Brown/Black*	MCC 6.1
	Green: CH B -	Brown: +	4	Gray/Black	Brown/Black*	MCC 6.1
PT14	Blue: -	Brown: +	5	Black/Gray	Brown/Black*	MCC 6.1
DPT04	Blue: -	Brown: +	6	Green/Blue	Brown/Black*	MCC 6.1
TT13	Blue: -	Brown: +	7	Blue/Green	Brown/Black*	MCC 6.1
DPT03	Blue: -	Brown: +	8	Orange/Black	Brown/Black*	MCC 6.1
			9			
			10			
CFM03	Blue: -	Brown: +	11	Blue/White**	Blue/Orange	MCC 6.1
	Black: FO -	Gray: FO+	12	Blue/White**	White/Blue	MCC 6.1

Table 8.6: Wiring of box 6.

Chapter 9

Electrical Cabinet

9.1 Overview

The electrical cabinet for pilot plant can be seen in figure 9.1. The electrical cabinet does not include any connection to the membrane setup.

Figure 9.1: Electrical Cabinet.

The electrical cabinet includes DIN rail-mounted terminal blocks in the bottom which associates the link between components supply and signals to rest of the electrical cabinet. The terminal blocks are divided into different sections for more convenient way to detect each

Example	**X1**	**.3**	**.1**	**.1**	**:L1**
Supply: X1 or Signal: X2					
Which section, separated by dividers					
Which terminal block in that specific section					
Which connection,on the terminal block, see figure 9.2					
Symbol indicator,on terminal block, if relevant					

Table 9.1: Terminal names.

connection. The terminal blocks terminal name are shown in table 9.1

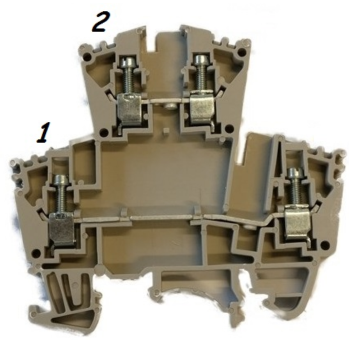


Figure 9.2: DIN rail-mounted terminal block reading illustration.

9.2 Sensor connections, conversion and filtering

The sensor and actuator signals must be 0-10V voltage signals with anti-aliasing filtering in order to be captured by the DAQ PCI-cards. All signals are therefore converted to voltages and filtered to remove high-frequency noise above $100Hz$.

Sensor signal types

Most of the sensors of the system utilize passive 4-20mA analog current signals, and some additionally have digital HART communication overlayed on this signal. The signal is converted to a voltage signal using a 470Ω 1% resistor connected between the sensor return signal and analog ground. In addition it is filtered using a 3.3uF capacitor in parallel, giving a 1-order low pass with cutoff frequency of approximately $100Hz$, which also eliminates most of the HART digital carrier signal.

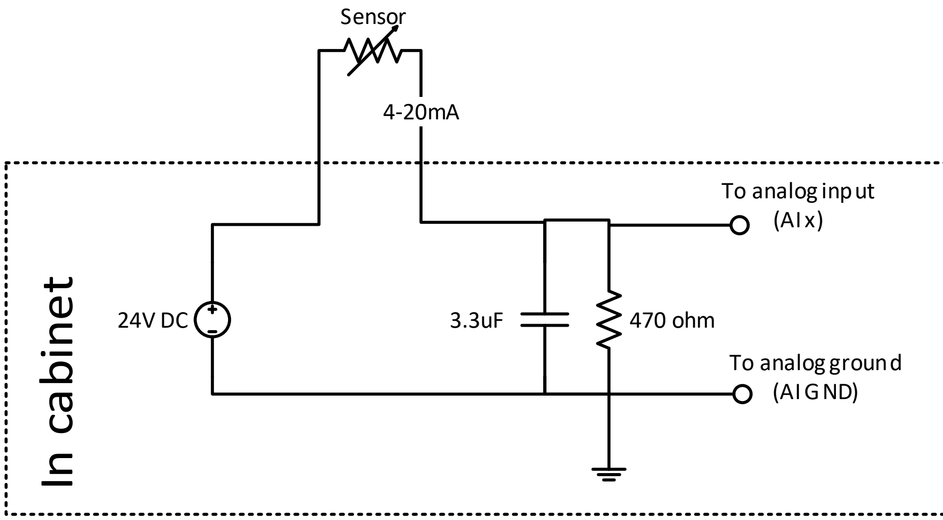


Figure 9.3: Passive 4-20mA sensor connection

Most devices that are separately powered utilize active 4-20mA signals which are connected as shown below:

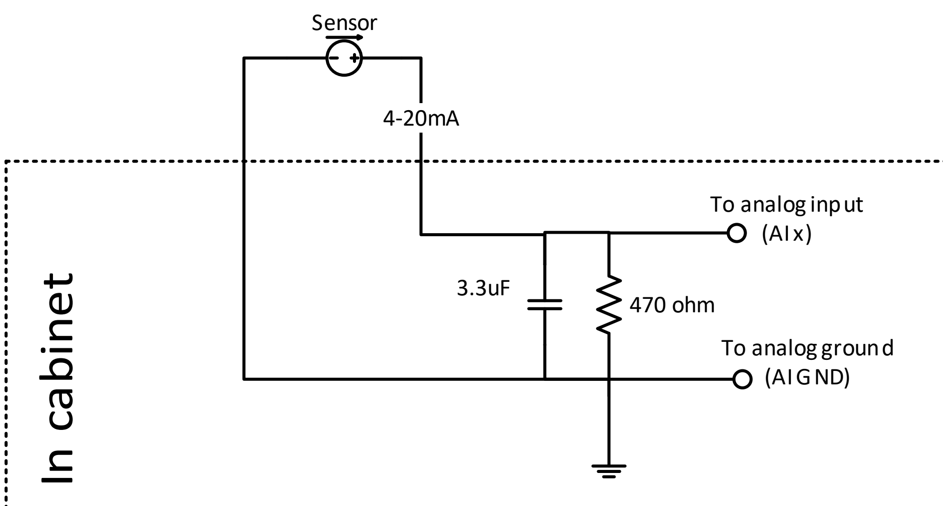


Figure 9.4: Active 4-20mA sensor connection

Feedback from actuators such as valves and air-flow-meters instead deliver a 0-10V or 2-10V analog voltage signal these are connected directly as shown below:

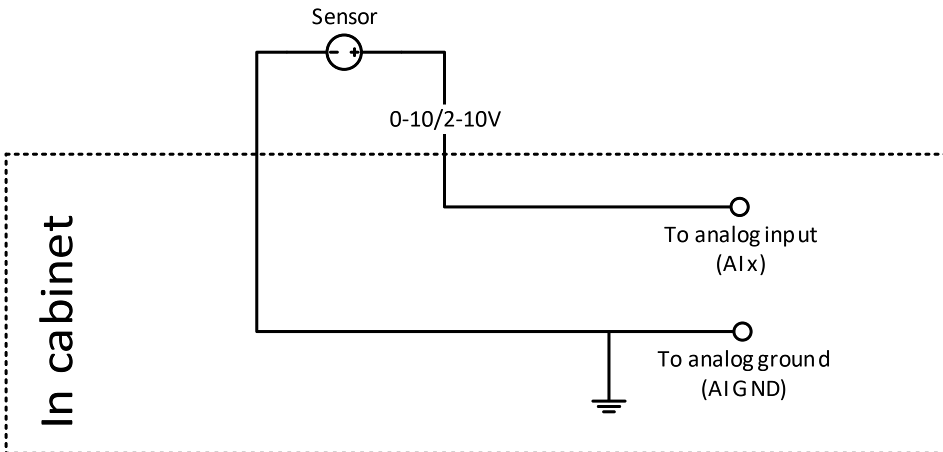


Figure 9.5: 0-10/2-10V sensor connection

Sensor connections

The sensor connections are described in an Access sheet which is attached to the documentation. More information of the Access sheet can be found in section 6

The following user defined details are noted for each sensor and actuator in the Access file, as shown in this example:

Electrical connection terminal X2.7.2:1

Tag number ACV01

Type Air flow meter

Min. safe operation 0

Max. safe operation 1

In addition some values are calculated automatically; the gain and offset for calculating values in real world units, given by the sensor type, and the internal connection to the PCI DAQ card, as given by the wiring table. An example of the calculated values are given below:

Offset 0.34722

Gain 0,1846

Channel 29

PCI slot [3,5]

These can be loaded to MATLAB structs using the function *readconnectionsheet* which can be seen in chapter 6:

This yields structs that can be loaded into the simulink model which is used to control the setup.

9.3 PCI-6229 card(s)

Four National instruments PCI-6229 cards are used for data capture and control in the setup, each card has the following capabilites.

- 32 Analog inputs (AI)
  - 16bit resolution
  - ±10V range (adjustable)
- 4 Analog outputs (AO)
  - 833 kHz update rate
  - 16bit resolution
  - ±10V range (adjustable)
- 48 Digital input/output (DIO)
  - 0-5V TTL compatible
  - $20 - 50k\Omega$ pulldown
  - $16/24mA$ sink/source rating

The manual for the card series can be accessed by clicking the icon below:

9.4 PCI-6704 card(s)

One NI PCI-6704 is used for actuator control, ie. the control valves (CV) and pumps (WP and OP) in the setup. The card has the following capabilities. Note that the outputs states are saved to static memory, so they are restored between powering on and off the setup.

- 16 Analog voltage outputs (AVO)
  - 833 kHz update rate
  - 16bit resolution
  - ±10V range (adjustable)
- 16 Analog current outputs (ACO)
  - 833 kHz update rate
  - 16bit resolution
  - ±10V range (adjustable)
- 8 Digital input/output (DIO)
  - 0-5V TTL compatible

- $20 - 50k\Omega$ pulldown
- $16/24mA$ sink/source rating

The manual for the card series can be accessed by clicking the icon below:

Terminal	Tag name	Fuse	Conductor signal & color
X1.1.1:L1	Supply to the circuit panel	–	Brown: L1
X1.1.2:L2			Gray: L2
X1.1.3:L3			Black: L3
X1.1.4:N			Blue: N
X1.1.5:			Yellow/Green: GND
X1.2.1.1:	PC outlet	F15	Brown:
X1.2.1.2:N			Blue:
X1.3.1.1:L1	Supply to AUX on the circuit panel		Brown: L1
X1.3.1.2:L2			Gray: L2
X1.3.1.1:L3			Black: L3
X1.3.2.2:N			Blue: N
X1.4.1.1:L1	VFD OP06	F8	Black: L1
X1.4.2.1:L2			Gray: L2
X1.4.3.1:L3			Brown: L3
X1.4.1.2:L1	VFD OP02	F7	Black: L1
X1.4.2.2:L2			Gray: L2
X1.4.3.2:L3			Brown: L3
X1.5.1.1:L1	WP02/01 Supply	F7	Brown: L1
X1.5.1.2:L2			Gray: L2
X1.5.2.1:L3			Black: L3
X1.5.2.2:N			–
X1.5.3.1:L1	WP01/02 Supply	F12	Brown: L1
X1.5.3.2:L2			Gray: L2
X1.5.4.1:L3			Black: L3
X1.5.4.2:N			–
X1.5.5.1:L1	HM01 Supply	F10	Brown: L1
X1.5.5.2:L2			Gray: L2
X1.5.6.1:L3			Black: L3
X1.5.6.2:N			Blue: N
X1.5.7.1:L1	RLP01 Supply	F10	Brown: L1
X1.5.7.2:L2			Gray: L2
X1.5.8.1:L3			Black: L3
X1.5.8.2:N			Blue: N
X1.5.9.1:L1	WP05 supply	F10	Brown: L1
X1.5.9.2:L2			Gray: L2
X1.5.10.1:L3			Black: L3
X1.5.10.2:N			–
X1.6.1.1			Brown:

Terminal	Tag name	Fuse	Conductor signal & color
X1.6.1.2	Emergency stop		Brown:
X1.7.1.1:L1		F14	Brown: L1
X1.7.1.2:N			Blue: N
X1.7.2.1:L1		F14	Brown: L1
X1.7.2.2:N			Blue: N
X1.7.3.1:L1		F14	Brown: L1
X1.7.3.2:N			Blue: N

Table 9.2: Terminal panel sheet part 1.

Terminal	Breakout board	Pin	Tag name	Fuse	Conductor signal & color
X2.1.1.1: -	–	–	VFM01 supply	F34	Blue: -
X2.1.1.2: +	–	–			Brown: +
X2.1.2.1: -	–	–	xxx? supply	F34	–
X2.1.2.2: +	–	–			–
X2.1.3.1: -	–	–	xxx?supply	F34	Blue: -
X2.1.3.2: +	–	–			Brown: +
X2.1.4.1: -	–	–	xxx?supply	F34	Blue: -
X2.1.4.2: +	–	–			Brown: +
X2.1.5.1: -	–	–	xxx? supply	F34	Blue: -
X2.1.5.2: +	–	–			Brown: +
X2.1.6.1: -	–	–	xxx? supply	F34	Blue: -
X2.1.6.2: +	–	–			Brown: +
X2.1.7.1: -	–	–	xxx? supply	F34	Blue: -
X2.1.7.2: +	–	–			Brown: +
X2.1.8.1: -	–	–	xxx? supply	F34	Blue: -
X2.1.8.2: +	–	–			Brown: +
X2.1.9.1: -	–	–	xxx? supply	F34	Blue: -
X2.1.9.2: +	–	–			Brown: +
X2.2.1.1: -	–	–	WP01		Brown: -
X2.2.1.2:	PCI6229 A/0	Pin 21; AO1			White: SP +
X2.2.2.1	–	–	WP02		Brown: -
X2.2.2.2	PCI6229 A/0	Pin 22, AO0			White: SP +
X2.2.3.1	–	–	HM01		Brown: -
X2.2.3.2	PCI6229 A/1	Pin 22; AO2			White: SP +
X2.2.4.1	–	–			–
X2.2.4.2	–	–			Green: on/off
X2.2.5.1	PCI6229 B/1	Pin 68; AI16	OP04		Black: FD +
X2.2.5.2	PCI6704	Pin 67; AO16			Grey: SP +
X2.2.6.1	–	–			Blue: -
X2.2.6.2	PCI6229 A/1	Pin 47; DO11			Brown: on/off
X2.2.7.1	PCI6229 A/0	Pin 34; AI8			Black: Mass Flow +
X2.2.7.2	PCI6704	Pin 66; AO1			Grey: SP +
X2.2.8.1	–	–			Blue: -

Terminal	Breakout board	Pin	Tag name	Fuse	Conductor signal & color
X2.2.8.2	PCI6229 A/1	Pin 19; DO12	AFM01		Brown: Mode switch +
X2.2.9.1	PCI6229 A/0	Pin 33; AI1	AFM02		Black: Mass Flow +
X2.2.9.2	PCI6704	Pin 31; AO2			Grey: SP +
X2.2.10.1	–	–			Blue: -
X2.2.10.2	PCI6229 A/1	Pin 51; DO13			Brown: Mode switch +
X2.2.11.1	PCI6229 A/0	Pin 66; AI9	AFM03		Black: Mass flow +
X2.2.11.2	PCI6704	Pin 63; AO3			Grey: SP +
X2.2.12.1	–	–			Blue: -
X2.2.12.2	PCI6229 A/1	Pin 16; DO14			Brown: Mode switch +
X2.3.1.1	–	–	CVX01		–
X2.3.1.2	PCI6229 A/1	Pin 43; DO18			Gray: +
X2.3.2.1	–	–			Blue: -
X2.3.2.2	–	–			Brown: +
X2.3.3.1	–	–	CVX02		–
X2.3.3.2	PCI6229 A/1	Pin 42; DO19			Gray: +
X2.3.4.1	–	–			Blue: -
X2.3.4.2	–	–			Brown: +
X2.3.5.1	–	–	CVX03		–
X2.3.5.2	PCI6229 A/1	Pin 41; DO20			Gray: +
X2.3.6.1	–	–			Blue: -
X2.3.6.2	–	–			Brown: +
X2.4.1.1:-	–	–	Supply MCC 3.2	F30	Blue: -
X2.4.1.2:+	–	–			Brown: +
X2.4.2.1	–	–	CV14	F30	Grey: ASR +
X2.4.2.2	PCI6229 C/0	Pin 22; AO0			Black: SP +
X2.4.3.1	–	–	CV13	F30	Pink: ASR +
X2.4.3.2	PCI6229 C/0	Pin 21; AO1			White: SP +
X2.4.4.1	PCI6229 C/0	Pin 26; AI13	DPT05	F30	Purple: -
X2.4.4.2	PCI6229 C/0	Pin 60; AI5	PT17	F30	Red/Blue: -
X2.4.5.1	PCI6229 C/0	Pin 61; AI12	TT15	F30	Grey/Pink: -
X2.4.5.2	–	–	–	–	–
X2.5.1.1	PCI6229 A/0	Pin 31; AI10	–	F35	–
X2.5.1.2	PCI6704	Pin 60; AO5			–
X2.5.2.1	–	–			–
X2.5.2.2	–	–			–
X2.5.3.1	PCI6229 A/0	Pin 30; AI3	CV07	F35	Black: ASR +
X2.5.3.2	PCI6229 A/1	Pin 21; AO3			Gray: SP +
X2.5.4.1	–	–			Blue: -
X2.5.4.2	–	–			Brown: +
X2.5.5.1	PCI6229 A/0	Pin 63; AI11	CV04	F35	Black: ASR +
X2.5.5.2	PCI6704	Pin 57; AO7			Gray: SP +
X2.5.6.1	–	–			Blue: -
X2.5.6.2	–	–			Brown: +
X2.5.7.1	PCI6229 A/0	Pin 28; AI4			Black: ASR +

Terminal	Breakout board	Pin	Tag name	Fuse	Conductor signal & color
X2.5.7.2	PCI6704	Pin 22; AO8	CV09	F35	Gray: SP +
X2.5.8.1	–	–	CV09	F35	Blue: -
X2.5.8.2	–	–	CV09	F35	Brown: +
X2.5.9.1	PCI6229 A/0	Pin 61; AI12	CV05	F35	Black: ASR +
X2.5.9.2	PCI6704	Pin 54; AO9	CV05	F35	Gray: SP +
X2.5.10.1	–	–	CV05	F35	Blue: -
X2.5.10.2	–	–	CV05	F35	Brown: +
X2.5.11.1	PCI6229 A/0	Pin 60; AI5	–	F35	–
X2.5.11.2	PCI6704	Pin 52; AO10	–	F35	–
X2.5.12.1	–	–	–	F35	–
X2.5.12.2	–	–	–	F35	–
X2.5.13.1	PCI6229 A/0	Pin 26; AI13	CV12	F35	Black: ASR +
X2.5.13.2	PCI6704	Pin 17; AO11	CV12	F35	Gray: SP +
X2.5.14.1	–	–	CV12	F35	Blue: -
X2.5.14.2	–	–	CV12	F35	Brown: +
X2.5.15.1	PCI6229 A/0	Pin 25; AI6	–	F35	–
X2.5.15.2	PCI6704	Pin 15; AO12	–	F35	–
X2.5.16.1	–	–	–	F35	–
X2.5.16.2	–	–	–	F35	–
X2.5.17.1	PCI6229 A/0	Pin 58; AI14	CV22	F35	Black: ASR +
X2.5.17.2	PCI6704	Pin 47; AO13	CV22	F35	Gray: SP +
X2.5.18.1	–	–	CV22	F35	Blue: -
X2.5.18.2	–	–	CV22	F35	Brown: +
X2.5.19.1	PCI6229 A/0	Pin 57; AI7	CV15	F35	Black: ASR +
X2.5.19.2	PCI6704	Pin 12; AO14	CV15	F35	Gray: SP +
X2.5.20.1	–	–	CV15	F35	Blue: -
X2.5.20.2	–	–	CV15	F35	Brown: +
X2.6.1.1	–	–	CFM05 supply	F35	Blue: -
X2.6.1.2	–	–	CFM05 supply	F35	Brown: +
X2.6.2.1	–	–	CFM05 CH A		Blue: -
X2.6.2.2	–	–	CFM05 CH A		Brown: +
X2.6.3.1	–	–	CFM05 CH B		Black: -
X2.6.3.2	–	–	CFM05 CH B		Gray: +
X2.6.4.1	PCI6229 C/0	Pin 31; AI10	PT06		Blue: -
X2.6.4.2	–	–	PT06		Brown: +
X2.6.5.1	PCI6229 C/0	Pin 65; AI2	TT07		Black: -
X2.6.5.2	–	–	TT07		Gray: +
X2.6.6.1	–	–	CVX04		–
X2.6.6.2	PCI6229 C/1	Pin 37; DO24	CVX04		Gray: +
X2.6.7.1	–	–	CVX04		Blue: -
X2.6.7.2	–	–	CVX04		Brown: +
X2.6.8.1					
X2.6.8.2					
X2.6.9.1					

Terminal	Breakout board	Pin	Tag name	Fuse	Conductor signal & color
X2.6.9.2					
X2.6.10.1					
X2.6.10.2					
X2.7.1.1	PCI6229 B/1	Pin 57; AI23	PT08	F31	Green/Black: -
X2.7.1.2	PCI6229 B/1	Pin 58; AI30	TT09	F31	Black/Green: -
X2.7.2.1	PCI6229 B/1	Pin 25; AI22	MLT02	F31	Black/Orange: CH A -
X2.7.2.2	PCI6229 B/1	Pin 26; AI29			Gray/Black: CH B -
X2.7.3.1	PCI6229 B/1	Pin 60; AI21	PT14	F31	Black/Gray: -
X2.7.3.2	PCI6229 B/1	Pin 61; AI28	DPT04	F31	Green/Blue: -
X2.7.4.1	PCI6229 B/1	Pin 28; AI20	TT13	F31	Blue/Green: -
X2.7.4.2	PCI6229 B/1	Pin 63; AI27	DPT03	F31	Orange/Blue: -
X2.7.5.1	–	–	–	–	–
X2.7.5.2	–	–	–	–	–
X2.7.6.1	PCI6229 B/0	Pin 41; FI1	CFM03	F31	White/Blue: F+
X2.7.6.2	PCI6229 B/1	Pin 30; AI19			Blue/Orange: D+
X2.7.7.1:-	–	–	Supply MCC 6.1	F31	Blue/White: -
X2.7.7.2:+	–	–			Brown/Black: +
X2.8.1.1	PCI6229 B/0	Pin 57; AI7	PT12	F31	Green/Black: -
X2.8.1.2	PCI6229 B/0	Pin 58; AI14	PT16	F31	Black/Green: -
X2.8.2.1	PCI6229 B/0	Pin 25; AI6	TT06	F31	Blue/Black: -
X2.8.2.2	PCI6229 B/0	Pin 26; AI13	PT05	F31	Black/Blue: -
X2.8.3.1	PCI6229 B/0	Pin 60; AI5	PT07	F31	Orange/Black: -
X2.8.3.2	PCI6229 B/0	Pin 61; AI12	PT10	F31	Black/Orange: -
X2.8.4.1	PCI6229 B/0	Pin 28; AI4	TT11	F31	Gray/Black: -
X2.8.4.2	PCI6229 B/0	Pin 63; AI11	PT20	F31	Black/Gray: -
X2.8.5.1	PCI6229 B/0	Pin 30; AI3	TT03	F31	Green/Blue: -
X2.8.5.2	PCI6229 B/0	Pin 31; AI10	PT15	F31	Blue/Green: -
X2.8.6.1	PCI6229 B/0	Pin 65; AI2	PT02	F31	Orange/Blue: -
X2.8.6.2	PCI6229 B/0	Pin 66; AI9	PT19	F31	Blue/Orange: -
X2.8.7.1	PCI6229 B/0	Pin 33; AI1	–	–	White/Blue: -
X2.8.7.2	PCI6229 B/0	Pin 34; AI8	PT03	F31	Blue/White: -
X2.8.8.1	PCI6229 B/0	Pin 68; AI0	TT04	F31	Black/Brown: -
X2.8.8.2	–	–	–	–	–
X2.8.9.1:-	–	–	Supply MCC 1.1	F31	–
X2.8.9.2:+	–	–			Brown/Black: +
X2.9.1.1	PCI6229 C/1	Pin 57; AI23	MLT01	F31	Green/Black: CH A -
X2.9.1.2	PCI6229 C/1	Pin 58; AI30			Black/Green: CH B -
X2.9.2.1	PCI6229 C/1	Pin 25; AI22	LT02	F31	Blue/Black: -
X2.9.2.2	PCI6229 C/1	Pin 26 ; AI29	TT05	F31	Black/Blue: -
X2.9.3.1	PCI6229 C/1	Pin 60 ; AI21	LT01	F31	Orange/Black: -
X2.9.3.2	PCI6229 C/1	Pin 61 ; AI28	TT14	F31	Black/Orange: -
X2.9.4.1	PCI6229 C/1	Pin 28 ; AI20	PT09	F31	Gray/Black: -
X2.9.4.2	PCI6229 C/1	Pin 63 ; AI27	TT12	F31	Black/Gray: -

Terminal	Breakout board	Pin	Tag name	Fuse	Conductor signal & color
X2.9.5.1	PCI6229 C/1	Pin 30 ; AI19	PT11	F31	Green/Blue: -
X2.9.5.2	PCI6229 C/1	Pin 31 ; AI26	PT04	F31	Blue/Green: -
X2.9.6.1	PCI6229 C/1	Pin 65 ; AI18	PT01	F31	Orange/Blue: -
X2.9.6.2	PCI6229 C/1	Pin 66 ; AI25	MFM04	F31	Blue/Orange: -
X2.9.7.1	PCI6229 C/1	Pin 33 ; AI17	–	F31	White/Blue:
X2.9.7.2	PCI6229 C/1	Pin 34 ; AI24	–	F31	Blue/white:
X2.9.8.1:-	–	–	Supply MCC 2.1	F31	
X2.9.8.2:+	–	–			
X2.9.9.1	PCI6229 C/1	Pin 68 ; AI16	CFM02_D	F31	Black/Brown: -
X2.9.9.2	PCI6229 C/0	Pin 57 ; AI7	CFM04_D	F31	Green/Black: -
X2.9.10.1	PCI6229 C/0	Pin 58; AI14	CFM01_D	F31	Black/Green: -
X2.9.10.2	PCI6229 B/0	Pin 3; FI0	CFM02_F	F31	Black/Blue: FO +
X2.9.11.1	PCI6229 C/0	Pin 41; FI1	CFM04_F	F31	Orange/Black: FO +
X2.9.11.2	PCI6229 C/0	Pin 3; FI0	CFM01_F	F31	Black/Orange: FO +
X2.9.12.1	PCI6229 C/0	Pin 25 ; AI6	MFM02	F31	Gray/Black:
X2.9.12.2	PCI6229 C/0	Pin 30 ; AI3	MFM01	F31	Black/Gray:
X2.9.13.1:-	–	–	Supply MCC 2.2	F31	Blue/Black: -
X2.9.13.2:+	–	–			Brown/Black: +
X2.10.1.1	PCI6229 B/0	Pin 17 ; DO1	CVX14	F30	Green: +
X2.10.1.2	PCI6229 B/0	Pin 52 ; DO0	CVX09	F30	Red: +
X2.10.2.1	PCI6229 B/0	Pin 47 ; DO3	CVX16	F30	Yellow: +
X2.10.2.2	PCI6229 B/0	Pin 49 ; DO2	CVX15	F30	Black: +
X2.10.3.1	PCI6229 B/0	Pin 51 ; DO5	CVX18	F30	Gray/Pink: +
X2.10.3.2	PCI6229 B/0	Pin 19 ; DO4	CVX17	F30	Red/Blue: +
X2.10.4.1	PCI6229 B/0	Pin 48 ; DO7	CVX20	F30	White: +
X2.10.4.2	PCI6229 B/0	Pin 16 ; DO6	CVX19	F30	Purple: +
X2.10.5.1	PCI6229 B/1	Pin 17 ; DO9	CVX10	F30	Brown: +
X2.10.5.2	PCI6229 B/1	Pin 52 ; DO8	CVX08	F30	Pink: +
X2.10.6.1:+	–	–	Supply MCC 3.1	F30	–
X2.10.6.2:-	–	–			Blue: -
X2.11.1.1:-	–	–	Supply MCC 4.1	F33	Blue: -
X2.11.1.2:+	–	–			Pink: +
X2.11.2.1	–	–	CV08	F33	Green/White: ASR+
X2.11.2.2	PCI6229 B/0	Pin 68; AO0			Gray: SP+
X2.11.3.1	–	–	CV11	F33	Yellow/Brown: ASR+
X2.11.3.2	PCI6229 B/0	Pin 33; AO1			Brown: SP+
X2.11.4.1	–	–	CFM06 CH A	F33	Yellow/White:
X2.11.4.2	–	–			White: +
X2.11.5.1	–	–	CFM06 CH B	F33	Gray/Pink: -
X2.11.5.2	–	–			Yellow: +
X2.11.6.1	PCI6229 C/0	Pin 34; AI8	DPT07	F33	Black: -
X2.11.6.2	PCI6229 C/0	Pin 63; AI11	DPT06	F33	Red: -
X2.11.7.1	–	–	PT18	F33	Green: -

Terminal	Breakout board	Pin	Tag name	Fuse	Conductor signal & color
X2.11.7.2	–	–	AFM04	F33	Red/Blue: +
X2.12.1.1:-	–	–	Supply MCC 5.1	F33	Brown/Yellow: -
X2.12.1.2:+	–	–			Blue: +
X2.12.2.1	–	–	CV03	F33	White/Yellow: ASR +
X2.12.2.2	PCI6229 C/1	Pin 22; AO2			Pink:SP +
X2.12.3.1	–	–	CV23	F33	Red/Blue: ASR +
X2.12.3.2	PCI6229 C/1	Pin 21; AO3			Red: SP +
X2.12.4.1	PCI6229 A/1	Pin 6; DO21	CVX06	F33	Green: +
X2.12.4.2	PCI6229 A/1	Pin 5; DO22	CVX07	F33	Yellow: +
X2.12.5.1	PCI6229 A/1	Pin 38; DO23	CVX05	F33	Black: +
X2.12.5.2					
X2.12.6.1					
X2.12.6.2					

Table 9.3: Terminal panel sheet part 2.