



Norwegian University of
Science and Technology

Finalizing the Wet Gas Laboratory

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Subsea Technology

Submission date: June 2017

Supervisor: Christian Holden, MTP

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



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MASTER'S THESIS
Spring 2017
for stud.techn. Daniel Nedregård

Finalizing the Wet Gas Compressor Laboratory

Aging gas fields experience a significant long-term reservoir pressure drop. This can be problematic, as pressure is needed to push the produced gas to the topside facility. One solution to this problem is to install a subsea gas compressor to artificially increase the gas pressure.

Compressors can be either dry or wet. Dry gas compressors cannot handle liquid in the gas stream, while wet gas compressors can handle some liquid in the gas stream. While dry gas compressors have been used for several years on-shore for a wide range of applications, wet gas compressors are fairly rare. Mathematical models of wet gas compressors useful for automatic control purposes are at present non-existent.

To aid in developing and verifying such models and control algorithms to exploit them, the Department of Mechanical and Industrial Engineering has been constructing a small-scale laboratory. The initial design was done fall semester of 2015 and initial construction during the spring semester of 2016. Construction has continued during the fall semester of 2016.

During the fall semester of 2016, several critical design flaws of the original design of the laboratory became apparent, delaying the completion of the laboratory.

In this task, the student will finalize the construction of the laboratory, to wit:

1. Complete the oil loop lubricating the compressor
2. Finish installing the electrical system
3. Design and implement the human/machine interface in LabView
4. Finalize the analog-to-digital and digital-to-analog connections necessary for the PC to communicate with sensors and actuators
5. Complete the installation of the turbocharger (compressor), ensuring that it operates as required/expected
6. Fix errors and design flaws that have come to light over the construction of the laboratory to the extent possible

At the end of the project, the laboratory should be fully operational within revised operational parameters.

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Summary

This report describes the final stages of development for the small scale wet gas compression test lab. The lab is located at the MTP Institute at NTNU in Trondheim, and it is built in the workshop at campus Valgrinda. The plans and designs for this lab were made in the autumn of 2015, this marked the start of this entire project. The construction phase started in the spring of 2016, this phase was mostly completed in the autumn of 2016. The electrical work was also the started in the second half of 2016. Most of the sensors and transmitters were wired at this time, and the empty electrical cabinet was mounted on the lab. Substantial amounts of time were spent making the lab ready for the next stage, this meant troubleshooting, pressure testing and correcting design flaws.

At the current stage, control system design and software development have been a major part of the project. The report also describes how the auxiliary systems have been completed. An example of this is compressor lubrication system. It provides a detailed description of how the lab has been completed, how it functions and how it should be operated. Future improvements and current operational limitations are also examined and reviewed. It discusses the final state of the control systems, as well as potential future control installments. The topic of health, safety, and environment is also included. The efforts made to meet HSE requirements are described in the report. The research topic of wet gas compression is also presented in introduction of the report.

At the end of this stage, the lab is operational, but it requires further optimization. Further work is required to tune controllers, this needs to be done to allow for wet gas experimentation. A flow meter needs to be installed, and the RPM and temperature measurements systems need to be improved.

Sammendrag

Denne rapporten beskriver ferdigstillingen av små skala våt gass kompressor laben ved MTP instituttet på NTNU i Trondheim. Laben er bygd på verkstedet som tilhører campus Valgrinda. Oppstarten av prosjektet startet i 2015, i oppstarts fasen ble design og funksjonalitet definert. Byggefasen startet på våren i 2016, denne fasen ble nesten helt ferdig i andre halvdel av 2016. Det elektriske arbeidet begynte også i denne fasen, de fleste sensorene og transmitterne ble koblet og det tomme sikringsskapet ble montert på laben. Denne fasen var stort sett dominert av feilsøking og feilretting. Trykktesting og tilsvarende tiltak ble gjort for å klargjøre laben for neste fase.

Kontroll system og programvare utvikling har vært hovedproblemstillingen i den nåværende prosjektfasen. I tillegg til dette beskriver rapporten også hvordan tilhørende systemer som kompressorens smøresystem har blitt installert. Rapporten gir også en detaljert beskrivelse av hvordan laben som helhet har blitt ferdigstilt, hvordan den fungerer og hvordan den skal brukes. Fremtidige forbedringspotensialer og operasjons begrensinger er også diskutert og undersøkt. Den reflekterer rundt kontroll systemenes funksjonalitet, så vel som potensialet for fremtidige kontroll forbedringer. Helse miljø og sikkerhet er også et sentralt tema i rapporten, en betydelig innsats har blitt lagt inn for å tilfredsstillende HMS krav til trygg drift. Forskningsfeltet våt gass kompresjon blir også presentert i rapporten introduksjon

Rapporten konkluderer med å si at laben er operativ ved semesterets slutt, men det foreligger et behov for fremtidige forbedringer. Mer arbeid kreves for å stille inn kontrollere på en slik måte som muliggjør våt gass eksperimenter. Man trenger også å installere et flyt meter, samt forbedre RPM og temperatur målesystemene.

Abbreviations

PI	Proportional Integral controller
PT	Pressure transmitter
TT	Temperature transmitter
TS	Temperature sensor
LS	Level Sensor
CV	Control Valve
VSD	Variable Speed Drive
HSE	Health Safety Environment
GVF	Gas Volume Fraction
RPM	Revolutions Per Minute
I/O	Input / Output
FAT	Factory Acceptance Test
SLL	Surge Limit Line

OPL	Operation Point Line
SD	Surge Distance
API	American Petroleum Institute
DC	Direct Current
AC	Alternating Current
DAQ	Data Acquisition
PT-100	Platinum Resistance - 100 (0 C° @100Ω)
USB	Universal Serial Bus
OSB	Oriented Strand Board (construction material)
PSV	Pressure Safety Valve
MDF	Medium Density Fibreboard (construction material)
PVC	Polyvinyl chloride (construction material)
P&ID	Process and Instrumentation Diagram
HMI	Human Machine Interface

Contents

Summary	v
Sammendrag	vii
Contents	xi
List of Figures	xiii
Preface	xv
1 Introduction	1
1.1 Background	1
1.2 Wet gas compression	2
1.3 Motivations for constructing a small scale test lab	4
1.4 Description of lab design	6
1.5 A continuation of previous work	8
1.6 Control system design	8
1.7 Scope of report	10
1.8 Structure of report	10
2 Theory	13
2.1 Modelling the compressor behavior	15
2.2 Compressor limitations	19
2.3 Control system design	21
2.4 Control valves	26
2.5 Gear pump	27
2.6 Gas liquid separation	28
2.7 Counter flow cooler	30
3 Construction and results	33

xi

Contents

3.1	Electrical systems	33
3.2	Factory acceptance tests (FAT) on electrical systems	46
3.3	Compressor setup	48
3.4	Construction required by HSE factors	53
3.5	Counter flow cooler blowout	57
3.6	FAT of Instrumentation and physical layout	58
4	Control system design	59
4.1	Control system requirements	59
4.2	Basic starting point control	61
4.3	Alarm system	66
4.4	FAT on basic control software	67
5	Discussion	69
5.1	Electrical design	69
5.2	Turbocharger lubrication system	70
5.3	Problems with IO setup	71
5.4	Reflections on current lab status	71
6	Conclusion	75
6.1	Future work	76
	Appendices	79
A	FAT tests	81
B	Datasheets excerpts	89
C	Schematics	115
D	Commissioning	121
	References	143

List of Figures

1.1	Effect of installing subsea compressor [20]	2
1.2	Gulfaks field layout [24]	3
1.3	P & ID of small scale test laboratory	5
1.4	High temperature section, Feb 2017	7
1.5	Low temperature section of test lab, May 2017	7
1.6	Basic control concept	8
1.7	Boundaries of centrifugal compressor operation	9
2.1	Working principle	14
2.2	Multistage centrifugal compressor [16]	14
2.3	Conservation of energy in pipe	15
2.4	Head of pump	17
2.5	Compressor map	18
2.6	Anti surge valve	20
2.7	Anti windup [15]	22
2.8	Distance to surge	25
2.9	Anti surge control system [23]	26
2.10	Gear pump principle [17]	27
2.11	Separator design [12]	29
2.12	Separator principle sketch [13]	30
2.13	Counter flow cooler principle	30
2.14	Counter flow cooler, [12]	31
3.1	Final arrangement of electrical cabinet	35
3.2	Initial arrangement of electrical cabinet [12]	36
3.3	The inside of the cabinet	37
3.4	Front panel controls	38
3.5	Soldered RPM sensor connection	39
3.6	DAQ setup	40

List of Figures

3.7	DAQ unit [7]	41
3.8	DAQ unit, I/O [7]	41
3.9	Current to voltage conversion	42
3.10	Current output module [8]	43
3.11	Resistance measurement	44
3.12	Temperature measurement breadboard	46
3.13	Working principle of turbocharger [26]	48
3.14	Turbocharger setup	49
3.15	Turbocharger lubrication	49
3.16	Initial oil loop setup	50
3.17	Final loop setup	50
3.18	Turbocharger mount	51
3.19	Oil restrictor	52
3.20	Oil restrictor mount	52
3.21	Oil inlet adapter	52
3.22	Design of safety wall	53
3.23	Movable wall	54
3.24	Final setup	54
3.25	PSV principle	54
3.26	Pressure release valve (PSV)	55
3.27	Control Station	56
3.28	Control station protection	56
3.29	Operator protection	57
3.30	Cooler lid [12]	58
4.1	Pressure zones	60
4.2	Front Panel (HMI)	61
4.3	Turbo control tab	62
4.4	Mixing control	63
4.5	Suction pressure control	64
4.6	Pressure monitoring	65
4.7	Alarm table	67
5.1	RPM sensor output	73

Preface

This thesis is written as the final work in the subsea engineering master degree at NTNU in Trondheim. I started out this two-year master degree program at NTNU in the autumn of 2015, it has been two challenging but fruitful years. The project that this thesis is a continuation of started out in the autumn of 2015. I took over the project in 2016 as a pre-project to my master thesis. It has been a slightly different journey than I first imagined starting out, the work were mainly supposed to encompass software design and control implementation, but as it turned out, many practical challenges stood before us. I see this as a valuable experience, the project contains all core elements of engineering, planning, research, testing, building, design, redrawing and troubleshooting. I have never before learned so much in such a short time. I would not have been able to complete this project without the support from my supervisor, my fellow students, my fiancée, and family.

Acknowledgments

At first, I want to thank my supervisor Christian Holden, who has been very helpful and always available when project related have problems occurred. He has given valuable insight and helped push the project forward. Also, a big thank you to Torstein Thode Kristoffersen and Sveinung Johan Ohrem for giving valuable feedback on this report. I also want to thank my fellow students in the university office, but first and foremost Njål Tengesdal. He helped out with redrawing and redesigning the electrical system, as well as helping out with practical problems throughout the semester. I also want to thank my fiancée and life companion Misghana Estifanos for always being supportive, she gives me a bigger reason to keep on working and completing this work in the best possible manner.

Daniel Nedregård

Trondheim, June 2017

Chapter 1

Introduction

As the world demand for energy is ever increasing, the easily extracted oil and gas is becoming harder to find. New technologies are being developed to allow for exploitation of fields that previously were considered unreachable. Oil and gas fields are discovered at ever increasing water depths at more remote conditions than ever before. This also makes it more important to maximize the recovery of the fields that are already in production. These factors combined with a financial push to maximize profitability, act as major drivers for investments in technology that increase recovery and production rates. Reduced extent installation and operation cost is a major concern for the industry to remain profitable in the years to come.

1.1 Background

Subsea gas compressors are used to increase production rates and to compensate for the natural drop in production pressure as the reservoirs are depleted. They are often part of a bigger subsea boosting system consisting of pumps, separators and injection trees. [9]. Since the oil and gas reservoirs today are found at ever increasing depths, and tie back distances to hosts or processing facilities keeps getting longer, the need for production boosting technology is increasing. Subsea compression technology will enable production in fields that otherwise would not be profitable [25]. In a gas field, the production is boosted using powerful centrifugal compressors that help the gas flow out of the reservoir more efficiently. The gas flows more easily by reducing the back pressure that is opposing the natural flow. In an oil field, pumps are used to both inject water into the reservoir and to lift the oil pressure to boost production. Conventional compressors and pumps require separators to ensure optimal performance. Typically the oil, water, and gas, are separated into three separate streams. Compressors are used to boost the gas flow, while pumps are used for pumping heavy oil and

1. Introduction

for reinjecting water into the reservoir. It is crucial that the compressors are only fed with dry gas, as conventional compressors are not designed to operate with liquids present in the flow. This means that the compressor technology that can handle multiphase streams would be an improvement on the conventional compressor technology used subsea.

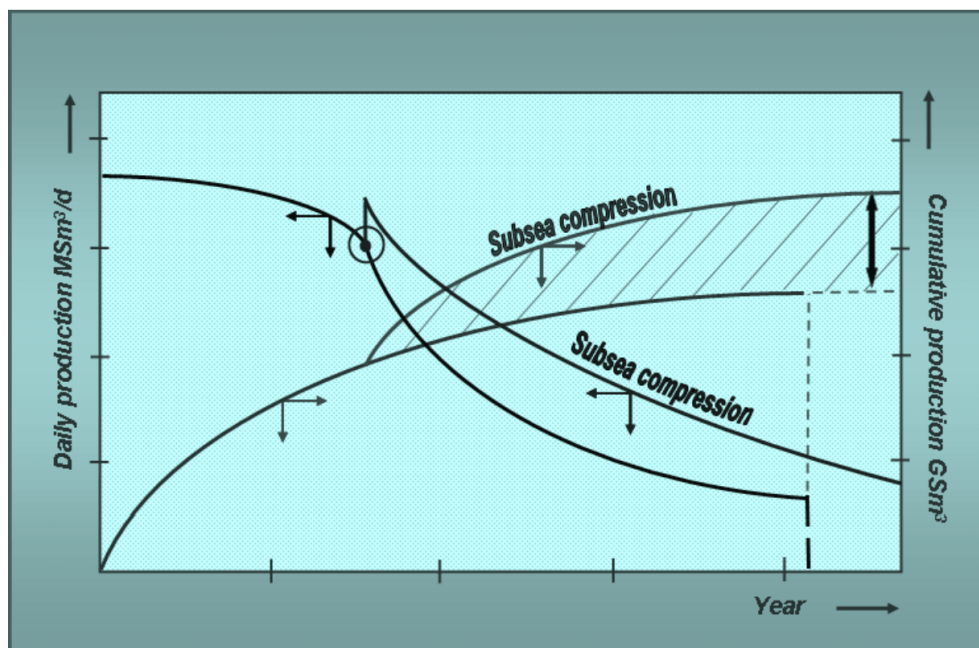


Figure 1.1: Effect of installing subsea compressor [20]

1.2 Wet gas compression

Wet gas compression is an ongoing research and development topic within the offshore oil and gas industry [20]. It is of great interest to the industry to develop subsea compressors that can operate efficiently with varying amounts of liquids present in the system. A major driver for the technology is the reduction of investment costs. Additional subsea processing technologies like separation systems will no longer be required for subsea compression as wet gas compressors can be utilized. As mentioned, conventional subsea compressors are not able to handle liquids, and they require dry gas to ensure proper operation and integrity.

The first subsea wet gas compressor was installed at Gullfaks in 2015, it is tied back to the Gullfaks C platform [4]. The field is located at a depth of 135-220 meters of water in block 34/10 on the Norwegian continental shelf [25]. Most of the produced gas from the Gullfaks C platform originates from the L, M and N production templates seen in Figure 1.2.

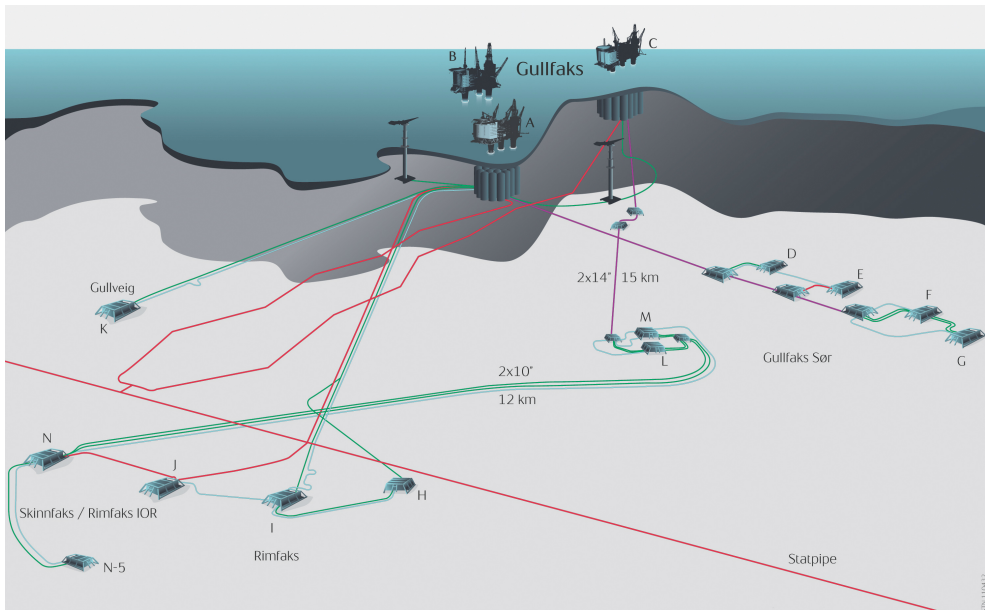


Figure 1.2: Gullfaks field layout [24]

Forecasts made on the production pressure in these templates showed that the natural drop in production pressure could be compensated for with a subsea compressor. It also showed that it could accelerate production with minimum impact on topside facilities. Additionally, installing a subsea compressor would result in higher production rates, optimization of flow conditions, reduced abandonment pressure and pressure drop in pipelines. An additional benefit is that the temperature conditions improve post compression, which reduces the chance of hydrate formations downstream of the compressor [11]. Low temperature combined with high pressure increases the risk of hydrate formation in pipelines. The compressor increases the temperature in the piping downstream of the compressor outlet, and thus it reduces the chance of hydrates forming and clogging the pipeline.

1.2.1 Challenges associated with wet gas compressors

The topic of wet gas compression is introducing a new set of challenges that needs to be addressed. Comparative experimental research on the performance and behavior of wet and dry gas compressors has been done and summarized in [6]. Based on this research, it can be said that the power needed to operate compressors increase significantly as liquid is introduced in the flow. Furthermore, the pressure ratio over the compressor is showed to increase when liquid is present. The opposite occurs with the temperature ratio, the liquid act as a coolant that reduce the temperature ratio over the compressor. Another consequence of introducing

1. Introduction

liquid into the gas stream, is a reduction in volumetric flow capacity. These facts show that there is still room for improvement on the performance of multiphase compressor systems. More research is also needed to predict and control the behavior of such systems [6].

Since the gas volume fraction GVF has such a profound effect on the compressor behavior, it is highly likely that the control system design approach has to be different than for conventional dry gas compressors. Small fluctuations in GVF and flow rate might affect the compressor dynamics in such a way that PI controllers might be insufficient for maintaining stable operation. The introduction of liquid in the gas flow affects the dynamics of the compressor, the pressure ratio and mass flow rate is increased. The power needed to maintain the angular velocity increases as well, this also affects the controller tuning required to maintain stable operation. It can not be assumed that a PI controller that maintains stable operation with dry gas, also will ensure stability when liquid enters the gas flow. The increased mass flow makes the compressor more susceptible to instabilities [27].

1.3 Motivations for constructing a small scale test lab

The Norwegian University of Science and Technology (NTNU) is a major participant in the research of wet gas compression. It has a single stage centrifugal compressor test facility that is dedicated to wet gas compression research [6]. The test lab is mostly occupied by the industry and higher level research, it is not available for small scale student assignments [12]. Building a small-scale test lab can make wet gas compression experimentation more available to students. The results found in smaller student assignments and projects could add to the knowledge on wet gas compression. Small scale tests could also be used to determine whether full-scale tests of certain scenarios are required. The work on designing and building such a small scale test lab started in the autumn of 2015 and the P&ID for the lab as it is in the beginning of 2017 can be seen in Figure 1.3.

1.3. Motivations for constructing a small scale test lab

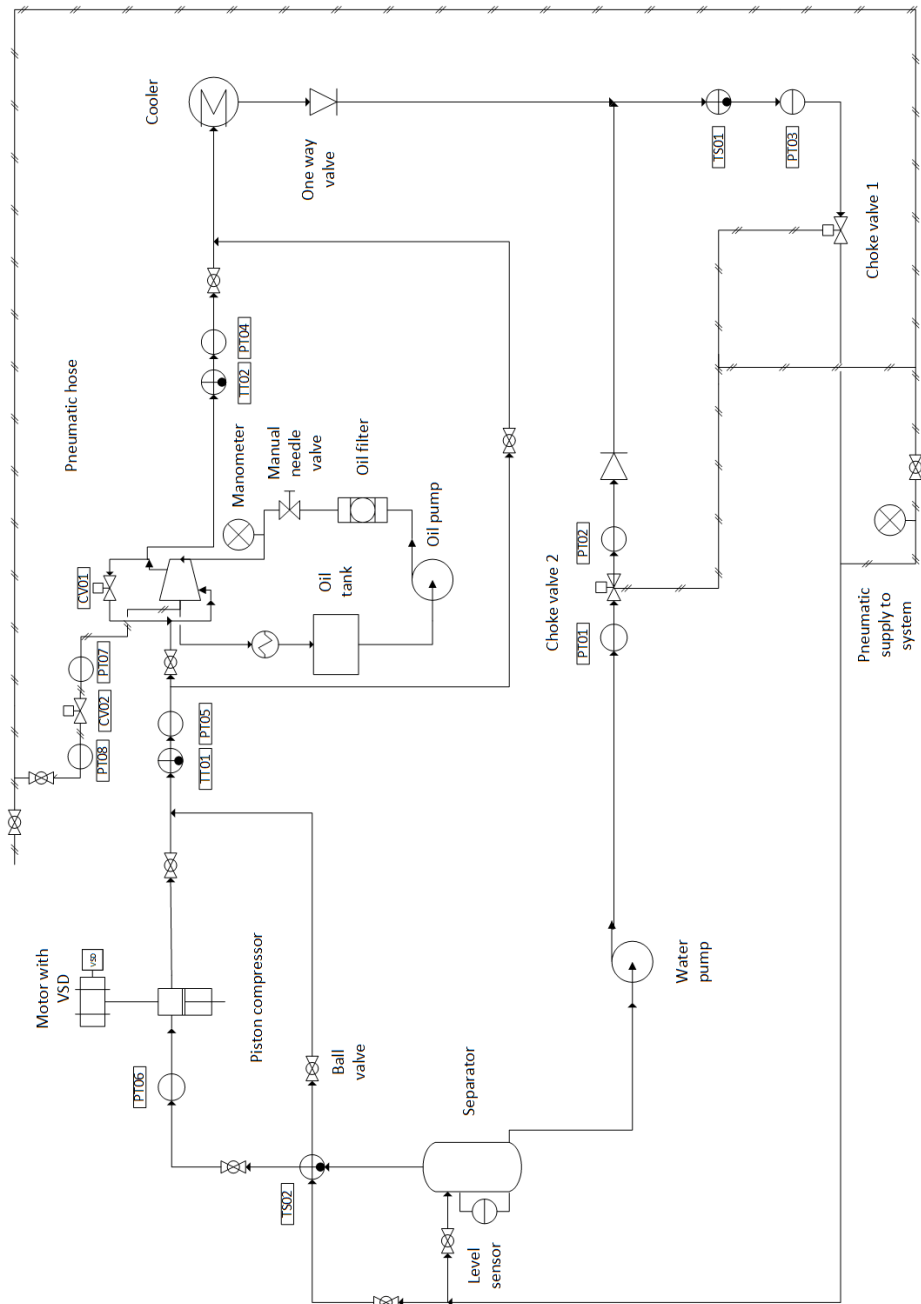


Figure 1.3: P & ID of small scale test laboratory

1.4 Description of lab design

The test lab is designed to emulate a subsea wet gas compression scenario. The lab is designed as a closed loop. When the lab is running in steady state operation, the compressor inlet conditions should remain stable. The compressor outlet pressure is reduced and the flow is cooled before returning to the compressor inlet. Water and air are used instead of oil and natural gas, the effect on the compressor dynamics will probably be comparative. Both cases represent a multiphase flow compression scenario, although water is slightly more dense than oil.

The first component on the lab is a gas/liquid separator, the flow can either be directed through it, or it can be bypassed using manual valves. A piston compressor is installed downstream of the separator, but it will not be part of the topic at this stage in the project. The piston compressor is installed with the intention of conducting dry gas compression experiments, and it could be part of future student projects. If the piston compressor is ever going to be used, it is crucial that it is only used for dry gas compression. Before the piston compressor can be used, the whole system needs to be drained. This must be done to prevent any droplets from entering the piston compressor inlet, the flow also needs to pass through the separator with the separator bypass line closed. The piston compressor can be bypassed leading the flow directly to the centrifugal compressor. When operating the centrifugal compressor, both wet and dry gas experiments can be done. A cooler is installed downstream of the centrifugal compressor. This is done since the compressed air is expected to leave the compressor at a high temperature. The cooler restore the compressor inlet temperature conditions. The temperature and pressure need to be reduced to compressor inlet conditions since the lab works like a closed loop. The cooler reduces the temperature before the pressure is reduced by Choke valve 1. The choke valve is installed to reduce the pressure to inlet conditions, thereby it controls the suction pressure of the centrifugal compressor. From the bottom of the separator, the water stream is pumped back into the air stream. A second choke valve, Choke valve 2, is therefore installed to control the outlet pressure of the water stream, this should ensure sufficient water flow. The water flow from the separator outlet merges with the airflow at a T-joint downstream of the cooler. The lab is divided into high and low-temperature sections, the high-temperature section of the lab can be seen in Figure 1.4. The low-temperature section can be seen in Figure 1.5.

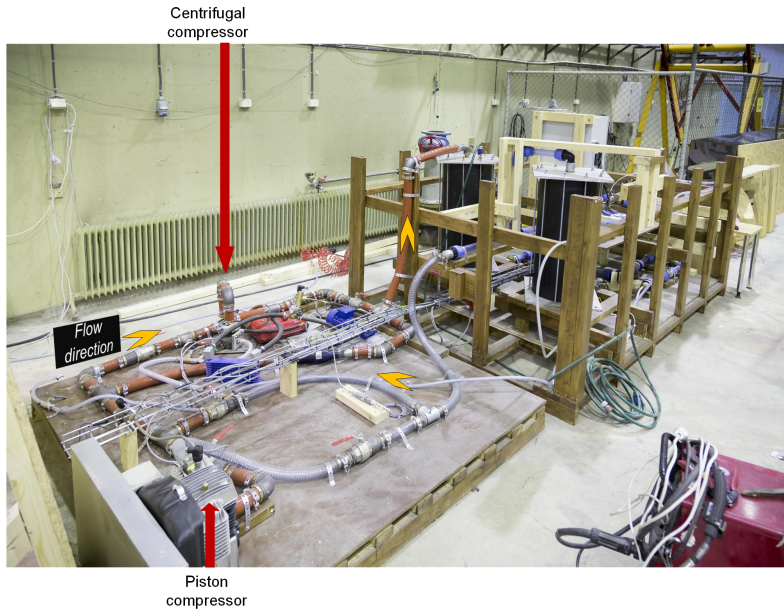


Figure 1.4: High temperature section, Feb 2017

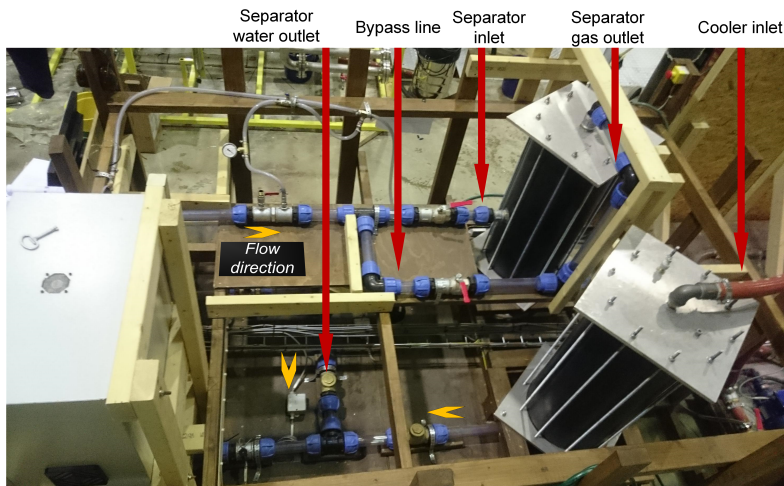


Figure 1.5: Low temperature section of test lab, May 2017

1.5 A continuation of previous work

This work done on this project has been divided into three previous stages. The initial designs and plans were made in the autumn of 2015, the objectives and motivations for the lab were defined at that time. The building and construction started in the spring of 2016, this work was conducted as a master thesis, the construction continued in the autumn of 2016. This was also when the electrical work was started, furthermore, pressure and leak testing was conducted at this stage. The work performed in this semester builds on all the previous stages in the project. In the current stage, the main goal is to design the software required for safe and optimal control of the lab. Before the lab can be operated, the remaining practical work needs to be performed. This includes wiring in the cabinet and completing LabView setup, as well as building safety structures and barriers that will protect bystanders in case of dangerous malfunction. The compressor lubrication system also needs to be tested to ensure that the integrity of the compressor is not compromised.

1.6 Control system design

The most challenging aspect of the current project stage is the control system design. The basic controller concept is shown in Figure 1.6, feedback from the plant is used to adjust control output. On this lab, valve positions are controlled to obtain the desired system behavior at the lab. The valve position is automatically adjusted to obtain the desired value for a chosen control variable.

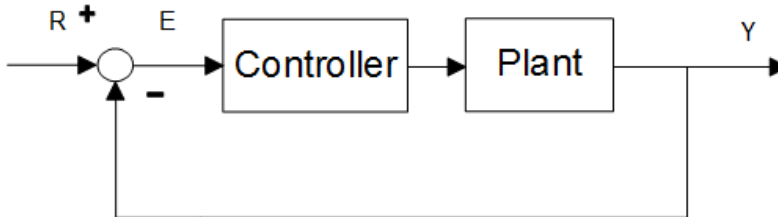


Figure 1.6: Basic control concept

Controlling a centrifugal compressor can be thought of as controlling multiple variables simultaneously. The compressors operating point is determined by the flow rate Q , the pressure ratio R and the angular velocity of the compressor ω , given in [rad/s]. Revolutions per minute [RPM] is also a commonly used to measure the velocity of a compressor. The operation point can be represented as a point a compressor map, an example is shown in Figure 1.7.

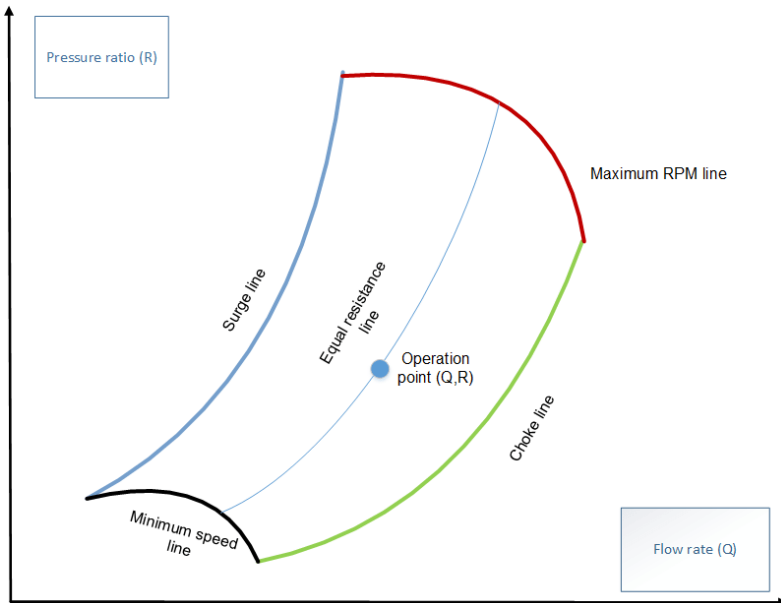


Figure 1.7: Boundaries of centrifugal compressor operation

The flow rate is affected by both the operational speed of the compressor, and the downstream resistance in the system. The equal resistance line is the trajectory of the operation point with varying RPM and constant downstream resistance. Downstream resistance also affects the pressure ratio, increasing the resistance reduces the flow rate and increases the pressure ratio. The control system should be able to move the operation point to any valid point on the compressor map. But the most important task for the control system is safety. If any pressure or temperature limit is exceeded, the system should shut down the compressor and minimize the downstream resistance. This is the first concern with regards to the control system.

RPM control will be the second concern with regards to the control system. A controller that regulates the shaft speed should be able to keep the compressor speed independent of other variables.

The second requirement with regards to control is stability, the compressor dynamics are stable as long as it operates within the boundaries of the compressor map. There are two instability regions in particular that the control system should avoid, surge and choke. These phenomena will be described in detail in the next chapter. Surge and choke occur when the operation point is moved too far to the left or right in the surge map.

1. Introduction

Another task is to be able to move the operation point. The controller should be able to move the operating of the compressor to the desired level of output pressure and flow. The controller will have to work together with the systems that keep the operation within defined safety zone, allowing free control of the operating point as long as the compressor is within its defined safety zone.

Deactivation of safety and stability systems might be necessary for experiments that aim to study the occurrence of unwanted dynamics. Free control of the compressors operation point lets the user experimentally derive the compressor map, this could then be compared with models that are derived analytically. Hence, it will be necessary to allow the user to freely control the compressor without the intervention of any safety system.

The following requirements are included in the control system, the order indicates the priority.

1. Safety systems, shut down if any safety limits are breached.
2. RPM control.
3. Operation point control.
4. Stability control, choke and surge avoidance.
5. Possibility to deactivate stability control.

1.7 Scope of report

This report documents the work that has been performed at the wet gas compression test lab in the spring semester of 2017. The report includes background theory and an introduction to the research topic of wet gas compression. Lastly, the report discusses and evaluates the condition of the test lab at the end of the semester. It reflects on the project as a whole, and it concludes by describing what the lab is capable of and what may be done in the future.

1.8 Structure of report

The introduction chapter should give the reader an introduction to the topic of wet gas compression. It should also provide an understanding of the motivation for building a small scale wet gas compression test lab. The function and design of the lab are described, the reader should get an overview of the system as a whole. Furthermore, it briefly describes the topic of control for centrifugal compressors as this is one of the major challenges at this and the next stage of this project. The control system requirements are described in the last part of the introduction chapter, this should remain important for the future as most aspects of the control system have not yet been implemented.

The second chapter describes the fundamental theory that the current and future work can build on, this includes a description of how centrifugal compressors operate and how they can be described mathematically. Anti-surge control theory is described through an example of a standardized approach. This could be an important topic to build on in the future when flow instrumentation has been installed. Finally, the chapter briefly describes control valves and how they regulate flow, as well as how to do flow estimations. The fundamental theory behind the various components at the lab is also briefly described.

The third chapter describes the work that has been performed at the lab during this semester. This includes all the electrical work, the data input and output communication setup (I/O), the lubrication setup of the compressor and the constructions as required by Health Safety and Environment (HSE) concerns. It also describes how the factory acceptance tests have been conducted, this is a part of the lab completion process.

The fourth chapter describes the control systems and the LabView program that has been designed to safely operate the lab. The basic functionality and the intended operation of the lab through the program is described in this chapter. It describes the algorithms used to run the lab, and how the user should use the program.

The fifth chapter discusses the work that has been performed, it primarily tries to justify why the project has been progressing more slowly than planned. Lastly, it reflects on how the lab performs as a whole at the end of this stage in the project.

At last, the sixth chapter makes concluding remarks regarding the status of the lab as it stands at the end of the project. It also gives recommendations for future work and describes future possibilities.

Chapter 2

Theory

This chapter aims to describe the general theory that this work builds on. It compiles the general theory with the intention of making it easier to find general descriptions that are used to make assumptions elsewhere in the report. The work is built on theory in the area of thermodynamics, flow, control, electronics and process technology. The type of compressor used in the lab is a centrifugal compressor, a reciprocating compressor is installed, but it is not used in this stage of the project.

2.0.1 Working principle of a centrifugal compressor

A centrifugal compressor increases the pressure in a gas by converting kinetic energy into potential energy [18]. The compressors used subsea are operated by electric motors that are turning a shaft with impellers mounted at the end, the rotating impellers accelerate the gas entering the inlet. This is shown in Figure 2.1. In subsea applications, multiple impellers are mounted on the same shaft with diffuser channels between each impeller, an example can be seen in Figure 2.2.

Each impeller stage increases the pressure in the gas, the pressure increases in the diffuser channels of the compressor. The higher volume in the diffuser decreases the gas velocity, this increases the pressure. Bernoulli's equation illustrates this phenomena 2.1.

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho gh_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho gh_2 \quad (2.1)$$

Bernoulli's equation shows the energy balance of a fluid traveling through a pipe [18]. The impeller increases the energy in the gas by increasing its velocity, this increases the term v_1 in 2.1. When gas traveling at high velocity enters the diffuser, the gas decelerates to v_2 .

2. Theory

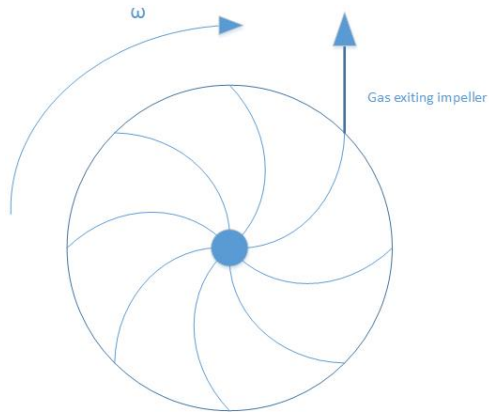


Figure 2.1: Working principle

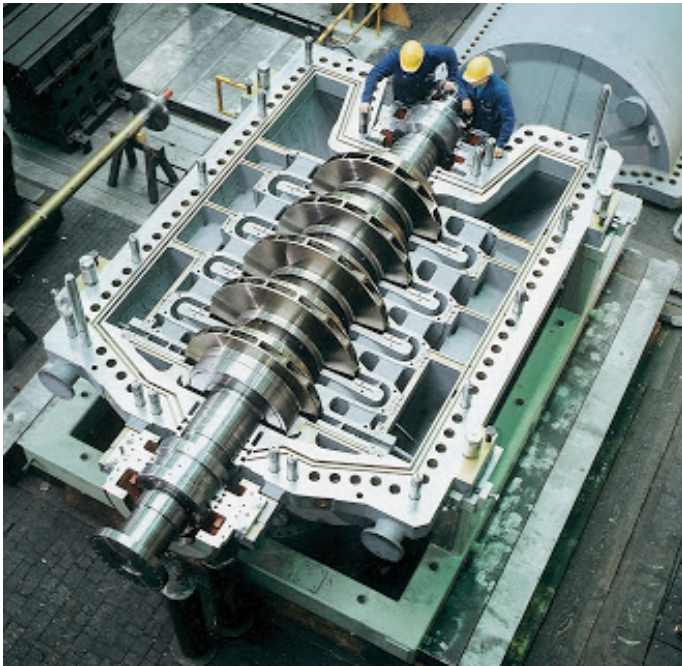


Figure 2.2: Multistage centrifugal compressor [16]

The deceleration is created by the higher volume in the diffuser channels. The energy that is added to the gas by the impeller is conserved, but it has taken the form of potential energy as higher static pressure. Looking at 2.1 it can be seen as $v_2 < v_1$ while $gh_1 = gh_2$, leads to $p_2 > p_1$. This is illustrated in Figure 2.3.

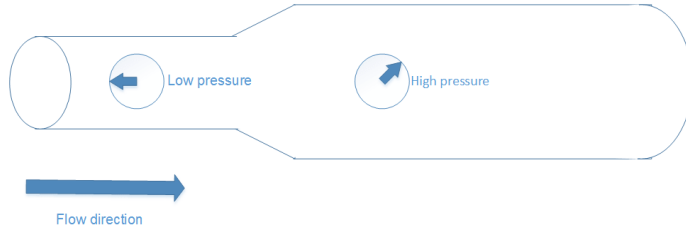


Figure 2.3: Conservation of energy in pipe

A single stage compressor is sufficient for this lab, although multistage compression is the typical industrial setup. The compressor mounted on this lab is powered by pressurized air. The compressor wheel is driven by a turbine, a valve is installed to control the airflow entering the turbine. This type of compressor would normally be mounted in a car, the engine exhaust gas normally drives the turbine wheel.

2.1 Modelling the compressor behavior

When the compressor is operating at a constant RPM, the torque from the turbine is equal to the torque from the impeller. This balance is given by 2.2 [18].

$$J\dot{\omega} = \tau_d - \tau_c \quad (2.2)$$

The inertia of the compressor wheel is given by J . The torque from the turbine is τ_d , while the torque from the impeller blade is τ_c .

The torque on the turbine is given as.

$$\tau_d = w_d r_d^2 C_d \quad (2.3)$$

Where C_d is the tangential entering velocity of the gas on the turbine, r_d is the radius of the turbine and w is the mass flow through the turbine. Similarly the torque from the compressor wheel is given as

$$\tau_c = w_c r_c^2 C_c. \quad (2.4)$$

Since the internal radius of the turbine and the compressor wheel is unknown, it has to be assumed that $r_c^2 = \sigma r_d^2$. Assuming that the turbocharger is operating at a constant angular velocity, the torque balance can be written as.

$$w_c \sigma r_d^2 C_c = w_d r_d^2 C_d \quad (2.5)$$

2. Theory

After some rearrangement, the mass flow through the compressor wheel is given by.

$$w_c = \frac{w_d C_d}{\sigma C_c} \quad (2.6)$$

2.1.1 Compression capacity

This section is drawn from the material found in [10]. One way of defining how much work a compressor is capable of delivering is to define its polytropic head. This is a common measure for compressor output capacity, and it is used in antisurge control systems as described in [23], [1]. When a compressor is lifting the pressure in a gas it can be viewed as a polytropic process. A polytropic process is given as

$$PV^n = C \quad (2.7)$$

where P denotes pressure and V is volume. A polytropic process is a thermodynamical process that obeys the relationship described in 2.7. The gas characteristics are affected by changes in pressure and volume. This effect is included in the description of a polytropic process. A constant C is given by any combination of pressure and volume, for a given amount of gas. The polytropic index n can be experimentally derived for any dynamic compressor. The type of thermodynamical process is given by the polytropic index, whether it is isobaric ($n=0$), isothermal ($n=1$) or isentropic ($n=c_p/c_v$). The polytropic process for centrifugal compressor will not fall perfectly into any of these categories. It is not isothermal, where no heat is accumulated or generated. Neither is it isentropic ($n = c_p/c_v$), where no heat is lost to the surroundings. The process for a dynamical compressor falls somewhere between isothermal and isentropic. Gas compression is a thermodynamical process where heat is generated. Some of this heat is lost to the surroundings. The polytropic index can be estimated by the inlet and outlet conditions of the compressor [10].

Specific work describes how much work is applied to the gas by the compressor, it can be quantified as [Nm/kg]. Dividing this number by the acceleration of gravity gives the head [m] of the compressor. Newton [N] is a derived unit of force, the SI base unit for [N] is [$\text{kg} \cdot \text{m} \cdot \text{s}^{-2}$]. Specific work [Nm/kg] can then be written as

$$N \cdot \frac{m}{kg} = \frac{kg \cdot m}{s^2} \cdot \frac{m}{kg} = \frac{m^2}{s^2} \quad (2.8)$$

where the head is found by dividing 2.8 with the unit for acceleration [$\text{m} \cdot \text{s}^{-2}$].

$$\frac{m^2}{s^2} / \frac{m}{s^2} = m \quad (2.9)$$

The output pressure for any given head will vary with the density of the gas, and the polytropic head is simply the head of a compressor which can be described by a polytropic process. Head can be understood most intuitively by describing a pump, where the head defines how many meters the pump can lift a liquid column. In a compressor, it represents the same logic where the liquid column has been replaced by a gas column. This is illustrated in Figure 2.4

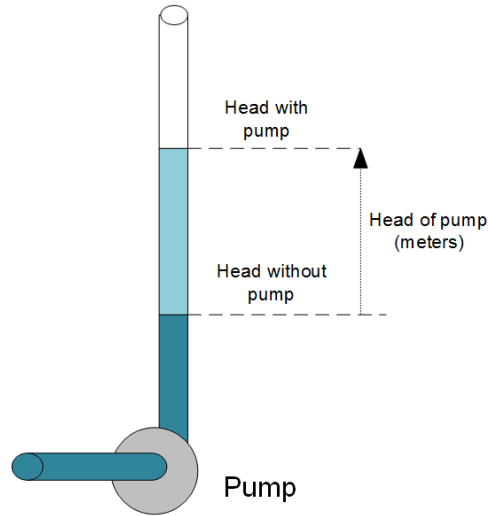


Figure 2.4: Head of pump

A centrifugal compressor can deliver varying amounts of head for different RPM values and flow rates, a compressor map is often used to visually represent what any given centrifugal compressor can deliver, this is shown in Figure 2.5

In Figure 2.5 the red lines represent the polytropic head that a typical centrifugal compressor can deliver, it is given for a constant RPM and varying flow rates. As the flow rate increases, the polytropic head delivered by the compressor decreases for a given RPM [23].

A simplified expression for the polytropic head of a compressor can be written as

$$H_p = \frac{ZRT_1}{M} \frac{\left(\frac{P_2}{P_1}\right)^n - 1}{n} \quad (2.10)$$

where n is the polytropic index, T_1 is the suction temperature, $Z = (Z_2 + Z_1)/2$ is the average compressibility and M is the molecular weight of the gas. P_1 represents the inlet pressure and P_2 represents the outlet pressure [23].

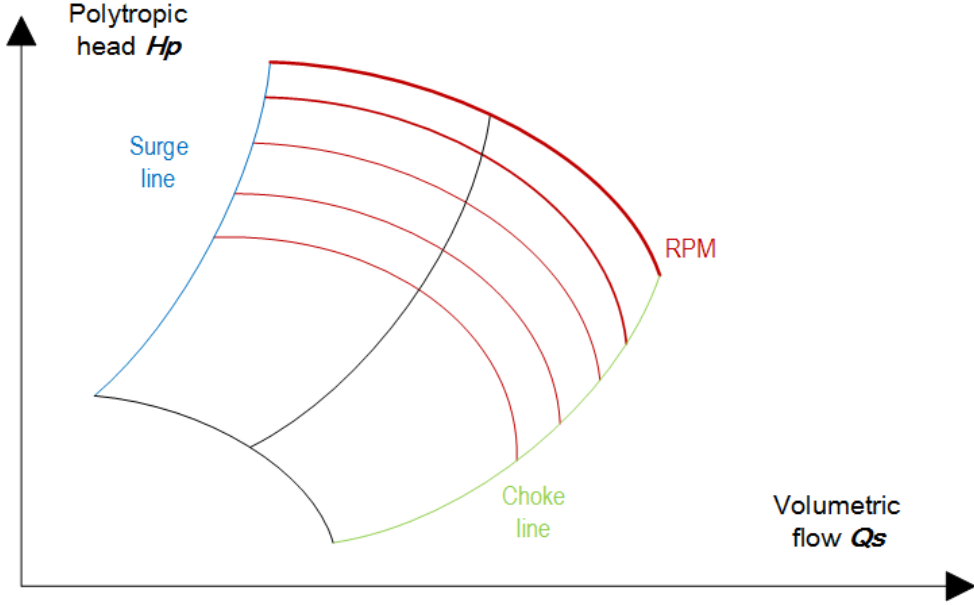


Figure 2.5: Compressor map

The flow of the gas at the suction point is given by as

$$Q_s = C \sqrt{\frac{\Delta P_o T_1 Z_1}{P_1 M}} \quad (2.11)$$

where C represents the flow coefficient of the flow metering device, and ΔP_o represents the differential pressure across a flow meter [23].

Another model for the compressor characteristic is given by

$$\Psi_c(w, \omega) = 1 + \left(\frac{\mu r_2^2 \omega^2 - \frac{r_1^2}{2} (\omega - \alpha w)^2 - k_f w^2}{c_p T_1} \right)^{\frac{\kappa}{\kappa-1}} \quad (2.12)$$

from [18]. This is based on the frequency and the mass flow of the turbocharger. The mass flow rate (kg/s) is given by w , and the angular velocity is given by ω . This model is built on the dynamics of the gas as it flows into the compressor wheel and is guided by the impeller towards the outlet. Factors like slipping and friction loss have been included.

The model gives the pressure ratio over the compressor Ψ_c , for a given mass flow and angular velocity. The term $\mu r_2^2 \omega^2$ gives the energy transfer as if the thermodynamical process was perfectly isentropic, μ is the energy transfer coefficient, r_2 is the impeller radius. The heat capacity ratio is given by $\kappa = c_p / c_v$, where c_v is the constant volume heat capacity of the

gas, and c_p is the constant pressure specific heat capacity of the gas. The inlet temperature is represented by T_1 .

The term $\frac{r_1^2}{2}(\omega - \alpha w)^2$ represents the incidence loss, this is the loss of energy that comes from the misalignment of the impeller blades and the gas stream. The term α in the expression for the incidence loss is given by $\alpha = \cot(\beta) \frac{1}{\rho r A}$, where β is the fixed impeller blade angle, r is the inlet radius, A is the inlet area and ρ is the inlet gas density.

The term $k_f w^2$ represents the friction loss, k_f is a constant that depends on the geometry of the impeller.

2.2 Compressor limitations

A centrifugal compressor is limited by five boundaries, the maximum RPM and gas flow, and the minimum RPM and gas flow. The compressor is also limited by the maximum torque which can be delivered by the turbine. This will effectively define the maximum RPM for any given system resistance. The system resistance primarily affects the volumetric flow rate, the compressor output pressure is indirectly affected. High system resistance produces high levels of head and low levels of flow, while low system resistance produces low levels of head and high levels of flow. The choke line is found at the maximum flow level for any given RPM. Choke occurs when local sonic velocity is achieved, at this point the flow rate will not increase by further reducing downstream system resistance. The surge line is found at the lower limit of the compressor flow rate capacity. High downstream resistance decreases the flow rate and increases the pressure ratio. The compressor goes into surge when it can no longer maintain its output pressure.

2.2.1 Surge

One of the most devastating conditions a compressor can experience is surge, surge is characterized by violent oscillations and big fluctuations in outlet pressure. High downstream resistance reduces the flow rate and increases the pressure downstream of the compressor. When the maximum output pressure of the compressor is exceeded, the air rushes the opposite way following the natural flow from high to low pressure. Flow reversal occurs since the energy delivered by the compressor is not high enough to maintain the flow rate at the given pressure ratio. A consequence of flow reversal is a drop in outlet pressure, this allows the compressor to rebuild the flow, but if the surge causing conditions are still present, the pressure will simply build up again before it collapses and flow reversal reoccurs. Surge usually occurs with a frequency of 0.3 - 3.3 cycles per second [23].

2. Theory

To prevent surge, an antisurge valve is usually present in a centrifugal compressor system. It is a valve that opens when surge is about to occur, it relieves some of the pressure on the outlet. It allows the gas on the outlet to flow back to the inlet without running through the compressor. This increases the flow through the compressor and helps it avoid surge. Maintaining a minimum level of flow prevents the compressor from experiencing surge. See Figure 2.6.

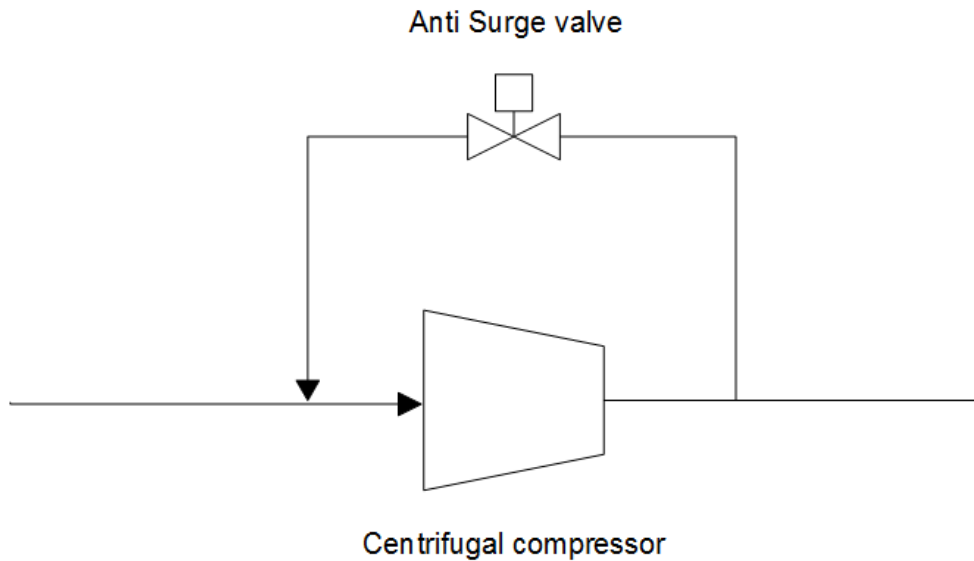


Figure 2.6: Anti surge valve

2.2.2 Choke

The compressor has a maximum limit in terms of flow rate at any given pressure ratio. Choke is defined at local sonic gas velocity in the compressor, the maximum flow rate has been reached. Any further decrease in downstream resistance or increase in RPM will not lead to an increase in flow rate. This phenomenon is called compressor choke or stonewalling. The flow is no longer steadily guided by the impeller, disruptive flow patterns emerge that limit the throughput of the compressor [19].

2.3 Control system design

During normal operation of a centrifugal compressor, a properly tuned proportional, integral and derivative (PID) controller is usually a satisfactory approach to achieve RPM and output pressure control [23] [21].

$$u = K_p e + K_i \int_0^t e dt + K_d \dot{e} \quad (2.13)$$

A PID controller generates a signal u based on the measured error e . The error is given by the difference between the actual and the desired control measurements. The three terms in 2.13 combine three effects. The first term is proportional to the error, the second accumulates errors over time, and the third respond to the rate of change in the error. The last term is often left unused in industrial applications, this is because of measurement noise [23]. The derivative term is very sensitive to high-frequency noise, this is why a well tuned PI controller is often preferred to a PID controller. It is also common to use multiple PI controllers simultaneously, multiple measurements can be controlled at the same time. The significance or weight of the different control outputs can be adjusted, and the combined signal determines the final control system behavior. [23].

A control signal that compensates for unwanted errors is generated based on the measured error. The relative contribution of the terms in the controller can be weighed by the constants K_p , K_i and K_d . These constants must be determined to obtain the desired controller behavior, this is called controller tuning. This can be done experimentally or analytically.

A common problem with PI and PID control is integral windup, this occurs when the actuator reaches its operational limit. An anti-windup strategy must be used to prevent the integral term from growing out of bounds. When error is growing and the physical limit of the actuator is reached, the integrator over-accumulates. The software used to build these controllers usually have built-in functionality to prevent this, an example of how the LabView development platform handles anti-windup can be seen in Figure 2.7. A saturation block is placed between the plant and the controller output. The saturation block limits the range of the control signal that reaches the actuator. The difference between the limited and the actual control signal is subtracted from the integral term using feedback. This is done when the controller output is higher than the upper limit of the saturation block.

2. Theory

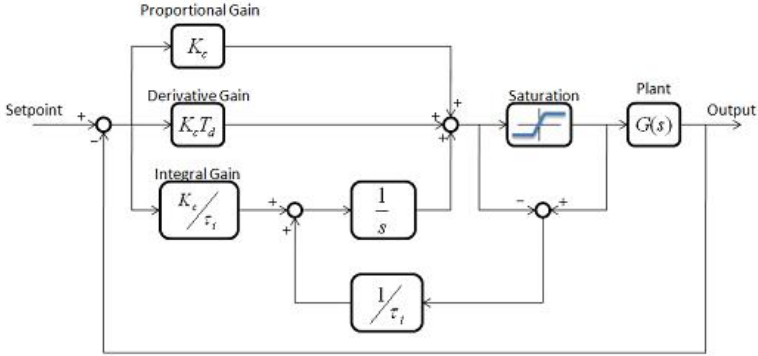


Figure 2.7: Anti windup [15]

2.3.1 Anti surge control

To be able to avoid unwanted conditions like surge, a more advanced control approach is necessary. A tried and tested approach to anti-surge control and recovery is described in [23], [1], [14]. These approaches will be briefly summarized in this section.

One of the major concerns with regards to centrifugal compressor control is surge avoidance and recovery. Getting maximum output from a compressor in terms of output pressure means that operation will be relatively close to the surge line. This makes it useful to accurately determine in real time how close the compressor is to surge. If downstream conditions change rapidly, it will be necessary to quickly adjust the operation point to avoid deep surge conditions. If surge occurs it will be necessary to pull the compressor out of surge conditions to restore normal operation.

As stated earlier, the operation point of the centrifugal compressor can be given by the flow rate and the pressure ratio, or polytropic head [23]. Using the latter, the flow rate at the inlet Q_s is given by

$$Q_s = A \cdot \sqrt{\frac{\Delta P \cdot T_s \cdot Z_s}{P_s \cdot M}} \quad (2.14)$$

and polytropic head H_p is given by

$$H_p = \frac{(Z_s + Z_d)}{2} \cdot \frac{R \cdot T_s}{M} \cdot \frac{\left(\frac{P_d}{P_s}\right)^{\frac{\kappa-1}{\kappa \cdot \eta}} - 1}{\frac{\kappa-1}{\kappa \cdot \eta}} \quad (2.15)$$

where the parameters are described in table 2.1, [23].

Parameter	Description
Q_s	Volumetric flow rate at compressor inlet
ΔP	Differential pressure across orifice type flow meter
A	Cross sectional area of inlet pipe
T_s	Suction temperature
Z_s	Compressibility at inlet
Z_d	Compressibility at outlet
P_s	Suction pressure
P_d	Discharge pressure
M	Molecular weight of gas
κ	Heat capacity ratio C_p/C_v
η	Compressor efficiency
H_p	Polytropic head (feet or meters)

Table 2.1: Parameters used to derive a measure of distance to surge

Looking at Table 2.1, it is clear that direct use of Q_s and H_p to determine the operation point pose a significant challenge in terms of the instrumentation required to achieve fast, reliable and effective control. The only variables that can be directly and reliably measured using industrial grade transmitters are temperature and pressure. The other parameters can technically be measured, but not in a way that satisfies the requirements of the closed loop control system [23].

To ensure that all the variables that are used in the control system can be directly measured, the equations can be reduced. Using the definition of a polytropic process

$$\left(\frac{P_d}{P_s}\right)^{n_p} = \frac{T_d}{T_s} \quad (2.16)$$

where n_p is the polytropic index for the specific compressor. The polytropic index for a given compressor is given by

$$n_p = \frac{\kappa - 1}{\kappa \cdot \eta} \quad (2.17)$$

where η is the compressor efficiency.

It is possible to reduce the expression for polytropic head H_p , and volumetric flow rate Q_s to expressions with only measurable variables. To remove the root in 2.14, the expression needs to be squared. The squared expression for the inlet flow rate is given as

$$Q_s^2 = A^2 \cdot \frac{\Delta P \cdot T_s \cdot Z_s}{P_s \cdot M} \quad (2.18)$$

2. Theory

Both expression the for Q_s^2 and H_p can be divided by a common factor $\beta = \frac{T_s - Z_s}{M}$, this gives the reduced expressions for the compressor operation point.

$$q_r^2 = Q_s^2 / \beta \quad (2.19)$$

$$h_{pr} = H_p / \beta \quad (2.20)$$

Omitting the constants in Q_s^2 and H_p lets the reduced expressions be written as

$$q_r^2 \propto \frac{\Delta P}{P_s} \quad (2.21)$$

$$h_{pr} \propto \frac{\left(\frac{P_d}{P_s}\right)^{n_p} - 1}{n_p} \quad (2.22)$$

where the expression for n_p is given by.

$$n_p = \frac{\log\left(\frac{T_d}{T_s}\right)}{\log\left(\frac{P_d}{P_s}\right)} \quad (2.23)$$

Note that the constants in 2.14 and 2.15 have been omitted to get 2.21 and 2.22. In the expression for H_p , the relationship between the compressibility at the inlet and the outlet of the compressor is treated as a constant. This is approximately correct within the operating range of most systems. The compressor map generated by the reduced coordinates become invariant to changes in gas parameters [23].

To find the surge limit line (SLL), the compressor has to be run into surge. The reduced coordinate operation point (h_{prS} , q_{rS}^2) where surge occurred can then be used to define the SLL. The SLL will later be used in the anti-surge controller to avoid surge.

$$SLL = h_{prS} / q_{rS}^2 \quad (2.24)$$

Similarly, the operation point line gradient (OPL) is calculated using the real time operation point of the compressor (h_{pr} , q_r^2).

$$OPL = h_{pr} / q_r^2 \quad (2.25)$$

Now the surge distance (SD) can be measured. It is given by

$$SD = OPL / SLL \quad (2.26)$$

If the compressor is running at normal operation, OPL will be smaller than SLL, this means that $SD < 1$. If the compressor is running in surge, OPL will be greater than SLL, in this case, $SD > 1$. This lets control system measure the distance to surge. See Figure 2.8 for an illustration of concept.

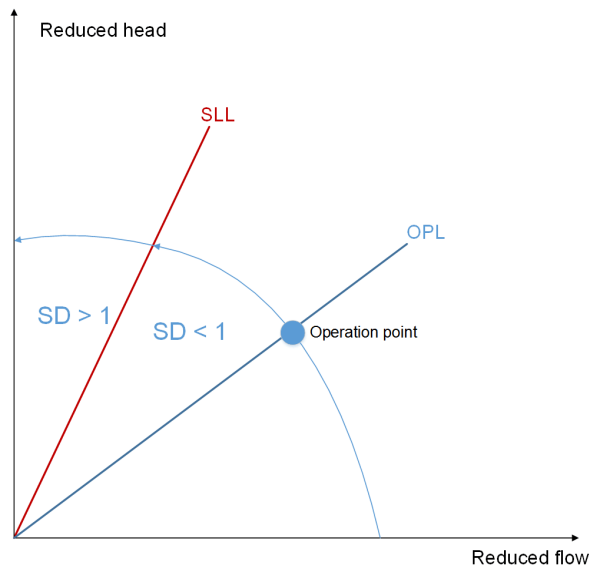


Figure 2.8: Distance to surge

The operation point line intersects origo and the operation point, moving the operation point vertically or horizontally changes the gradient. The surge limit line is constant and pre-defined by 2.24, this is done by finding an actual point that leads the compressor to surge. The value of SD indicates where the operation point is with regards to surge.

The basis for anti-surge control is formed by measuring the distance to surge. When the operating point is far from surge, normal PI control can be used. But as the operating point gets closer to surge, an open loop control response can be added to the PI control signal. This can help the compressor avoid surge conditions [23]. A complete anti-surge control system is illustrated in Figure 2.9.

2. Theory

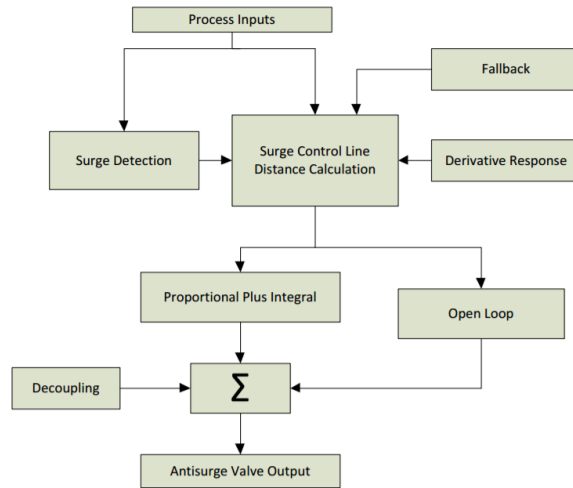


Figure 2.9: Anti surge control system [23]

The core parts of the system are comprised of the process inputs, the surge distance calculation system, and the PI and open loop controllers. The derivative response block looks at peak changes in flow and affects the control system only when the operation point is close to surge. The surge detection system shuts down the system if all other anti-surge control attempts have failed.

2.4 Control valves

A control valve is a device that regulates the cross-sectional area that a fluid is flowing through. There are many different types of valves used in industrial applications. The valves used on this lab are motorized valves with a positioner mechanism, this allows the operator to vary the flow rate with precision. The compressible flow through a control valve is usually calculated with empirically derived equations like

$$Q_1 = \frac{519 \cdot K_v}{\sqrt{\frac{\rho T_1}{\Delta p \cdot p_2}}} \quad (2.27)$$

$$Q_2 = \frac{K_v \cdot 259.5 \cdot p_1}{\sqrt{\rho \cdot T_1}} \quad (2.28)$$

A valve constant K_v is used in these equations. This constant is given by the amount of water in $[\text{m}^3/\text{h}]$ that will flow through the valve when the pressure drop is 1 bar [2].

With the inlet pressure given as p_1 and the outlet pressure as p_2 , the differential pressure is used to determine the equation used to calculate the flow rate [22]. The flow rate can be calculated from 2.27, if the outlet pressure is greater than half of the inlet pressure as in $p_2 > 0.5 \cdot p_1$. If the differential pressure across the valve is higher, more specifically if the inlet pressure is more than twice the magnitude of the outlet pressure, $p_2 < 0.5 \cdot p_1$. The flow can be estimated as in 2.28. In both equations T_1 is the inlet temperature, ρ is the gas density, K_v is the flow constant found in the valve datasheets, p_1 is the inlet pressure, and p_2 is the outlet pressure. The differential is given by Δp .

2.5 Gear pump

Two gear pumps are installed on the lab, one helps the water flow out from the bottom of the separator, the other pump lubricates the turbocharger. This section is drawn from the information found in [17] and [3]. A gear pump works by introducing two rotating gears in the stream. The gears rotate in opposite directions, this pushes the liquid out through the discharge port [3]. This principle is shown in Figure 2.10.

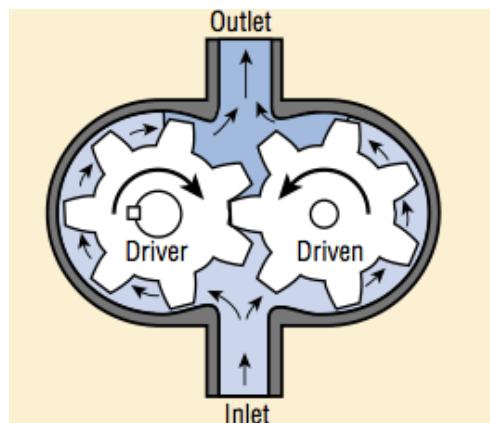


Figure 2.10: Gear pump principle [17]

2. Theory

Typically such a pump is operating at a constant speed, this means that it will try to deliver a constant flow rate. Since liquids are incompressible, a constant amount of liquid flows out from the discharge port for each gear rotation. The pressure delivered by a gear pump is determined by the flow resistance and the amount of torque the pump can deliver. The input power P_{in} delivered to a gear pump can be described as

$$P_{in} = T \cdot \omega \quad (2.29)$$

where T is torque and ω is the angular velocity. The power lost P_{loss} is a function of friction f , and viscous effects μ . Thus the output power P_{out} delivered by the fluid is given by

$$P_{out} = P_{in} - P_{loss} = \Delta p \cdot Q = T \cdot \omega - P_{loss} \quad (2.30)$$

where Q is the volumetric flow rate and Δp is the differential pressure across the inlet and outlet of the pump. Since the outlet power is slightly less than the input power, it is common to use a constant η to describe the relationship, as in

$$P_{out} = \eta \cdot P_{in} \quad (2.31)$$

2.6 Gas liquid separation

A gas/liquid separator is used on the lab, this was built by the master students working on the lab in 2016. A vertical gas-liquid separator uses gravity to separate the phases, the separator has one inlet and two outlets. The multiphase flow enters the inlet, the gas exits at the top outlet and the liquid flow out from the bottom outlet. The separator design used at the lab is shown in Figure 2.11. The principle sketch of a vertical gas-liquid separator is shown in Figure 2.12.

The standard condition gas volume flow capacity of a vertical gas liquid separator can be estimated using

$$Q_{s.c} = A \cdot K \cdot \sqrt{\frac{\rho_l - \rho_g}{\rho_g} \frac{p T_{s.c}}{p_{s.c} T z}} \quad (2.32)$$

where $Q_{s.c}$ is the gas flow rate at standard conditions, A is the separator cross sectional area, ρ_l and ρ_g is the liquid and gas density, K is the separation constant, T and $T_{s.c}$ is the actual temperature and the standard condition temperature and lastly z is the compressibility factor [12].

Note that the difference in density determines the flow capacity, this is a natural consequence of gravity separation. Water and air have a density difference of (1000-1.28) kg/m³

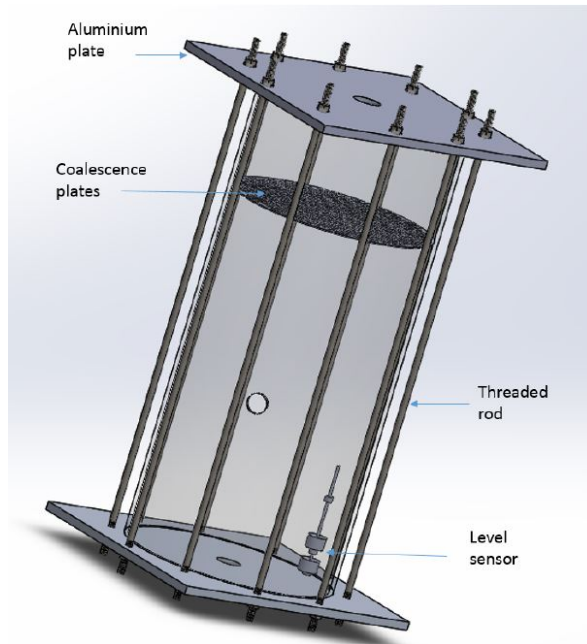


Figure 2.11: Separator design [12]

$= 998.72 \text{ kg/m}^3$. This is slightly higher than for oil and natural gas, for instance $(800 - 0.80) \text{ kg/m}^3 = 799.20 \text{ kg/m}^3$. It is therefore expected that the standard condition gas flow capacity of air and water separation will be higher than for oil and gas separation. The flow capacity is also affected by the cross sectional area and the separation constant. API recommends a separation constant of 0.05 m/s [12].

2. Theory

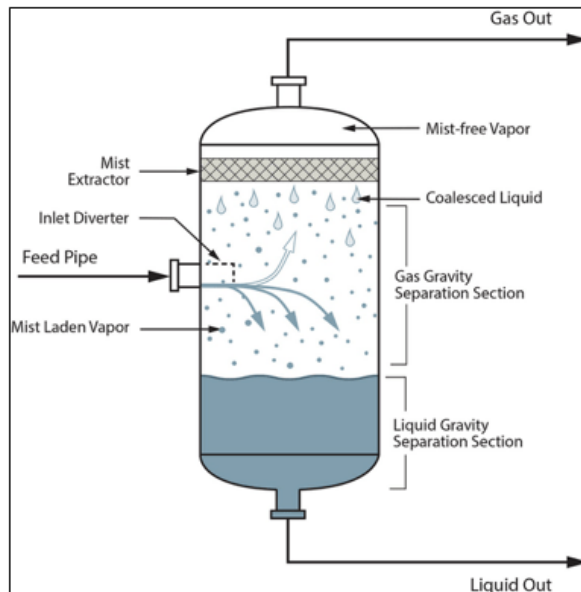


Figure 2.12: Separator principle sketch [13]

2.7 Counter flow cooler

A counter flow cooler is installed downstream of the turbocharger, this was also built by the master students working on the lab in 2016. The hot gas discharged from the compressor needs to be cooled before it enters the plastic piping on the low-temperature zone on the lab. The piping on this side can not tolerate temperatures above 60 degrees Celsius, it is therefore crucial that a cooler is installed.

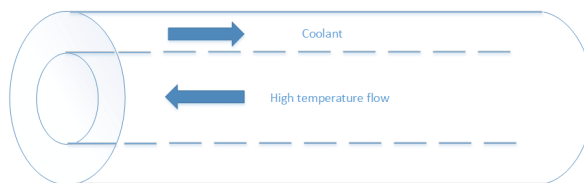


Figure 2.13: Counter flow cooler principle

A counter flow cooler works by exchanging heat between two liquids. The liquids flow in opposite directions, this increases the average temperature difference. Higher average temperature differences increase the efficiency of the cooler. The principle is shown in Figure 2.13.

A double-pipe is used to illustrate the counter flow cooler principle. The inner pipe is used to transport the high-temperature flow, the heat is transported through the pipe wall and into the coolant which flows through the outer pipe. In this way, the heat can be transported out of the system. The coolant is usually circulated in an additional system, this is done to discharge the heat continuously.

The heat transfer \dot{Q} in a counter flow cooler is given by

$$\dot{Q} = UA_o\Delta T_{LMTD} \quad (2.33)$$

where U represents the heat transfer coefficient, A_o is the heat transfer area and ΔT_{LMTD} is the logarithmic mean temperature difference between the coolant and the hot flow. ΔT_{LMTD} is given by

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (2.34)$$

where ΔT_1 is the temperature difference between at the top of the cooler, and ΔT_2 is the temperature difference at the bottom of the cooler 2.33. The exact design of the cooler is shown in Figure 2.14.

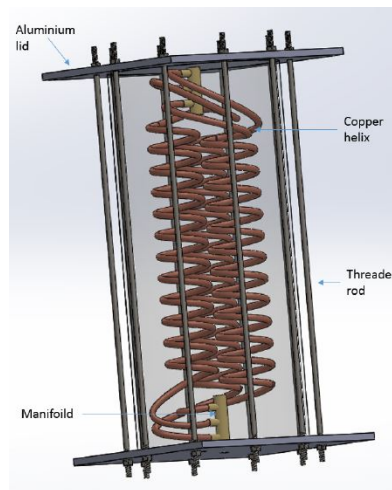


Figure 2.14: Counter flow cooler, [12]

The hot air flows from the top of the cooler to the bottom outlet, the copper piping transports the hot air. Tap water is used as a coolant, this flows from the bottom of the cooler. A tap water outlet is mounted at the top of the cooler, the heated water is transported to a sink through a water hose.

Chapter 3

Construction and results

This chapter describes the work that has been done to make the lab operational. Significant amounts of work have been dedicated to complete the design and wiring of the electrical systems, correcting errors in turbocharger configuration and oil supply system. In addition to this, efforts have been made to meet HSE requirements. Barriers and protective shields have been constructed in case of dangerous malfunction.

3.1 Electrical systems

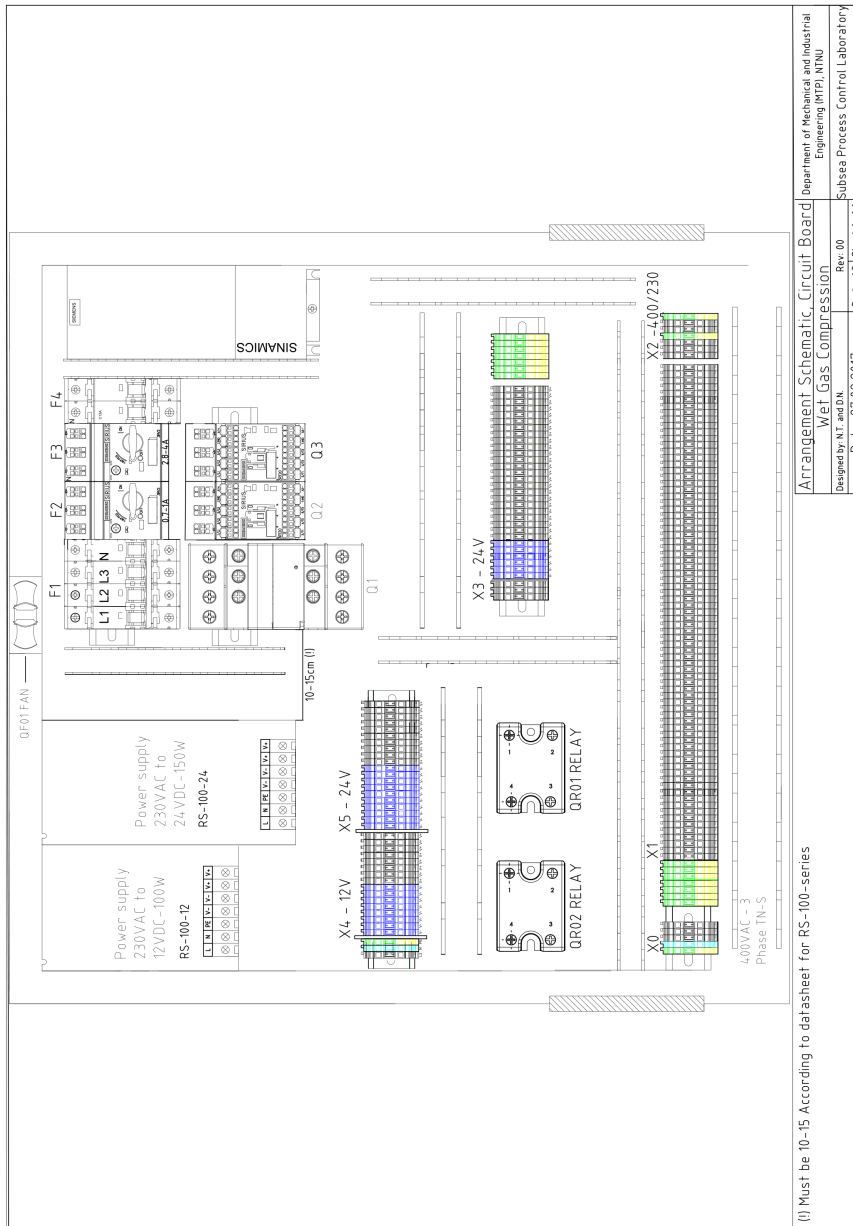
The original plans and designs for the electrical system had to be redesigned and redrawn before the completion of the electrical work could be performed. The initial designs were not satisfactory and could not be used. Logical errors were discovered in the schematics, and they were also hard to read. It was therefore considered less time consuming to redraw everything, this meant that the arrangement of the electrical cabinet and all the electrical circuits were redesigned and redrawn. The original arrangement drawings of the cabinet did not account for all the space needed to wire the components and transmitters. This is evident in the number of terminal blocks included in the original drawing. Some components also needed to be replaced. Since the cabinet is supplied with 400 V, a four pole fuse is required by law. A three pole fuse was bought by the previous students, this could therefore not be used. A contactor for the oil pump was also missing. This section describes the new design of the electrical system, it also describes the function of each of the electrical circuits.

3. Construction and results

3.1.1 The cabinet

The electrical cabinet serves as the main station for all the components at the lab. All the instrumentation, IO, signals and power are tied together in the cabinet. The cabinet is powered by 400 V AC. Since the piston compressor and oil pump require 400 V supply, while the water pump only requires 230 V. Since the piston compressor is intended to run at different angular velocities, a frequency converter is required. It can set the rotational speed of the motor driving the piston compressor. A 12 V and 24 V DC supply unit is installed to supply the sensors and the valves with power, these units are powered by 230 V. Furthermore, contactors and fuses that protect the various components at the lab are installed, all the units that require electrical power needs fuse protection. If any short circuit were to occur, it is important that the circuit is broken to protect the equipment. Two relays are mounted in the cabinet, one of them will turn on and off the water pump. The level sensor in the separator works like a simple switch, this closes the supply circuit on the relay. Which in turn closes the supply circuit on the contactor, this actuates the water pump. The other relay actuates the anti-surge valve, the valve is an on or off valve, and it is opened by a 24 V signal.

All the components are shown in Figure 3.1. This represents the final layout, which differs from the original design significantly. The original drawing can be seen in Figure 3.2. The most apparent difference between the two designs is the number of terminal blocks. In the new design, enough terminal blocks have been included to ensure that there is enough space for all the wiring. The Arduino in the original drawing has been removed, a simple relay does the same job the Arduino was intended for. The Arduino was included to control the water pump, but because of the working principle of the level sensor in the separator, a relay will be sufficient. This had the added benefit of making space for the second relay. Njål Tengesdal helped out with redesigning of the electrical systems, he finished the new corrected drawings for all the circuits.



Arrangement Schematic, Circuit Board		Department of Mechanical and Industrial Engineering (MPEI, NNU)
Well Gas Compression		Subsea Process Control Laboratory
Designed by: N.T. and D.N.	Rev: 00	
Date: 27.02.2017	Scale: A3	Sheet 1 of 1

Figure 3.1: Final arrangement of electrical cabinet

3. Construction and results

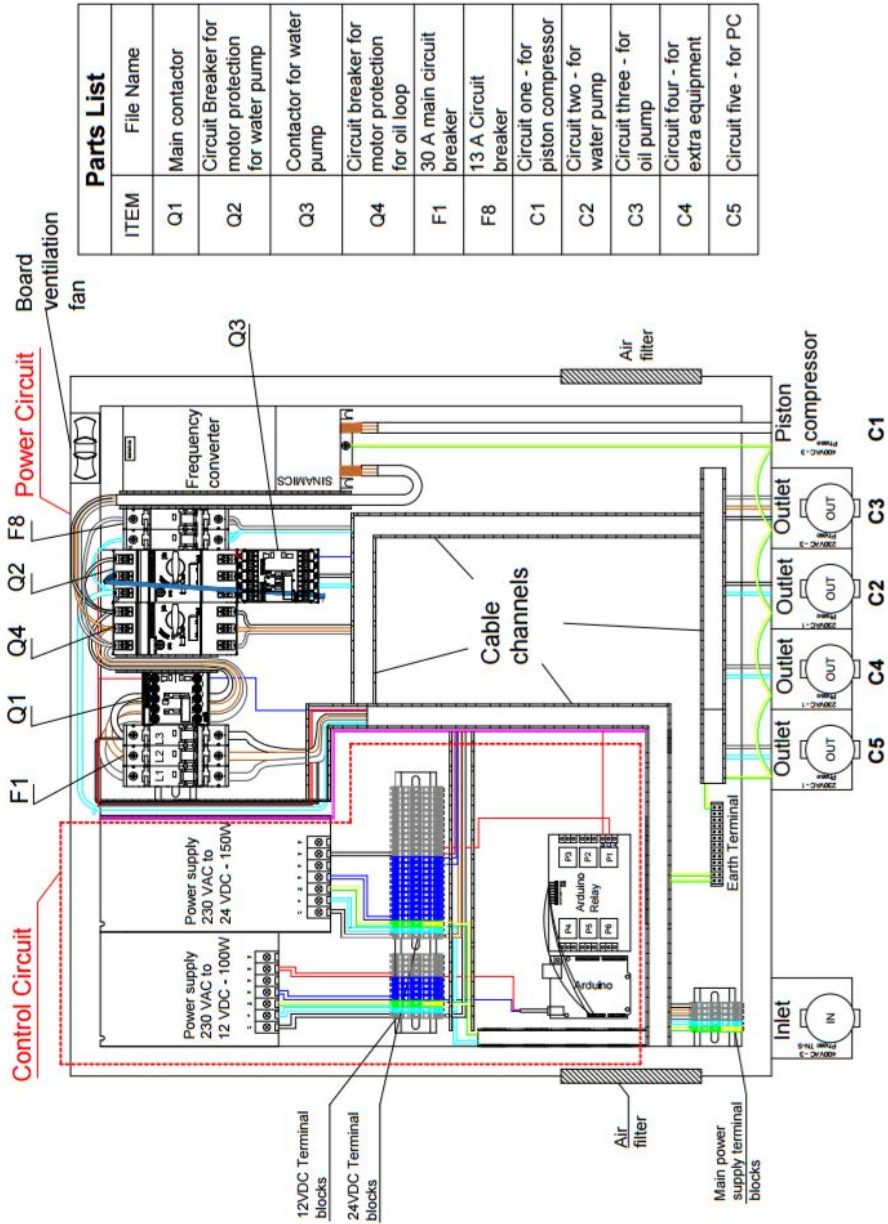


Figure 3.2: Initial arrangement of electrical cabinet [12]

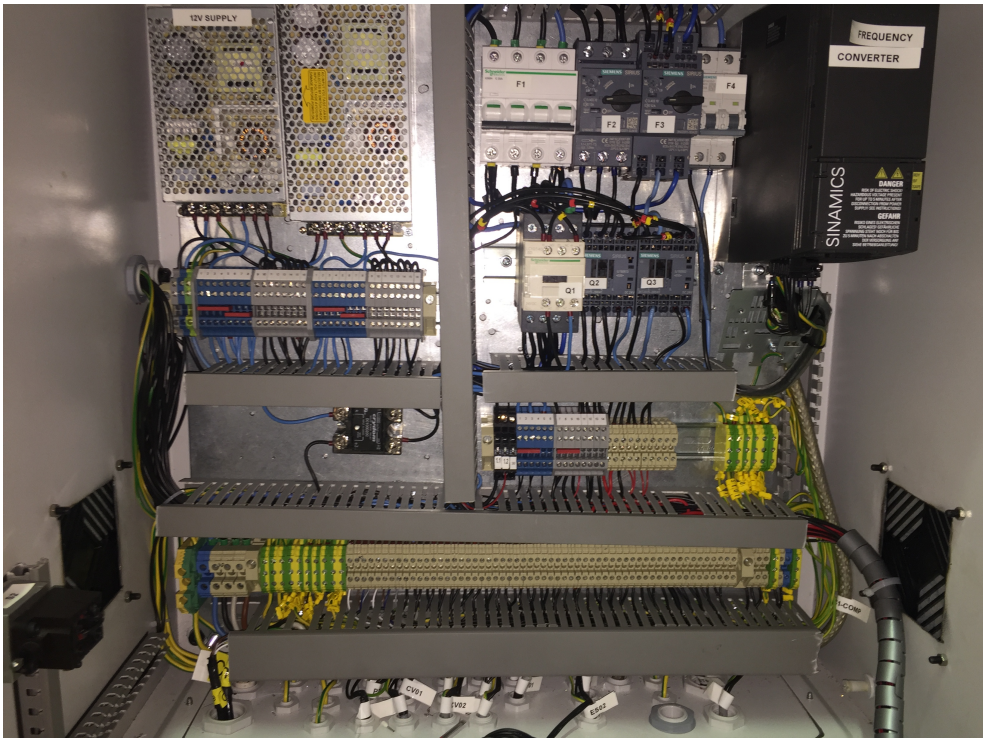


Figure 3.3: The inside of the cabinet

The inside of the cabinet can be seen in Figure 3.3, this picture was taken before the second relay was installed.

The front panel

The front panel of the cabinet allows the operator to turn on the main circuit, powering the pumps and the variable speed drive. As well as it allows the operator to turn the control valves and the oil pump on or off. This panel can be seen in Figure 3.4.

3.1.2 The individual circuits

The cabinet holds the various circuits that are required for the lab to operate, the corrected drawings for all the circuits described in this subsection are found in Appendix C. FAT tests were performed to ensure that these drawings represent the actual system, the FAT test results can be found in Appendix A.

3. Construction and results



Figure 3.4: Front panel controls

Main circuit

The main circuit is where the 400 V power supply distributes to the various motors and components on the lab. The oil pump utilizes the full 400 V, while the water pump uses 230 V. The motor intended to drive the reciprocating compressor is powered through the frequency converter running on 400 V. The 12 V DC and 24 V DC power sources are powered by 230 V AC.

24 V circuit

The 24 V circuit supply the control valves with power, as well as delivering power to the fan and the indicator lights on the front door. Lastly, it powers and controls the antisurge valve through a relay. The anti-surge valve control was not part of the original design.

12 V circuit

The 12 V circuit supply the pressure transmitters, the operational amplifiers and the current output module. This will be described later in the report. The 12 V circuit was originally only intended to power the pressure transmitters.

3.1.3 Compressors RPM sensor and high-temperature measurement

The RPM sensor for the turbocharger needed to be connected through the cabinet to the data acquisition units, this had not been done in the earlier stages of the project. The wiring harness that was bought by the previous students did not match the sensor, this meant that another solution was required. Normally, this type of sensor would connect through an adapter to connects with a gauge that shows the RPM. From looking at the sensor's datasheet, it became clear that it needed three wires. It requires 5 V supply, a wire to read the output signal, and a ground wire. The data acquisition units (DAQ) have 5 V digital output supply, as well as they can read input voltage. The sensor was therefore connected through the cabinet directly to the DAQ units. The sensor transmits a high-frequency voltage signal that is translated to RPM. The pins of the sensor were soldered to the wires before they were insulated. This is shown in Figure 3.5.

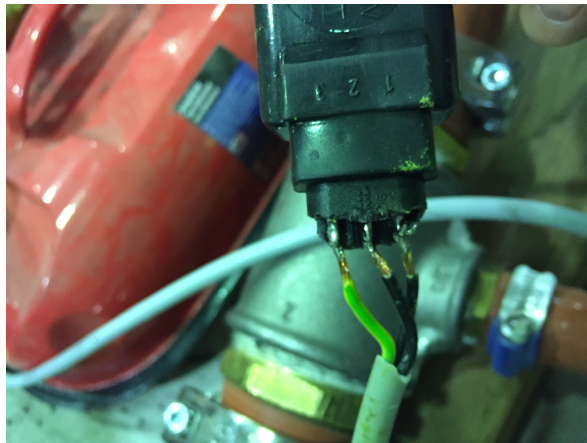


Figure 3.5: Soldered RPM sensor connection

3. Construction and results

The temperature sensors, (PT-100 resistance elements) came with a 3.5 mm mini jack connection. It was necessary to reconfigure the connection method to enable reading of the resistance value at the control station. The resistance value on from the sensor is directly translatable to temperature. The wires were cut, and by using a multimeter the exposed wires reading the electrical resistance were located. These leads were then soldered with two wires going to the electrical cabinet. They were thoroughly insulated after soldering. The resistance could now be measured between two terminal blocks in the cabinet.

3.1.4 Data I/O

The sensor data is acquired using four NI-DAQ 6001 USB units. An illustration of the units is shown in Figure 3.7. The layout of the DAQ units outside the cabinet is shown in Figure 3.6.

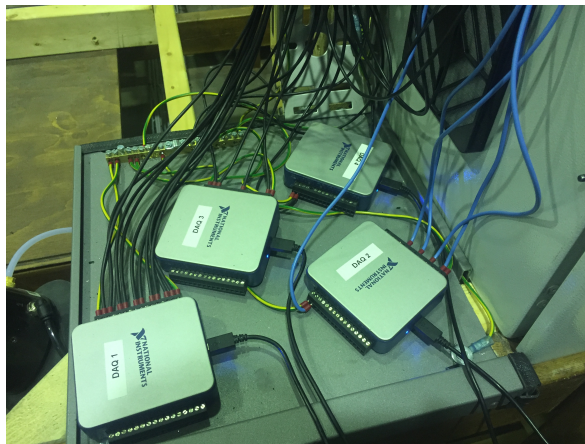


Figure 3.6: DAQ setup

The USB units can both read and supply voltage, and they are designed to work with the software development program (LabView). The analog inputs are wired to the left side of the units, this data is transmitted to the computer through micro USB. The USB DAQ unit has two sides, see Figure 3.8, the left side is for analog I/O, the right side is for digital I/O. There is a total of 8 single-ended analog input channels and 2 analog output channels on each USB DAQ. The digital I/O will remain unused, although the 5V supply on the right side will be used to supply the turbocharger speed sensor.

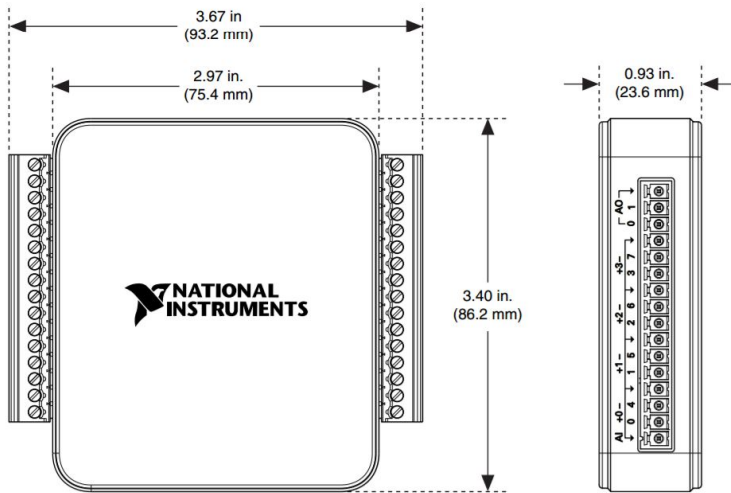


Figure 3.7: DAQ unit [7]

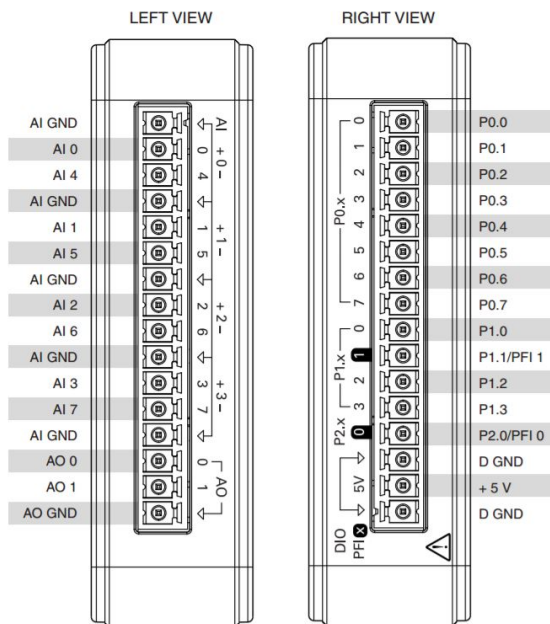


Figure 3.8: DAQ unit, I/O [7]

3. Construction and results

Pressure readings

The pressure transmitters on the lab are wired to the DAQ labeled DAQ1. These pressure sensors transmit a voltage signal between 0-10 V, this correlates with a pressure reading ranging from 0-10 barg. Hence, the signal can be read directly by DAQ units.

Valve control

The control valves are controlled by a 4-20 mA signal. The set point input resistance on the control valves are 500 Ω . This meant that the DAQ voltage output channels could be wired directly to the control valves. According to Ohms law, the output range of 0-10 V should have generated a 0-20 mA current when the load is 500 Ω . The principle is identical to wiring a 500 Ω resistance in parallel with a 4-20 mA signal transmitter. The voltage read at the input will correspond with the 4-20 current. This is shown in Figure 3.9.

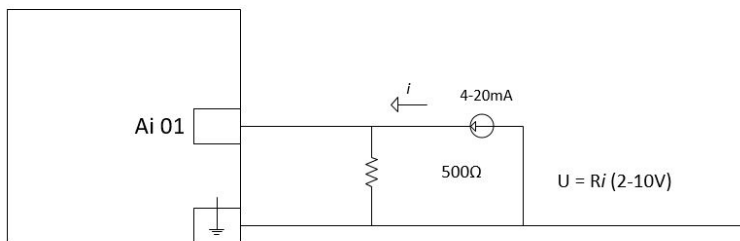


Figure 3.9: Current to voltage conversion

A problem was discovered when the voltage output was connected to the control valves. The analog output did not have enough power to provide 10 volts with a 500 Ω load. Incrementally increasing the output level revealed that the maximum current delivered by the DAQ was 9 mA. This meant that the valve could only be opened 25 % with the USB DAQ. This is why an NI-9265 current output module was ordered, this is connected to the computer through Ethernet. It has 4 analog output channels, each channel outputs a signal between 4-20 mA. Which is what the control valves use as their setpoint. The module is shown in Figure 3.10.



Figure 3.10: Current output module [8]

The anti-surge valve (CV01) is an exception to this problem. The valve can only be fully open or fully closed. The signal for fully open is 24 V, while fully closed is 0 V. The maximum output of the DAQ unit is 10 V, this means that the DAQ can not open the valve by itself. A relay between the 24 V DC supply in the cabinet and the valve is used as an on/off switch, the relay can be controlled by the DAQ. The valve is thereby indirectly controlled by the DAQ analog output.

Temperature readings

The temperature is measured using passive resistance (PT-100) elements. A PT-100 element is built of a material that changes its electrical resistance with variations in temperature. Standardized PT-100 schematics lets the electrical resistance be converted to temperature. Since the DAQ units only measure voltage, it is necessary to convert electrical resistance into a voltage reading. A current regulator and an operational amplifier can be used to perform this task. The current regulator used is a Texas Instruments LM134H/NOPB, it can handle supply voltages from 0.1 - 40 V. The output current is controllable between 1 μA - 10 mA. The datasheet is found in Appendix B. The circuit required to perform this conversion is shown in Figure 3.11.

3. Construction and results

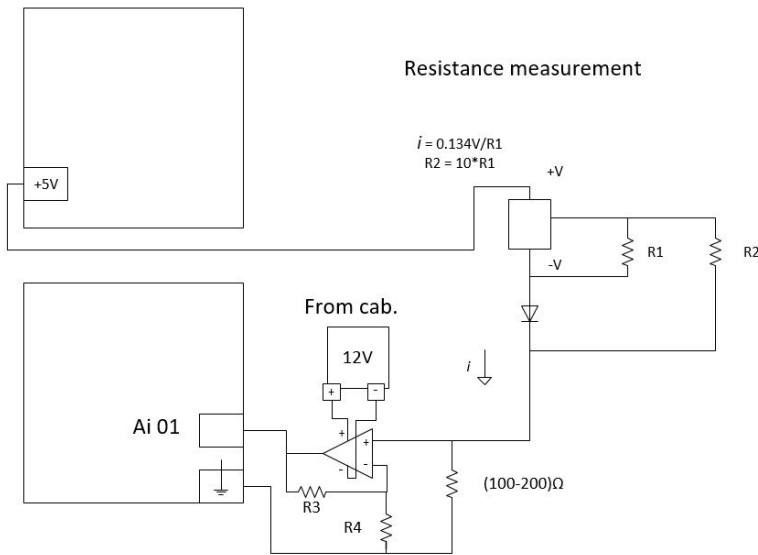


Figure 3.11: Resistance measurement

A DAQ unit supplies a current regulator with 5 V. The current regulator is calibrated to deliver 10 mA, this is done by choosing the resistors R_1 and R_2 .

$$i_{set} = \frac{0.134V}{R_1} \quad (3.1)$$

$$R_2 = 10 \cdot R_1 \quad (3.2)$$

This current will generate a voltage across the variable resistance element, an operational amplifier is used to amplify this voltage. The amplifier is powered by the 12 V supply in the cabinet.

It is desirable to get as much current as possible from the current regulator. This is done to generate the highest possible voltage drop over the variable resistor. To get the best possible measuring resolution, as much of 0-10 V range must be utilized. With a desired current of 10 mA, from 3.1 and 3.2 the required $R_1 = 13.4 \Omega$, which gives $R_2 = 134 \Omega$ from 3.2.

With a resistance range from 100 - 200 Ω , a correlating voltage of 1-2 V will be generated. The output voltage of the operational amplifier (op-amp) is given by

$$V_{out} = V_{in} \left(1 + \frac{R_3}{R_4}\right) \quad (3.3)$$

From 3.3, $V_{in} = 1-2$ V, using $R_3 = 500 \Omega$ and $R_4 = 2000 \Omega$. The output voltage yields $V_{out} = 4-8$ volt. The op-amp used is a Texas Instruments TLC251CP. The op-amp specifications can be found in Appendix B.

When the resistors were ordered, the closest to 13.4 ohms found was 14 ohm. All the resistors were adjusted accordingly, this is shown in Table 3.1. These resistor values give an expected output voltage between 4.04 and 8.04 V correlating with 100-200 Ω .

Resistor	Value
R1	14 Ω
R2	140 Ω
R3	2000 Ω
R4	475 Ω

Table 3.1: Resistor values

The components were connected on a breadboard according to Figure 3.11, the result can be seen in Figure 3.12. The temperature sensors are connected to the breadboard, and the DAQ unit reads the voltage V_{out} from the operational amplifiers. The resistance can be calculated from Ohms law, $i_{set} = 9.57mA$.

$$R = \frac{V_{in}}{9.57mA} \quad (3.4)$$

The input voltage on the op-amp is given by

$$V_{in} = \frac{V_{out}}{1 + R_3/R_4} \quad (3.5)$$

The resistance of the PT element can then be calculated by.

$$R = \frac{V_{out}}{9.57 \cdot 10^{-3} (1 + R_3/R_4)} \quad (3.6)$$

The temperature in degrees Celsius can be calculated from a PT-100 resistance table, assuming that the relationship between temperature and resistance is linear the temperature can be calculated using the following expression.

$$C^\circ = (R - 100) \cdot 2.67 \quad (3.7)$$

3. Construction and results

The approximated linear gradient is 2.67. At $100\ \Omega$ the temperature is 0 degrees Celcius, at $200\ \Omega$ the temperature is 267 degrees Celcius. Since a linear approximation will be satisfactory for this application, the gradient can be estimated to $\Delta C^\circ / \Delta \Omega = 267/100 = 2.67$.

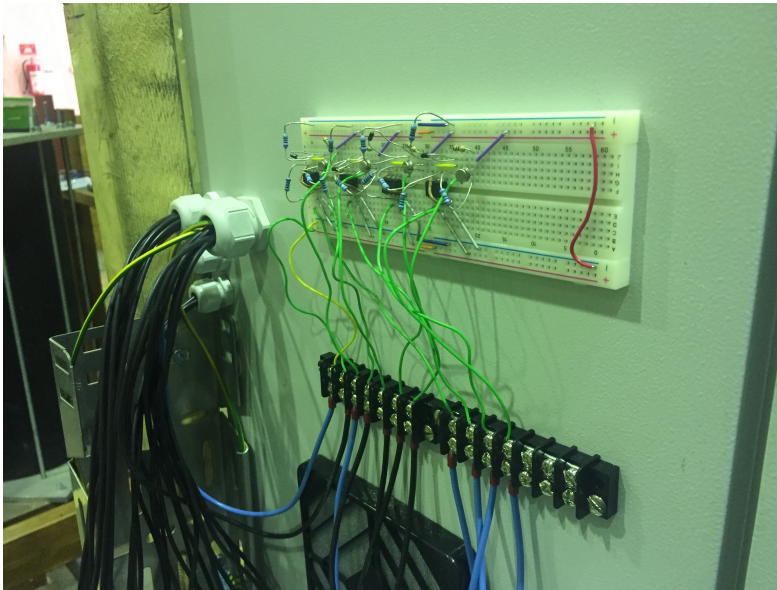


Figure 3.12: Temperature measurement breadboard

When the breadboard was connected the DAQ units, the temperature measurements were discovered to be slightly higher than expected. This was corrected by calibrating the sensors, and by using the measured values in 3.6. A multimeter was used to measure the actual output current of each of the current regulators. The ratio of the input and output voltage of the operational amplifiers were also measured. The temperature reported by each sensor were calculated using these measurements instead of the theoretical values. Furthermore, a bucket of ice water was used to determine the $0\ C^\circ$ point, this was done for all the sensors. An offset was added in the temperature calculation program. This was done to ensure that all the sensors were reporting $0\ C^\circ$ when placed in ice water.

3.2 Factory acceptance tests (FAT) on electrical systems

Factory acceptance tests (FAT), had to be performed on all the circuits and connections on the rig. Such tests are conducted prior to starting up the system for the first time, this is done to minimize the presence of detectable errors. Any error that could potentially lead to damage of equipment, or pose a safety threat to personnel is especially prioritized. This section describes how the FAT on the electrical systems was conducted. The schematics used

3.2. Factory acceptance tests (FAT) on electrical systems

to conduct the tests can be found in Appendix A, the notes taken during the tests are included in these documents.

3.2.1 Main circuit

The main circuit was tested doing a point by point comparison of the wiring of the system with the main circuit drawing. The corrected main circuit drawing can be found in Appendix C, the FAT drawing is found in Appendix A. In addition to checking wiring location, the quality of each connection was tested. The point to point electrical conductivity was tested using a multimeter. The quality of the physical connections was tested by subjecting the wire to a slight pull.

The test uncovered a minor error in the main circuit drawing, it indicated that the wires going from the fuses F2 and F3 should go to a terminal block, before going to the contactors Q2 and Q3. The corrected main circuit drawing can be found in Appendix C. Additionally, a loose wire from F4 was discovered, this was corrected during the test.

3.2.2 24 V circuit

An identical test as described in the previous section was performed on the 24 V DC circuit. During this test, it was discovered that the jumper wires on X5 were improperly connected. A bad quality connection on the relay controlling the water pump was found and corrected. Additionally, a spare fuse was drawn as connected. This was corrected, the fuse will probably be used in the future to connect a flow meter.

3.2.3 12 V circuit and DAQ connections

To perform a FAT on the 12 V circuit and the DAQ units, the schematics for the wiring of the terminal blocks were used. They include the 12 V circuit and connections going in and out of the cabinet. This test, combined with the FAT for the 24 V and the main circuit will comprise the entire electrical system. During the test, the quality of the connections going all the way from the internal connections on the sensor to the DAQ was checked, and the signal transmission was tested. Multiple problems were discovered and corrected in this test, including but not limited to the need to replace the M12 connections on the choke valves, as well as the numbering and order of some components. The schematics for the terminal block connections were revised, after this test and all errors were corrected. The details can be found in Appendix A.

3.3 Compressor setup

The centrifugal compressor on the lab is a Garrett GT2252 turbocharger, this would normally be installed in a car engine. The working principle of a turbocharger is shown in Figure 3.13.

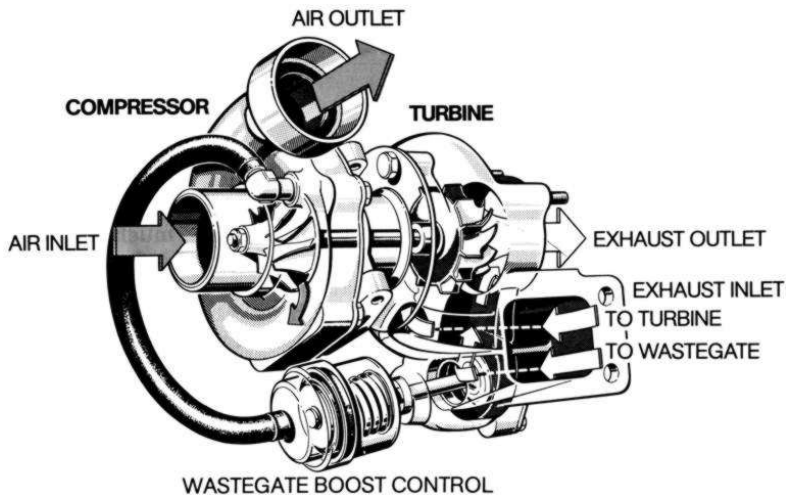


Figure 3.13: Working principle of turbocharger [26]

The turbocharger is normally supplied with oil from the engine, and the turbine is driven by the exhaust gas. In this external setup, a lubrication and air supply system are required. A built-in pneumatic air supply system is installed in the workshop where the lab is constructed, this is used to feed the turbine. The turbocharger lubrication system is described in the next section. A control valve is used to control the airflow to the turbine, this allows the operator to control the RPM of the compressor wheel. A valve on the turbine side of the compressor opens when the compressor output pressure reaches a predefined level, this lets some of the air bypass the turbine. The wastegate seen in Figure 3.13 controls this. In the context of this lab, it is important that the adjustment nut on the wastegate rod is tightened as much as possible, this increases the pressure required to open the valve. Since the compressor should be used for experimentation, it is important that the boost is limited by the capacity of the compressor, not the wastegate setting. The turbocharger setup on the lab is shown in Figure 3.14 and 3.15.

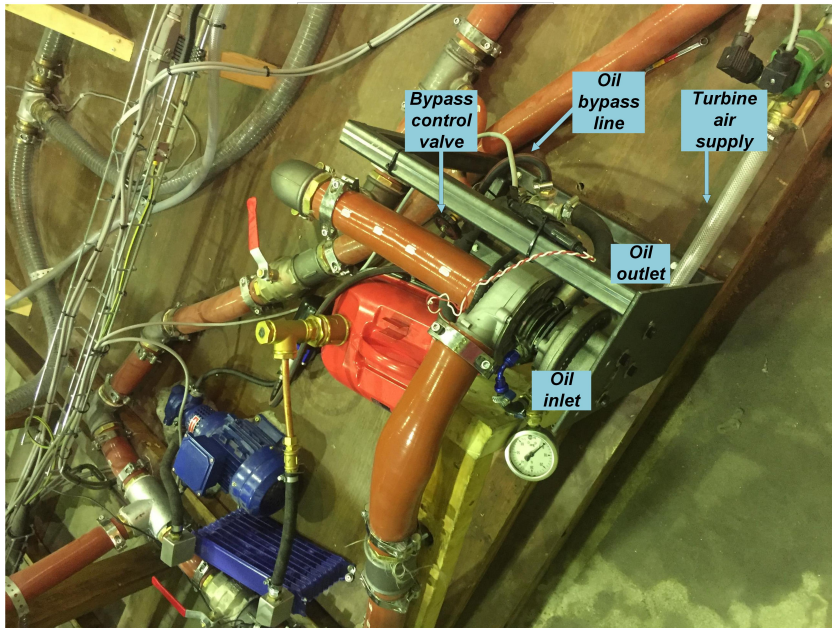


Figure 3.14: Turbocharger setup

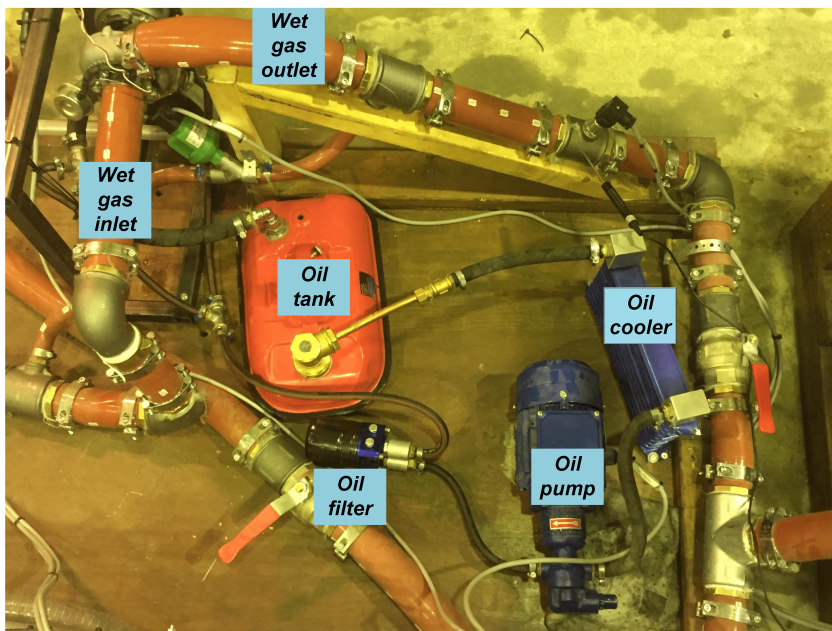


Figure 3.15: Turbocharger lubrication

3. Construction and results

3.3.1 Compressor lubrication system

The Garret GT2252 turbocharger makes use of a ball bearing system instead of a journal bearing system. Ball bearing turbochargers from Garrett requires an oil pressure at the oil inlet between 2.7 and 3 barg [5]. To supply the turbocharger with oil, an oil pump by Pompe Morgan is mounted on the lab. This pump can operate at a pressure of 6 bar with a flow rate of 1.98 l/min. The oil needs to be pushed through a filter to ensure that no particles accumulate and cause any damage to the turbocharger. A cooler is installed to prevent the oil temperature from becoming too high. The lubrication system was originally designed as in Figure 3.16. To ensure that the pump was working and that oil circulation was sufficient, the pump was tested without the turbocharger in the loop. This was done to avoid forcing too much oil through the ball bearings. The test confirmed that the pump was working, but no significant pressure buildup was observed with the control valve fully open. Closing the valve increased the oil pressure upstream of the valve. The gear pump can only build up pressure when it pushes against an obstruction, this is a logical consequence of the pumps working principle. The gears rotate at a constant speed, this ensures a constant flow through the loop. But if the flow resistance downstream of the pump is small, the oil will flow easily, and no pressure buildup will occur. The design in Figure 3.16 assumes that the turbocharger oil inlet gives the pump enough resistance to build up sufficient pressure. The valve is installed to reduce the pressure reaching the inlet.

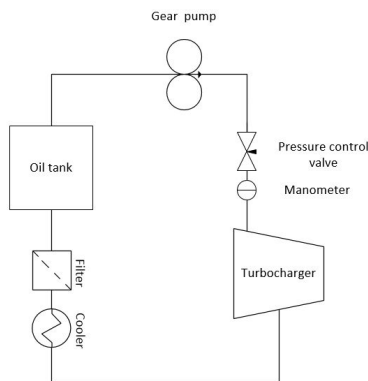


Figure 3.16: Initial oil loop setup

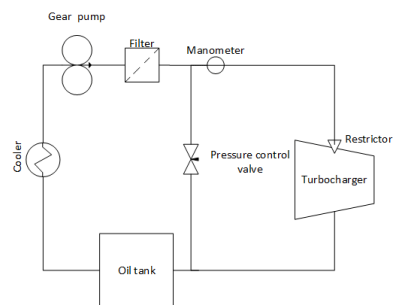


Figure 3.17: Final loop setup

Running the pump using the setup in Figure 3.16 resulted in major leaks from the turbocharger gaskets. The flow resistance downstream of the turbocharger oil outlet became too great when the filter and cooler were placed according to Figure 3.16. The oil was accumulating inside the bearing housing, the gaskets could not contain the pressure buildup. Additionally, insufficient pressure buildup on the oil inlet was observed. Research done on

turbocharger lubrication indicated that the oil outlet should be configured vertically, and the outlet hose diameter should be as large as possible to minimize flow resistance. At this point, the outlet was configured horizontally. The oil loop needed to be reconfigured, both in terms of where the various components are placed, as well as the orientation of the turbocharger. According to the turbocharger manufacturer, Garrett, the oil outlet should be oriented in such a way that the oil flow works with gravity. A frame was built to solve this problem, the turbocharger was vertically bolted onto the frame, this is shown in Figure 3.18. This allowed the oil to flow directly back to the oil tank without any obstruction.



Figure 3.18: Turbocharger mount

The components in the oil loop had to be placed differently. The new design can be seen in Figure 3.17. The cooler is placed at the pump inlet, this is to avoid any obstructions at the turbocharger oil outlet. The low oil pressure at the oil inlet was solved using a 1 mm inlet diameter oil restrictor. These components are normally used when the oil pressure is too high, and flow needs to be restricted. But they can also be used to create pressure by giving the pump something to push against. Now, the valve will be used to reduce pressure by letting some of the oil flow back to the tank through a bypass line. An oil flow restrictor is shown in Figure 3.19, the actual installation of the restrictor on the inlet can be seen in Figure 3.20. The inlet hose is mounted on the restrictor through an adapter, this is shown in Figure 3.21. The internal diameter of the inlet hose is 1/4", the outlet hose is 3/4".

3. Construction and results



Figure 3.19: Oil restrictor

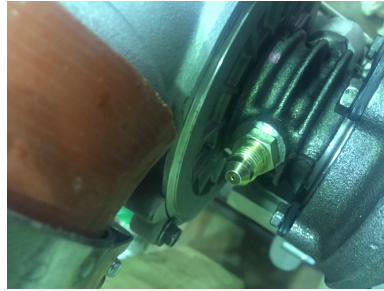


Figure 3.20: Oil restrictor mount

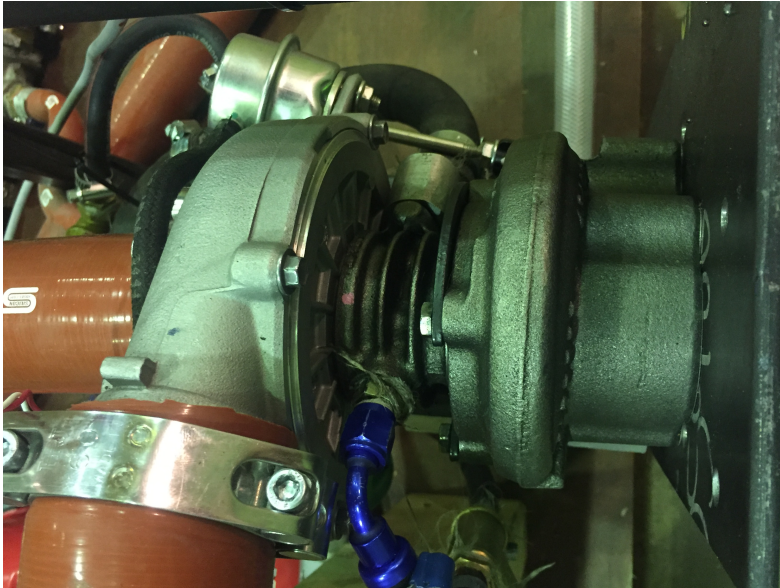


Figure 3.21: Oil inlet adapter

3.4 Construction required by HSE factors

Health safety and environment (HSE) is an umbrella term, it is used to describe the laws, rules, guidance's, regulations and processes used to ensure the safety for people and the environment. The lab operation of this project carries some risk factors, to minimize the risk for everyone involved, it is important to systematically perform an HSE analysis. The HSE factors of the lab were evaluated by both Statoil and NTNU, and from that evaluation, the following list of necessary improvements was made.

1. Build safety walls around the entire lab to protect bystanders from blowouts.
2. Install safety valve on the separator.
3. Install temperature measurement in oil loop.
4. Set up danger signs on components or valves that might be hot.
5. Install cordon to keep bystanders out of danger zones.
6. Setup contact information in case of leakage or other problems.

3.4.1 Safety walls

Since the lab transports hot pressurized air, there is always a potential for dangerous blowouts. Such a blowout will release high amounts of energy potentially slinging debris or hot gas towards bystanders. A wall design, shown in Figure 3.22 will protect bystanders from hot gas and debris. A double plastic glass window is installed, this is done to let visitors observe the lab during operation. OSB sheets and 2" X 4" wood will be used as construction materials since they are both strong and low-cost materials.

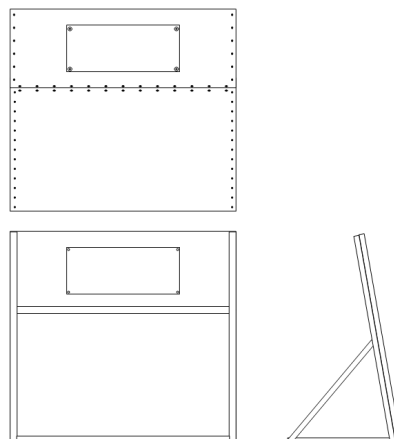


Figure 3.22: Design of safety wall

3. Construction and results

One of the walls are movable as the design in Figure 3.22 indicates, it will support itself by the frame. The other wall will build on the same design, but it will be mounted directly to the lab. Having one of the walls movable allows for some flexibility in terms potentially having to move the lab and changing the preferred location for bystanders. It also provides space for any potential future work.



Figure 3.23: Movable wall

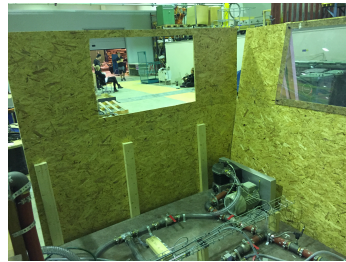


Figure 3.24: Final setup

3.4.2 Safety valve

The installation of a pressure release valve on the separator was required. The valve should release the pressure before the mechanical limits of the fittings and piping are reached. The piping and fittings can endure a maximum pressure of 10 barg. Hence, the chosen safety valve opens at this pressure level. A hole was drilled at the top of the separator, this was then threaded to allow for a proper installation of the valve.

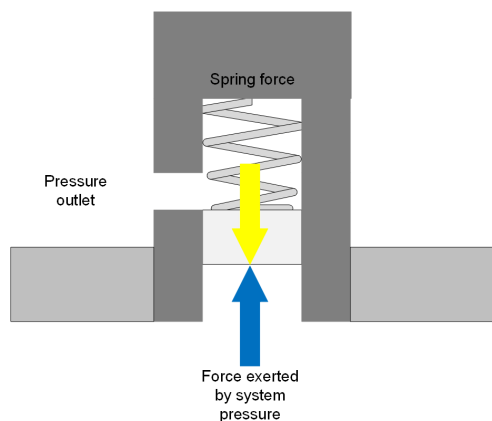


Figure 3.25: PSV principle

3.4. Construction required by HSE factors

A PSV is a normally closed spring loaded valve. The static system pressure exerts a force on the valve stem, this contracts the spring which holds the stem in place. The stem is pushed back far enough to create an outlet when the maximum pressure has been reached. This equalizes the pressure. This principle sketch is shown in Figure 3.25.



Figure 3.26: Pressure release valve (PSV)

3.4.3 Control station protection

The control station is shown in Figure 3.27. The control station is exposed to blowouts from the cooler and the separator. A see-through plastic shield was therefore installed, this should protect both the operator and the computer setup. The finished installation of the shield is shown in Figure 3.28. Any blowout in the piping underneath the cabinet, or right behind the control station could potentially harm the operator. An MDF plate was therefore mounted in the frame facing the control station. This is shown in Figure 3.29.

3. Construction and results



Figure 3.27: Control Station



Figure 3.28: Control station protection



Figure 3.29: Operator protection

3.5 Counter flow cooler blowout

When the counter flow cooler was tested for the first time, the gasket at the top of the cooler got displaced by the water pressure. The gasket is located between the PVC body and the aluminum lid. The top of the cooler is shown in Figure 2.14. It was previously assumed that the cooler was not required to handle any significant pressure build-up. The outlet and inlet flow should be identical, hence, no significant pressure build up was expected. It can be difficult to avoid a situation where too much water is entering the cooler, especially since the water flow can not be measured. Pressure build up could also easily occur if outlet flow is accidentally restricted.

Measures were taken to prevent future blowouts. For the rubber gaskets at the top and bottom of the cooler to be properly fitted, the aluminum lid had to be loosened. The cooler lid is shown in Figure 3.30. Bolts at both ends of the rods are used to fasten to the lid. To prevent gasket slippage and future blowouts, the bolts were tightened evenly. A torque limiter was used to achieve symmetrical pressure. All the bolts were tightened to 20 Nm of torque.

3. Construction and results

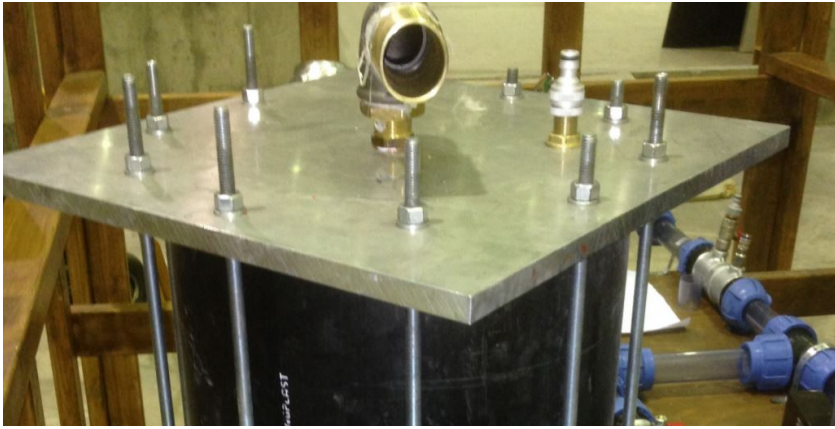


Figure 3.30: Cooler lid [12]

3.6 FAT of Instrumentation and physical layout

To perform a FAT on the instrumentation and the physical layout of the rig, a P&ID printout was used to do a point by point comparison with the actual rig. The location and numbering of every component were compared with the rig to ensure that the P&ID actually represents the real system. The test revealed that the P&ID was missing the turbocharger bypass line. The water inlet valve for the system was also missing, the P&ID drawing was then corrected. As previously discussed, the oil loop had to be redesigned at a later stage in the project, this change is included in the P&ID in Appendix C.

Chapter 4

Control system design

The control system design requirements were described in the introduction. The control system should ensure that the desired behavior from the compressor is obtained, as well as ensuring the safety of personnel and equipment. It should be part of a program that provides a human machine interface (HMI), this should let the operator change settings and modes of lab operation. The logic and code should be designed in such a way that future improvements and extensions easily could be installed. The program described in this report has been developed in the LabView development platform by National Instruments.

4.1 Control system requirements

There are two choke valves on the lab that control the pressure in the system. Choke valve 1 (see P&ID) in Figure 1.3 control the compressor suction pressure in the system. The control system needs to incorporate a controller that obtains the desired suction pressure. The second choke valve, Choke valve 2, controls the mixing pressure. The water coming from the separator is combining with the airflow from the cooler in a T-junction. The water pressure (PT02), needs to be slightly higher than the airflow pressure (PT03) and the suction pressure (PT05). This guarantees a steady water flow from the separator. The outlet pressure of the separator would in this way be higher than the inlet pressure of the compressor and the outlet pressure of the cooler. This means that the water would naturally flow from high to low pressure in the desired direction. The controller should ensure that choke valve 2 should move in the direction of open if PT03 is lower than PT02, it should move in the direction of closing if PT03 is higher than the setpoint $PT03 = PT02 + 0.3 \text{ bar}$. The water pump should build enough pressure to match PT02 with PT03. See Figure 1.3 for a complete system overview. Together, the two choke valves should maintain the pressure zones seen in Figure 4.1, red, yellow and green indicate high, medium and low-pressure zones respectively.

4. Control system design

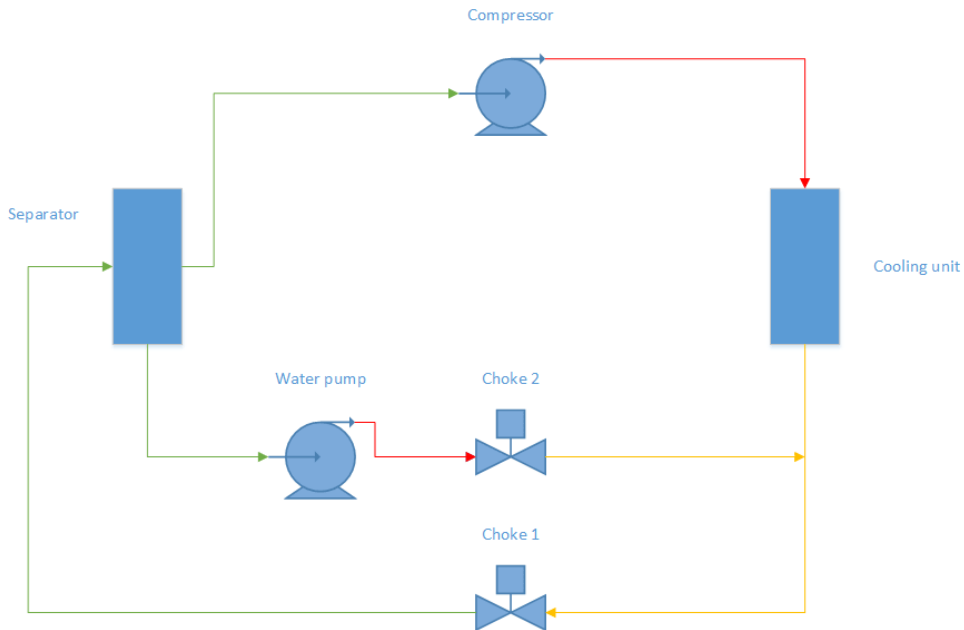


Figure 4.1: Pressure zones

The centrifugal compressor is controlled by a valve that controls the airflow to the turbine. PI control is used to determine the valve position. As a starting point, RPM should be used as a measurement for the controller, if the RPM is too high the valve should close, and vice versa.

There are two temperature zones on the lab, the plastic pipes on the low-pressure side can tolerate temperatures up to 60 C°, and the silicon hoses on the high-pressure side can tolerate temperatures up to 200 C° [12]. Therefore, the control system should continually measure temperature to check if levels keep within specified boundaries. If any temperature limit is exceeded, the choke valves should open fully, this would help the gas distribute evenly in the system. The turbine control valve should close, this would stop the turbocharger from adding more energy into the system, and the antisurge valve should open to relieve the compressor outlet pressure. The same shut-down procedure should be triggered if any pressure reading exceeds the maximum pressure of 6 barg. This forms the requirements for the basic control system that should be used in the start-up phase of the lab.

4.2 Basic starting point control

In LabView, a basic control system that meets the requirements of the previous section needs to be designed. The operator of the lab is presented with an HMI front panel as shown in Figure 4.2.

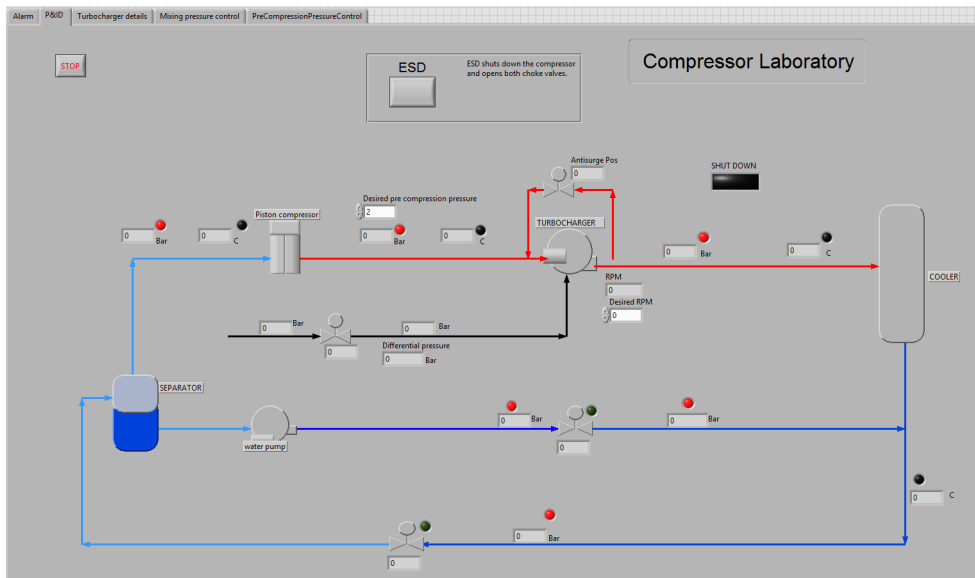


Figure 4.2: Front Panel (HMI)

From the front panel, the operator can set the desired RPM value and suction pressure, as well as read the pressure and temperature levels on the lab. The valve position and feedback is also given on the front panel. If any pressure or temperature reading exceeds its limit and the lab goes in shut down mode. Warning lamps and alarms will indicate this in the process overview and alarm list. In the alarm list, it is possible to retrieve information regarding where and when something went wrong. By clicking the tabs, the operator can select between the P&ID view, an alarm list and a more detailed view of the turbocharger parameters and the individual controllers. The operator can choose to run the lab in manual mode, this bypasses the controllers and allows the valve positions to be manually set by the operator.

The front panel has multiple tabs that present the user with different information. Each controller has a designated tab that allows the user to both simulate and tune the controller behavior. For the turbocharger, this has been extended with a compressor map that lets the user determine the operation point the turbocharger, see Figure 4.3. However, this requires the installation of a flow meter.

4. Control system design

When the simulation button is pressed, the program stops using the data input from the DAQ units. It lets the user give the controllers simulated data input, this functionality is included to be able to observe controller behavior. This could be beneficial when changes need to be made in the control systems. The controller input can be adjusted by the operator, and by plotting the controller output the operator can determine whether or not this controller dynamic should be tested on the actual system. This can be done individually for each of the controllers. They have designated simulation buttons that select between real or simulated data input. A boolean indicator is used to give the operator feedback when the setpoint has been reached, this makes it easier to determine if the controller is working in a satisfying manner.

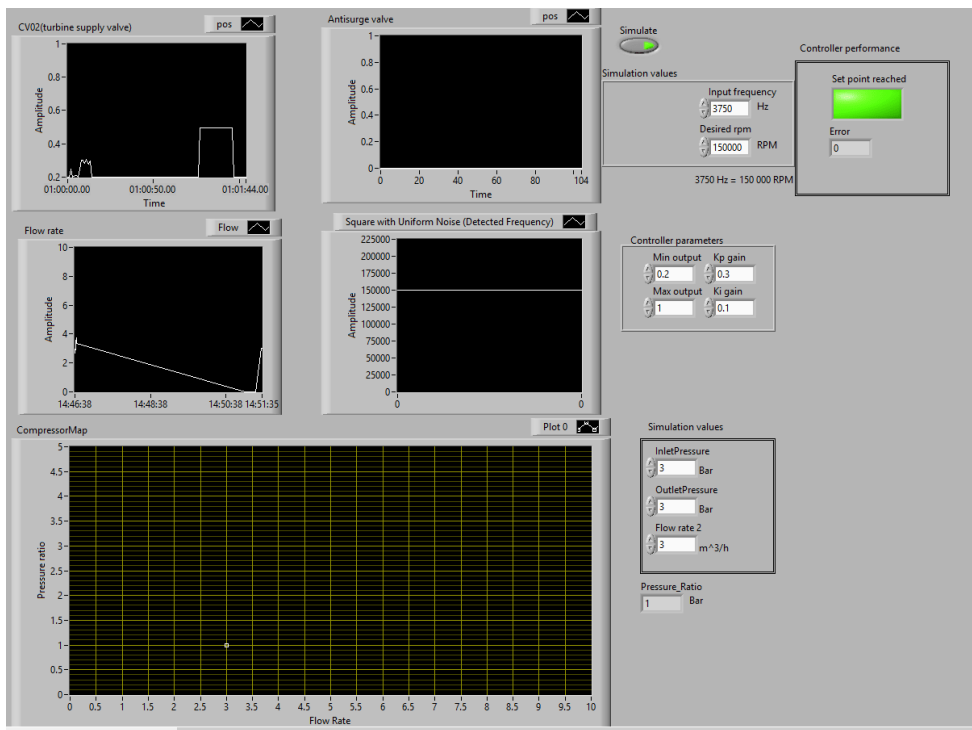


Figure 4.3: Turbo control tab

The mixing controller tab is shown in Figure 4.4, the user can determine emulated pressure values to observe how the choke valve would respond. The controller tuning parameters can be tested directly from the tab. The controller setpoint is the static pressure downstream of the cooler, plus an additional 0.3 bar. This is to ensure a steady flow of water out of the separator, as discussed in the control system requirements section.

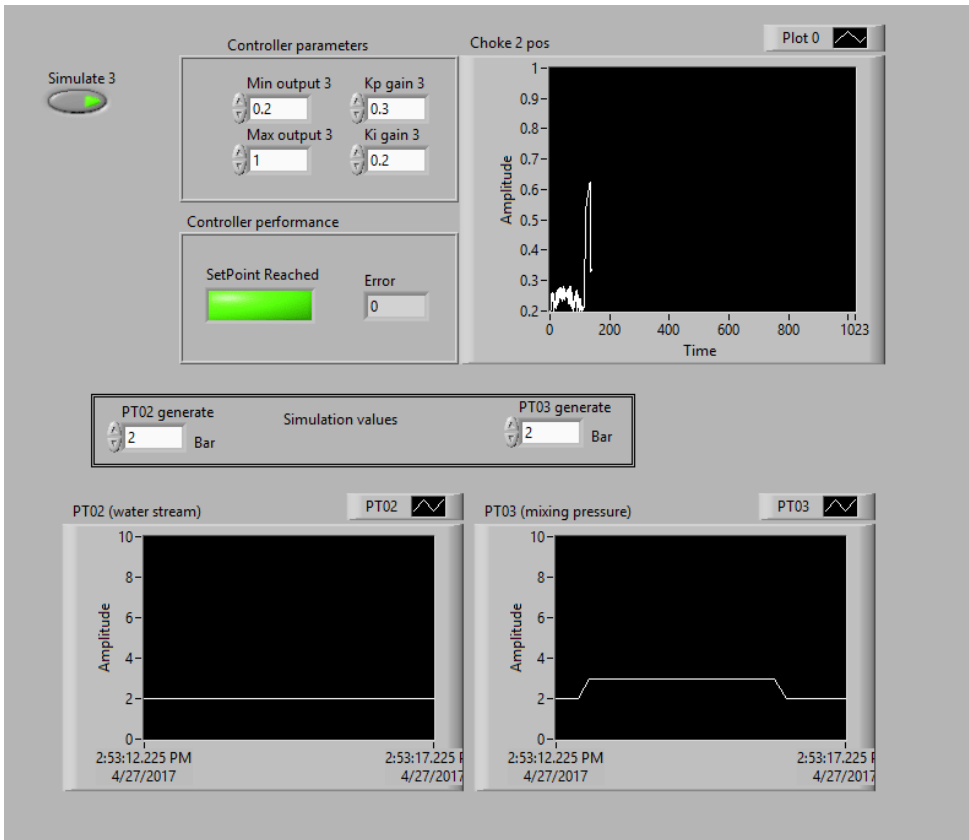


Figure 4.4: Mixing control

The compressor inlet pressure controller tab is very similar, but the setpoint is constant, the tab is shown in Figure 4.5.

4.2.1 Pressure and temperature limits

The lab has two types of piping that are rated at different temperature and pressure capacities, therefore the information coming from the temperature and pressure transmitters are constantly compared to their respective maximum value. If the maximum value for temperature or pressure is exceeded at any point in the lab, a boolean variable called shut-down is set equal to true. This triggers case structures that are responsible for valve control, shut down procedure is identical for both temperature and pressure breach. A LabView case structure lets a controller or set of code run on a condition.

4. Control system design

In this case, the condition is that the temperature and pressure remain within set boundaries. If the condition changes, the controller can be replaced by a constant output value. In this case, the valve position is set to a constant value instead of being determined by the controller. Indicator lamps in the front panel show which transmitter reported a safety breach, the alarm list gives a more detailed view. This is shown in Figure 4.6, the same logic is used to monitor temperature.

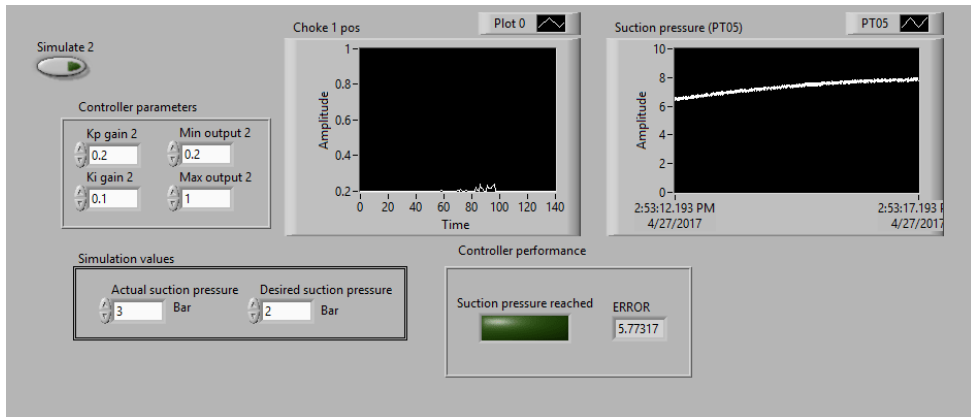


Figure 4.5: Suction pressure control

4.2.2 Pressure control

Two PI controllers are used to control the pressure levels in the lab. One of them controls the mixing pressure, the other controls the compressor inlet pressure. It is crucial that the pressure of the water stream from the separator is sufficient to merge with the airflow coming from the cooler outlet. This is done by using the cooler outlet pressure, including a small safety margin as the setpoint for the mixing pressure controller, Choke valve 2 will then control the output pressure from the separator. If the pressure or temperature is too high at any point on the lab, both of the choke valves will open fully.

The inlet pressure or suction pressure of the turbocharger is controlled by Choke valve 1, a PI controller is used. As a consequence of controlling the compressor suction pressure, the pressure upstream of choke valve 1 will vary. This means that pressure of the cooled stream from the cooler outlet will be affected by the compressor suction pressure setpoint. See the P&ID in Appendix C.

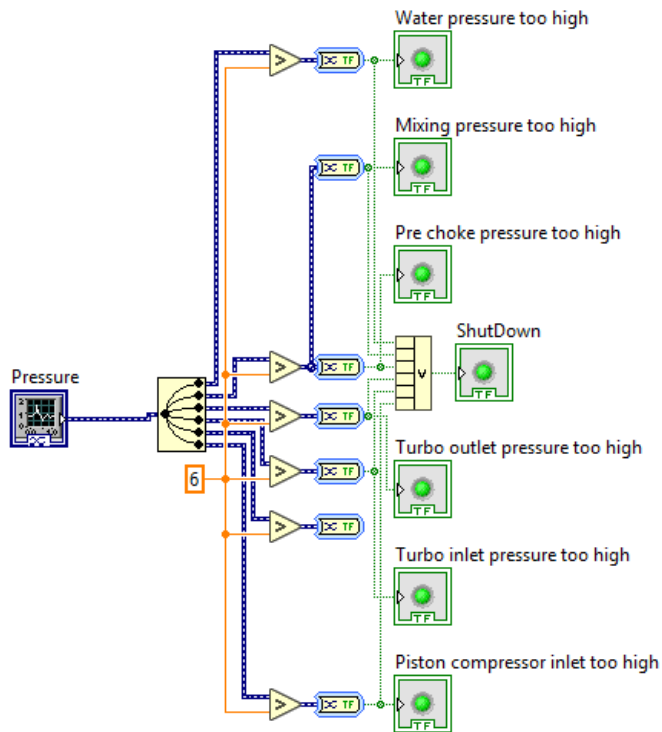


Figure 4.6: Pressure monitoring

4. Control system design

4.2.3 RPM control

The amount of air that is fed to the compressor turbine, controls the RPM of the compressor wheel. For this, a simple PI controller is used, however, it has not been tuned. The RPM is determined by reading the data from the RPM sensor where the signal is translated from a high-frequency pulse to actual RPM data. Every time an impeller blade moves past the sensor, a current is induced. The integrated circuit in the sensor divides the output frequency by eight. Many compressor wheels have an eight blade configuration, although, this is not always the case. Given the number of blades, the RPM of the compressor can be calculated. The compressor on this lab has 12 blades, this means that the RPM is given by

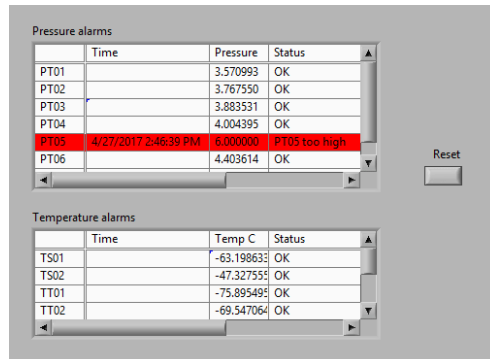
$$RPM = f \cdot \frac{8 \cdot 60}{12}, \quad (4.1)$$

where f is the measured frequency in hertz.

The desired RPM value is set at the front panel by the operator. The setpoint and RPM data is processed by a simple PI controller with anti-windup. The controller output sets the turbine valve position, which controls the air supply to the turbine. RPM control can in this way be established.

4.3 Alarm system

When the lab goes in shutdown mode due to a too high pressure or temperature reading somewhere. The alarm list is designed to tell the operator where and when a variable was violated, it also writes the information to a file creating a log of all parameter violations. This can be useful if the lab needs future improvement or reconfigurations. The alarm list is a simple table that shows real-time data as well as it indicates whether or not the levels are within acceptable range. To restore normal operation after an alarm has been triggered, the reset button has to be pressed. However, normal operation will not be restored as long as pressure and temperature values have not returned to normal.



The screenshot displays two tables of alarm data. The top table, titled 'Pressure alarms', lists six sensors (PT01-PT06) with their respective pressure values and status. The PT05 row is highlighted in red, showing a pressure of 6.000000 and the status 'PT05 too high'. The bottom table, titled 'Temperature alarms', lists four sensors (TS01, TS02, TT01, TT02) with their respective temperature values and status, all of which are 'OK'. A 'Reset' button is visible to the right of the pressure alarm table.

Pressure alarms			
	Time	Pressure	Status
PT01		3.570993	OK
PT02		3.767550	OK
PT03		3.883531	OK
PT04		4.004395	OK
PT05	4/27/2017 2:45:39 PM	6.000000	PT05 too high
PT06		4.403614	OK

Temperature alarms			
	Time	Temp C	Status
TS01		-63.19863	OK
TS02		-47.32755	OK
TT01		-75.89549	OK
TT02		-69.54706	OK

Figure 4.7: Alarm table

4.4 FAT on basic control software

The basic control software intended as a starting point for more advanced control had to be tested to ensure minimum risk at start up. This program is designed to make sure that the lab will operate within temperature and pressure limitations, and that all the control valves are operated within their range. It also looked at the control algorithms to check if they operate correctly, but not necessarily optimally. Each function of the control system and program was tested. Each controller was tested with simulation values, this confirmed that the controllers operated within the range of the actuators, that the anti-windup function was working and that the valves moved in the correct direction. The schematics used to conduct this test can be found in Appendix A.

Chapter 5

Discussion

Initially, the plan was to have the lab fully operational with functional control algorithms at the end of the semester. However, due to design and equipment errors, this goal was unattainable. The lab was made operational, but it only works by setting the valve positions in the HMI. To obtain automatic control, the controllers need to be tuned, and the instrumentation needs to be improved. This chapter discusses and describes the troubleshooting, it aims to justify why things took longer than planned, and why the initial goals could not be met.

5.1 Electrical design

Since the electrical design by the previous students was partially flawed and insufficient in quality, the systems needed to be redesigned and redrawn before they could be built. This was not clear at the start of the project. Time was spent continuously discovering faults, redesigning and reordering as the problems emerged. When a fault is discovered, the process of redesigning and troubleshooting has to begin, this could mean that additional equipment is required. If the fault is found in a subsystem, the redesign has to take into account how the fault relates to other parts of the system as a whole. This scenario is especially true in the case of the electrical system. This can become very time-consuming.

The keyword when it came to time consumption is continuous fault discovery. The system is built up of many parts, and only when these parts come together the problems arrive. A good example of this is the cable gates in the cabinet, they were severely undersized, but this was not clear at the start. During the work done to install the cabinet, it became apparent that more space for the cables was required. This meant that connecting the cabinet took longer than expected, new cable gates needed to be bought and the cables effectively had to be installed twice.

5. Discussion

The most time-consuming design error was the temperature measurement system. The initial design said nothing of how the PT-100 element resistance value was intended to be read with the DAQ equipment that had been bought. It was therefore assumed that the DAQ equipment was able to read electrical resistance directly. When it was discovered that this was not the case, a temperature measurement breadboard had to be designed.

Another issue was the DAQ unit location, this was not included in the plans made by the previous students. Since the space in the cabinet was already limited, the DAQ units had to be placed outside the cabinet through holes that were drilled in the cabinet wall. The cabinet should have been bigger in the first place to make space for the DAQ units. This would also leave room for spare terminal blocks and make future additional installments a possibility.

5.2 Turbocharger lubrication system

As stated earlier in the report, the original design of the turbocharger lubrication setup was not good enough. This was not discovered before the oil pump was tested, and the oil pump was tested quite late in the project. The electrical systems and high voltage power supply had to be approved by professionals before the oil pump could be used. The test revealed that the oil lubrication system was not functioning as intended, no significant pressure buildup at the turbocharger oil inlet was observed. This was a surprise to both the student and the supervisor, no clear solution was available. The early ideas surrounded the pump capacity with regards to flow and pressure, it was discussed whether or not the pump needed to be replaced. During testing with a needle valve at the pump outlet, it was observed that the pump was easily able to generate a pressure of 4-5 barg upstream of the valve. But a gear pump can only generate pressure when there is a flow resistance on the outlet. The next idea was to move the valve to the turbocharger outlet, this was not a good idea. Major oil leaks from all gaskets confirmed this. According to the turbocharger manufacturer, the oil pressure at the inlet should be between 2.7 - 3 barg, additionally the manufacturer states that using an oil restrictor could be a last resort solution to ensure that too much oil is not flowing to the ball bearings. Based on this information, an oil restrictor was bought, this gave the pump enough flow resistance to build up the required pressure. Combined with a bypass oil line and a return valve, the inlet pressure could be adjusted. This lets the operator adjust the inlet pressure to 3 barg. Another concern was the orientation of the turbocharger. The oil outlet needed to be configured in such a way that the oil flow from the bearing housing was as unrestricted as possible. A frame had to be built to lift the turbocharger up and let the oil flow out as vertically.

The problems described above turned out to be bigger than anyone involved in the project could predict, this explains why the project was delayed.

5.3 Problems with IO setup

Another major issue explaining why the project fell short of the initial plans, was the I/O setup. It was wrongly assumed that the equipment bought for data collection and control, DAQ USB 6001, was going to work with all the sensor and actuators on the lab. This equipment was ordered by the students working on the project in the spring of 2016. From looking at the control valve datasheets, the product code revealed that the valves needed a 4-20 mA current control signal to operate. The valves can be ordered in two control signal configurations, either 0-10 V or 4-20 mA. Since the USB DAQ delivers 0-10 V, it was natural to assume that the valve was ordered accordingly. The temperature sensors are passive PT-100 resistance elements, the resistance value directly translates to temperature. Again, the DAQ units only read and write voltage, not current or resistance. This was first apparent when the I/O was tested with the equipment at the lab. During the software development phase and the completion of the electrical systems and the oil loop, the assumption was that the DAQ units were ordered with the equipment at the lab in mind. This meant that a resistance to voltage conversion circuit had to be designed, as well as a circuit that converts voltage signals to current signals. After designing and waiting for the required components to arrive, the breadboard was wired and tested. The temperature measurement was too inaccurate and noisy. Through calibration and filtering the temperature measurement was made satisfactory with regards to safety, but not with regards to research. The temperature measurements setup was calibrated using ice water as the 0 C° point. A PT-100 table is used to determine the temperature from this baseline point. As a last resort to increase accuracy, measured values of current and voltage on the breadboard components are used to calculate the PT-100 resistance value. This is used instead of theoretical current and voltage values.

The turbine air supply valve has 500 Ω resistance at the inlet, this should translate the 0-10 output voltage supply to 0-20 mA current, but the DAQ is unable to provide an output of 10 volts with a 500 Ω load. To control the valves, new analog output cards had to be bought, the NI 9265 analog output cards deliver the expected 20 mA current, thereby the problem was solved. Reading a 4-20 mA transmitter input signal can be done on the USB DAQ analog inputs, a 500 Ω resistor can be wired between the input and ground, this translates the current signal to a voltage signal.

5.4 Reflections on current lab status

As of now, the lab is operational, but without the reciprocating compressor running in the loop. All the control valves can be manually controlled from the front panel in LabView, and the foundation for PI control tuning is incorporated in the program. The program can be run in either manual or auto mode, but for the auto mode to work, the tuning of the PI

5. Discussion

controllers need to be performed. The tuning can either be done experimentally or by the use of mathematical models.

5.4.1 Instrumentation

The instrumentation systems are working, but the temperature measurement system is not accurate enough for research purposes, and the RPM measurement is unstable over 160 000 RPM. The temperature measurement accuracy is satisfactory with regards to safety, but to do research on wet gas compression it is important to find a way to improve this system in the future. The pressure measurement system works perfectly.

The RPM measurement system works as long as the turbocharger is turning slower than 160 000 RPM. When the speed of the turbocharger passes 160 000 RPM, the sensor output frequency detection algorithm alternates between 4000 and 5000 Hz, this corresponds to 160 000 and 200 000 RPM. The RPM signal looks clear when observing the raw data from the RPM sensor, the raw data signal is shown in Figure 5.1. This means that the problem is probably not noise related. It is at this point unclear if this problem is rooted in the DAQ unit, the sensor, the USB communication protocol or the code. When simulating a square wave signal in the program, instead of acquiring raw data, the frequency detection code works without any problems. This could be an indication that the problem is hardware related. Note that the phenomena occur at a perfectly round number, this could hint at a built-in restriction, either in the sensor or in the DAQ unit. The sensor wiring method to the DAQ was changed from single-ended to differential measurement. This was done to reduce any potential noise as much as possible. The 5V supply was changed from the DAQ +5 V output to the NI 9265 current output, it is wired with a resistor in parallel to ground. The measured output voltage to the sensor is now 5.5 V. This was done to ensure that the sensor had enough power to perform the measurement. These changes did not remove the instability in the RPM measurement. In the future, a rising edge detection algorithm should be tested, the digital input side of the DAQ should also be tested. The DAQ units do not have an internal clock on the digital input, but an external clock could be used. This could be an investigation that can be conducted in the future.

5.4.2 LabView program

The final LabView program lets the operator control the lab manually and safely. Safety systems are engaged at all times, and the lab automatically shuts down if any temperature or pressure levels exceeds the built-in limitations. The temperature and pressure data is also logged. An alarm list gives the operator an indication of where and when something went wrong, this needs to be reset and normal pressure and temperature levels needs to be restored before the lab can regain operation. For the future, it is firstly important to tune the PI con-

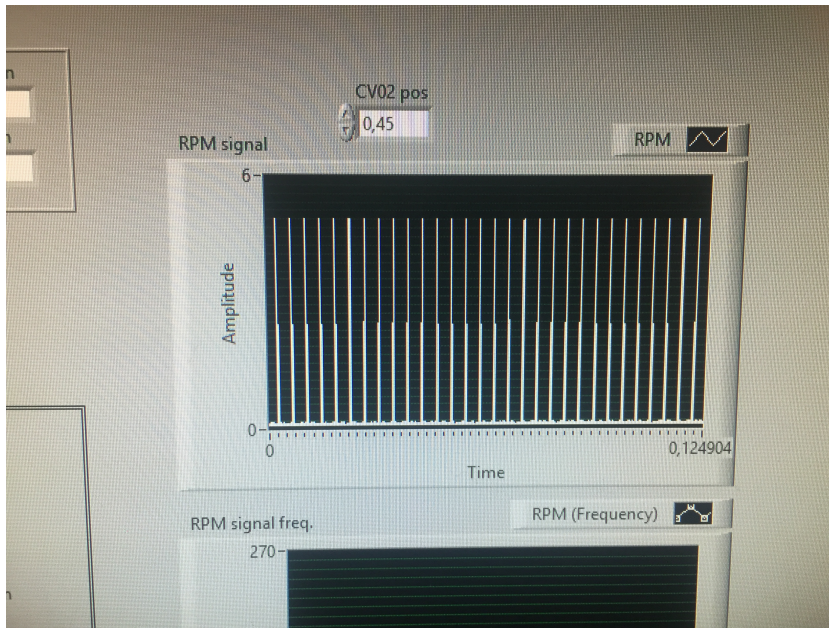


Figure 5.1: RPM sensor output

trollers, secondly, the data logging functionality can be improved. The alarm logging system is very primitive and does not really function as well as it is intended, this is also the case with pressure and temperature data logging. Ideally, this could be improved upon by sorting the data into multiple files in a format that can be analyzed by software like Matlab or Excel. For experimental research, data logging functionality is essential. It should be possible to extend the program with a tab that allows for more advanced data logging functionality. Automated experiments are something that could be interesting to combine with sophisticated data logging. For instance, one experiment could run the turbocharger from minimum to maximum RPM while the parameters are logged in a format that can be analyzed in Matlab. This data could then be compared with existing models, this is the cornerstone of research, comparing theories with real data.

5.4.3 Compressor performance

Since the volume upstream of the compressor is significantly larger than it would be in a car, where the compressor normally would be installed. The compressor struggles to build any significant pressure ratio without increasing the pressure in the piping prior to compression. If the piping is not pressurized, the suction flow to the compressor becomes very limited. Testing with 1 barg pressure in the piping prior to start-up gave a pressure ratio of 2.2 at

5. Discussion

approximately 160 000 RPM. The outlet temperature of the compressor was also lower than expected, running the compressor continuously for several minutes gave a maximum output temperature of around 70 degrees Celsius. The turbine air supply can drive the turbocharger upwards towards 200 000 RPM, but the exact number is unclear because of the issues regarding the RPM measurement, as discussed in the previous subsection.

5.4.4 Cooler leak

At the later stages of the project, the cooler was shown to leak. Measures were taken to avoid this in the future, but it will remain important to not let too much water flow to the cooler. A steady stream of water should be observed from the outlet hose when the cooler is running. But high volumetric flow rates are not required for the cooler to operate optimally. In the master thesis written in 2016, [12], it was calculated that with an air flow of 1.25 kg/min and a temperature of 220 C°. The cooler would be able to reduce the temperature to 20 C° with a water stream of only 12.6 kg/min, or approximately 12.6 l/min. Since the centrifugal compressor is not able to heat the outlet flow to this temperature, the water flow through the cooler can safely be operated at much lower flow rates than 12 liters per minute.

5.4.5 Turbine air supply

The compressor turbine is run by the compressed air supply installed in the workshop, the initial tests seemed to indicate that air supply capacity was insufficient, the maximum RPM achieved on the compressor was around 10 000. By inspecting the connection point it was clear that the diameter of the connection point was too small. Replacing this to a 3/4" permanent connection gave enough supply to run the turbocharger at sufficient speeds. In the initial test phase, the turbocharger RPM was declining after a few minutes of testing. This meant that the workshop air supply system was unable to sustain the compressor at peak performance for more than a few minutes at a time. After a few minutes of operation, the pressure in the pneumatic supply system had dropped from 8.5 barg to 3 barg. This could mean that the lab can not be operated continuously with the current air supply system, peak performance can only be obtained in short bursts. The decline in pressure also means that the choke valves will not get the required air pressure to keep open, since the valves are pneumatically actuated. If the lab is intended to run for longer periods of time, another supply system must be used.

Chapter 6

Conclusion

The lab has been made operational during this semester. The electronic systems have been completed, the lubrication system is working, the I/O systems are running, and a software framework which monitors and controls the lab has been designed. A PI control framework is used, but not tuned, this is the case for all the control valves except the anti-surge valve. This valve can only be fully open or fully closed. The combination of these systems allows the lab to operate within the safety boundaries defined by the HSE requirements.

The lab is only fully operational in manual mode, the operator needs to set the valve positions from the front panel. A small-scale literature study has investigated the possibility of integrating anti-surge control by the use of a differential pressure based flow meter. Differential pressure based flow meters are recommended since standardized anti-surge control algorithms make use of the differential pressure measurement. It is highly recommended that this is installed in the future. The reciprocating compressor has been left out of the scope at this stage, as it is not part of the wet gas compression topic, but it remains a potential future installment. The remaining job regarding the installment of the reciprocating compressor is to connect the frequency converter and complete the setup towards the computers systems, the details of this has not been examined. There are still potential improvements that can be made, the temperate measurement is not very accurate, and the RPM measurement can be unstable. With regards to HSE, a few details remain. Another safety wall needs to be installed, in addition to a cordon that keeps bystanders at a safe distance. It recommended that this remains a high priority and that it is completed before the lab is ready for wet gas research.

6. Conclusion

6.1 Future work

The lab still has remaining systems that need to be installed. With regards to HSE, another wall needs to be built to protect bystanders and a chain needs to be set up to prevent unauthorized personnel standing too close to the operational equipment. With regards to the functionality of the lab, a flow meter should be installed to allow for more sophisticated control of the turbocharger. The flow meter can be used to identify surge lines and generate compressor maps. If the lab is to be used as intended, this should be the main priority. It will be very challenging to make any accurate predictions or observations on how wet gas compression differs from dry gas compression without proper flow measurement. The controllers need to be set up and tuned properly and the program needs to be extended to include wet gas compression modes.

6.1.1 The LabView program

In the LabView program, the main future priority should be to tune the controllers, but before this can be done, the RPM measurement problems have to be solved. The main potential improvement at this stage in the LabView program besides control is sophisticated logging functions, at this point, the pressure and temperature data are written to text files. But in the future, it could be beneficial to log all parameters and to be able to log data when certain conditions are met. As an example, the outlet pressure of the turbocharger could be logged while the RPM is increasing from minimum to maximum. A certain RPM level could then be used as a trigger for data logging. The data files should be logged in a format that Matlab or Excel can process for further data analysis.

6.1.2 Operation issues

In addition to the RPM measurement problem, another problem needs to be solved before the controllers can function properly. The compressor was not able to increase the pressure in the piping downstream of the cooler. This means that the choke valves will not be able to regulate the pressure level in the low-temperature zone, neither the suction pressure of the compressor. The suction pressure control valve, Choke valve 1, did not affect the pressure at the compressor inlet, nor did it affect the pressure ratio over the compressor.

There is also a problem with the separator design. The amount of water required in the system to trigger the water pump is higher than the amount of water required for wet gas research. This can be solved by replacing the level sensor inside the separator. Another solution would be to rewire the water pump contactor to trigger on a user command instead of the amount of water in the system.

When the current operation problems have been solved, the control algorithms needs to be tuned. Eventually, more advanced control algorithms could be implemented.

6.1.3 Flow measurement

As the lab operates at the end of this stage project, no flow measurement system is installed or ordered. This should be done in the future to allow for more advanced control and analysis of the turbocharger behavior. Without flow measurement, it is not possible to accurately determine the operation point of the turbocharger. Anti-surge controllers depend on flow measurement, and as described earlier in the report, standardized anti-surge algorithms exist that can be used if a differential pressure based flow meter is installed.

Appendices

Appendix A

FAT tests

FAT performed: Check internal connections on terminal blocks and components

Signature:

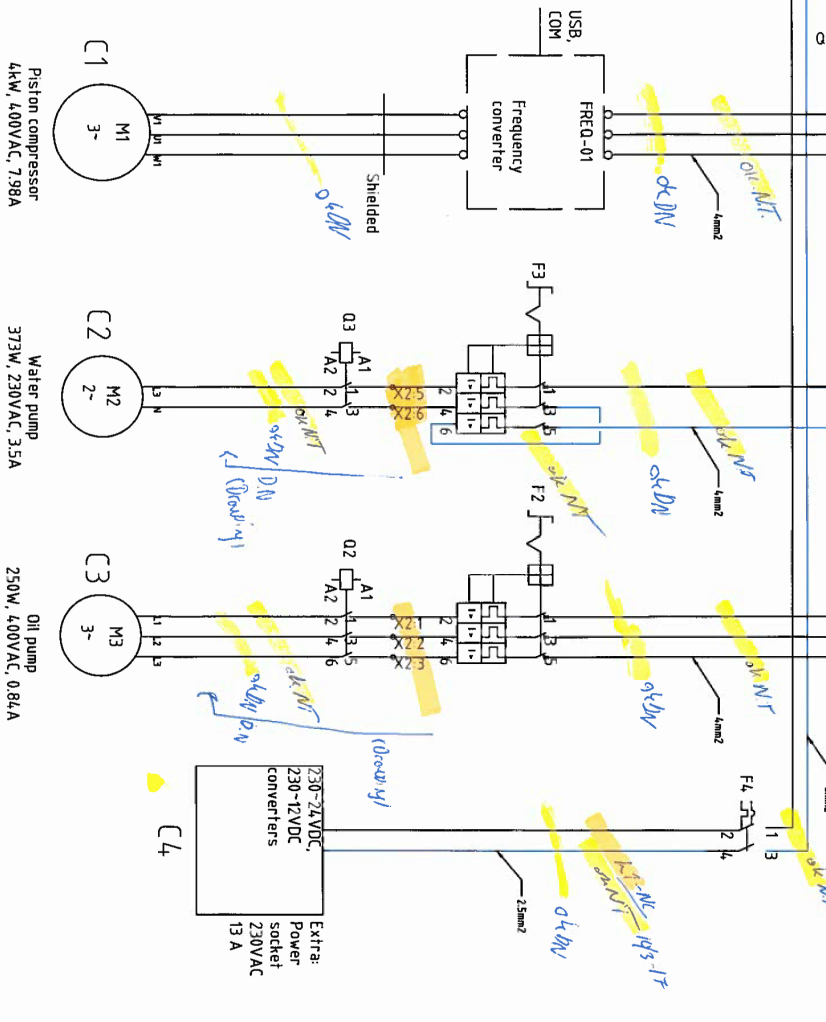
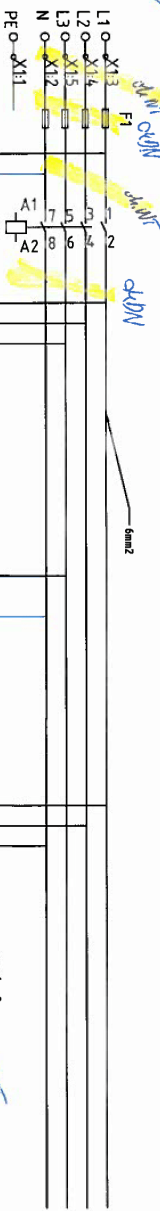
M. J. Tapachok

Date:

18/3-17

Frank W. Brown

18-3-17



Piston compressor
4kW, 400VAC, 7.98A

Water pump
373W, 230VAC, 3.5A

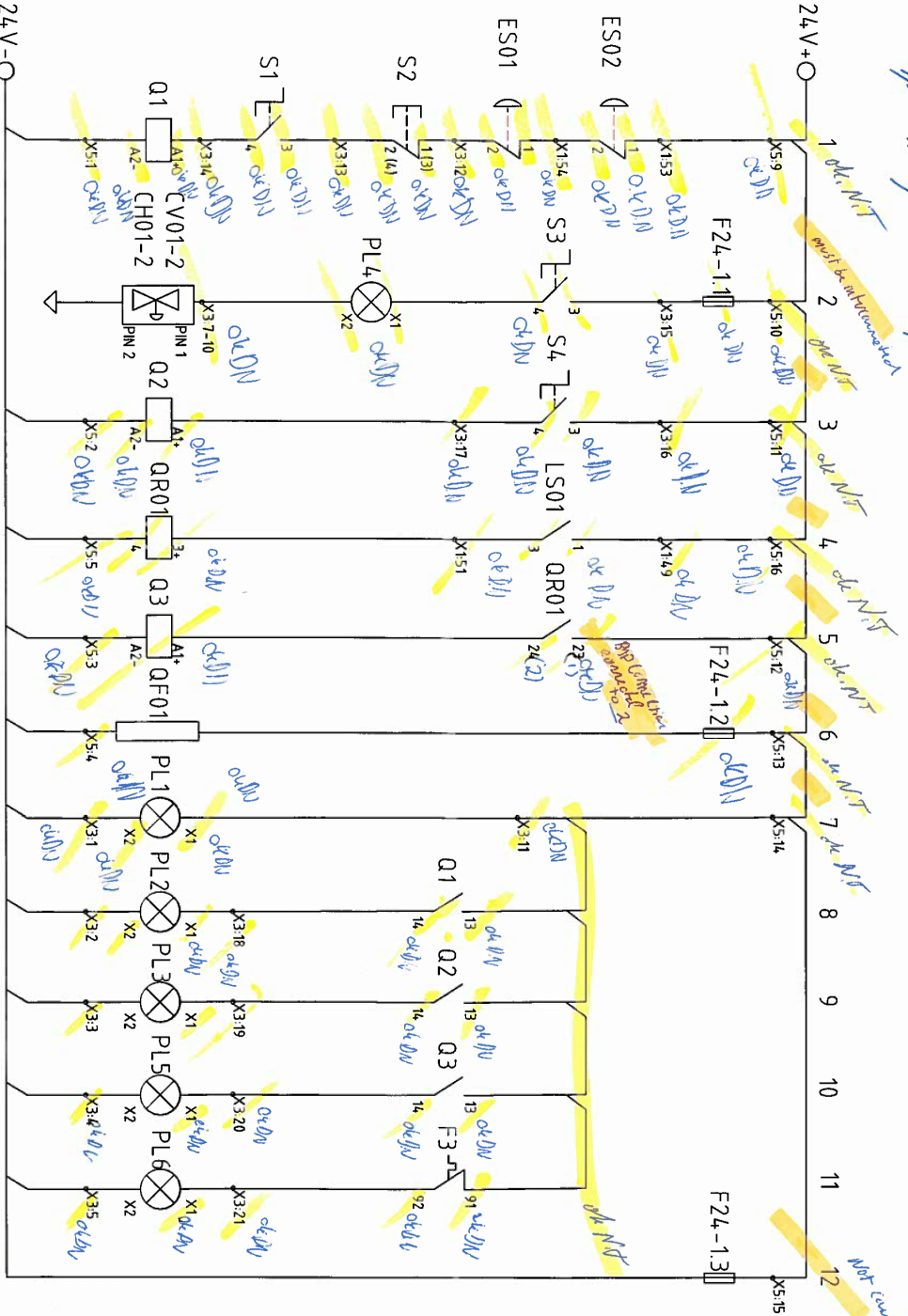
Oil pump
250W, 400VAC, 0.84A

Item	Description
01	Main Circuit Relay
02	Contact. Oil pump
03	Contact. Water pump
F1	Main fuse, 30A
F2	Motor protection relay, oil pump
F3	Motor protection relay, water pump
F4	Fuse, Control Circuit: 230-24/12VDC converter, equipment etc.
C1	Circuit, Piston compressor
C2	Circuit, Water pump
C3	Circuit, Oil pump

400/230V Main Circuit
Wet Gas Compression
Department of Mechanical and Industrial Engineering (MTP), NTNU
Subsea Process Control Laboratory


Designed by: N.T.
Rev. 00
Date: 28.02.2017
Scale: A3 | Sheet 1 of 1

FAT performed: Check internal connections on terminal blocks and components
 Signature: *[Signature]* Date: 10/18-17
 Signature: *[Signature]* Date: 10/18-17

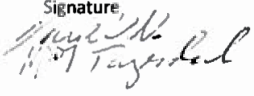


Item	Description
F24-11	Element fuse, TB, Control Valves, 5x20mm T3.15A Slow blow
F24-12	Element fuse, TB, QR01 Fan, 5x20mm 0.530A Quick blow
F24-13	Element fuse, Terminal Block, SPARE, 5x20mm T3.15A Slow blow
ES02	Emergency Stop, Field
ES01	Emergency Stop, Panel
S1	Start, main circuit Q1
S2	Stop, Door switch
S3	Start, control valves
S4	Start, Oil pump
QR01	Relay, dir. 24V to Q2
Q1	Contractor, Main
Q2	Contractor, Oil pump
Q3	Contractor, Water pump
F3	Motor protection switch, NC
QF01	Simulate water pump not running
PL1	Cabinet fan
PL2	Lamp, Signal Power on
PL3	Lamp, Main circuit
PL4	Lamp, Oil pump on
PL5	Lamp, Control valves on
PL6	Lamp, Motor protection tripped for C2

1 NC FS01 2 NC FS02 3 NO S2 4 NO
 Drawing is made with S2 in NC closed position.
 NOTE: Wired with NO pair (Door open, open connection)

Nořok 
~~-OK~~

FAT: Shall check quality of connection as well as checking that connection is in correct location according to schematic.
 Completed?

Signature:  Date [dd.mm.yyyy]: 15.03.17
 15.03.17

DAQ description			
AI	Analog Input	Alx.1	Single ended gnd [pin 1]
AO	Analog Output	Al1.1	Diff. Ended gnd [ch1 . pin 1]
DAQ1 (AI):	PT01 - PT08 (8/8) 8 ch 0 -> 7		
DAQ1 (AO):	CV01-CV02 control signal (2/2) C		
DAQ2(AI):	TS01-TS02 TT01-TT02 (8/8) 4ch		
DAQ2(AO):	RPM sensor voltage (1/2)		
DAQ3(AI):	Choke1-Choke2-CV01-CV02 p. feedback, (6/8) 8 ch		
DAQ3(AO):	Choke1-Choke2 control signal (2/2)		
DAQ4(AI):	Flow - RPM		
DAQ4(AO):			

X7 -> NY X5
 X6 -> NY X4

X3.7 FEIN NR.

PIN IN	DESCRIPT.	X0	PIN OUT	PIN IN	DESCRIPT.	X1	PIN OUT
Supply PE	PE	1		1	CHOKE 1 - 24V-7	1W	X7.15
Supply N	N	2	F1-4	2		2 Br Blue	DAQ3 AO x.0 setpoint
Supply L1	L1	3	F1-1	3		3 Br Blue	DAQ3 AI x.0 pos. Feed
Supply L2	L2	4	F1-2	4		4 Br Blue	DAQ3 AI x.1 on/off Feed
Supply L3	L3	5	F1-3	1	CHOKE 2	5W	X7.16 - X3.5
				2		6 Br Blue	DAQ3 AO x.1 control
				3		7 Bl	DAQ3 AI x.2 pos. feed
				4		8 Gr	DAQ3 AI x.3 on/off feed
				1	PT01	9	X6.12 X4.9
				2	-	10	X6.4 X4.1
				3	-	11	DAQ1 AI x.0
				1	PT02	12	X6.13 X4.10
				2	-	13	X6.5 X4.2
				3	-	14	DAQ1 AI x.1
				1	PT03	15	X6.14
				2	-	16	X6.6
				3	-	17	DAQ1 AI x.2
				1	PT04	18	X6.15
				2	-	19	X6.7
				3	-	20	DAQ1 AI x.3
				1	PT05	21	X6.16
				2	-	22	X6.8
				3	-	23	DAQ1 AI x.4
				1	PT06	24	X6.18
				2	-	25	X6.9
				3	-	26	DAQ1 AI x.5
				1	TS01	27	DAQ2 AI 0.0
				2	-	28	DAQ2 AI 0.4
				1	TS02	29	DAQ2 AI 1.1
				2	-	30	DAQ2 AI 1.5
				1	CV01	31	X7.12 X3.9
				2	-	32	DAQ1 AO x.0 control 1/0
				3	-	33	DAQ3 AI x.4 p. feed
				1	CV02	34	X7.14 X3.10
				2	-	35	DAQ1 AO x.1 4-20mA
				3	-	36	DAQ3 AI x.6 p. feed

INTERNAL CONNECTIONS

OR NI-DN

20

PIN IN	DESCRIPT.	X4-12V	PIN OUT
		1	
		2	
		3	
		4	
		5	
		6	
		7	
		8	
		9	
		10	
		11	
		12	
		13	
		14	
		15	

INTERNAL CONNECTIONS

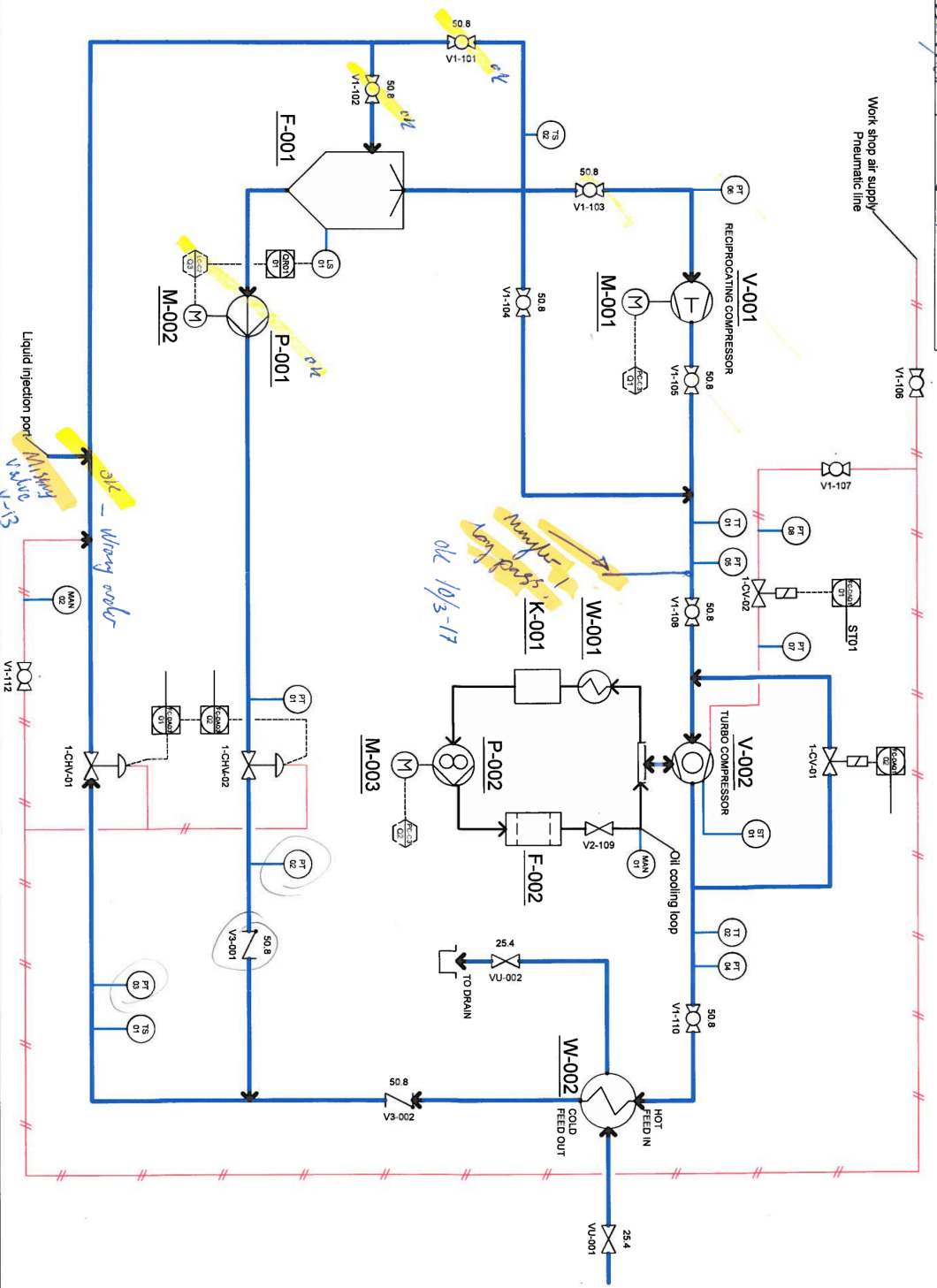
PIN IN	DESCRIPT.	X5-24V	PIN OUT
		1	
		2	
		3	
		4	
		5	
		6	
		7	
		8	
		9	
		10	
		11	
		12	
		13	
		14	
		15	
		16	
		17	
		18	
		19	
		20	
		21	
		22	
		23	
		24	
		25	

INTERNAL CONNECTIONS

1	PT07	37	X6.17
2	-	38	X6.10
3	-	39	DAQ1 AI x.6
1	PT08	40	X6.19
2	-	41	X6.11
3	-	42	DAQ1 AI x.7
1	TT01	43	DAQ2 AI 2.2
2	-	44	DAQ2 AI 2.6
1	TT02	45	DAQ2 AI 3.3
2	-	46	DAQ2 AI 3.7
Pin 1 5V	ST01	47	DAQ2 AO x.0
Pin 3	-	48	DAQ4 AI 1.1
1	LS01	49	X5:16
2	-	50	
3	-	51	QR01 +3
4	-	52	
1	ES02	53	
2	-	54	
3	-	55	
4	-	56	
		57	

DOE
switched
wrong
connection

FAT: Control labeling on field and diagram components and if correctly positioned
 Signature: *[Handwritten Signature]* Date: 10/25-17
 Signature: *[Handwritten Signature]* Date: 10/23-17



Module:
 W - Heat Exchanger | F - Separator | K - Reservoir (Oil) | P - Pump, Motor
 M - Motor
 V1 - Ball Valve | V2 - Check Valve | V3 - Check Valve | VU - Valve Utility | CV - Control Valve | CW - Close Control Valve
 L5 - Level Sensor | T5 - Temperature Sensor | TT - Temperature Transmitter
 ST - Speed Transmitter | PT - Pressure Transmitter | MM - Meter
 PC - Pressure Controller | LC - Level Controller | FC - Flow Controller
 DAC - Data Acquisition (for Measurement and Control)

P&ID for process laboratory		Department of Mechanical and Industrial Engineering (MTP), NTNU	
Wet Gas Compression		Subsea Process Control Laboratory	
Designed By: N.T. DNK	Rev 01		
Date: 10.03.2017	Scale: A3 Sheet 1 of 1		

FAT (Basic Control Software)

Function	Working(simulation)
RPM controller	Yes
Choke control (mixing pressure)	Yes
Inlet pressure control	Yes
Shut down (temperature trigger)	Yes
Shut down (pressure trigger)	Yes
Data output to DAQ	Yes
Data input from DAQ	Yes
Constant voltage to RPM sensor	Yes
Stop function	Yes
On/Off indicators	Yes
Warning indicators	Yes

At this point in the project, the controllers are identified as working if the control output remains within specified boundaries and responds correctly to change in error. The triggers are identified as working if the shut down function is activated whenever any pressure or temperature reading exceeds its limit. The data out function is considered functional if the DAQ assist block receives values without any errors. The input is considered functional if the readings from the DAQ assist stay in the specified range. Otherwise this check should ensure that basic functionality is adequate and that minimal risk of injury to equipment or personnel is present. More advanced functions will be implemented and tested at a later stage in the project.

Signature: Naail Abdelaziz 16.03.17

Signature: Hot T. Gardner 20/3/17

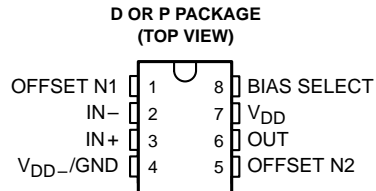
Appendix B

Datasheets excerpts

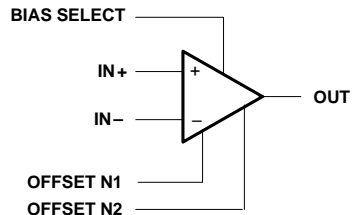
TLC251, TLC251A, TLC251B, TLC251Y LinCMOS™ PROGRAMMABLE LOW-POWER OPERATIONAL AMPLIFIERS

SLOS001F – JULY 1983 – REVISED MARCH 2001

- **Wide Range of Supply Voltages**
1.4-V to 16-V
- **True Single-Supply Operation**
- **Common-Mode Input Voltage Range**
Includes the Negative Rail
- **Low Noise . . . 30 nV/√Hz Typ at 1-kHz**
(High Bias)
- **ESD Protection Exceeds 2000 V Per**
MIL-STD-883C, Method 3015.1



symbol



description

The TLC251C, TLC251AC, and TLC251BC are low-cost, low-power programmable operational amplifiers designed to operate with single or dual supplies. Unlike traditional metal-gate CMOS operational amplifiers, these devices utilize Texas Instruments silicon-gate LinCMOS™ process, giving them stable input offset voltages without sacrificing the advantages of metal-gate CMOS.

This series of parts is available in selected grades of input offset voltage and can be nulled with one external potentiometer. Because the input common-mode range extends to the negative rail and the power consumption is extremely low, this family is ideally suited for battery-powered or energy-conserving applications. A bias-select pin can be used to program one of three ac performance and power-dissipation levels to suit the application. The series features operation down to a 1.4-V supply and is stable at unity gain.

These devices have internal electrostatic-discharge (ESD) protection circuits that prevent catastrophic failures at voltages up to 2000 V as tested under MIL-STD-883C, Method 3015.1. However, care should be exercised in handling these devices as exposure to ESD may result in a degradation of the device parametric performance.

Because of the extremely high input impedance and low input bias and offset currents, applications for the TLC251C series include many areas that have previously been limited to BIFET and NFET product types. Any circuit using high-impedance elements and requiring small offset errors is a good candidate for cost-effective use of these devices. Many features associated with bipolar technology are available with LinCMOS™ operational amplifiers without the power penalties of traditional bipolar devices. Remote and inaccessible equipment applications are possible using the low-voltage and low-power capabilities of the TLC251C series.

In addition, by driving the bias-select input with a logic signal from a microprocessor, these operational amplifiers can have software-controlled performance and power consumption. The TLC251C series is well suited to solve the difficult problems associated with single battery and solar cell-powered applications.

The TLC251C series is characterized for operation from 0°C to 70°C.

AVAILABLE OPTIONS

T _A	V _{IOmax} AT 25°C	PACKAGED DEVICES		CHIP FORM (Y)
		SMALL OUTLINE (D)	PLASTIC DIP (P)	
0°C to 70°C	10 mV	TLC251CD	TLC251CP	TLC251Y
	5 mV	TLC251ACD	TLC251ACP	—
	2 mV	TLC251BCD	TLC251BCP	—

The D package is available taped and reeled. Add the suffix R to the device type (e.g., TLC251CDR). Chips are tested at 25°C.

LinCMOS is a trademark of Texas Instruments.

PRODUCTION DATA information is current as of publication date. Products conform to specifications per the terms of Texas Instruments standard warranty. Production processing does not necessarily include testing of all parameters.

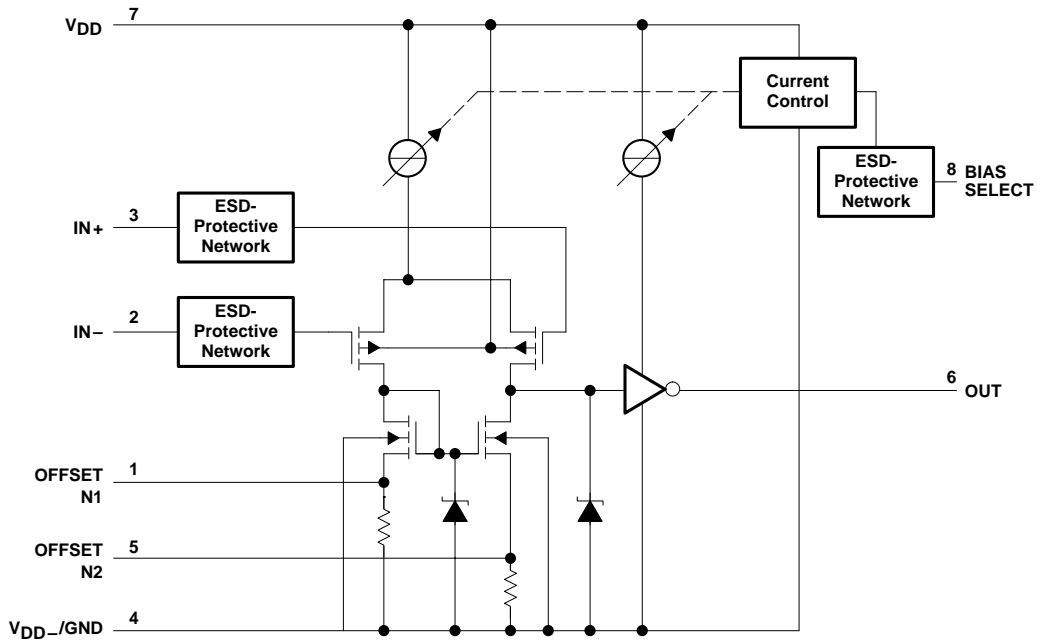
 **TEXAS
INSTRUMENTS**

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TLC251, TLC251A, TLC251B, TLC251Y
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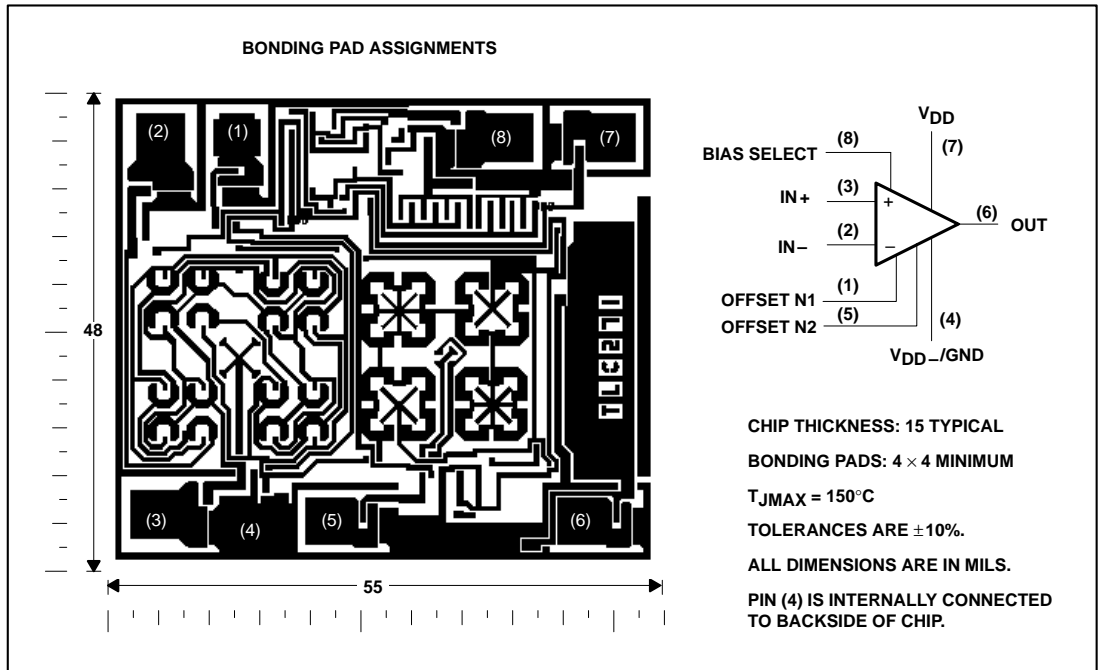
schematic



TLC251, TLC251A, TLC251B, TLC251Y
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LOW-POWER OPERATIONAL AMPLIFIERS
SLOS001F – JULY 1983 – REVISED MARCH 2001

TLC251Y chip information

These chips, properly assembled, display characteristics similar to the TLC251C. Thermal compression or ultrasonic bonding may be used on the doped-aluminum bonding pads. Chips may be mounted with conductive epoxy or a gold-silicon preform.



TLC251, TLC251A, TLC251B, TLC251Y
LinCMOS™ PROGRAMMABLE
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absolute maximum ratings over operating free-air temperature range (unless otherwise noted)†

Supply voltage, V_{DD} (see Note 1)	18 V
Differential input voltage, V_{ID} (see Note 2)	± 18 V
Input voltage range, V_I (any input)	-0.3 V to 18 V
Duration of short circuit at (or below) 25°C free-air temperature (see Note 3)	unlimited
Continuous total dissipation	See Dissipation Rating Table
Operating free-air temperature range, T_A	0°C to 70°C
Storage temperature range	-65°C to 150°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds	260°C

† Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

- NOTES:
1. All voltage values, except differential voltages, are with respect to V_{DD-}/GND .
 2. Differential voltages are at $IN+$ with respect to $IN-$.
 3. The output may be shorted to either supply. Temperature and/or supply voltages must be limited to ensure the maximum dissipation rating is not exceeded.

DISSIPATION RATING TABLE

PACKAGE	$T_A \leq 25^\circ\text{C}$ POWER RATING	DERATING FACTOR ABOVE $T_A = 25^\circ\text{C}$	$T_A = 70^\circ\text{C}$ POWER RATING
D	725 mW	5.8 mW/°C	464 mW
P	1000 mW	8.0 mW/°C	640 mW

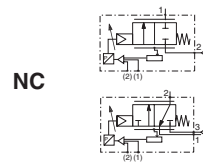
recommended operating conditions

	MIN	MAX	UNIT
Supply voltage, V_{DD}	1.4	16	V
Common-mode input voltage, V_{IC}	$V_{DD} = 1.4$ V	0	V
	$V_{DD} = 5$ V	-0.2	
	$V_{DD} = 10$ V	-0.2	
	$V_{DD} = 16$ V	-0.2	
Operating free-air temperature, T_A	0	70	°C
Bias-select voltage	See Application Information		



PROPORTIONAL VALVES WITH POSITIONER^D

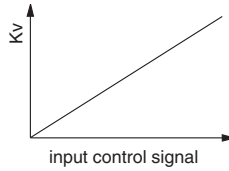
pressure operated
all standard connection types



2 way
3 way
Series
290/390

FEATURES

- Precise, quick-acting and robust valve suitable for use in outside industrial environments
- Exceptional long service life
- Variable flow proportional to the control signal
- Real-time control
- Ready-to-use valve
- The positioner can be directly connected to an external sensor (double loop control)
- Power saving function and no air consumption when position is reached
- Manual valve operator
- LED indicators for valve status display



GENERAL

Differential pressure 0 to 16 bar [1 bar = 100 kPa]
Maximum allowable pressure 16 bar
Ambient temperature range 0°C to +50°C
Maximum viscosity 600 cSt (mm²/s)
Pilot fluid Air or inert gas, filtered 25 µm, unlubricated, condensate-free and water-free (observe the pressure dew point)⁽⁶⁾
Pilot pressure 4 to 8 bar
Pilot fluid temperature 0°C to +50°C
Response time See page V402-7
Fluids For type, temperature and materials compatibility, see the catalogue pages for the standard valves V410, V420, V431 and V703

ELECTRICAL CHARACTERISTICS

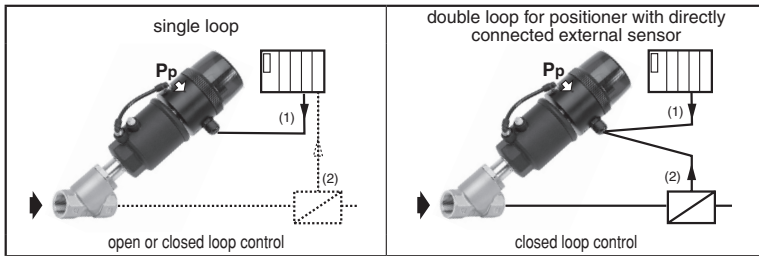
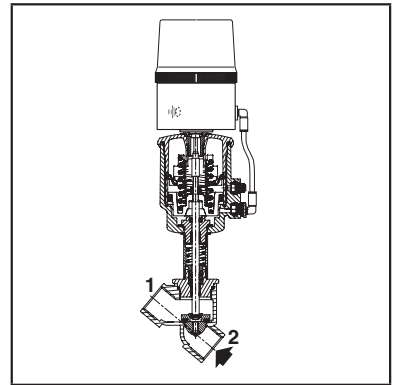
Setpoint reached output ON/OFF, 24 V PNP / max. 500 mA
Analog position feedback signal 0-10 V / 4-20 mA
Analog setpoint 0-10V (R_{in} = 200 kΩ); 4-20 mA (R_{in} = 250 Ω)
Nominal supply voltage 24 V DC ± 10%, max. ripple 10%
Power 7,6 W (3,6 W, setpoint reached)
Connection Screw terminals, cable gland (cable Ø 5-10 mm) or connection M12 (CNOMO E03.62.520.N)
Degree of protection IP66 (EN 60529)
Electromagnetic compatibility EMC 2004/108/EC
Regulation characteristics Hysteresis < 2% ; Accuracy < 2 % ; Repeatability < 1 %

CONSTRUCTION

Valve construction See sections D and F
Valve disc (2/2) Profiled disc, stainless steel and PTFE
Valve disc (3/2) Standard disc
Positioner body Aluminium anodised
Cable gland Plastic (cable Ø 5-10 mm)
Cover PA 12, transparent



B



⁽¹⁾ Setpoint
⁽²⁾ Value measured by the process sensor

SPECIFICATIONS (NC valves, fluid entry under the disc)

analog setpoint	suffix for proportional valve and positioner ⁽³⁾ delivered assembled							
	fail in last position ⁽⁴⁾				fail close ⁽⁵⁾			
	2 way		3 way ⁽⁷⁾		2 way		3 way ⁽⁷⁾	
	cable gland	M12	cable gland	M12	cable gland	M12	cable gland	M12
Positioner^D, single loop								
0 - 10 V DC	PDB64	PDB68	B64	B68	PDB66	PDB70	B66	B70
4 - 20 mA	PDB65	PDB69	B65	B69	PDB67	PDB71	B67	B71
Positioner^D, double loop								
0 - 10 V DC	-	-	-	-	PDB72	PDB74	B72	B74
4 - 20 mA	-	-	-	-	PDB73	PDB75	B73	B75

⁽³⁾ Place the indicated suffix after the catalogue number of the valve selected.
⁽⁴⁾ Valve disc remains in its last position on loss of power.
⁽⁵⁾ Valve returns to closed position on loss of power.

⁽⁶⁾ The actuator exhaust air is used to ventilate the electronics housing.
⁽⁷⁾ Top orifice of this version is not tight, for the tight version contact us.

VALVE SPECIFICATIONS

pipe size (DN)	orifice size	pilot pressure (bar)			operator diameter	flow coefficient (Kv), programmable opening of proportional valve					
						2 way, threaded		2 way, flanges		3 way, threaded	
		min.		max. ⁽¹⁾		bronze, stainless steel (E290) (V410) clamp / butt welding (S290) (V420)	bronze (T290) (V431)		bronze (E390) (V703)		
		(mm)	2 way ⁽²⁾	3 way			(mm)	(m ³ /h)	(l/min)	(m ³ /h)	(l/min)
NC - Normally closed, entry under the disc											
1/2 (15)	15	3 / 5	2 / 3	8	63	4,6	77	-	-	6	100
3/4 (20)	20	3 / 5	-	8	63	7,1	118	-	-	-	-
		-	3 / 5	8	63	-	-	-	-	9,6	160
1 (25)	25	3 / 5	3 / 5	8	63/90	15	250	11	183	16,2	270
1 1/4 (32)	32	3 / 5	5	8	63/90	21	350	14	233	24	400
		3 / 5	3 / 5	8	125	22	367	15	250	-	-
1 1/2 (40)	40	4	3 / 5	8	63/90	29	483	21	350	42,9	715
		4	5	8	125	44	733	32	533	42,9	715
2 (50)	50	4	5	8	63/90	40	667	26,5	442	52,8	880
		4	5	8	125	66	1100	44	733	52,8	880
2 1/2 (65)	65	4	-	8	90	72	1200	-	-	-	-
		4	-	8	125	84	1400	-	-	-	-

⁽¹⁾ For best control loop operation, we recommend the following pilot pressures:

max. 3 bar (valve with 1,5 bar operator) ; max. 5 bar (valve with 2,5 bar operator) ; max. 7 bar (valve with 4 bar operator)

⁽²⁾ 3 bar (valve with 2,5 bar operator) ; 5 bar or 4 bar (valve with 4 bar operator)

OPTIONS AND ACCESSORIES

- Standard 2/2 NC valve, fluid entry under the disc, with profiled disc only, use suffix PD, example: E290A016PD
- Female M12 connector: straight
 - 5 pins, with screw terminals, catalogue number: **88100256**
 - Supply cable 5 m, 5 x 0,25 mm², catalogue number: **88130212**
 - Supply cable 5 m, 6 x 0,5 mm², catalogue number: **88100728**
 - Supply cable 10 m, 6 x 0,5 mm², catalogue number: **88100730**
- APC software for modification of control parameters (software required for double loop control) available for download at: www.asco.com
- RS-232 converter, 2 m cable with 9 pin Sub-D connector for PC link, catalogue number **88100732**
- Oxygen service (except DN 65), pressure limited to 15 bar, temperature limited to + 60°C, suffix **N**
- Vacuum applications up to 1,33 10⁻³ mbar, suffix **VM**
- Other pipe connections are available on request

INSTALLATION

- Pilot port G 1/8 according to ISO 228/1
- Compatible with ASTM 1, 2 and 3 oils
- Installation/maintenance instructions are included with each valve
- LED indicators for operating status display and diagnostic functions (Unit can be rotated through 360° around the centreline of the valve operator)

status	hold position
	valve OPEN
	valve CLOSED
	valve moves to open
	valve moves to close
	positioner in initialisation mode
diagnostics	positioner in manual mode
	setpoint > 20,5 mA / 10,25 V
	setpoint < 3,5 mA
	positioner not initialised
	component error



Electrical connection:

Positioner^D, single loop

screw terminals



1	+ 24 V DC, supply	1
2	GND supply	3
3	+ setpoint (0-10 V or 4-20 mA)	2
4	GND setpoint	3
6	disc position feedback	4
7	+ 24V ON/OFF output	5

Positioner^D, double loop

screw terminals



1	+ 24 V DC, supply	1
2	GND supply	3
3	+ setpoint (0-10 V or 4-20 mA)	2
4	GND setpoint	3
5	external sensor input	4
7	+ 24V ON/OFF output	5

SPARE PARTS KITS

	spare parts kit no.	
	cable gland (cable Ø 5-10 mm)	Positioner ^D only connection M12
Fail position maintained, single loop		
0-10 V	60566108	60567108
4-20 mA	60566308	60567308
Fail close, single loop		
0-10 V	60566118	60567118
4-20 mA	60566318	60567318
Fail close, double loop		
0-10 V	60566418	60567418
4-20 mA	60566518	60567518
Mounting kit		
all	C140423	C140423

ORDERING EXAMPLES:

E	290 A 016	PDB64
E	390 A 016	B64
E	290 A 059	PDB68
E	290 A 102	PDB71

pipe thread ————
basic number ———— suffix

ORDERING EXAMPLES KITS:

C131204	
C140206	
C140205	VM

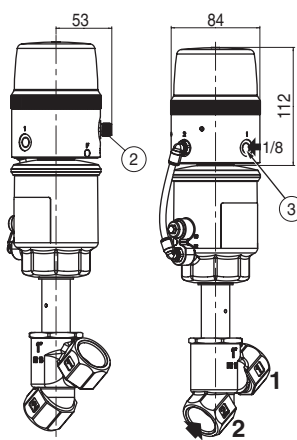
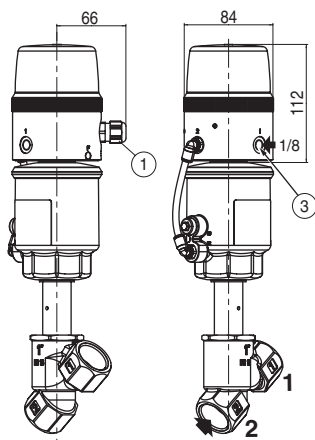
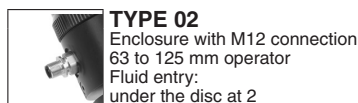
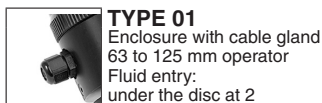
basic number ———— suffix

pipe size (DN)	spare parts kit no.		
	bronze, stainless steel (E290) clamp / butt welding (S290)	bronze (T290)	bronze (E390)
Valve disc seals			
1/2 (15)	C131204 ⁽¹⁾	-	C140021 ⁽¹⁾
3/4 (20)	C131205 ⁽¹⁾	-	C140022 ⁽¹⁾
1 (25)	C131206 ⁽¹⁾	C140017 ⁽¹⁾	C140023 ⁽¹⁾
1 1/4 (32)	C131207 ⁽¹⁾	C140018 ⁽¹⁾	C140024 ⁽¹⁾
1 1/2 (40)	C131208 ⁽¹⁾	C140019 ⁽¹⁾	C140025 ⁽¹⁾
2 (50)	C131209 ⁽¹⁾	C140020 ⁽¹⁾	C140026 ⁽¹⁾
2 1/2 (65)	C131622 ⁽¹⁾	-	-

⁽¹⁾ Standard suffix VM is also applicable to kits (see V435).

- Not available.

DIMENSIONS (mm), WEIGHT (kg)



① M16 x 1,5 mm cable gland (cable Ø 5-10 mm)

② M12 connection

③ G 1/8 pilot connection

Weight of positioner without valve: 0,3 kg

LM134/LM234/LM334 3-Terminal Adjustable Current Sources

 Check for Samples: [LM134](#), [LM234](#), [LM334](#)

FEATURES

- Operates From 1V to 40V
- 0.02%/V Current Regulation
- Programmable From 1 μ A to 10mA
- True 2-Terminal Operation
- Available as Fully Specified Temperature Sensor
- \pm 3% Initial Accuracy

DESCRIPTION

The LM134/LM234/LM334 are 3-terminal adjustable current sources featuring 10,000:1 range in operating current, excellent current regulation and a wide dynamic voltage range of 1V to 40V. Current is established with one external resistor and no other parts are required. Initial current accuracy is \pm 3%. The LM134/LM234/LM334 are true floating current sources with no separate power supply connections. In addition, reverse applied voltages of up to 20V will draw only a few dozen microamperes of current, allowing the devices to act as both a rectifier and current source in AC applications.

The sense voltage used to establish operating current in the LM134 is 64mV at 25°C and is directly proportional to absolute temperature (°K). The simplest one external resistor connection, then, generates a current with \approx +0.33%/°C temperature dependence. Zero drift operation can be obtained by adding one extra resistor and a diode.

Applications for the current sources include bias networks, surge protection, low power reference, ramp generation, LED driver, and temperature sensing. The LM234-3 and LM234-6 are specified as true temperature sensors with ensured initial accuracy of \pm 3°C and \pm 6°C, respectively. These devices are ideal in remote sense applications because series resistance in long wire runs does not affect accuracy. In addition, only 2 wires are required.

The LM134 is specified over a temperature range of -55°C to +125°C, the LM234 from -25°C to +100°C and the LM334 from 0°C to +70°C. These devices are available in TO hermetic, TO-92 and SOIC-8 plastic packages.

Connection Diagrams

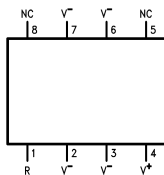


Figure 1. SOIC-8 Surface Mount Package
(LM334M; LM334M/NOPB; LM334MX;
LM334MX/NOPB)
See Package Number D

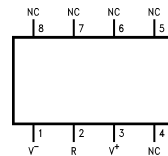


Figure 2. SOIC-8 Alternative Pinout Surface Mount Package
(LM334SM; LM334SM/NOPB; LM334SMX;
LM334SMX/NOPB)
See Package Number D

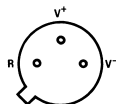


Figure 3. TO Metal Can Package (Bottom View)
See Package Number NDV



Figure 4. TO-92 Plastic Package (Bottom View)
See Package Number LP



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Application as a Zero Temperature Coefficient Current Source

Adding a diode and a resistor to the standard LM134 configuration can cancel the temperature-dependent characteristic of the LM134. The circuit shown in [Figure 15](#) balances the positive tempco of the LM134 (about +0.23 mV/°C) with the negative tempco of a forward-biased silicon diode (about -2.5 mV/°C).

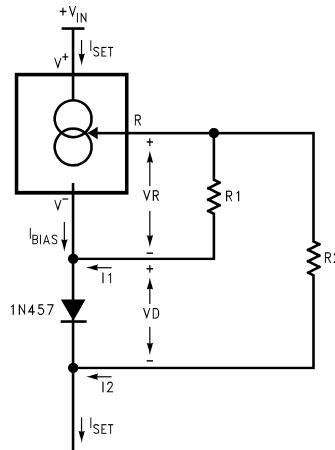


Figure 15. Zero Tempco Current Source

The set current (I_{SET}) is the sum of I_1 and I_2 , each contributing approximately 50% of the set current, and I_{BIAS} . I_{BIAS} is usually included in the I_1 term by increasing the V_R value used for calculations by 5.9%. (See **CALCULATING R_{SET}** .)

$I_{SET} = I_1 + I_2 + I_{BIAS}$, where

$$I_1 = \frac{V_R}{R_1} \quad \text{and} \quad I_2 = \frac{V_R + V_D}{R_2} \quad (5)$$

The first step is to minimize the tempco of the circuit, using the following equations. An example is given using a value of +227 μ V/°C as the tempco of the LM134 (which includes the I_{BIAS} component), and -2.5 mV/°C as the tempco of the diode (for best results, this value should be directly measured or obtained from the manufacturer of the diode).

$$\begin{aligned} I_{SET} &= I_1 + I_2 \\ \frac{dI_{SET}}{dT} &= \frac{dI_1}{dT} + \frac{dI_2}{dT} \\ &\approx \frac{227 \mu\text{V}/^\circ\text{C}}{R_1} + \frac{227 \mu\text{V}/^\circ\text{C} - 2.5 \text{mV}/^\circ\text{C}}{R_2} \\ &= 0 \quad (\text{solve for tempco} = 0) \end{aligned} \quad (6)$$

$$\frac{R_2}{R_1} \approx \frac{2.5 \text{mV}/^\circ\text{C} - 227 \mu\text{V}/^\circ\text{C}}{227 \mu\text{V}/^\circ\text{C}} \approx 10.0 \quad (7)$$

With the R_1 to R_2 ratio determined, values for R_1 and R_2 should be determined to give the desired set current. The formula for calculating the set current at $T = 25^\circ\text{C}$ is shown below, followed by an example that assumes the forward voltage drop across the diode (V_D) is 0.6V, the voltage across R_1 is 67.7mV (64 mV + 5.9% to account for I_{BIAS}), and $R_2/R_1 = 10$ (from the previous calculations).

$$\begin{aligned}
 I_{\text{SET}} &= I_1 + I_2 + I_{\text{BIAS}} \\
 &= \frac{V_R}{R_1} + \frac{V_R + V_D}{R_2} \\
 &\approx \frac{67.7 \text{ mV}}{R_1} + \frac{67.7 \text{ mV} + 0.6\text{V}}{10.0 R_1} \\
 I_{\text{SET}} &\approx \frac{0.134\text{V}}{R_1}
 \end{aligned} \tag{8}$$

This circuit will eliminate most of the LM134's temperature coefficient, and it does a good job even if the estimates of the diode's characteristics are not accurate (as the following example will show). For lowest tempco with a specific diode at the desired I_{SET} , however, the circuit should be built and tested over temperature. If the measured tempco of I_{SET} is positive, R_2 should be reduced. If the resulting tempco is negative, R_2 should be increased. The recommended diode for use in this circuit is the 1N457 because its tempco is centered at 11 times the tempco of the LM134, allowing $R_2 = 10 R_1$. You can also use this circuit to create a current source with non-zero tempcos by setting the tempco component of the tempco equation to the desired value instead of 0.

EXAMPLE: A 1mA, Zero-Tempco Current Source

First, solve for R_1 and R_2 :

$$\begin{aligned}
 I_{\text{SET}} \approx 1 \text{ mA} &= \frac{0.134\text{V}}{R_1} \\
 R_2 &= 134 \Omega = 10 R_1 \\
 R_2 &= 1340 \Omega
 \end{aligned} \tag{9}$$

The values of R_1 and R_2 can be changed to standard 1% resistor values ($R_1 = 133\Omega$ and $R_2 = 1.33\text{k}\Omega$) with less than a 0.75% error.

If the forward voltage drop of the diode was 0.65V instead of the estimate of 0.6V (an error of 8%), the actual set current will be

$$\begin{aligned}
 I_{\text{SET}} &= \frac{67.7 \text{ mV}}{R_1} + \frac{67.7 \text{ mV} + 0.65\text{V}}{R_2} \\
 &= \frac{67.7 \text{ mV}}{133} + \frac{67.7 \text{ mV} + 0.65\text{V}}{1330} \\
 &= 1.049 \text{ mA}
 \end{aligned} \tag{10}$$

an error of less than 5%.

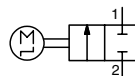
If the estimate for the tempco of the diode's forward voltage drop was off, the tempco cancellation is still reasonably effective. Assume the tempco of the diode is $2.6\text{mV}/^\circ\text{C}$ instead of $2.5\text{mV}/^\circ\text{C}$ (an error of 4%). The tempco of the circuit is now:

$$\begin{aligned}
 \frac{dI_{\text{SET}}}{dT} &= \frac{dI_1}{dT} + \frac{dI_2}{dT} \\
 &= \frac{227 \mu\text{V}/^\circ\text{C}}{133\Omega} + \frac{227 \mu\text{V}/^\circ\text{C} - 2.6 \text{ mV}/^\circ\text{C}}{1330\Omega} \\
 &= -77 \text{ nA}/^\circ\text{C}
 \end{aligned} \tag{11}$$

A 1mA LM134 current source with no temperature compensation would have a set resistor of 68Ω and a resulting tempco of

$$\frac{227 \mu\text{V}/^\circ\text{C}}{68\Omega} = 3.3 \mu\text{A}/^\circ\text{C} \tag{12}$$

So even if the diode's tempco varies as much as $\pm 4\%$ from its estimated value, the circuit still eliminates 98% of the LM134's inherent tempco.



FEATURES

- High flow due to angled seat design
- Anti-waterhammer design (fluid entry under the disc)
- Actuator rotatable through 360°
- Maintained valve position in case of power failure
- Fluid isolation between electrical actuator and valve body
- LED valves status display
- The valves satisfy Pressure Equipment Directive 97/23/EC, article 3.3
- The motorized valves comply with the essential requirements of EMC Directive 2004/108/EC (EN-IEC 61000-6-2 et EN-IEC 61000-6-4) and Low Voltage Directive 2006/95/EC (EN-IEC 60730)

GENERAL

Differential pressure	See «SPECIFICATIONS» [1 bar =100 kPa]
Maximum allowable pressure	10 bar
Ambient temperature range	-10°C to +50°C
Maximum viscosity	600 cSt (mm ² /s)
Actuating time	< 1 s (opening) / < 1 s (closing)

fluids (*)	temperature range (TS)	seal materials (*)
air and gas groups 1 & 2 water, oil, liquids groups 1 & 2	-10°C to +90°C	NBR (nitrile)

CONSTRUCTION

MATERIALS IN CONTACT WITH FLUID

(*) Ensure that the compatibility of the fluids in contact with the materials is verified

Valve body	AISI 316L
Stuffing box housing	PBT, GF 30% (glass fibre reinforced)
Stem valve	Stainless steel, AISI 303
Stuffing box packing	NBR
Wiper seal	NBR
Disc seal	NBR

OTHER MATERIALS

Top cover operator	Translucent polyamide (PA)
AC to DC housing (AC)	PA66, GF 30% (ball fibre reinforced)

ELECTRICAL CHARACTERISTICS

Connector	Spade plug (cable Ø 6-10 mm)
Connector specification	ISO 4400 / EN 175301-803, form A
Power consumption	12 W mean, 0 W hold Max. pic current: 0,7 A
Visualisation valve (switching)	LED
Electrical safety (adapter AC to DC)	IEC 335 (EN-IEC 60730), class 2
Electrical enclosure protection	IP65 (EN 60529)
Standard voltages	DC (=) : 24V ±10 %, max. ripple 5% (EN-IEC 61131-2) AC (-) : 110V to 250V / 50-60 Hz ⁽¹⁾

RECOMMENDATION FOR MAXIMUM DUTY CYCLE

Ambient temperature +20°C	9 cycles/min ⁽²⁾
Ambient temperature +50°C (max.)	4 cycles/min ⁽²⁾

ACCESSORIES

AC to DC adapter: 110V to 250V/50-60 Hz	code: P290CA430078001
24V to 48V /50-60 Hz ±10 % (contact us)	code: P290CA430078002

OPTIONS (contact us)

Valve body/stem 316L and FPM (fluoroelastomer) disc seal (*)
M12 connector adapter
Fail closed (close on loss of power)

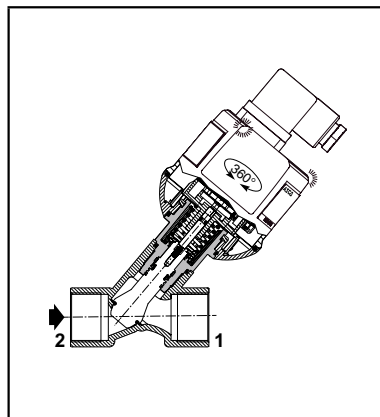
(*) Ensure that the compatibility of the fluids in contact with the materials is verified.

⁽¹⁾ 24 V to 48 V AC /50-60 Hz, contact us.

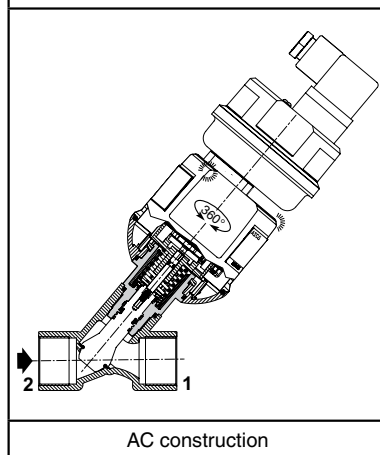
⁽²⁾ For other cycles, contact us.



D



DC construction



AC construction

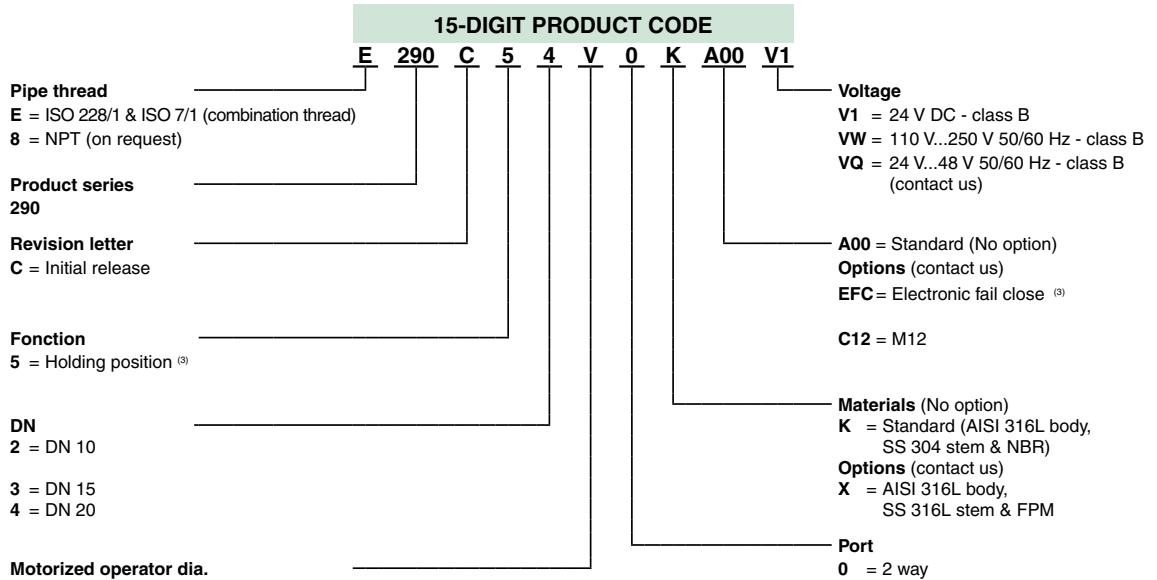
SPECIFICATIONS

piping (ISO 6708)		flow coefficient Kv		operating pressure differential (bar)		operator diameter	thread type	dimensions / type (1)	15-DIGIT PRODUCT CODE			
pipe size	DN			min.	max.				stainless steel AISI 316L	voltage code		
		(m³/h)	(l/min)	air, water, oil (*)		(mm)						
Motorized valve, entry under the disc												
3/8	10	2,7	45	0	6	67	G*	1	E290C52V0KA00			
1/2	15	3,8	63	0	5	67	G*	1	VQ	VW	V1	
3/4	20	6	100	0	4	67	G*	1	E290C54V0KA00			

(1) For dimensions, see drawing(s) for each construction type on the following page(s).

(2) Contact us.

(*) Ensure that the compatibility of the fluids in contact with the materials is verified.

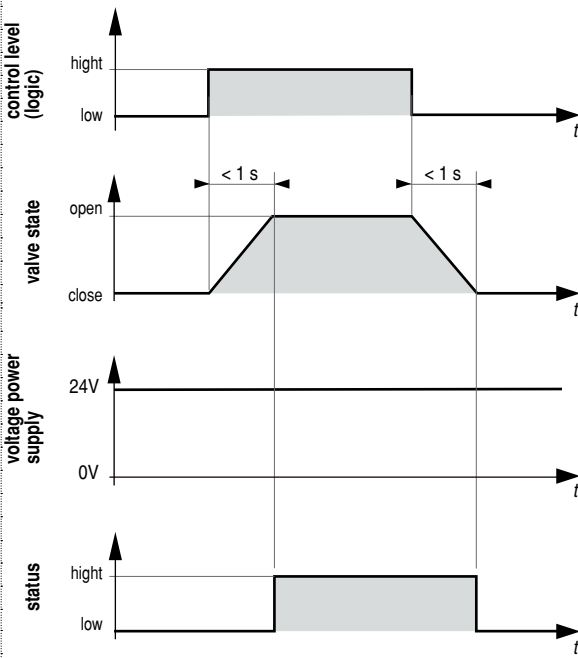


INSTALLATION

status	valve OPEN	green
	valve CLOSED	orange
	valve moves to open	green flashing
	valve moves to close	orange flashing

OPERATING DIAGRAM

standard (holding position)



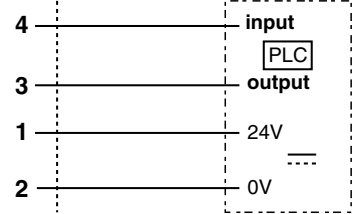
WIRING DC

24 V / DC

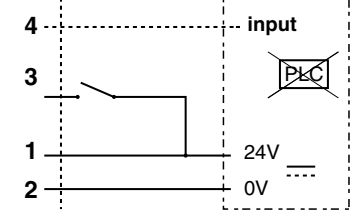


1	24 V / DC
2	0 V
3	control
4	state return (valve to PLC)

With PLC

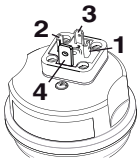


Without PLC



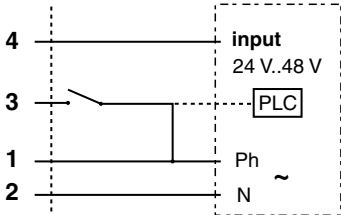
WIRING (AC)

24 V...48 V / AC 50/60 Hz ⁽¹⁾

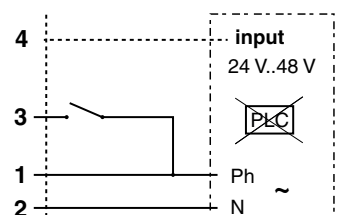


1	phase (Ph)
2	neutral (N)
3	control
4	state return (valve to PLC)

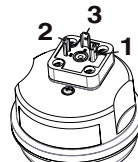
With PLC



Without PLC

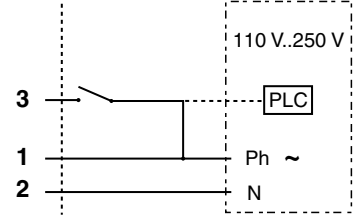


110 V...250 V / AC 50/60 Hz

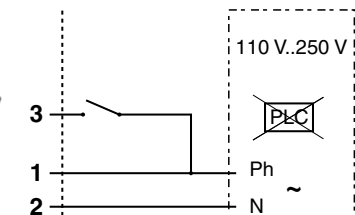


1	phase (Ph)
2	neutral (N)
3	control
-	-

With PLC



Without PLC



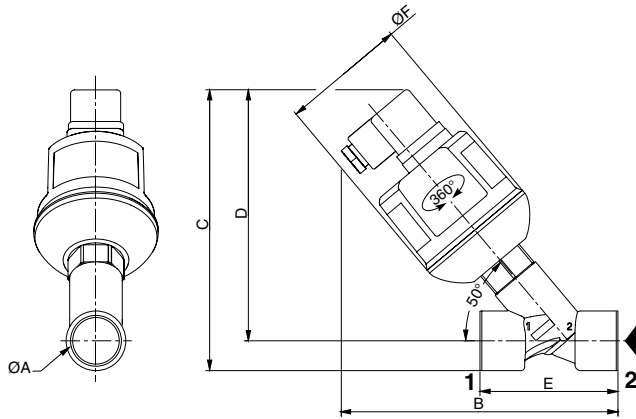
⁽¹⁾ Contact us.

DIMENSIONS (mm), WEIGHT (kg)



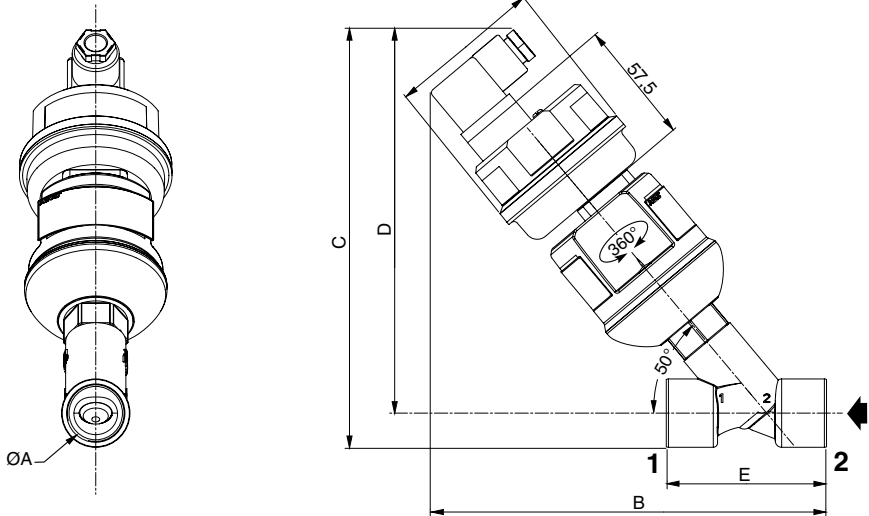
TYPE 01

DC version
67 mm motorized operator
Fluid entry: under the disc at 2
ISO 4400 connector



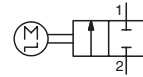
TYPE 02

AC version (accessories)
67 mm motorized operator
Fluid entry: under the disc at 2
ISO 4400 connector



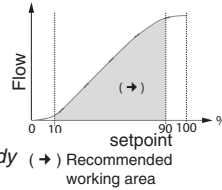
type	Ø A	B	C	D	E	Ø F	weight ⁽¹⁾
DC version							
01	3/8	135	141	129	55	67	0,55
	1/2	142	145	131	65	67	0,55
	3/4	150	152	136	75	67	0,55
AC version							
02	3/8	171	189	175	55	71	0,65
	1/2	178	191	177	65	71	0,65
	3/4	186	196	180	75	71	0,65

⁽¹⁾ Incl. connector.



FEATURES

- Long service life
- Variable flow proportional to the control signal
- Ready-to-use valve
- High flow due to angled seat design
- Anti-waterhammer design (fluid entry under the disc)
- Actuator rotatable through 360°
- Holding position of the valve in case of power failure
- Fluid isolation between motorised actuator and valve body
- LED indicators for valve status display
- Valve tight at closing position (FCI 70-2 class V)
- Vacuum operation up to 10⁻² mbar
- The valves satisfy Pressure Equipment Directive 97/23/EC, article 3.3
- The proportional motorised valves comply with the essential requirements of EMC Directive 2004/108/EC (EN-IEC 61000-6-2 et EN-IEC 61000-6-4)
- The valves satisfy all relevant EC Directives and with the provisions of the Directive RoHS 2



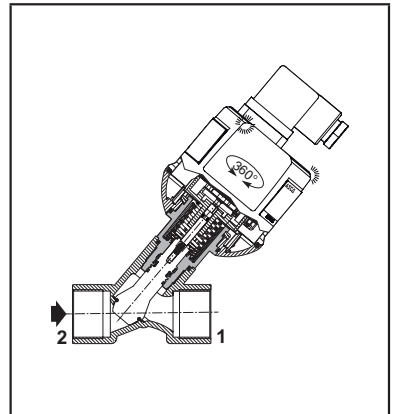
GENERAL

Differential pressure	See «SPECIFICATIONS» [1 bar =100 kPa]
Maximum allowable pressure	10 bar
Ambient temperature range	-10°C to +50°C -10°C to +40°C (for steam at 145°C)
Maximum viscosity	600 cSt (mm ² /s)
Actuating time	< 1,3 s (full opening) / < 1,3 s (full closing)

fluids (*)	temperature range (TS)	seal materials (*)
air and gas groups 1 & 2 water, oil, liquids groups 1 & 2	-10°C to +90°C	NBR (nitrile)
steam	up to +145°C	FPM (fluoroelastomer)

CONSTRUCTION

MATERIALS IN CONTACT WITH FLUID		
(*) Ensure that the compatibility of the fluids in contact with the materials is verified		
	NBR / PBT «K»	FPM / 316L «X»
Valve body	AISI 316L	AISI 316L
Stuffing box housing	PBT, GF reinforced	AISI 316L
Stem valve	AISI 316L	AISI 316L
Stuffing box packing	NBR	FPM
Wiper seal	NBR	FPM
Disc seal	NBR	FPM



OTHER MATERIALS

Top cover operator	Translucent polyamide (PA)
---------------------------	----------------------------

ELECTRICAL CHARACTERISTICS

Connector	Spade plug (cable Ø 6-10 mm)
Connector specification	ISO 4400 / EN 175301-803, form A
Motor consumption	12 W in operation, < 2 W holding phase/set point position Max. peak current: 0,7 A
Visualisation valve (switching)	LED
Electrical enclosure protection	IP65 (EN 60529)
Standard voltages	DC (=) : 24V ±10 %, max. ripple 5%
Setpoint	0-10 V (input resistance = 10 kΩ) 4-20 mA (input resistance = 500 Ω)
Flow regulation characteristics	Linearity ±5%; hysteresis < 5%; accuracy <3%; sensitivity < 3%; repeatability <3%

(*) Ensure that the compatibility of the fluids in contact with the materials is verified.
(1) Contact us.

OPTIONS

M12 connector adapter ⁽¹⁾

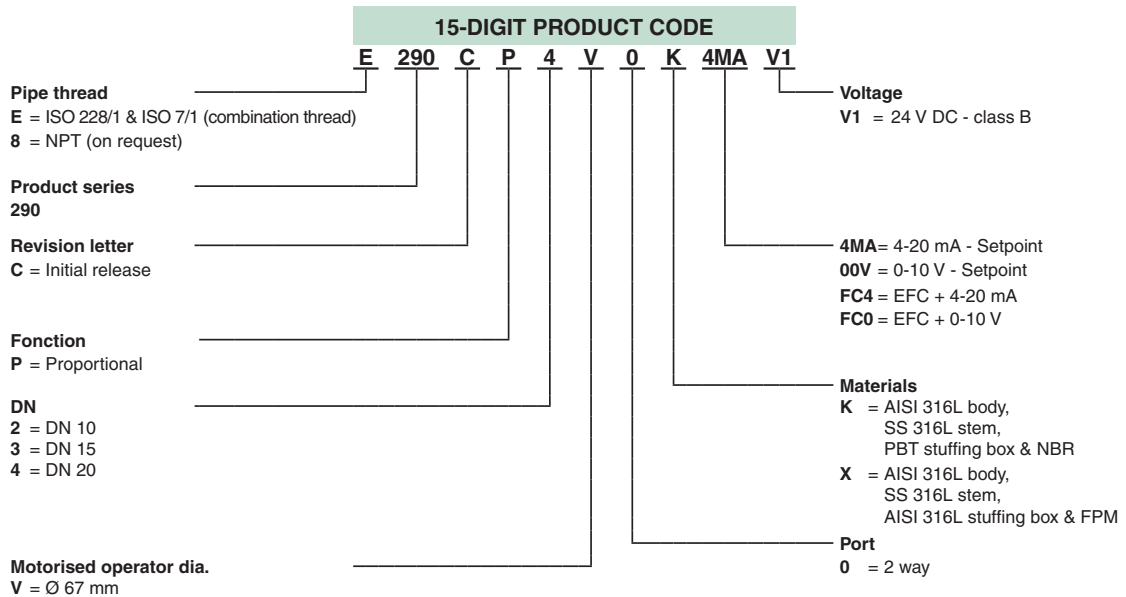
⁽¹⁾ Contact us.

SPECIFICATIONS

piping (ISO 6708)		flow coefficient Kvs (100% opening)		operating pressure differential (bar)			operator diameter	thread type	dimensions / type ⁽²⁾	15-DIGIT PRODUCT CODE	
pipe size	DN	(m³/h)	(l/min)	min.	max.					basic code	voltage code
					air, water, oil (*)	steam	24 V/DC				
Motorised valve, entry under the disc (4-20 mA) - NBR / PBT «K» version											
3/8	10	2,7	45	0	6	-	67	G*	1	E290CP2V0K4MA	V1
1/2	15	3,8	63	0	5	-	67	G*	1	E290CP3V0K4MA	
3/4	20	6	100	0	4	-	67	G*	1	E290CP4V0K4MA	
Motorised valve, entry under the disc (0-10 V) - NBR / PBT «K» version											
3/8	10	2,7	45	0	6	-	67	G*	1	E290CP2V0K00V	V1
1/2	15	3,8	63	0	5	-	67	G*	1	E290CP3V0K00V	
3/4	20	6	100	0	4	-	67	G*	1	E290CP4V0K00V	
Motorised valve, entry under the disc (4-20 mA) - FPM / 316L «X» version											
3/8	10	2,7	45	0	6	4	67	G*	1	E290CP2V0X4MA	V1
1/2	15	3,8	63	0	5	4	67	G*	1	E290CP3V0X4MA	
3/4	20	6	100	0	4	4	67	G*	1	E290CP4V0X4MA	
Motorised valve, entry under the disc (0-10 V) - FPM / 316L «X» version											
3/8	10	2,7	45	0	6	4	67	G*	1	E290CP2V0X00V	V1
1/2	15	3,8	63	0	5	4	67	G*	1	E290CP3V0X00V	
3/4	20	6	100	0	4	4	67	G*	1	E290CP4V0X00V	

⁽²⁾ For dimensions, see drawing(s) for each construction type on the following page(s).

(*) Ensure that the compatibility of the fluids in contact with the materials is verified.




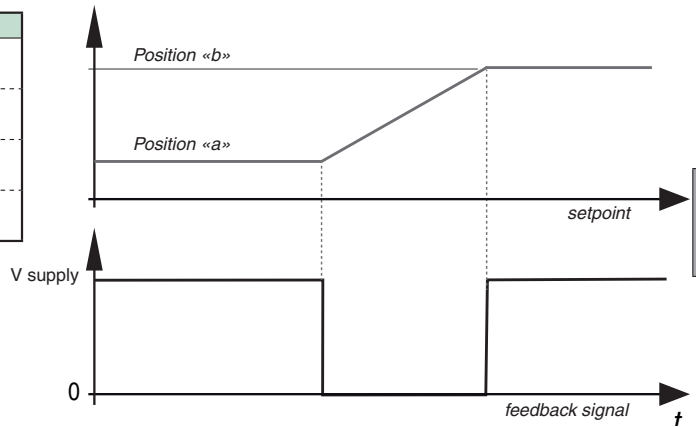
INSTALLATION

• The valves can be mounted in any position without affecting operation	
• Pipe connections (G*) have standard combination thread according to ISO 228/1 and ISO 7/1	
• Other pipe connections are available on request	
• Installation/maintenance instructions are included with each valve	
• 2D/3D CAD models - <i>in 3D</i>	
• LED indicators for operating status display	
status : valve OPEN	green
status : valve CLOSED	orange
status : valve moves to open	green flashing
status : valve moves to close	green flashing

WIRING DC

24 V ±10 % / DC

	1	24 V / DC
	2	0 V
	3	setpoint (0-10 V or 4-20 mA)
	4	feedback signal (24 V switch)

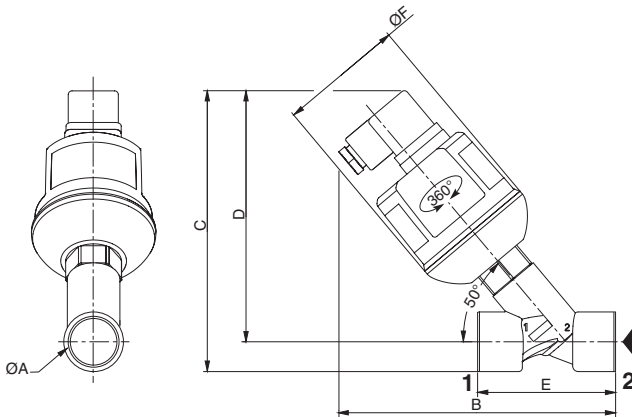


DIMENSIONS (mm), WEIGHT (kg)



TYPE 01

DC version
67 mm motorised operator
Fluid entry: under the disc at 2
ISO 4400 connector



type	Ø A	B	C	D	E	Ø F	weight ⁽¹⁾	
							NBR / PBT «K»	FPM / 316L «X»
DC version								
01	3/8	135	141	129	55	67	0,40	0,45
	1/2	142	145	131	65	67	0,45	0,55
	3/4	150	152	136	75	67	0,55	0,65

⁽¹⁾ Incl. connector.

Pressure Measurement Transmitters for basic requirements

SITRANS P200
for gauge and absolute pressure

2

Overview



The SITRANS P200 pressure transmitter measures the gauge and absolute pressure of liquids, gases and vapors.

- Ceramic measuring cell
- Gauge and absolute measuring ranges 1 to 60 bar (15 to 1000 psi)
- For general applications

Benefits

- High measuring accuracy
- Rugged stainless steel enclosure
- High overload withstand capability
- For aggressive and non-aggressive media
- For measuring the pressure of liquids, gases and vapors
- Compact design

Application

The SITRANS P200 pressure transmitter for gauge and absolute pressure is used in the following industrial areas:

- Mechanical engineering
- Shipbuilding
- Power engineering
- Chemical industry
- Water supply

Design

Device structure without explosion protection

The pressure transmitter consists of a piezoresistive measuring cell with a diaphragm installed in a stainless steel enclosure. It can be used with a connector per EN 175301-803-A (IP65), a round plug M12 (IP67), a cable (IP67) or a cable quick screw connection (IP67) connected electrically. The output signal is between 4 and 20 mA or 0 and 10 V.

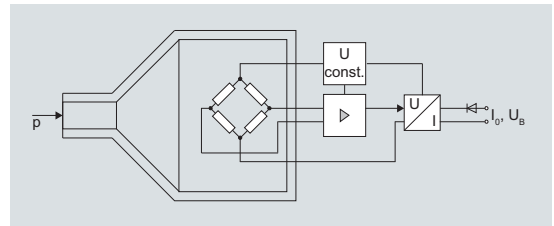
Device structure with explosion protection

The pressure transmitter consists of a piezoresistive measuring cell with a diaphragm installed in a stainless steel enclosure. It can be used with a connector per EN 175301-803-A (IP65) or a round plug M12 (IP67) connected electrically. The output signal is between 4 and 20 mA.

Function

The pressure transmitter measures the gauge and absolute pressure of liquids and gases as well as the level of liquids.

Mode of operation



SITRANS P200 pressure transmitters (7MF1565-...), functional diagram

The ceramic measuring cell has a thin-film resistance bridge to which the operating pressure p is transmitted through a ceramic diaphragm.

The voltage output from the measuring cell is converted by an amplifier into an output current of 4 to 20 mA or an output voltage of 0 to 10 V DC.

The output current and voltage are linearly proportional to the input pressure.

Pressure Measurement

Transmitters for basic requirements

SITRANS P200 for gauge and absolute pressure

Technical specifications

Application	Liquids, gases and vapors measurement
Mode of operation	
Measuring principle	Piezo-resistive measuring cell (ceramic diaphragm)
Measured variable	Gauge and absolute pressure
Inputs	
Measuring range	
• Gauge pressure	1 ... 60 bar (15 ... 870 psi)
- Metric	
- US measuring range	15 ... 1000 psi
• Absolute pressure	0.6 ... 16 bar a (10 ... 232 psia)
- Metric	
- US measuring range	10 ... 300 psia
Output	
Current signal	4 ... 20 mA
• Load	($U_B - 10\text{ V}$) / 0.02 A
• Auxiliary power U_B	DC 7 ... 33 V (10 ... 30 V for Ex)
Voltage signal	0 ... 10 V DC
• Load	$\geq 10\text{ k}\Omega$
• Auxiliary power U_B	12 ... 33 V DC
• Power consumption	< 7 mA at 10 k Ω
Characteristic curve	Linear rising
Measuring accuracy	
Error in measurement at limit setting incl. hysteresis and reproducibility	<ul style="list-style-type: none"> • Typical: 0.25 % of full-scale value • Maximum: 0.5 % of full-scale value
Step response time T_{99}	< 5 ms
Long-term stability	
• Lower range value and measuring span	0.25 % of full-scale value/year
Influence of ambient temperature	
• Lower range value and measuring span	0.25 %/10 K of full-scale value
• Influence of power supply	0.005 %/V
Conditions of use	
Process temperature with gasket made of:	
• FPM (Standard)	-15 ... +125 °C (+5 ... +257 °F)
• Neoprene	-35 ... +100 °C (-31 ... +212 °F)
• Perbunan	-20 ... +100 °C (-4 ... +212 °F)
• EPDM	-40 ... +145 °C (-40 ... +293 °F), usable for drinking water
Ambient temperature	-25 ... +85 °C (-13 ... +185 °F)
Storage temperature	-50 ... +100 °C (-58 ... +212 °F)
Degree of protection (to EN 60529)	<ul style="list-style-type: none"> • IP 65 with connector per EN 175301-803-A • IP 67 with M12 connector • IP 67 with cable • IP 67 with cable quick screw connection
Electromagnetic compatibility	<ul style="list-style-type: none"> • acc. EN 61326-1/-2/-3 • acc. NAMUR NE21, only for ATEX versions and with a max. measuring deviation $\leq 1\%$

Design	
Weight	Approx. 0.090 kg (0.198 lb)
Process connections	See dimension drawings
Electrical connections	<ul style="list-style-type: none"> • Connector per EN 175301-803-A Form A with cable inlet M16x1.5 or 1/2-14 NPT or Pg 11 • M12 connector • 2 or 3-wire (0.5 mm²) cable ($\varnothing \pm 5.4\text{ mm}$) • Cable quick screw connection
Wetted parts materials	
• Measuring cell	Al ₂ O ₃ - 96 %
• Process connection	Stainless steel, mat. No. 1.4404 (SST 316 L)
• Gasket	<ul style="list-style-type: none"> • FPM (Standard) • Neoprene • Perbunan • EPDM
Non-wetted parts materials	
• Enclosure	Stainless steel, mat. No. 1.4404 (SST 316 L)
• Rack	Plastic
• Cables	PVC
Certificates and approvals	
Classification according to pressure equipment directive (PED 97/23/EC)	For gases of fluid group 1 and liquids of fluid group 1; complies with requirements of article 3, paragraph 3 (sound engineering practice)
Lloyds Register of Shipping (LR)	Applied
Germanischer Lloyds Register of Shipping (GL)	Applied
American Bureau of Shipping (ABS)	Applied
Bureau Veritas (BV)	Applied
Det Norske Veritas (DNV)	Applied
Drinking water approval (ACS)	Applied
GOST	Applied
Explosion protection	
Intrinsic safety "i" (only with current output)	Ex II 1/2 G Ex ia IIC T4 Ga/Gb Ex II 1/2 D Ex ia IIIC T125 °C Da/Db
EC type-examination certificate	SEV 10 ATEX 0146
Connection to certified intrinsically-safe resistive circuits with maximum values:	$U_i \leq 30\text{ V DC}$; $I_i \leq 100\text{ mA}$; $P_i \leq 0.75\text{ W}$
Effective internal inductance and capacity for versions with plugs per EN 175301-803-A and M12	$L_i = 0\text{ nH}$; $C_i = 0\text{ nF}$

Pressure Measurement Transmitters for basic requirements

SITRANS P200 for gauge and absolute pressure

Selection and ordering data

Order No.

Order code

SITRANS P 200 pressure transmitters for pressure and absolute pressure for general applications

D) 7MF 15 6 5 -

Characteristic curve deviation typ. 0.25 %

Wetted parts materials: Ceramic and stainless steel + sealing material

Non-wetted parts materials: stainless steel

Measuring range	Overload limit		Burst pressure				
	Min.	Max.					
For gauge pressure							
0 ... 1 bar (0 ... 14.5 psi)	-0.4 bar (-5.8 psi)	2.5 bar (36.26 psi)	> 2.5 bar (> 36.3 psi)	▶	3 BA		
0 ... 1.6 bar (0 ... 23.2 psi)	-0.4 bar (-5.8 psi)	4 bar (58.02 psi)	> 4 bar (> 58.0 psi)	▶	3 BB		
0 ... 2.5 bar (0 ... 36.3 psi)	-0.8 bar (-11.6 psi)	6.25 bar (90.65 psi)	> 6.25 bar (> 90.7 psi)	▶	3 BD		
0 ... 4 bar (0 ... 58.0 psi)	-0.8 bar (-11.6 psi)	10 bar (145 psi)	> 10 bar (> 145 psi)	▶	3 BE		
0 ... 6 bar (0 ... 87.0 psi)	-1 bar (-14.5 psi)	15 bar (217 psi)	> 15 bar (> 217 psi)	▶	3 BG		
0 ... 10 bar (0 ... 145 psi)	-1 bar (-14.5 psi)	25 bar (362 psi)	> 25 bar (> 362 psi)	▶	3 CA		
0 ... 16 bar (0 ... 232 psi)	-1 bar (-14.5 psi)	40 bar (580 psi)	> 40 bar (> 580 psi)	▶	3 CB		
0 ... 25 bar (0 ... 363 psi)	-1 bar (-14.5 psi)	62.5 bar (906 psi)	> 62.5 bar (> 906 psi)	▶	3 CD		
0 ... 40 bar (0 ... 580 psi)	-1 bar (-14.5 psi)	100 bar (1450 psi)	> 100 bar (> 1450 psi)	▶	3 CE		
0 ... 60 bar (0 ... 870 psi)	-1 bar (-14.5 psi)	150 bar (2175 psi)	> 150 bar (> 2175 psi)	▶	3 CG		
Other version, add order code and plain text: Measuring range: ... up to ... bar (psi)						9 AA	H 1 Y
For absolute pressure							
0 ... 600 bar a (0 ... 8.7 psia)	0 bar a (0 psia)	3 bar a (43.51 psia)	> 2.5 bar a (> 36.3 psia)		5 AG		
0 ... 1 bar a (0 ... 14.5 psia)	0 bar a (0 psia)	2.5 bar a (36.26 psia)	> 2.5 bar a (> 36.3 psia)	▶	5 BA		
0 ... 1.6 bar a (0 ... 23.2 psia)	0 bar a (0 psia)	4 bar a (58.02 psia)	> 4 bar a (> 58.0 psia)	▶	5 BB		
0 ... 2.5 bar a (0 ... 36.3 psia)	0 bar a (0 psia)	6.25 bar a (90.65 psia)	> 6.25 bar a (> 90.7 psia)	▶	5 BD		
0 ... 4 bar a (0 ... 58.0 psia)	0 bar a (0 psia)	10 bar a (145 psia)	> 10 bar a (> 145 psia)	▶	5 BE		
0 ... 6 bar a (0 ... 87.0 psia)	0 bar a (0 psia)	15 bar a (217 psia)	> 15 bar a (> 217 psia)	▶	5 BG		
0 ... 10 bar a (0 ... 145 psia)	0 bar a (0 psia)	25 bar a (362 psia)	> 25 bar a (> 362 psia)	▶	5 CA		
0 ... 16 bar a (0 ... 232 psia)	0 bar a (0 psia)	40 bar a (580 psia)	> 40 bar a (> 580 psia)	▶	5 CB		
Other version, add order code and plain text: Measuring range: ... up to ... mbar a (psia)						9 AA	H 1 Y
Measuring ranges for gauge pressure (only for US market)							
(0 ... 15 psi)	(-5.8 psi)	(35 psi)	(> 35 psi)		4 BB		
(3 ... 15 psi)	(-5.8 psi)	(35 psi)	(> 35 psi)		4 BC		
(0 ... 20 psi)	(-5.8 psi)	(50 psi)	(> 50 psi)		4 BD		
(0 ... 30 psi)	(-5.8 psi)	(80 psi)	(> 80 psi)		4 BE		
(0 ... 60 psi)	(-11.5 psi)	(140 psi)	(> 140 psi)		4 BF		
(0 ... 100 psi)	(-14.5 psi)	(200 psi)	(> 200 psi)		4 BG		
(0 ... 150 psi)	(-14.5 psi)	(350 psi)	(> 350 psi)		4 CA		
(0 ... 200 psi)	(-14.5 psi)	(550 psi)	(> 550 psi)		4 CB		
(0 ... 300 psi)	(-14.5 psi)	(800 psi)	(> 800 psi)		4 CD		
(0 ... 500 psi)	(-14.5 psi)	(1400 psi)	(> 1400 psi)		4 CE		
(0 ... 750 psi)	(-14.5 psi)	(2000 psi)	(> 2000 psi)		4 CF		
(0 ... 1000 psi)	(-14.5 psi)	(2000 psi)	(> 2000 psi)		4 CG		
Other version, add order code and plain text: Measuring range: ... up to ... psi						9 AA	H 1 Y
Measuring ranges for absolute pressure (only for US market)							
(0 ... 10 psia)	(0 psia)	(35 psia)	(> 35 psia)		6 AG		
(0 ... 15 psia)	(0 psia)	(35 psia)	(> 35 psia)		6 BA		
(0 ... 20 psia)	(0 psia)	(50 psia)	(> 50 psia)		6 BB		
(0 ... 30 psia)	(0 psia)	(80 psia)	(> 80 psia)		6 BD		
(0 ... 60 psia)	(0 psia)	(140 psia)	(> 140 psia)		6 BE		
(0 ... 100 psia)	(0 psia)	(200 psia)	(> 200 psia)		6 BG		
(0 ... 150 psia)	(0 psia)	(350 psia)	(> 350 psia)		6 CA		
(0 ... 200 psia)	(0 psia)	(550 psia)	(> 550 psia)		6 CB		
(0 ... 300 psia)	(0 psia)	(800 psia)	(> 800 psia)		6 CC		
Other version, add order code and plain text: Measuring range: ... up to ... psia						9 AA	H 1 Y

▶ Available ex stock

Pressure Measurement

Transmitters for basic requirements

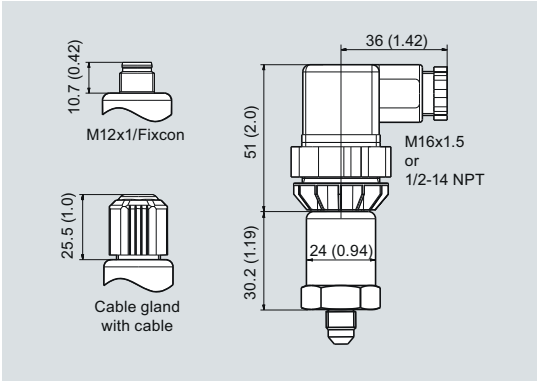
SITRANS P200
for gauge and absolute pressure

Selection and ordering data	Order No.	Order code
SITRANS P 200 pressure transmitters for pressure and absolute pressure for general applications D)	7MF1565 - - - - -	
Accuracy typ. 0.25 %		
Wetted parts materials: Ceramic and stainless steel + sealing material		
Non-wetted parts materials: stainless steel		
Output signal		
4 ... 20 mA; two-wire system; power supply 7 ... 33 V DC (10 ... 30 V DC for ATEX versions)	▶	0
0 ... 10 V; three-wire system; power supply 12 ... 33 V DC	▶	10
Explosion protection (only 4 ... 20 mA)		
None	▶	0
With explosion protection EEx ia IIC T4	▶	1
Electrical connection		
Connector per DIN EN 175301-803-A, stuffing box thread M16 (with coupling)	▶	1
Round connector M12 per DIN EN 60139-9 (not for gauge pressure ranges ≤ 16 bar)		2
Connection via fixed mounted cable, 2m (not for type of protection "Intrinsic safety I")		03
Cable quick screw connection PG9 (not for type of protection "Intrinsic safety I")		04
Connector per DIN EN 175301-803-A, stuffing box thread 1/2"-14 NPT (with coupling)		5
Connector per DIN EN 175301-803-A, stuffing box thread PG11 (with coupling)		6
Special version		9
Process connection		
G½" male per EN 837-1 (½" BSP male) (standard for metric pressure ranges mbar, bar)	▶	A
G½" male thread and G1/8" female thread		B
G¼" male per EN 837-1 (¼" BSP male)		C
7/16"-20 UNF male		D
¼"-18 NPT male (standard for pressure ranges inH ₂ O and psi)		E
¼"-18 NPT female		F
½"-14 NPT male		G
½"-14 NPT female		H
7/16"-20 UNF female		J
M20x1.5 male		P
Special version		Z
		P1Y
Sealing material between sensor and enclosure		
Viton (FPM, standard)	▶	A
Neoprene (CR)		B
Perbunan (NBR)		C
EPDM		D
Special version		Z
		Q1Y
Version		
Standard version	▶	1
Further designs		
Supplement the order no. with "-Z" and add order code.		
Manufacturer's test certificate M per DIN 55340, Part 18 and ISO 8402 (calibration certificate) supplied	C11	
Oxygen application, oil and grease-free cleaning (only in conjunction with the sealing material Viton between sensor and enclosure)	E10	
▶ Available ex stock		
D) Subject to export regulations AL: N, ECCN: EAR99H.		

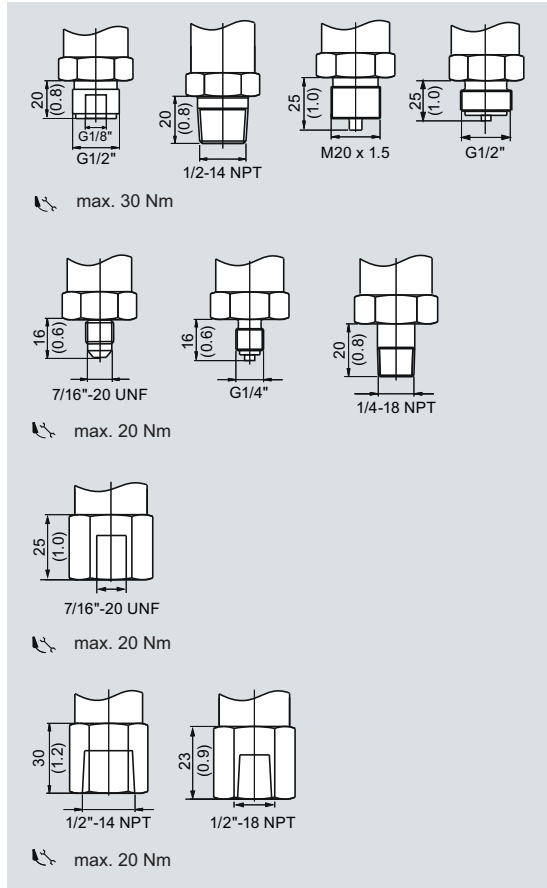
Pressure Measurement Transmitters for basic requirements

SITRANS P200
for gauge and absolute pressure

Dimensional drawings



SITRANS P200, electrical connections, dimensions in mm (inch)



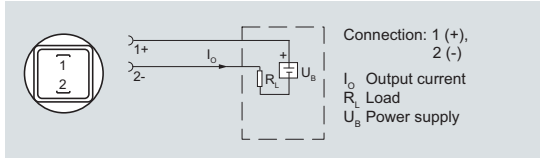
SITRANS P200, process connections, dimensions in mm (inch)

Pressure Measurement Transmitters for basic requirements

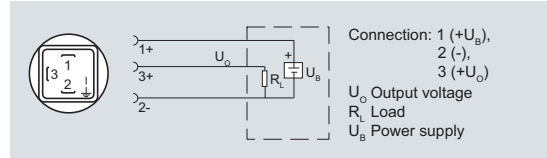
SITRANS P200
for gauge and absolute pressure

2

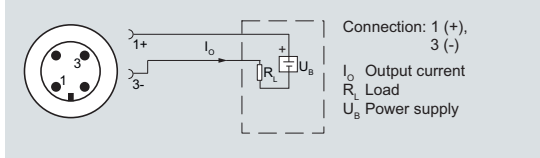
Schematics



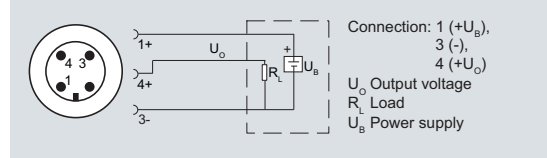
Connection with current output and connector per EN 175301



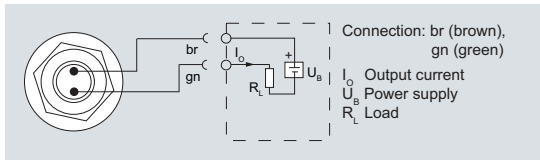
Connection with voltage output and connector per EN 175301



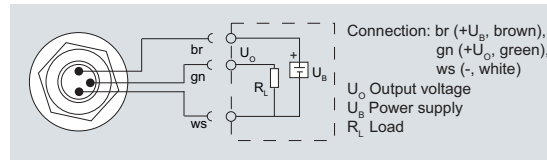
Connection with current output and connector M12x1



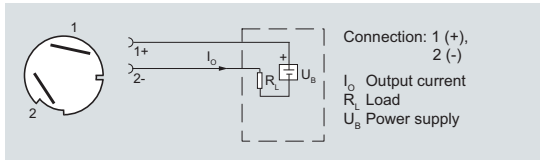
Connection with voltage output and connector M12x1



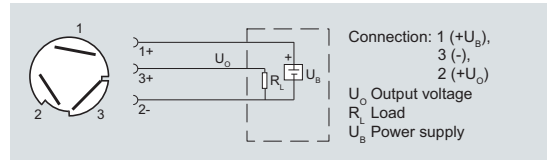
Connection with current output and cable



Connection with voltage output and cable



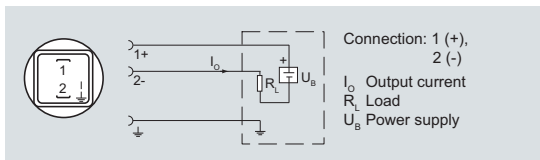
Connection with current output and cable quick screw connection



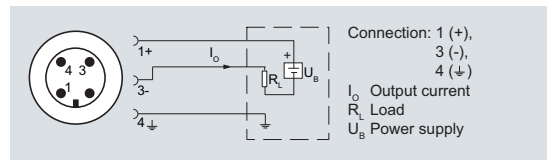
Connection with voltage output and cable quick screw connection

Version with explosion protection: 4 ... 20 mA

The grounding connection is conductively bonded to the transmitter enclosure

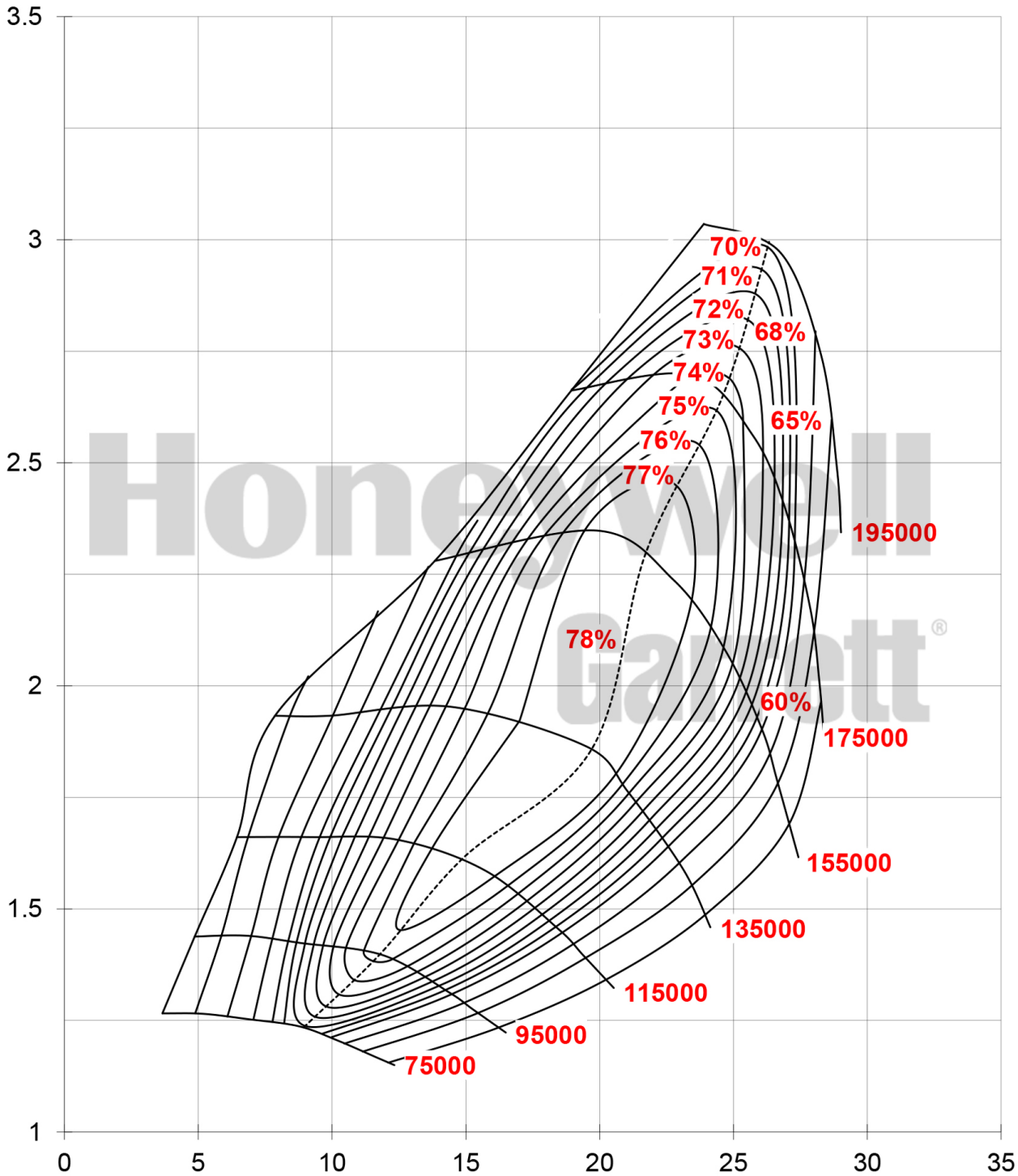


Connection with current output and connector per EN 175301 (Ex)



Connection with current output and connector M12x1 (Ex)

PRESSURE RATIO



CORRECTED AIR FLOW (LBS/MIN)

Appendix C

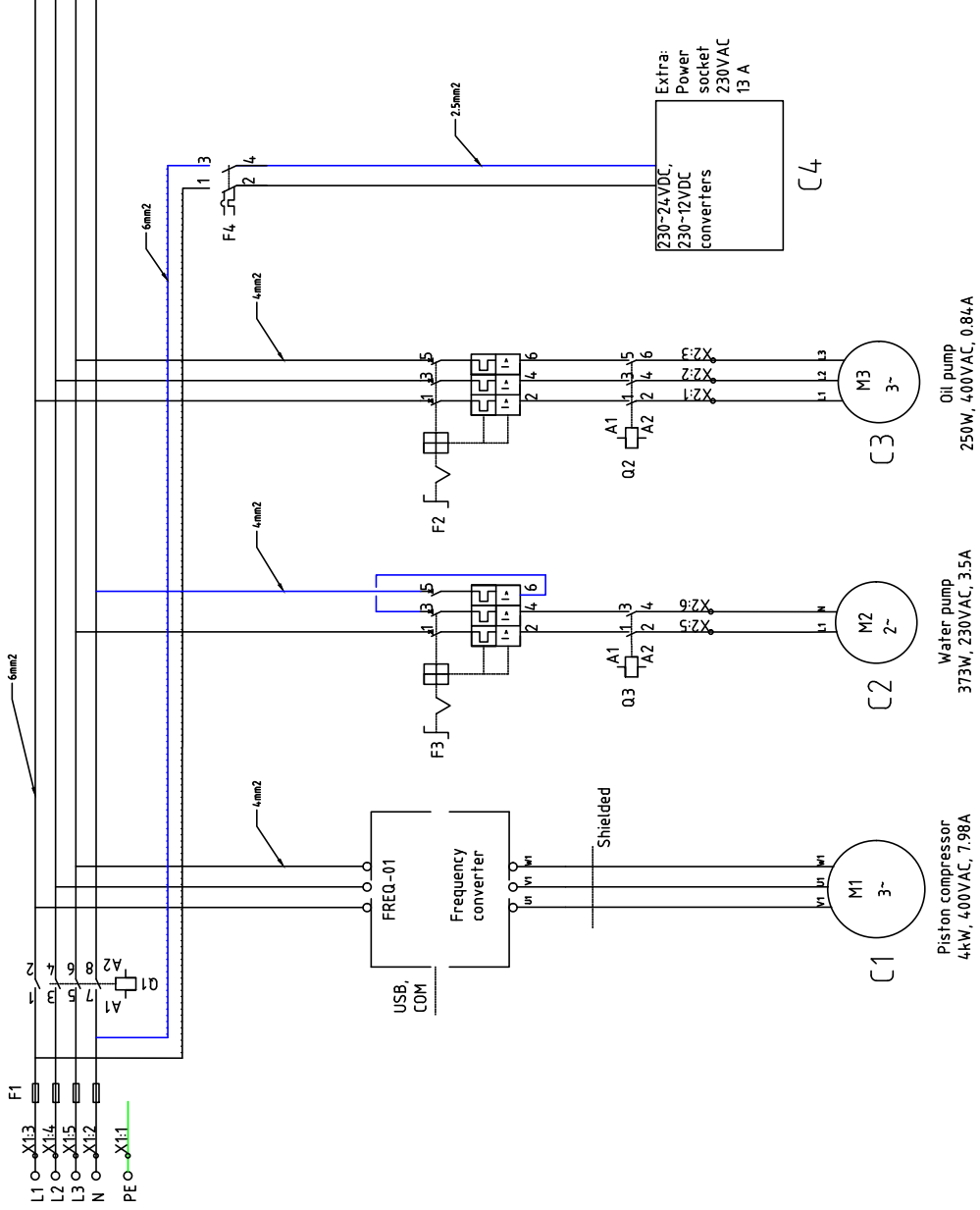
Schematics

FAT performed: Check internal connections on terminal blocks and components

Signature:

Date:

Item	Description
Q1	Main Circuit Relay
Q2	Contactor, Oil pump
Q3	Contactor, Water pump
F1	Main fuse, 30A
F2	Motor protection relay, oil pump
F3	Motor protection relay, water pump
F4	Fuse, Control Circuit: 230-24/12VDC converter, equipment etc.
C1	Circuit, Piston compressor
C2	Circuit, Water pump
C3	Circuit, Oil pump



400/230 V Main Circuit
 Wet Gas Compression
 Designed by: N.T.
 Date: 28.02.2017

Piston compressor
 4kW, 400VAC, 7.98A

Water pump
 373W, 230VAC, 3.5A

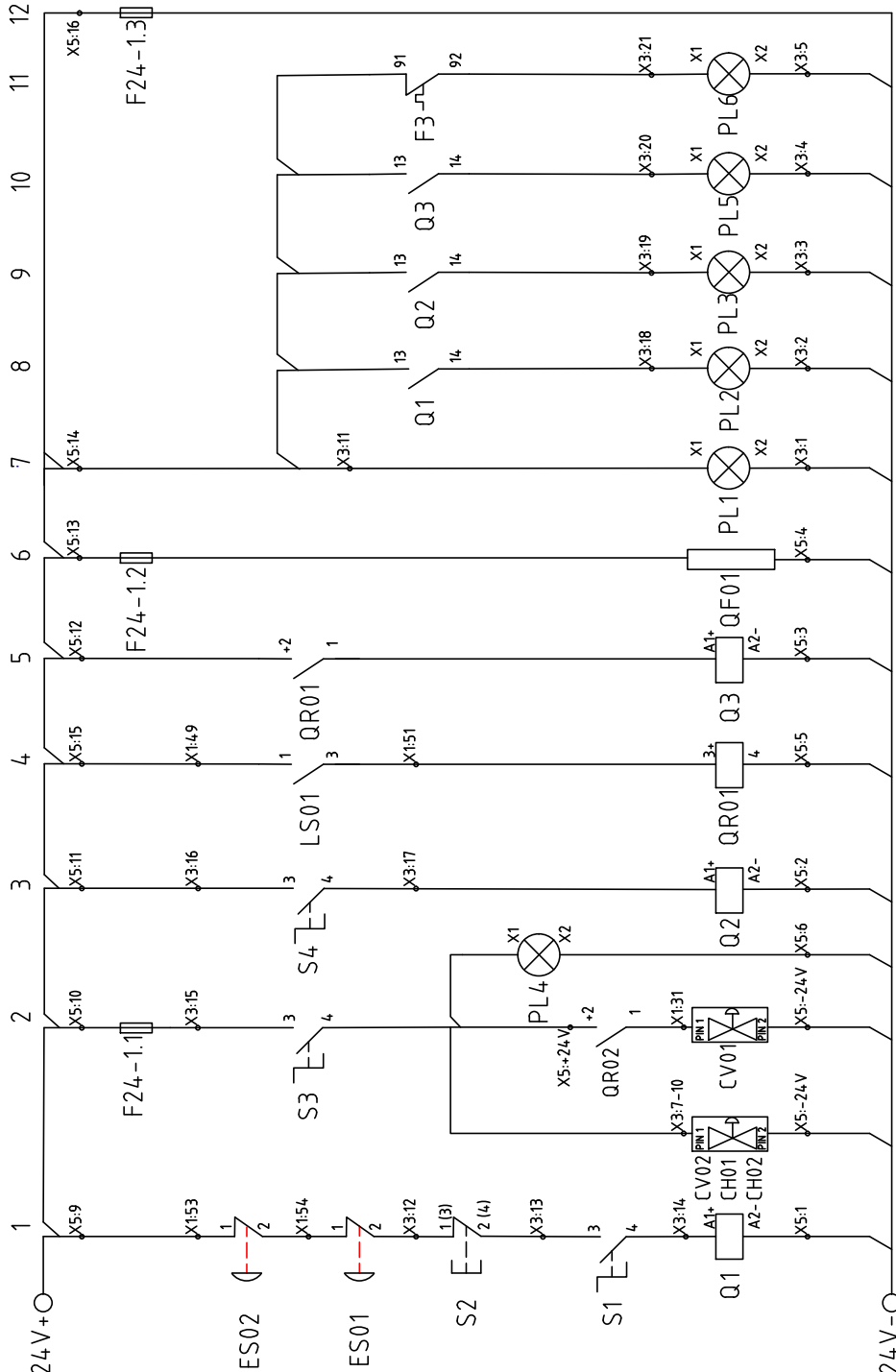
Oil pump
 250W, 400VAC, 0.84A

Department of Mechanical and Industrial
 Engineering (MTP), NTNU
 Subsea Process Control
 Laboratory

FAT performed: Check internal connections on terminal blocks and components

Signature: _____ Date: _____
 Signature: _____ Date: _____

Item	Description
F24-11	Element fuse, TB, Control Valves, 5x20mm T3.15A Slow blow
F24-12	Element fuse, TB, QF01 Fan, 5x20mm 0.630A Quick blow
F24-13	Element fuse, Terminal Block, SPARE, 5x20mm T3.15A Slow blow
ES02	Emergency Stop, Field
ES01	Emergency Stop, Panel
S1	Start, main circuit Q1
S2	Stop, Door switch
S3	Start, control valves
S4	Start, Oil pump
QR01	Relay, dir. 24V to Q2
QR02	Relay, dir. 24V to CV01 - A. Surge
Q1	Contactor, Main
Q2	Contactor, Oil pump
Q3	Contactor, Water pump
F3	Motor protection switch, NC Simulate water pump not running
QF01	Cabinet fan
PL1	Lamp, Signal Power on
PL2	Lamp, Main circuit
PL3	Lamp, Oil pump on
PL4	Lamp, Control valves supply on
PL5	Lamp, Water pump on
PL6	Lamp, Motor protection tripped for C2



1 ES01 2 ES02 3 S2 4 S3	1 3 2 4 1 2 3 4	24 VDC Control Circuit Wet Gas Compression Designed by: N.T. Date: 27.02.2017	Department of Mechanical and Industrial Engineering (MTP), NTNU Subsea Process Control Laboratory

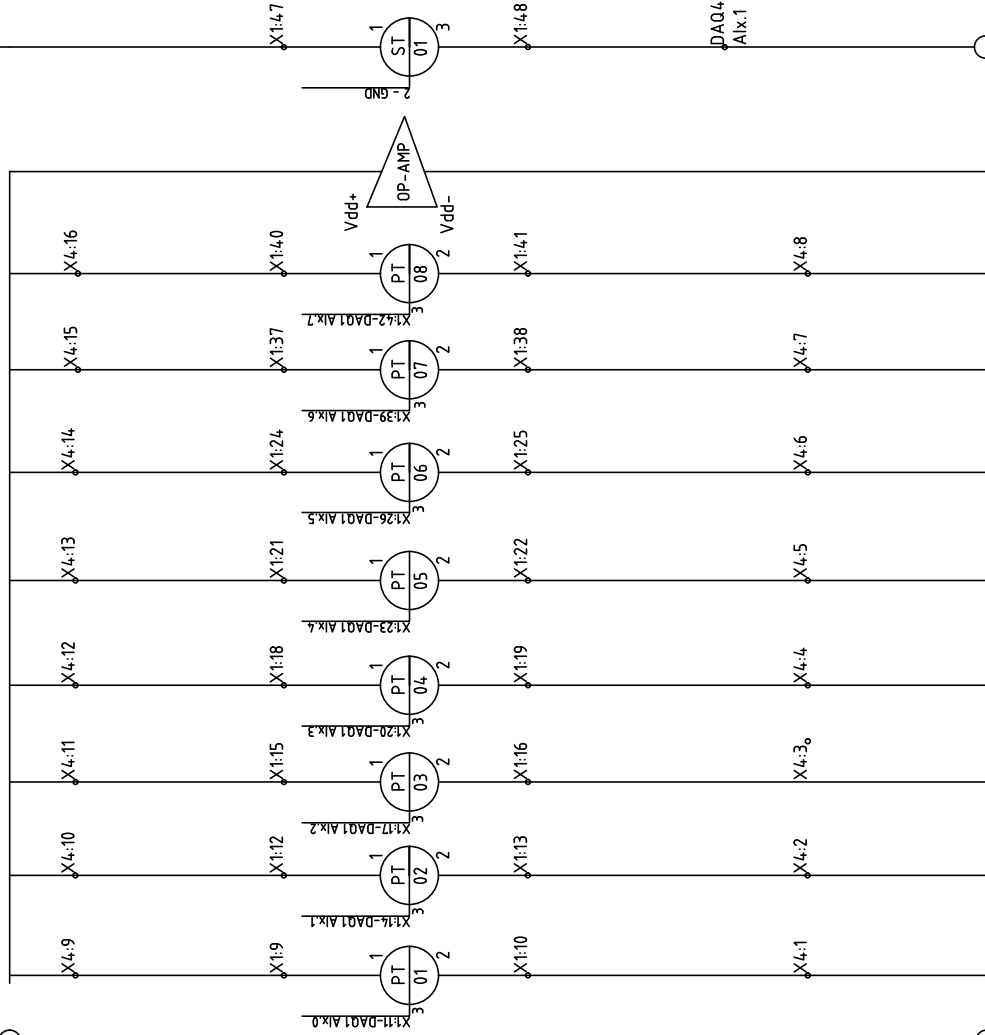
COMMENTS:
 1. S2 wired with NO pair (Drawing illustrated closed circuit (door closed))
 2. X5:15, F24-1.3 is spare branch for flow meter circuit (not connected 13/3)

FAT performed: Check internal connections on terminal blocks and components

Signature: _____ Date: _____
 Signature: _____ Date: _____

NOTE:
 - DAQ1 A1x.1 -> Single ended grounding
 - DAQ1 A11.1 -> Differential ended grounding

12V + O



12V - O

NOMENCLATURE	
DAQx	Data Acquisition Unit, no x
PT	Pressure Transmitter
ST	Speed Transmitter
OP-AMP	Operational amplifier

12 VDC Control circuit

Wet Gas Compression

Designed by: N.T.

Rev: 01

Date: 27.02.2017

Scale: A4

Sheet 1 of 1

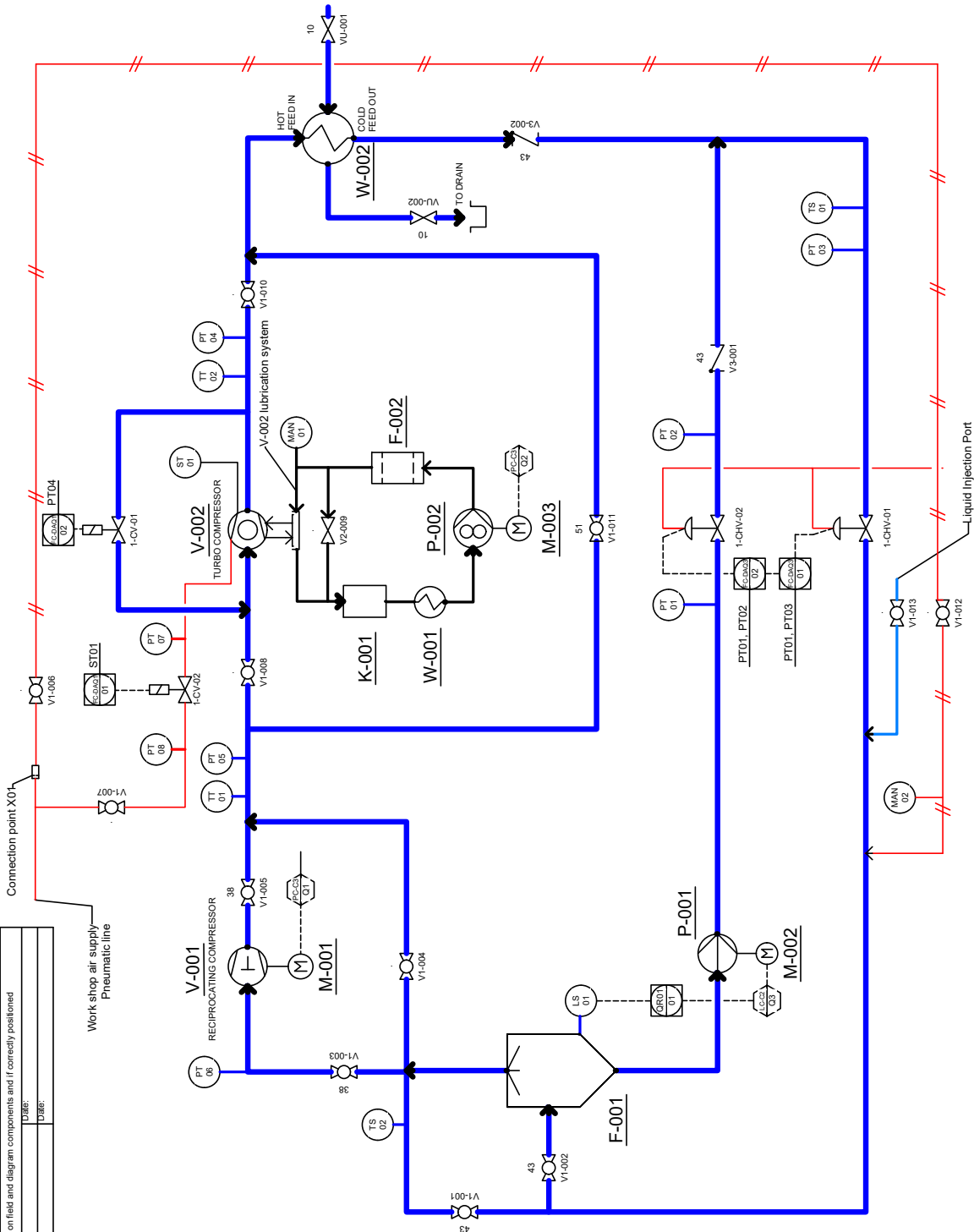
Department of Mechanical and Industrial Engineering (MTP), NTNU
 Subsea Process Control Laboratory

FAT:	Thou Shall check quality of connection as well as checking that connection is in correct location according to schematic.				
Completed?	Signature		Date [dd.mm.yyyy]		
1					Supply PE PE 1
2					Supply N N 2 F1 - 4
3					Supply L1 L1 3 F1 - 1
DAQ description					
AI	Analog Input	AIx.1	Single ended gnd [pin 1]		
AO	Analog Output	AI1.1	Diff. Ended gnd [ch1 . pin 1]		
DAQ1 (AI):	PT01 - PT08 (8/8) 8 ch 0 -> 7				1 C3-OP-L1 1 Q2.2
DAQ1 (AO):	CV01 control signal (1/2) ch				2 C3-OP-L2 2 Q2.4
DAQ2(AI):	TS01-TS02 TT01-TT02 (4/8) 8ch				3 C2-OP-L3 3 Q2.6
DAQ2(DO):	5V to speed transmitter				PE C3-OP-PE 4
DAQ3(AI):	Choke1-Choke2 p. feedback, (6/8) 8 ch				1 C2-WP-L 5 Q3.2
DAQ3(AO):					2 C2-WP-N 6 Q3.6
DAQ4(AI):	Flow - RPM				PE C2-WP-PE 7
DAQ4(AO):					
CM (AO):	Choke 1-2, CV01 control signal (3/4) ch				

PIN IN	DESCRIPT.	X1	PIN OUT
1 White	CHOKE 1	1	X3.7
2 Brown	-	2	Current module AO x.1 setpoint
3 Blue	-	3	DAQ3 AI x.0 pos. feed
4 Grey	-	4	feedback (not connected)
1	CHOKE 2	5	X3.8
2	-	6	Current module AO x.2 control
3	-	7	DAQ3 AI x.2 pos. feed
4	-	8	feedback (not connected)
1	PT01	9	X4.9
2	-	10	X4.1
3	-	11	DAQ1 AI x.0
1	PT02	12	X4.10
2	-	13	X4.2
3	-	14	DAQ1 AI x.1
1	PT03	15	X4.11
2	-	16	X4.3
3	-	17	DAQ1 AI x.2
1	PT04	18	X4.12
2	-	19	X4.4
3	-	20	DAQ1 AI x.3
1	PT05	21	X4.13
2	-	22	X4.5
3	-	23	DAQ1 AI x.4
1	PT06	24	X4.14
2	-	25	X4.6
3	-	26	DAQ1 AI x.5
1	TS01	27	DAQ2 AI x.0
2	-	28	GND
1	TS02	29	DAQ2 AI x.1
2	-	30	GND
1	CV01	31	X3.9
2	-	32	DAQ1 AO x.0 through (QR02 +3)

PIN IN	DESCRIPT.	X1	PIN OUT
3	-	33	GND
1	CV02	34	X3.10
2	-	35	CM AO x.0
3	-	36	GND
1	PT07	37	X4.15
2	-	38	X4.7
3	-	39	DAQ1 AI x.6
1	PT08	40	X4.16
2	-	41	X4.8
3	-	42	DAQ1 AI x.7
1	TT01	43	DAQ2 AI x.2
2	-	44	GND
1	TT02	45	DAQ2 AI x.3
2	-	46	GND
Pin 1 5V	ST01	47	DAQ4 5V
Pin 3	-	48	DAQ4 AI x.1
1	LS01	49	X5:16
2	-	50	
3	-	51	QR01 +3
4	-	52	
1	ES02	53	
2	-	54	
3	-	55	
4	-	56	
		57	

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 Date: _____
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Workshop air supply - Pneumatic line Connection point X01		Non-Reference: W - Heat Exchangers F - Separator K - Reservoir (00) P - Pump M - Motor drive V1 - Ball valve V2 - Needle Valve V3 - Check Valve VU - Valve Utility CV - Control Valve CHV - Choke Control Valve LS - Level Sensor TS - Temperature Sensor TT - Temperature Transmitter ST - Speed Transmitter PT - Pressure Transmitter MAN - Manometer PC - Pressure Controller LC - Level Controller FC - Flow Controller DAQ - Data Acquisition Unit Measurement and Control I/O
Workshop air supply - Pneumatic line Connection point X01		
Workshop air supply - Pneumatic line Connection point X01		
Workshop air supply - Pneumatic line Connection point X01		Legend: K - Reservoir (00) P - Pump M - Motor drive V1 - Ball valve V2 - Needle Valve V3 - Check Valve VU - Valve Utility CV - Control Valve CHV - Choke Control Valve LS - Level Sensor TS - Temperature Sensor TT - Temperature Transmitter ST - Speed Transmitter PT - Pressure Transmitter MAN - Manometer PC - Pressure Controller LC - Level Controller FC - Flow Controller DAQ - Data Acquisition Unit Measurement and Control I/O
Workshop air supply - Pneumatic line Connection point X01		Department of Mechanical and Industrial Engineering (MTP), NTNU Subsea Process Control Laboratory
Workshop air supply - Pneumatic line Connection point X01		P&ID for process laboratory Wet Gas Compression Designed by: N.T. DN Date: 13.03.2017
Workshop air supply - Pneumatic line Connection point X01		Rev: 06-24/05-17, N.T. Scale: A4 Sheet 1 of 1

Appendix D

Commissioning

Startup, operation and shutdown procedure

Wet Gas Compression Laboratory

May 2017

Subsea Process Control Laboratory

Title:		
<h1>Wet Gas Compression</h1>		
Dok. no.: 01	Rev. no.: 05	Date: 24.05.2017

Author(s): Njål Tengesdal	
Validity of this document: Wet Gas Compression laboratory, control cabinet, Labview software	
Faculty: Faculty of Engineering (IV)	Contact: Christian Holden, phone: 735 93 782
Department: Department of Mechanical and Industrial Engineering	

Approval signature:	Date:
1.	
2.	
3.	

Table of Contents

1	Introduction	4
1.1	Operating scenarios	4
1.2	Nomenclature	4
1.3	Table nomenclature	5
2	HMS	6
2.1	Contact information	6
3	Commissioning	7
3.1	Laboratory startup	8
3.1.1	Dry gas startup	10
3.1.2	Wet gas startup	10
4	Laboratory operation (Case A – F)	12
4.1	Wet gas compression cases	12
4.2	Dry gas compression cases	15
5	Shut down procedure	18
6	Troubleshooting	19
7	References	20

1 Introduction

This document is made with the sole intention to ensure safe and efficient operation of the wet gas compression laboratory at MTP Valgrinda. The procedure of startup, operation and shutdown of the facility is based on the theoretical design made by [1] and [2].

The laboratory (lab) is a *Subsea Process Control Facility*, with the purpose of simulating the environment of a subsea installation. This includes piping, gas-liquid separation, gas compression (piston and centrifugal type) cooling with heat exchangers and control valves. The lab is instrumented with pressure, temperature, level and speed transmitters to complete the control system signal acquisitions for optimal control.

1.1 Operating scenarios

Modes of operations:

- Case A. Subsea separation and gas compression. Separator, piston and centrifugal compressor are active *
- Case B. Subsea separation and gas compression. Piston compressor is bypassed
- Case C. Direct wet gas compression. Direct inlet wet gas to the centrifugal compressor, bypassing both the separator and the piston compressor
- Case D. Dry Gas Compression, bypassing the separator (No liquid injected) **
- Case E. Dry Gas Compression II, only piston compressor is active (No liquid injected)
- Case F. Dry Gas Compression III, only centrifugal compressor is active (No liquid injected).

* The piston compressor is not recommended to operate in the wet gas scenario. Please consult the laboratory responsible, or move on to Case B or C.

** Case D - F follows the same start up protocols as A-C.

Note: The piston compressor is intended to be controlled by a variable frequency drive (VFD) located in the control cabinet, adjusting the speed of the crankshaft.

The procedures A-F explained in this document will have the system [Piping and Instrumentation Diagram \(P&ID\)](#) as reference available, included in Appendix A.

1.2 Nomenclature

- | | |
|--------|--------------------------|
| - VFD | Variable frequency drive |
| - GVF | Gas Volume Fraction |
| - LVF | Liquid Volume Fraction |
| - Barg | Bar gauge |

1.3 Table nomenclature

This section explains the columns in the startup, operational and shutdown table procedures.

1. MANUAL VALVE ADJUSTMENT PROCEDURE BEFORE STARTUP			
2. Step	3. Action/Activity	4. Description/check	5. Confirm/check

1. Headline, explaining the objective for the list of tasks
2. Operation steps, indicating the number of the current and following steps to be executed
3. Action or activity to be performed at the current step
4. Descriptive text of what the action or activity yields and/or an indication of what to check for in the environment
5. Confirm or check the result of the action or activity performed in 3.

2 HMS

The wet gas compression facility must be operated with **at least two** persons present to avoid harm or damage to personnel and equipment.

1. **Never** operate the facility without the permission from laboratory responsible (see Section 3).
2. **Follow** the workshop rules where the facility is stationed
3. **Use** hard boots and eye wear protection when operating the facility
4. **Never** open the control cabinet with electrical wiring without consulting trained personnel

For guidelines and regulations on performing work and experiments at NTNU laboratory and workshops, please consult the *Laboratory and Workshop Handbook* found at:

<https://innsida.ntnu.no/wiki/-/wiki/English/Laboratory+and+workshop+handbook>

Regulations for health, safety and environment according to NTNU in *HSE-Handbook for NTNU*:

http://www.ntnu.no/c/document_library/get_file?uuid=bb98f1f9-a03d-4380-95d8-94e248ae7069&groupId=10137

2.1 Contact information

Laboratory Responsible:

Christian Holden Phone: 735 93 782 Email: christian.holden@ntnu.no

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Electrical guidance and campus service

Lab inspector: Jørn Ove Blokkum Phone: 918 97 417 Email: jorn.blokkum@ntnu.no

Lead Discipline: Frode Dahl Phone: 918 97 376 Email: frode.dahl@ntnu.no

3 Commissioning

This section contains the startup procedure for dry gas and wet gas in the laboratory. Technical data on the laboratory is included in Table 3.1

Table 3.1 Volume specifications for the laboratory

Item	Description	Volume [m^3]
Piping	Plastic, rubber and silicon piping	0.0380
F-001	Vertical gas-liquid separator	0.0967
W-002	Heat exchanger, cooling	0.0012
Total volume	Piping, F-001, W-002	0.1359

Gas volume fraction (GVF) and liquid volume fraction (LVF) measurements are included in Table 3.2. These are based on calculated values, and there may exist deviation from the real process conditions.

Table 3.2 GVF and LVF for the laboratory

GVF [%]	LVF [%]	V_{water} [l]	V_{water} [l]**	V_{gas} [m^3]	V_{gas} [m^3]**
95	5	6.795	1.96	0.1291	0.00196
96	4	5.436	1.568	0.1305	0.00157
97	3	4.077	1.176	0.1318	0.00118
98	2	2.718	0.784	0.1332	0.000784
99	1	1.359	0.392	0.1345	0.000392
99.5	0.5	0.6795	0.196	0.1352	0.000196
100	0	0	0	0.1359	0

** - no separation

3.1 Laboratory startup

This section contains the preliminary procedure for startup and initiation of the facility with dry or wet gas. The following operations indicated in the section tables **must be followed from Table 1 to 3.**

1. MANUAL VALVE ADJUSTMENTS PRIOR LABORATORY STARTUP			
Step	Action/Activity	Description/check	Confirm/check
1	Close pneumatic supply valve	Close the supply valve located in the work shop	-
2	Connect pneumatic supply line to rig	Connect the rig pneumatic supply line from V1-006 to the connection point X01	-
3	Close V1-007	Manual air supply valve to turbine inlet	Leakages around quick-release connection
4	Close V1-006	Air supply valve to pneumatic line	-
5	Close V1-012	Air supply valve to pipeline	-
6	Open pneumatic supply valve	Open the work shop pneumatic supply valve to pressurize the supply line	Leakages around quick-release connection
7	Connect VU-001 to W-002 inlet	Connecting the hose to area water supply for the counter flow cooler	Leakages at the bottom connection
8	Connect water hose to W-002 outlet	Connect outlet of W-002 to water hose and place it in the area drainage	-
9	Open VU-001	Open the water supply valve approximately 10-20%	Leakages, steady flow from the cooler to the drainage
10	Proceed to Table 2.	-	-

2. LABORATORY POWER SUPPLY CONNECTION			
Step	Action/Activity	Description/check	Confirm/check
1	Close the control cabinet door	Closing the door allows powering the main circuit.	For foreign objects inside the cabinet
2	Connect the main power cord	Locate and connect the main power cord (400V-red) to the main socket (red below cabinet)	Connection is proper
3	ES01-02 to NC	Check if the emergency stop switches are set to NC (pull out)	The system will not be power if ES01-02 = NO
4	Turn S1 to ON	System on/off switch S1	PL2 = green

5	Turn S3 to ON	24 VDC power supply to control valves	PL4 = green
6	Verify water pump circuit	Check if the water pump circuit has a fault	PL6 = No light If RED, go to Section 6
7	Verify cabinet fan running	Check if the cabinet fan (QF01) is operational and working	If not, go to Section 6
8	Proceed to Table 3.	-	-

3. LABORATORY SOFTWARE STARTUP			
Step	Action/Activity	Description/check	Confirm/check
1	Start Labview Software	Locate the software in the start menu	-
2	Run global.vi	.vi located in folder "Labview/global/global.vi"	-
3	Connect DAQ to USB	Connect the DAQ to the USB port on the computer	-
4	Set to RUN mode	Set the Labview program to run (upper left corner arrow)	-
5	Verify transmitter readings	Pressure and temperature readings	Readings reflect real values
6	Verify safe working conditions	Locate the alarm list in the HMI and acknowledge	Alarm list, post-fault logs
7	Check control valve positions	Locate the control valve positioning feedback in the HMI and check with Table 3.3	0% - closed 100% - open
8	Proceed to Section 3.1.1 or 3.1.2		

Table 3.3 – Control valve positions

Control valve positioning protocol			
Item	Description	Value	Check
CH01	Choke valve downstream of check valve V3-002	Full open, 1 (100%)	-
CH02	Choke valve downstream of water pump P-001	Full open, 1 (100%)	-
CV01	Anti-surge compressor control valve	Fully closed, 0 (0%)	-
CV02	Turbine air supply valve	Fully closed, 0 (0%)	-

3.1.1 Dry gas startup

After performing the tasks in Section 3.1, the dry gas startup can be executed.

DRY GAS STARTUP			
Step	Action/Activity	Description/check	Confirm/check
1	Close V1-013	Liquid injection port valve	Connection leakages
2	Close V1-012	Rig air supply valve to pipeline	-
3	Open V1-007	Manual air supply valve to turbine inlet	-
4	Open V1-006	Rig air supply valve	-
5	Open V1-012	Rig air supply valve to pipeline	MAN02 = 2 barg
6	Close V1-012	Air supply to piping valve after step 4 is done	Leakages (large decline in pressure at MAN02)
7	Proceed to CASE D-F	-	-

3.1.2 Wet gas startup

After performing the tasks in Section 3.1, the wet gas startup can be executed.

WET GAS STARTUP			
Step	Action/Activity	Description	Confirm/check
1	Close V1-007	Manual air supply valve to turbine inlet	Leakages around quick-release connection
2	Close V1-006	Rig air supply valve	-
3	Close V1-012	Rig air supply valve to pipeline	-
4	Close V1-001	Bypasses separator (F-001)	-
5	Close V1-002	Close separator inlet valve (F-001)	-
6	Close V1-003	Close inlet supply to piston compressor (V-001)	-
4	Close V1-005	Close outlet to piston compressor (V-001)	-
5	Close V1-011	Centrifugal compressor (V-002) bypass	-
6	Measure system LVF	Measure LVF for pipeline volume to achieve desired GVF	According to <i>Table 3.1</i>
7	Connect supply to V1-013	Liquid injection hose to the injection port	-

8	Fill liquid	Pour measured liquid into the system	Check for leakage around port
9	Close V1-013	Liquid Injection port valve	-
10	Connect supply to X01	Work shop air supply hose to air supply connection	Leakages around quick-release connection
11	Open V1-006	Rig air supply valve	-
12	Open V1-012	Rig air supply valve to pipeline	MAN02 = 2 barg
13	Close V1-012	Rig air supply valve to pipeline	-
14	Open V1-007	Manual air supply valve to turbine inlet	Leakages around turbine inlet
15	Proceed to Case A-C	-	-

4 Laboratory operation (Case A – F)

4.1 Wet gas compression cases

Case A: Subsea separation and gas compression (Separator, piston compressor and centrifugal compressor)			
Step	Action/Activity	Description	Check
1	Open VU-001	Supply counter flow cooler (W-002) with water	Leakages around connections
2	Close V1-001	Close separator (F-001) bypass	-
3	Close V1-004	Close piston compressor (V-001) bypass	-
4	Close V1-011	Close bypass valve for centrifugal compressor (V-002)	-
5	Open V1-002	Open separator (F-001) inlet valve	-
6	Open V1-003	Open piston compressor (V-001) inlet	-
7	Open V1-005	Open piston compressor (V-001) outlet	-
8	Open V1-008	Open centrifugal compressor (V-002) inlet	-
9	Open V1-010	Open centrifugal compressor (V-002) outlet	-
10	Switch S3 to ON	Turn on the oil pump, centrifugal compressor cooling	Check green light at PL3
Software steps			
1	Set desired set point for V-002 speed	Done in Labview, global.vi. This will gradually supply the turbine with air to generate torque to the compressor shaft	Leakages around centrifugal compressor
2	Read PT04	Read pressure at V-001 outlet	Verify if reading is below 6 barg
3	Fix speed of V-001	Set to constant speed, check if control algorithm ensures this	-

Case B: Subsea separation and gas compression (Separator and Centrifugal Compressor)			
Step	Action/Activity	Description	Check
1	Open VU-001	Supply counter flow cooler (W-002) with water	Leakages around connections
2	Close V1-001	Close separator (F-001) bypass	-
3	Close V1-003	Close piston compressor (V-001) inlet	-
4	Close V1-005	Close piston compressor (V-001) outlet	-
5	Open V1-002	Open separator (F-001) inlet	-
6	Open V1-004	Bypass piston compressor (V-001)	-
7	Close V1-011	Close centrifugal compressor (V-002) bypass	-
8	Switch S4 to ON	Turn on the oil pump, centrifugal compressor cooling	Check green light at PL3
Software steps			
1	Turn ON the frequency converter	Switch the power supply on to the frequency converter.	-
2	Set desired speed for V-001	In PROGRAM set the VFD frequency to (see documentation for conversion between frequency and speed)	-
3	Read PT05	Read pressure at outlet of V-001	Verify if ok/reached desired
4	Set desired set point for V-002 speed	Done in Labview, global.vi. This will gradually supply the turbine with air to generate torque to the compressor shaft	Leakages around centrifugal compressor
5	Read PT04	Read pressure at V-001 outlet	Verify if reading is below 6 barg
6	Fix speed of V-001	Set to constant speed, check if control algorithm ensures this	-

Case C: Direct inlet wet gas compression (Centrifugal Compressor)			
Step	Action/Activity	Description	Check
1	Open VU-001	Supply counter flow cooler W-002 with water	Leakages around connections
2	Close V1-002	Close separator (F-001) inlet	-
3	Close V1-003	Close piston compressor (V-001) inlet	-
4	Close V1-005	Close piston compressor (V-001) outlet	-
5	Close V1-011	Close centrifugal compressor (V-002) bypass	-

6	Open V1-001	Bypass separator (F-001)	-
7	Open V1-008	Open centrifugal compressor (V-002) inlet	-
8	Open V1-010	Open centrifugal compressor (V-002) outlet	-
9	Switch S4 to ON	Turn on the oil pump, centrifugal compressor cooling	Check green light at PL3
Software steps			
1	Gradually open CV-02	Gradually supply the turbine with air to generate torque to the compressor shaft	Leakages around centrifugal compressor
2	Set desired set point for V-002 speed	Done in Labview, global.vi. This will gradually supply the turbine with air to generate torque to the compressor shaft	Leakages around centrifugal compressor
3	Read PT04	Read pressure at V-001 outlet	Verify if reading is below 6 barg
4	Fix speed of V-001	Set to constant speed, check if control algorithm ensures this	-

4.2 Dry gas compression cases

Case D: Dry Gas Compression, piston and centrifugal compressor			
Step	Action/Activity	Description	Check
1	Open VU-001	Supply counter flow cooler (W-002) with water	Leakages around connections
2	Close V1-002	Close separator (F-001) inlet	-
3	Open V1-003	Open piston compressor (V-001) inlet	-
4	Open V1-005	Open piston compressor (V-001) outlet	-
5	Close V1-004	Close piston compressor (V-001) bypass	-
6	Close V1-011	Close centrifugal compressor (V-002) bypass	-
7	Open V1-001	Bypass separator (F-001)	-
8	Open V1-008	Open centrifugal compressor (V-002) inlet	-
9	Open V1-010	Open centrifugal compressor (V-002) outlet	-
10	Switch S4 to ON	Turn on the oil pump, centrifugal compressor cooling	Check green light at PL3
Software steps			
1	Turn ON the frequency converter	Switch the power supply on to the frequency converter.	-
2	Set desired speed for V-001	In PROGRAM set the VFD frequency to (see documentation for conversion between frequency and speed)	-
3	Read PT05	Read pressure at outlet of V-001	Verify if ok/reached desired
4	Set desired set point for V-002 rpm	Done in Labview, global.vi. This will gradually supply the turbine with air to generate torque to the compressor shaft	Leakages around centrifugal compressor
5	Read PT04	Read pressure at V-001 outlet	Verify if reading is below 6 barg
6	Fix speed of V-001	Set to constant speed, check if control algorithm ensures this	-

Case E: Dry Gas Compression, piston compressor			
Step	Action/Activity	Description	Check
1	Open VU-001	Supply counter flow cooler (W-002) with water	Leakages around connections

2	Close V1-002	Close separator (F-001) inlet	-
3	Open V1-001	Open separator (F-001) bypass	-
4	Open V1-003	Open piston compressor (V-001) inlet	-
5	Open V1-005	Open piston compressor (V-001) outlet	-
6	Close V1-004	Close piston compressor (V-001) bypass	-
7	Open V1-011	Open centrifugal compressor (V-002) bypass	-
8	Close V1-008	Close centrifugal compressor (V-002) inlet	-
9	Close V1-010	Close centrifugal compressor (V-002) outlet	-
Software steps			
1	Turn ON the frequency converter	Switch the power supply on to the frequency converter.	-
2	Set desired speed for V-001	In PROGRAM set the VFD frequency to (see documentation for conversion between frequency and speed)	-

Case F: Dry Gas Compression, centrifugal compressor			
Step	Action/Activity	Description	Check
1	Open VU-001	Supply counter flow cooler (W-002) with water	Leakages around connections
2	Close V1-002	Close separator (F-001) inlet	-
3	Open V1-001	Open bypass of separator (F-001)	-
4	Close V1-003	Close piston compressor (V-001) inlet	-
5	Close V1-005	Close piston compressor (V-001) outlet	-
6	Open V1-004	Open bypass of piston compressor (V-001)	-
7	Close V1-011	Close bypass for centrifugal compressor (V-002)	-
8	Open V1-008	Close centrifugal compressor (V-002) inlet	-
9	Open V1-010	Close centrifugal compressor (V-002) outlet	-
10	Switch S4 to ON	Turn on the oil pump, centrifugal compressor cooling	Check green light at PL3
Software steps			
1	Set desired set point for V-002 rpm	Done in Labview, global.vi. This will gradually supply the turbine with air to generate torque to the compressor shaft	Leakages around centrifugal compressor
2	Read PT04	Read pressure at V-001 outlet	Verify if reading is below 6 barg
3	Fix speed of V-001	Set to constant speed, check if control algorithm ensures this	-

5 Shut down procedure

The following operation table shows the procedure to perform a shutdown of the laboratory.

Shutdown - Manual instructions			
Step	Action/Activity	Description	Check
1*	Ramp down M-001	Ramp down the speed of the piston compressor to avoid damage to internal crankshaft	Verify that the compressor is not running
2	Go to step 1 in software instructions	-	-
3	Switch S4 to OFF	Shutting off the oil pump for centrifugal compressor cooling	-
4	Close VU-001	Shut off the water supply to counter flow cooler (W-002)	-
5	Open V1-002	Open separator (F-001) inlet	-
6	Close V1-013	Ensure the air supply valve is closed	-
7	Close workshop air supply valve	Close the work shop air supply valve and ensure there are no pressure at rig supply point X01	-
8	Open V1-006	Rig air supply valve	-
9	Open F-001 drainage valve	Locate the drainage hose for F-001 and gradually open to depressurize system	-
10	Close F-001 drainage valve	Ensure that the air is at 0 barg at MAN02, if not = wait with closure of F-001 drainage valve	MAN02 = 0 (1 atm)
11	Go to step 3 in Software instructions	-	-
Shut down - Software / Electrical steps			
1	Set global.vi to <initiate manual shutdown>	Shut down ensures opening of all critical valves to reduce pressure in the system	-
2	Go back to step 3 in manual instructions	-	-
3	Switch S1 to OFF	Shutting off the power supply to M-001 to 3	-
4	Disconnect DAQ from USB	-	-

* Can be excluded if not operating with piston compressor in test loop

6 Troubleshooting

1. No readings from measurement I/O
Solution proposal: Check USB connection to computer. Restart Labview and locate potential wire breaks to control cabinet.
2. Program goes to SHUTDOWN MODE immediately
Solution proposal: Check the pressure and temperature readings of the system, and if the values are beyond what is recommended.
3. PL6 light is red, water pump **is not running** or motor protection circuit breaker has tripped
Solution proposal: Turn of the system equipment. Switch off the power supply (S1) and call certified personnel to inspect the water pump and control cabinet.
4. Cabinet fan is not working
Solution proposal: Turn of the system equipment. Switch off the power supply (S1) and call certified personnel to inspect the fan circuit inside the control cabinet

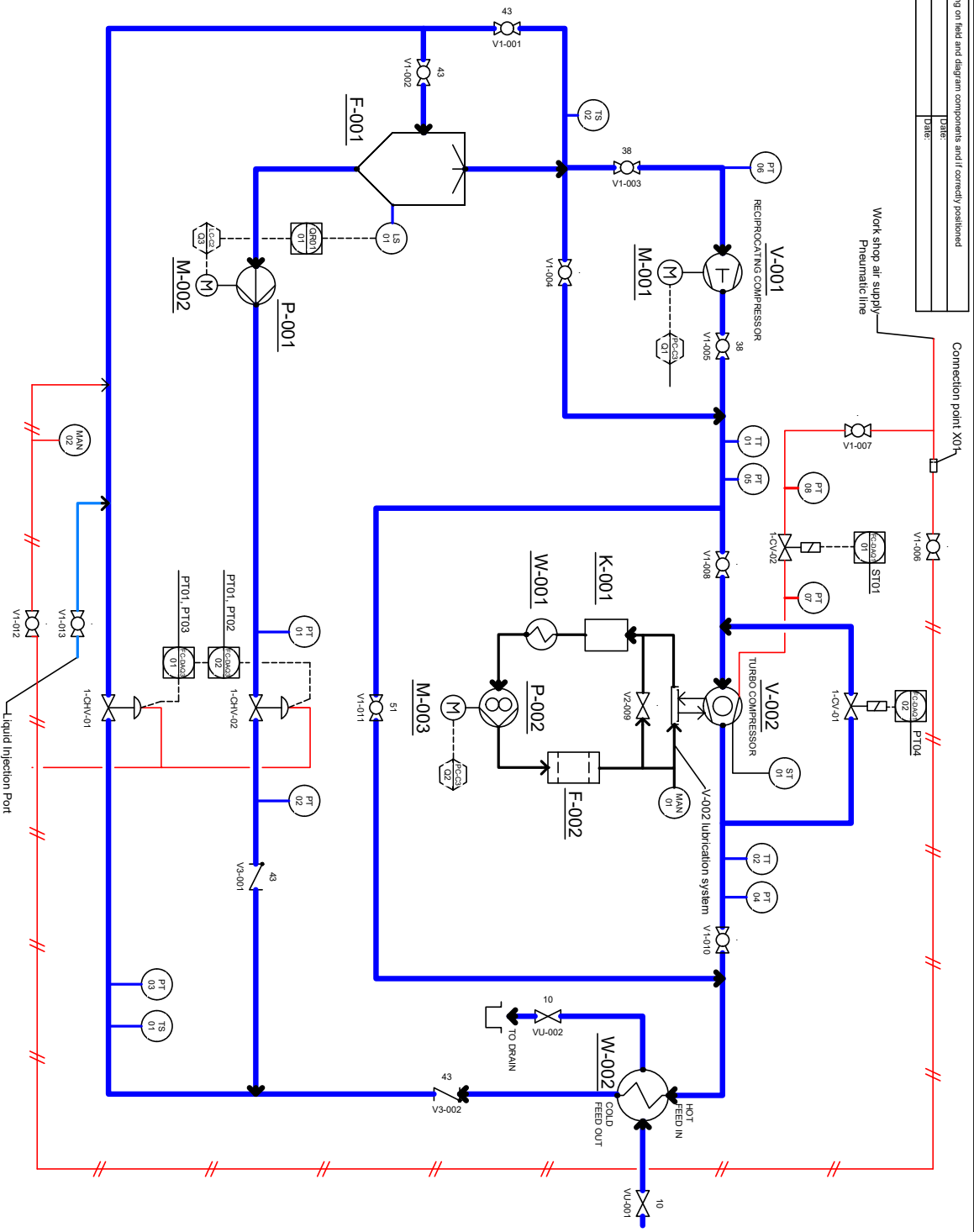
Comment to 3: PL6 is wired on the NC pair on the motor protection relay for C2-water pump circuit. This ensures that when the circuit is powered and the water pump is not running, the pilot light glows. This is a design issue, since the motor protection relay does not have a separate contact pair for fuse trip. Therefore, it is wired to the NC pair.

If non of the above is a solution, please consult laboratory responsible.

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FAT: Control labeling on field and diagram components and if correctly positioned
 Signature: _____ Date: _____
 Signature: _____ Date: _____



Legend:
 W - Heat Exchangers | F - Separator | K - Reservoir (Oil) | P - Pump | M - Motor drive
 V1 - Ball Valve | V2 - Needle Valve | V3 - Check Valve | VU - Valve Utility | CV - Control Valve | CHV - Choke Control Valve
 LS - Level Sensor | TS - Temperature Sensor | TT - Temperature Transmitter | ST - Speed Transmitter | PT - Pressure Transmitter | MAN - Manometer
 FC - Pressure Controller | LC - Level Controller | FC - Flow Controller | DAA - Data Acquisition Unit (Measurement and Control I/O)

Legend:
 P&ID for process laboratory
 Wet Gas Compression
 Designed by: N.T. JON
 Rev: 06-24/05-17 N.T.
 Date: 13.03.2017
 Scale: A4
 Sheet 1 of 1

**Department of Mechanical and Industrial Engineering (MTP), NTNU
 Subsea Process Control Laboratory**

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