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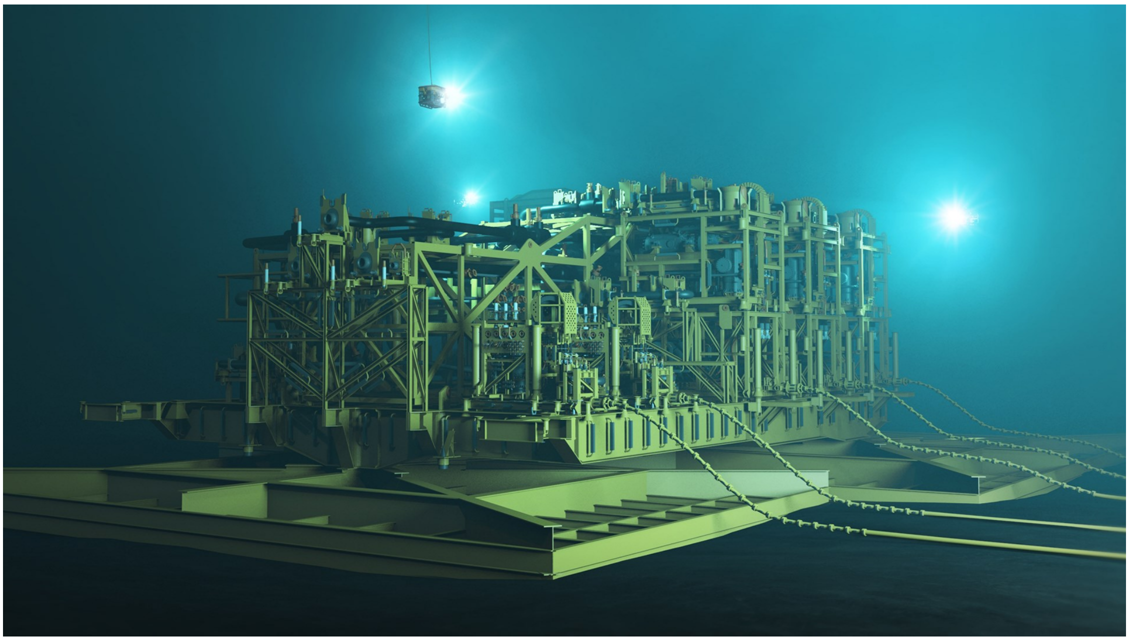

Nitrogen Commissioning of a Subsea Compression Station

An investigation of how process equipment intended for natural gas is affected by operating with nitrogen

Master's thesis in Sustainable Energy Systems

PHILIP JONSSON

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
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www.chalmers.se

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Supervisor: Andrew Grant, Aker Solutions
Examiner: Henrik Ström, Mechanics and Maritime Sciences

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Department of Mechanics and Maritime Sciences
Division of Fluid Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: 3D render of the subsea compression station. Courtesy of Aker Solutions [1].

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Abstract

In some cases, offshore natural gas production requires compression to transport the gas onshore. To increase resource efficiency, the compression can be done on the seabed instead of on topside. Unmanned subsea compression stations are low carbon solutions to natural gas extraction, where losses common to topside platform processing are mitigated, often with the added benefit of increasing well lifetime. After installation on the seabed, the station is commissioned using nitrogen to test process equipment and process safety systems, prior to introducing hydrocarbons. As the system is designed for hydrocarbons, operating conditions with nitrogen may be different with regards to compressor performance, cooling etc. Incorrect operation with N2 might cause catastrophic damage of equipment.

This work, carried out in cooperation with Aker Solutions, aims to investigate the effects of nitrogen on the operation of a subsea compression station. Specific focus is placed on individual process equipment by investigating the thermodynamics at play using process simulations. The thesis content is limited to the commissioning activities related to a compressor, where it is operated in a closed loop. Nitrogen gas is compressed and recycled to a cooler and a scrubber before re-entering the compressor. In addition process gas is extracted from the compressor to provide compressor motor cooling.

Process simulations are carried out using the dynamic process simulator K-Spice. Results are discussed and analyzed, where limiting factors and recommendations of commissioning activities with nitrogen are presented. It was shown that nitrogen will significantly limit the operating envelope of the compression station.

Keywords: Nitrogen, Methane. Subsea, Compression, K-Spice, Process, Thermodynamics, Natural Gas, Production

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Philip Jonsson, Gothenburg, June 2023

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Introduction

1.1 Aim

Aker Solutions is constructing a compression station for the production of natural gas for energy production. During installation of the station, a commissioning phase is carried out where compressors are operated with nitrogen gas instead of the intended process fluid, which is a mix of natural gas and condensate (liquid hydrocarbons). This is done in a closed loop where the nitrogen is run through a passive cooler and scrubber before being sent to the compressors and later recycled back. The compressor is then tested by running different sequences and altering operating conditions to evaluate the readiness of the station, before the hydrocarbons are introduced to the system. A key goal of the commissioning activities is to map as much as possible of the compressor operating envelope.

The properties of the hydrocarbon fluid are different to the properties of nitrogen, which implies that differences in operating conditions are to be expected. Owing to the differences in fluid properties, valuable information can be gained on the operability of the station by analyzing the differences when running with hydrocarbons or nitrogen. This can yield data on how the station will actually run based on the operating data gained from running on nitrogen, before any hydrocarbons are introduced.

The thesis will investigate the differences in running a compressor station using nitrogen instead of hydrocarbons. Process equipment that is significantly affected by operating with nitrogen will be investigated as well as the reasons for this. Recommendations for performing commissioning activities for a subsea compression station and similar systems will be given.

1.2 Subsea production and processing systems

Subsea production systems almost always include subsea christmas trees, flowlines and manifolds, and increasingly subsea processing operations are also present. Subsea christmas trees are named after their similarity to christmas trees. They are an assembly of valves, spools and fittings placed on the well and are used to regulate the flow coming from the well. Flowlines from the well connect to the manifolds where production from several wells enter and are combined into one flowline, in order to send the flow to the correct location.

Subsea processing systems are systems which process well fluids subsea. In this case that is a subsea compression station which provides pressure boosting of natural gas and small amounts of condensate. Compression is required to maintain similar production rates from a gas field for as long as possible.

An attractive solution to keep CAPEX low is the transport of both natural gas and condensate in a common pipeline for further processing on-shore. This creates a demand for a minimum flow velocity as the multiphase nature of the flow in the pipeline could become unstable or generate slugs if the velocities inside are too low. If the compression is done close to the well, on the seabed, the density of gas in the pipeline will be higher than for topside processing, reducing the velocity, which can decrease the required pipeline diameter [2]. Subsea compression stations delay the onset of these unstable flow regimes within the export pipeline since a lower pressure in the well (lower suction pressure) is accepted. Figure 1.1 shows the flowsheet of a typical subsea compression process with dry gas compression and mixing of boosted liquids with compressed gas.

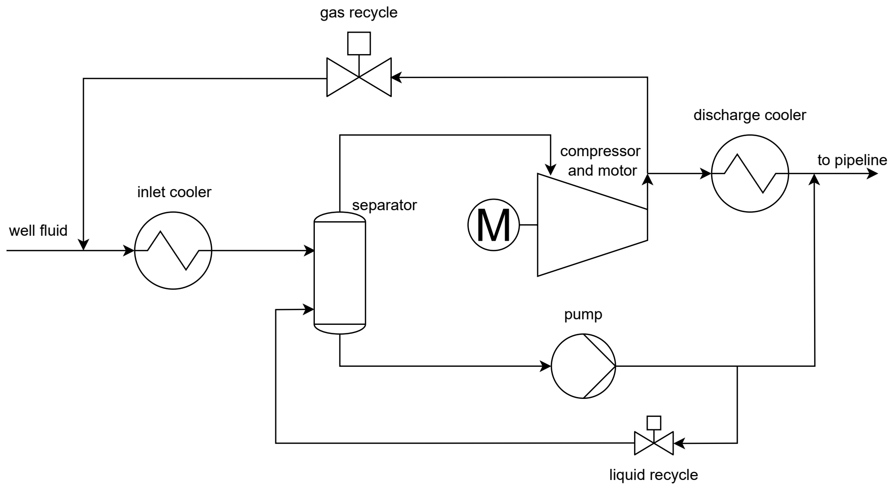


Figure 1.1: Flowsheet of a typical subsea compression process

The reasons for using a subsea compression station are plenty. A main reason for its application is the demand for reduction of CAPEX and OPEX. These are reduced due to the reduction in amount of equipment which would otherwise be needed for topside systems, such as floating structures. OPEX is reduced in the form of lower personnel costs since remote operation does not require on-site personnel with extensive training required [2]. The lifetime of the well is also increased due to the higher velocities that can be achieved in the pipeline.

1.3 Ethical considerations

Energy production from natural gas is an important and reliable component of energy systems around the world. It also makes it possible for countries that have been dependent on coal to reduce their carbon emissions for energy production

[3]. As the energy demand in many countries is increasing fast, this makes the transition to renewable energy a great challenge. Instead of expanding coal or oil production natural gas can quickly provide energy at a lower carbon footprint, as specific emissions from natural gas can be 50% and 20% lower compared to coal and oil respectively [4]. It can be argued that the expansion should be done by fossil-free energy, however natural gas provides a middle ground in cutting out the worst emitters, i.e. coal and oil, while allowing implementation of renewables in the energy system through the provision of dispatchable power when the wind is not blowing or the sun is not shining. Subsea compression stations allow for more efficient natural gas extraction which can reduce the emissions coupled with the extraction of natural gas [1]. Reduction in emissions from fossil fuel extraction can yield a large reduction in greenhouse gas emissions as extraction processes are responsible for up to 10% of global emissions [5].

Development of subsea processing systems can help natural gas extraction in the North sea by increasing production and prolonging the life of fields. Thus reducing European reliance of natural gas from Russia.

Natural gas also plays a role in regulating power where the energy system is dominated by intermittent energy sources, i.e. solar and wind, as gas turbines are designed to easily be brought on- and off- line in a short time span. This is especially important where the intermittent sources are a large share of the energy system and other regulating power sources are not at a mature enough level, such as hydrogen or batteries.

The subsea compression stations are also unmanned, which greatly reduces risk for operators. The alternative is an offshore platform, which brings many risk factors for the operators working there.

2

Theory

The aim of this chapter is to present necessary background information for the thesis work. First a description of the process investigated is given, followed by the underlying theory behind the K-spice solver and how thermodynamic calculations are handled. Finally relevant background and theory is provided about equipment and how equipment that sees nitrogen will be influenced by nitrogen compared to natural gas from a process and thermodynamic point of view.

2.1 Process description

The compression station consists of three compressors working in parallel to compress natural gas for export from the seabed to further onshore processing [1]. In short the gas will first enter a cooler that passively cools the fluids using the surrounding seawater. Next the fluids enters the scrubber, which is a separator, where liquids are separated from the gas. The gas is then sent to the compressors where the pressure is increased. After this the gas is cooled in a discharge cooler and then sent for pipeline export. The liquids are boosted by a pump and later commingled with the compressed gas and sent to export.

During the commissioning phase the compressors operate in recycle in a closed loop running with nitrogen as the process fluid. Commissioning activities are done with nitrogen as it is an inert gas and is often utilized for commissioning in a safe atmosphere [6]. In recycle operation the gas is routed through the anti-surge lines after the compressor, which sends the gas back to the inlet cooler. In the anti-surge line the pressure of the gas is reduced by a valve in order to handle the pressure increase achieved from the compressors.

Normally the function of the anti-surge system is to avoid surge in the compressor, which is when the compressor is running at too high speeds for the flow through the compressor. The anti-surge system then routes gas back to the compressor to increase the flow over the compressor so that surge is avoided, at the cost of extra energy needed to increase the pressure of recycled gas [7].

A schematic of the simulated system can be seen in figure 2.1.

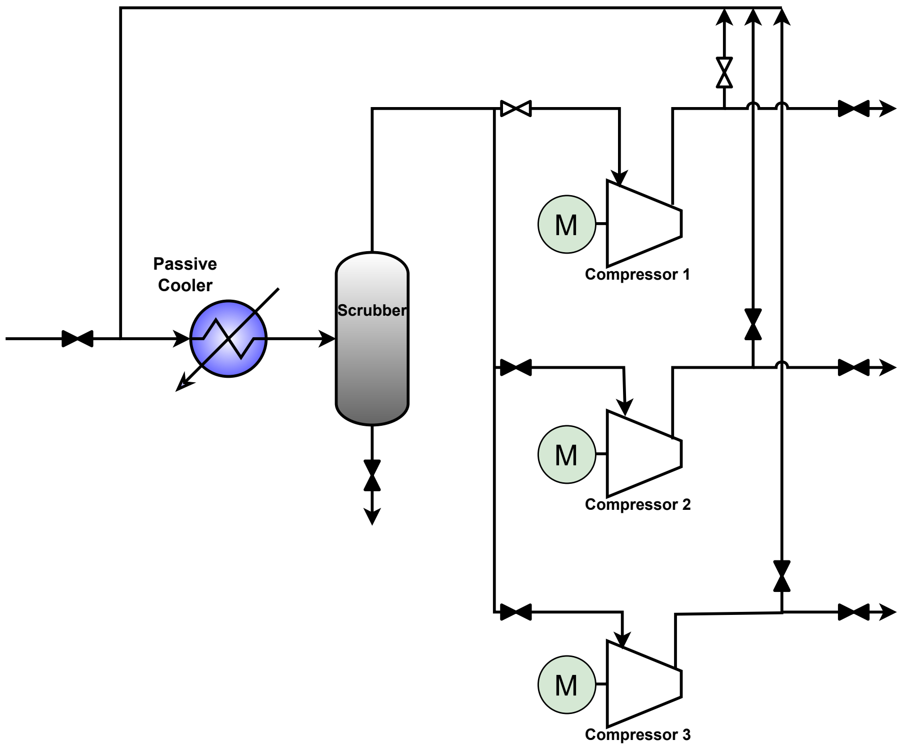


Figure 2.1: Flowsheet of the closed loop cycle.

From the picture above the system has three compressors in parallel operation, however during commissioning only one compressor is operated at a time. The other compressors as well as the pump are isolated by valves.

2.2 Process modeling

2.2.1 Dynamic process simulation

A dynamic process simulator solves mass and energy balances in a process system in a time-varying manner by introducing time derivatives to conservation equations. The equations are then solved using numerical methods with implicit integration in order to solve the process system. More specifically, the model is a collection of calculation blocks that are calculated in sequence, in order to obtain the solution and thereby the process behaviour. A unit operation is represented by these blocks, such as vessels, compressors, valves, and so on. Each unit operation contains algorithms that perform the required calculations for that block. The blocks build up the model by being connected to each other, where the connection is represented by for example flow of material, flow of power or a signal [8].

The dynamic behaviour of the process stems from the fact that process equipment typically has a holdup volume, which results in a time delay between when changes are made at inlet and when the change is seen at the outlet. The holdup model can be different depending on type of process equipment and its function. The holdup comes from fluid accumulation in the equipment, which has the basic equation [9]:

$$Accumulation = Flow\ in - Flow\ out \tag{2.1}$$

In K-spice, the conservation equations are set-up and solved by creating a Pressure-flow network (P-F Network).

2.2.2 Pressure-Flow Network

In a P-F network the model is divided into cells (unit operation), where each cell contains a pressure node and a flow element. The flow element defines flow between pressure nodes. The pressures feeding into the flow element come from pressure nodes between the flow element. The pressure is calculated in the pressure node based on the flow from the flow elements [8].

Based on this, each unit operation will have at least 2 equations that will combine to describe the relationship between the flows and the pressures in the network. A valve will have a resistance equation that defines a flow based on inlet and outlet pressures, and a flow relation that describes the flow through the valve. A typical resistance equation for a valve is [10],

$$F = k\sqrt{P_{in} - P_{out}} \tag{2.2}$$

where F is mass flow, P is pressure and k is flow conductance for the valve. Similarly, a typical flow relation for a valve is,

$$F_{in} = F_{out} \tag{2.3}$$

since a valve typically will have negligible holdup, i.e. the valve does not have any significant hold-up volume.

Similar equations can be set-up for other unit operations, such as mixers, compressors, pipe segments, and so on. For a vessel with two outlets, the equations will be a pressure relation and a volume balance relation. If neglecting elevation head the pressure relations is,

$$P_{vessel} = P_{in} = P_{out,1} = P_{out,2} \tag{2.4}$$

which yields three equations. The volume balance equation is given by [8],

$$\frac{dP_{vessel}}{dt} = f\Big(P, T, holdup, flows\Big) \tag{2.5}$$

where P is the pressure in the vessel, T is temperature, holdup is holdup time in the vessel and flows are the flows in and out of the vessel.

Combining a valve and the vessel as in figure 2.2, shows a simple process.

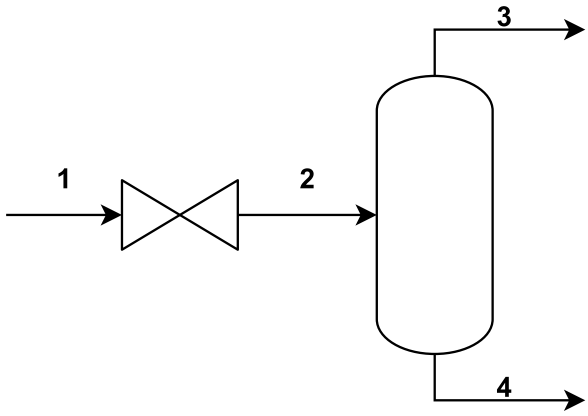


Figure 2.2: Example of a simple flowsheet

In this flowsheet there are 4 streams and one vessel, which will have a holdup. To fully define this P-F network there will be 9 variables to solve (2 per stream and one for the holdup). The holdup is not a part of the P-F network but is required to solve the volume balance equation in the vessel [8]. From before the valve yields 2 equations and the vessel yields 4 equations. This leaves three variables which must be defined. This is the same number of streams that crosses the system boundaries.

If the system instead was a closed loop there would be no stream variables needed to be defined and the flow through the system will be entirely defined by other inputs into the system, for example compressor power/speed or valve positions. These inputs could then be interpreted as variables crossing the system boundaries, since apart from the initial conditions these will be the attributes determining the flow in the system.

2.2.3 Thermodynamics

Process modeling requires thermodynamic models for calculating the thermodynamic properties and phase equilibrium. The modeling of process equipment will most often provide the fluid composition as well as two specifications for each stream (such as pressure and temperature). The rest of the thermodynamic properties must then be modeled by thermodynamic models, such as by using an equation of state model.

For the work in this thesis, the application Multiflash is used to generate the thermodynamic properties. For faster simulations, the thermodynamic properties can be generated in tables based on temperature, pressure and component compositions. This will allow the thermodynamic property to be found using table lookup, instead of calculating the property equations for each time-step and iteration, which is more computationally demanding.

2.3 Process equipment

This section describes the different process equipment that will be present in the model. How the equipment is modeled is also presented. Of note is that some equipment is not always modeled based on physical properties but rather by more rough assumptions or by fitting equations to simulation or test data, which is often used for commercial models where accuracy for that specific use is required (for instance, the inlet cooler).

2.3.1 Compressors

Compressors increase the pressure of gas by increasing the kinetic energy of the gas with an impeller. The energy is then converted to static pressure when the gas flow is slowed down through a diffuser inside the compressor.

The compressor is modeled using compressor curves, which relate the pressure differential to the compressor speed and volume flow [7]. A typical compressor characteristic curve is shown in figure 2.3.

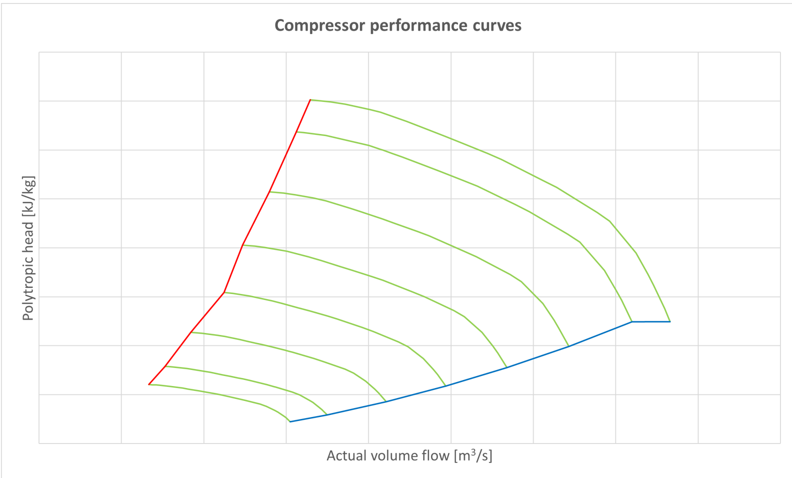


Figure 2.3: A typical compressor characteristic curve

The figure shows the surge line to left (red line) and the stonewall line to the right (blue line). As the operating point reaches the surge line, the remedy is to either increase the flow through the compressor or to decrease the compressor speed and vice versa for approaching stonewall line.

Tis particular type of compressor (HOFIM) has a cooling gas off-take between impellers internally in the compressor, and therefore the compressor is modeled as two stages to allow for the cooling gas to be modeled accurately.

Key characteristics of the compressor that needs to be captured [11]:

- Compressor curves: Performance map of the compressor that captures the efficiency and head gain from the compressor depending on the compressor speed and volume flow.

- Heat generated in the compressor motor: to capture the required amount of gas to extract to the cooling gas loop in order to cool the motor during operation.

Compressor head is a way of representing pressure increase and shows how much energy is required to transfer a mass unit of gas to a given pressure. For a real compressor this is called polytropic head. The polytropic head for a compressor will depend on the molecular weight, compressibility factor and the polytropic exponent of the fluid. This relationship can be seen in the equation for calculating polytropic head (constant entropy) of a compressor, which shows absorbed compressor power per kg of gas for a given pressure increase [7][11],

$$H_p = \left(\frac{n}{n-1}\right)\left(\frac{ZRT_1}{MW}\right)\left(\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right) \tag{2.6}$$

where H_P is the polytropic head (kJ/kg), n is the polytropic exponent (which is related to the heat capacity ratio and polytropic efficiency of the compressor), Z is the compressibility factor, R is the gas constant, MW is the molecular weight, T is temperature and P is the pressure (index 1 being suction and 2 discharge).

The head of the compressor is related to the power required by the compressor, where the head increase of the compressor will be the power demand of the compressor minus losses. It can be seen from equation 2.6 that if the mass flow increases the power required by the compressor will have to increase to reach the same discharge pressure.

A compressor generally has a maximum allowed power, as well as a maximum allowed torque. The power demand of a compressor will depend on the type of fluid and the desired discharge pressure. Compressor torque has the following relation [12],

$$Power = Torque \cdot \omega \tag{2.7}$$

Where ω is the angular velocity in rad/s and can be calculated from the compressor speed in RPM. Looking at equations 2.6 and 2.7, the maximum limit that will be reached is dependent on the mass flow through the compressor, as well as the type of fluid used.

Surge

Surge is a condition in compressor operation where the compressor is operating at lower flows than it is designed for. This leads to flow reversal within the compressor which results in unstable flow and fluctuating load on the compressor bearings [7]. Operating in this region therefore could cause damage to the compressor and has to be avoided. This is avoided by having an anti-surge recycle line such that if the flow unexpectedly reduces, the recycle line can increase the flow over the compressor in order to protect it.

During commissioning activities the anti-surge line is used as a main process line for recycling the nitrogen. Due to this the anti-surge control system will be temporarily modified to avoid entering surge conditions. In reality if surge conditions were to occur the anti-surge valve would be opened and the compressor speed reduced.

Stonewall

Operating in stonewall condition is not as extreme as surge, however it might still be damaging to the internal components of the compressor. Stonewall occurs when the flow velocity inside the compressor approaches Mach number 1. In these conditions an increase in flow corresponds with a steep decrease in head [13].

Operating in stonewall conditions should also be avoided during commissioning activities. Depending on the initial conditions of the closed loop it may not even be possible to reach stonewall conditions, if the amount of gas in the system is too low.

2.3.2 Compressor motor cooling

The heat transfer from the compressor casing to the ambient seawater is not enough and therefore cooling of the compressor motor is done by process gas. This is done by extracting gas from the middle of the compressor and routing it into the compressor motor. The temperature of the motor is a critical value as exceeding the allowed temperature might damage the compressor. For a subsea processing station this is of extra importance as replacing equipment is both costly and time consuming, compared to equipment that is not subsea. [2].

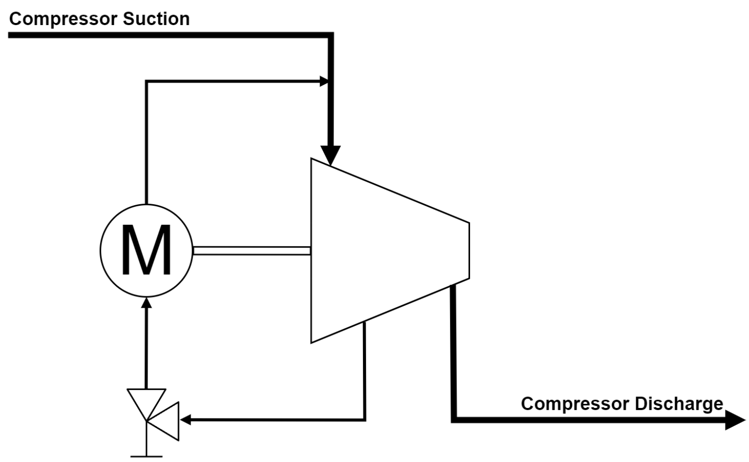


Figure 2.4: Flowsheet of the motor cooling gas system.

A simplified flowsheet of the compressor motor cooling gas system can be seen in figure 2.4. Cooling gas is extracted from the compressor after the second impeller in the compressor. A valve limits the amount of gas extracted to not recycle more gas than what is required. The gas is then routed to a gas scrubber which is there as a safety measure to ensure that no liquids reach the motor of the compressor. The cooling requirement from the motor is based on input by the compressor vendor and takes the form as heat flow based on compressor power. Heat flow to the gas from the motor is modeled as heat addition to the gas.

After the scrubber, gas is sent to the compressor motor where it will take heat from the motor. Thus cooling the motor by heating the cooling gas. The motor is not allowed to reach a set temperature, if that temperature is reached the control system will initiate a trip and the compressor will be shutdown. After the gas has cooled the motor it is routed back to the compressor suction. Routing more gas than is required will reduce the efficiency of the compressor, since more gas is recycled and therefore compressed unnecessarily.

The opening of the cooling gas valve is primarily based on a function of the compressor speed, a simplified sketch of this can be seen in figure 2.5.

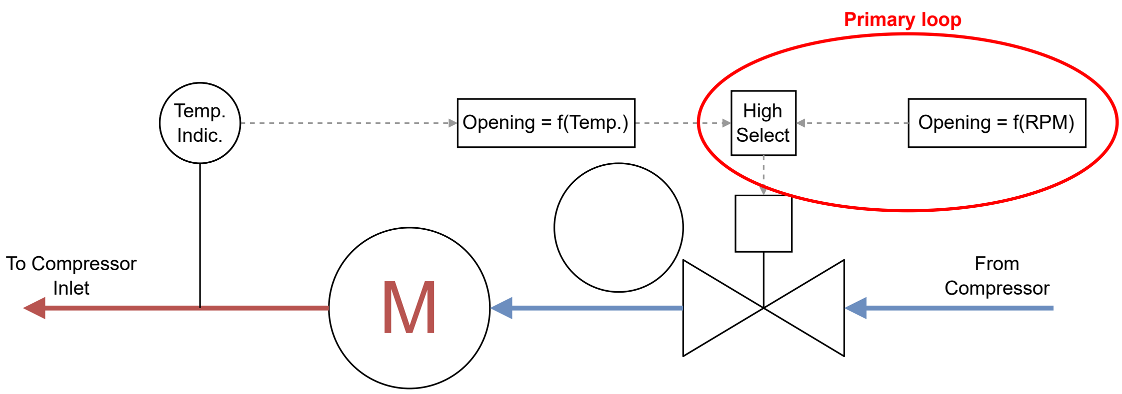


Figure 2.5: Sketch of the controls logic determining the amount of cooling gas flow to the motor.

The valve position is also connected to the temperature of the gas exiting the motor, where a temperature indicator sends the measured value to a controller that calculates the required opening and sends a signal to open the cooling gas valve to reach a certain temperature set-point. The final valve position is then chosen by a high-select function, which commands the actual valve position to be the highest of the two signals. If the temperature of the gas exiting the motor is at the temperature set-point, the cooling gas system is more strained than it would be at an equivalent compressor operating point during normal production.

2.3.3 Passive cooler

The cooler is a passive cooler which uses the surrounding ambient seawater as cooling medium. The duty of a cooler is given by,

$$Q = OHTC \cdot A \cdot \Delta T_{lm} \tag{2.8}$$

where Q is the heat flow, $OHTC$ is the overall heat transfer coefficient ($\frac{W}{m^2K}$), A is the heat exchanging area and ΔT_{lm} is the logarithmic mean temperature difference [14]. As the heat exchanger is designed, the area of the cooler is known. The inlet temperature will also be known from the process simulations. The other terms in equation 2.8 are unknown (Q, $OHTC$, ΔT_{lm}). These terms will be dependent on the conditions of the fluid entering the heat exchanger, such as mass flow, inlet temperature, etc. A correlation has been made which relates the $OHTC$ with the inlet temperature and mass flow. This leaves two unknowns in equation 2.8. To solve this an extra equation is needed which is the enthalpy change [14]:

$$\Delta H = Q = \dot{m} C_p \Delta T \tag{2.9}$$

Where ΔH is the change in enthalpy which is the same as energy lost Q, $\dot{m}$ is the mass flow, C_p is the specific heat capacity and ΔT is the temperature difference between the inlet and outlet.

Combining equations 2.8 and 2.9 allows all variables to be solved and the outlet temperature of the cooler can be determined.

Of note is that the cooler OHTC-correlation was done for natural gas, which means that it will not be as accurate for methane, since the thermodynamic properties of these are different. The accuracy of the OHTC-correlation for nitrogen is therefore unknown.

2.3.4 Gas scrubber

The role of the gas scrubber in offshore gas processing systems is to separate liquids from the gas, such that the compressors can operate with as dry gas as possible. Operating with dry gas is important, as liquids or contaminants might cause corrosive damage to compressor internals, which would be costly and require time intensive replacement of equipment.

Depending on which phase is dominant, the separator can be vertical or horizontal. If the gas phase is dominant there exist advantages with a vertical separator. A wide range of internal equipment exist that can be used in a scrubber, depending on the capacity, required efficiency of separation and type of contaminants or droplets. The simplest type of separation is with the aid of gravitational force where phases separate due to density differences. Other types use momentum and centrifugal force or coalescing equipment to handle small droplet sizes [15].

As the nature of this thesis assumes that there is only gas inside the system, phase separation will not be of importance. The gas scrubber can therefore be modeled as a vessel which will have a hold-up time, pressure drop and heat loss to the ambient seawater on the outside of the vessel.

2.3.5 Piping

The piping will have effects on the simulation and will need to be modeled. Piping will act as a holdup, produce a pressure drop and have heat flow. Holdup comes from the fact that there will be delay between fluids reaching different process equipment. Pressure drop is due to effects such as friction, elevation and pipe bends, which will impact the fluid. These factors depend on material selection due to roughness, size of bends and length of the piping [16]. Heat flow comes from the fact that the outside of the pipes are exposed to the ambient seawater which might have non-negligible heat transfer effects, although some piping has insulation which would make the heat transfer practically negligible.

2.3.6 Valves

The sizing and modeling of valves is done using the valve flow coefficient (C_v), which is interpreted as flow rate through a valve with a given pressure drop. The equation for valve sizing with incompressible fluids is:

$$C_v = Q\sqrt{\frac{SG}{\Delta P}} \tag{2.10}$$

where Q is volumetric flow rate, SG is specific gravity of the fluid and ΔP is the pressure drop over the valve [17]. Closing a valve will decrease the valve coefficient. Flow through a valve is therefore dependent on the opening of the valve and the available pressure drop over that valve, a high pressure drop over a valve will therefore yield a higher flow and vice versa.

2.4 Considerations for nitrogen

Equipment of extra interest for the analysis in this thesis is process equipment which has its effectiveness or properties changed by operating with nitrogen. The fluids will go through the compressor (where gas is also extracted to cool the motor in the cooling gas system), inlet cooler, gas-liquid separator and back to the compressor. Nitrogen will affect the compressor, the cooling gas system and the inlet cooler. As stated before the role of the scrubber is to separate gas from liquid and will therefore not have its effectiveness or properties changed in any significant way for the analysis done in this work.

Relating to the process as a whole, the heat balance of the closed loop will be of importance and the different thermodynamic properties will significantly alter the process.

$$Acc. = Q_{Motor} + Q_{compressor} - Q_{inletcooler} \tag{2.11}$$

Where for steady operation the accumulation term needs to equal zero. Implying that if the accumulation term is other than zero the fluids in the process will increase or decrease their energy until steady state is reached.

2.4.1 Thermodynamic properties

In Table 2.1 a comparison of nitrogen and methane for some fluid properties is shown. The fluid properties are calculated from thermodynamic models using Multiflash. As can be seen there are some differences, with the largest difference being specific heat capacity.

Table 2.1: Fluid properties for N_2 and CH_4 at 20°C and 150bara.

	Density	Conductivity	Heat capacity	Viscosity	Z-factor	Heat cap. ratio
	kg/m^3	W/m/K	J/kg/K	Pa·s	-	-
N_2	172,8	0,0251	1279	2,15E-05	0,998	1,62
CH_4	125,4	0,0335	3394	1,68E-05	0,787	1,87

Heat capacity

A large difference in thermodynamic properties between nitrogen and natural gas is the difference in specific heat capacity. The physical basis of heat capacity is how much energy the atom or molecule can store per increase in temperature unit. Temperature reflects the average kinetic energy of the particles in the measured sample. In "ordinary" conditions an isolated particle (atom) can only store a significant amount of energy in the form of kinetic energy, which directly translates to an increase in temperature. Polyatomic gases on the other hand are able to store energy in other forms as well, such as rotation. A linear molecule, i.e. nitrogen, has 2 rotational degrees and a non-linear molecule will have more, such as methane [18].

Nitrogen is the gas used during commissioning activities due to being an inert gas. It is desired that the gas used during commissioning has similar thermodynamic properties to the production fluid, while also being inert. However, inert gases are often mono- or diatomic (due to increased reactivity of more complex molecules) which leads to the conclusion that better alternatives to nitrogen, from a heat capacity perspective, are hard to come by.

2.4.2 Inlet cooler

The design equation for the inlet cooler is, as stated before, based on computational fluid dynamic (CFD) simulation which correlates the OHTC with inlet temperature and mass flow. This work has been done based on natural gas and not for nitrogen and therefore a difference is to be expected when nitrogen is in the cooler. The fluid properties density, conductivity, heat capacity and viscosity are of importance, since these properties will affect the heat transfer coefficient in the cooler [19]. Density will determine velocity through the cooler, conductivity will affect how efficiently heat is transferred, heat capacity will affect the final temperature (thus the temperature driving force) and viscosity will impact the nature of the flow in the pipes as more turbulent flow yields more mixing and therefore better heat transfer.

A comparison of some fluid properties is seen in table 2.1. Nitrogen has higher density, which will decrease the velocity of the gas inside the pipes, this will increase the residence time in the cooler and therefore yield better heat transfer. Lower thermal conductivity means that heat will transfer less efficiently in the gas which leads to worse heat transfer. Lower heat capacity means that the gas will exit at a lower temperature, however as the exit temperature will be lower the temperature driving force of the cooler will be lower and the absolute heat transferred will be lower. This effect will also make the positive effects of having a higher residence time in the cooler to diminish. Higher viscosity will decrease the turbulence and mixing of the gas inside the pipes which will decrease the heat transfer. Based on this it can be assumed that the OHTC of the cooler will be lower for nitrogen compared to methane. From equation 2.11 a reduction in the amount of cooling from the inlet cooler will mean that more heat will be accumulated in the system.

2.4.3 Compressor

The performance of the compressor as well as the compressor characteristic curve will change with different gas properties. A higher gas molecular weight yields higher flow rates and consequently higher pressure ratio at the same power, from looking at equation 2.6. A higher molecular weight is also connected to a higher efficiency and lower losses implying that the required power decreases at the same discharge pressure and massflow. Compressibility factor will also influence the compressor operation where a higher compressibility factor causes the gas to flow at a lower Mach number yielding lower pressure ratio. However an increase in compressibilty factor increases the efficiency which offsets the pressure ratio decrease for lower flows. The difference is seen at higher compressor speed and flow where a higher compressibility factor will yield lower pressure ratio. A lower heat capacity ratio leads to a decreased efficiency implying an increase in required power to obtain the same pressure ratio. A lower heat capacity ratio is also connected to a higher discharge temperature at the same massflow, since heat capacity ratio is connected to specific heat capacity [20].

From this the expected effect of operating the compressor with nitrogen is difficult to anticipate as the differing properties of nitrogen and methane, seen in Table 2.1, will lead to both positive and negative effects on compressor performance. It is clear that the discharge temperature of the compressor will be higher for nitrogen which will impact temperatures througout the process.

2.4.4 Cooling gas system

The gas for the cooling of the motor is extracted about halfway through the compressor. After this extraction the extracted gas is expanded through a valve which will cool the gas by the Joule-Thomson effect. The resulting cooling of the gas is beneficial to the nature of the cooling gas loop, which is to cool the motor. Joule-Thomson effect describes the temperature change of a real gas as it is forced through a valve. During the Joule-Thomson effect the enthalpy is constant and is defined as,

$$H = U + PV \tag{2.12}$$

where H is enthalpy, U is internal energy, P is pressure and V is volume. Over the valve the PV term is increased which means that internal energy, U, must decrease leading to a decrease in temperature. The temperature decrease can be described by the Joule-Thomson coefficient (μ_{JT}),

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_H \tag{2.13}$$

which gives a relation between pressure drop and temperature decrease. The Joule-Thomson coefficient is different for different gases [21].

Simplifying and rearranging Equation 2.13 the resulting temperature from expansion over a valve can be given as,

$$T_2 = -\mu_{JT}(P_1 - P_2) + T_1 \tag{2.14}$$

where T_2 is the resulting temperature. Assuming that the pressure before the expansion is 150bar, the pressure after the expansion is 140 bar and the temperature before the expansion is 300K the following temperatures are given:

Table 2.2: Effect of Joule-Thomson cooling with N_2 and CH_4, values for μ_{JT} are taken at condition 1.

	T_1 (K)	P_1 (MPa)	P_2 (MPa)	μ_{JT} (K/MPa)	T_2 (K)
N_2	300	150	140	0,975	**298**
CH_4	300	150	140	2,256	**295**

As can be seen from table 2.2 the temperature of N_2 will be higher than for CH_4 due to N_2 having a lower value of the Joule-Thomson coefficient. This will likely lead to a decreased effectiveness of the cooling gas system when N_2 is used, since the temperature of the gas reaching the motor is higher. However, if a higher pressure is obtained from nitrogen operation for the same compressor speed, positive effects will be gained for the cooling gas system as the gas will be cooled to a lower temperature from the J-T effect.

The mass flow of gas that is able to be extracted to the motor will also differ. Since the flow of gas over the cooling gas valve is dependent on the volume flow, it can be expected that in nitrogen operation a higher massflow through the cooling gas system can be achieved, owing to the difference in densities.

The amount of gas required will also be different, due to the difference in heat capacities. The heat capacity for nitrogen is lower (see Table 2.1) which means that a higher massflow of nitrogen is required to cool the same amount of heat from the motor. A higher volume flow over the cooling gas valve will be required for nitrogen operation since the relative difference for nitrogen and methane in density do not cancel out the difference in heat capacity, with the density of nitrogen being around 1.4 times higher and specific heat capacity around 2.7 times lower.

Based on this the cooling gas system will likely be more heavily constrained by nitrogen operation when compared to natural gas. The cooling gas system will also be more heavily constrained with nitrogen due to the increased discharge temperature of the compressor.

3

Methods

3.1 Model building and modification

To investigate how the compression station will operate using nitrogen the dynamic process simulation software K-Spice was, which is commonly used in the oil & gas industry. The K-Spice simulation model used for the compressor station at regular production was provided as a starting point for this thesis, i.e. not for closed loop operation. For the simulations with hydrocarbons as the process fluid some minor modification of the model is required to make the system a closed loop. For example pressurizing the system to the desired initial pressure or altering the control system so that it can operate while running in a closed loop.

For simulating nitrogen more modificataions are required. These are: changing the thermodynamic package that is used, as K-Spice uses a third-party software for thermodynamic properties; specifying different parameters of the inlet cooler to better replicate the performance with nitrogen; changing the compressor performance curves for nitrogen operation; resolving other errors that might arise from having nitrogen as the main process fluid (such as various thermodynamic calculations connected to the model).

3.1.1 Inlet Cooler

As the calculation and correlation for the performance of the inlet cooler is highly dependent on natural gas being the fluid, CFD analysis of the cooler with nitrogen was performed. A simulation will show how the effectiveness of the cooler will be changed when the process fluid is nitrogen. The conditions for the CFD analysis will be for a realistic case where nitrogen is the process fluid in the closed loop. The massflow for the CFD analysis was 165 kg/s and the inlet temperature 27°C.

From this analysis the OHTC of the inlet cooler for these specific conditions can be found. With this the error of OHTC for the inlet cooler correlation for nitrogen can be estimated and the correlation can be corrected for nitrogen operation. To gain more reliable results entirely new correlations for nitrogen operations should be generated, however that is outside of the scope for this thesis.

3.2 Simulations

The simulation of interest is a closed loop and therefore the initial pressure inside the closed loop will be a very important factor. The initial pressure will impact the massflow going through the compressor.

The goal of the thesis is to investigate the effects of the system when it is operated using nitrogen instead of natural gas. The simulations are therefore carried out using the following steps with both nitrogen and natural gas for different initial pressures.

1. Pressurize the system to the required initial pressure, with the compressor offline.
2. Close the valve used to pressurize the system in order to make the system a closed loop, run the simulation until pressures and temperatures inside the network have settled.
3. Start the compressor and run at minimum speed, let simulation run for 30 min (simulation time).
4. Increase the speed of the compressor sequentially, while tracking if alarms are triggered at the different speeds. Let simulation run for 30 min at each speed.

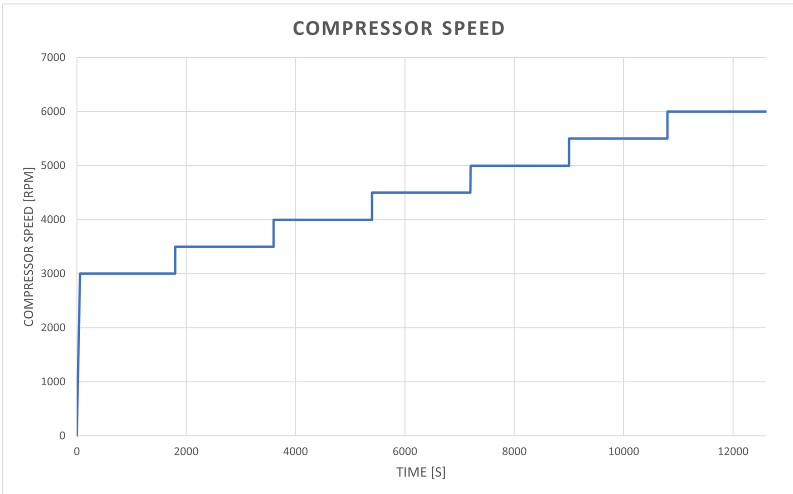


Figure 3.1: Compressor speed ramp-up.

The compressor speed will be the main variable during the simulations, the commanded speed to the compressor can be seen in figure 3.1. The compressor will not always reach these speeds as there are other limitations that will inhibit set speed, such as maximum power to the compressor or maximum torque.

These steps will imitate actual commissioning activities where the aim is to operate the compressor at different speeds and flowrates to ensure that the compressor is functioning as expected over as much as possible of the compressor envelope. It is therefore of interest to investigate at what speeds, flowrates and pressures the compressor will operate safely at with nitrogen and what equipment or thermodynamic effects will be the limiting factor.

For these simulations the anti-surge valve will be completely open. This is done to be as far away from surge conditions as possible, since surge will likely cause damage to the compressor. Initial pressures used are: 100 bar, 135 bar and 150 bar. These are selected due to 100 bar and 150 bar being in the lower and higher range of inlet pressures the compression station will see in regular production. 135 bar is the approximate ambient pressure of the surrounding seawater at the depth where the compressor station will be located [22].

A simulation was also done where the compressor is operating at constant power with nitrogen and the opening of anti-surge manipulated by being closed in 20% increments. A fictional controller was set-up such that the power is kept constant by altering the speed of the compressor as the anti-surge valve is closed. The reason for this controller is to be able to investigate the effects of changing the massflow and pressure in the system. In reality the compressor speed would have been kept constant, which would mean that the power demand from the compressor would change. This simulation will highlight the effects of: increasing the pressure over the compressor and decreasing flow over the compressor, which will move the operating point of the compressor closer to the surge line.

Trend data of properties are extracted after the simulation is run where the properties are saved every two seconds. The fluid properties tracked are:

1. Pressures across equipment
2. Temperatures across equipment
3. Total massflow
4. Cooling gas massflow
5. Compressor operating point
6. Compressor motor heat

3.3 Analysis

The results of the simulations were analyzed by extracting the above mentioned properties at different points throughout the closed loop. Properties of interest from the simulations were plotted, and the effects of using nitrogen compared to natural gas was analyzed and discussed.

The equipment that is most greatly affected by using nitrogen was investigated, to see how the equipment performs. From the results of this thesis:

- Present recommendations for commissioning and operation of the compressor station with nitrogen.
- Present recommendations for commissioning and operation in general for similar systems.
- Aid in a better understanding of thermodynamic effects during commissioning activities.

- Avoid accidental damage to equipment during commissioning activities.

4

Results

In this chapter results from the simulations are presented. First the CFD analysis of the inlet cooler with nitrogen is presented along with the steps taken to alter the inlet cooler in the process model to accommodate nitrogen. Next simulation results for the closed loop running with hydrocarbons as well as nitrogen are presented. The impact of the OHTC alteration is also shown. Finally, simulation results for the closing of the anti-surge valve are presented

4.1 CFD analysis of the inlet cooler

A CFD analysis of the inlet cooler was run with nitrogen as the process fluid to evaluate the impact of nitrogen on the overall heat transfer coefficient. Figure 4.1 shows the temperature field of the inlet cooler. The lower heat capacity of nitrogen means that a low temperature is reached far upstream in the cooler. This reduces the temperature driving force of the cooler as temperature the process fluid is approaching the ambient seawater temperature

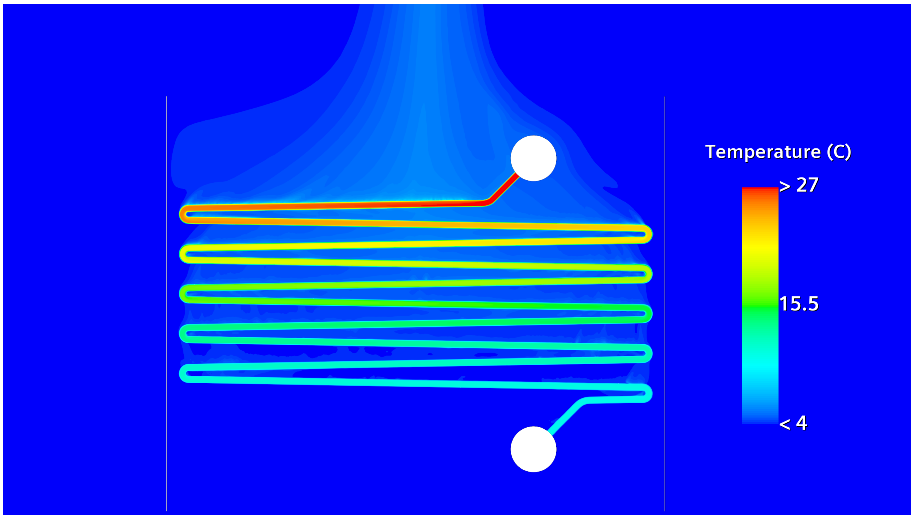


Figure 4.1: Temperature field of the inlet cooler CFD simulation

Table 4.1: Results from the CFD simulation of the inlet cooler.

T_{in} [°C]	T_{out} [°C]	LMTD [°C]	OHTC $\left[\frac{W}{m^2K}\right]$	OHTC (corr.) $\left[\frac{W}{m^2K}\right]$	Diff.
27	10	13	231	287	80.5%

The calculated OHTC from the CFD simulation was approximately 80% of the OHTC from the correlation that has been developed for the inlet cooler. This reduction is added to the correlation for the simulations where the station is operated with nitrogen.

4.2 Ramping compressor speed

In this section, results from the simulations of the closed loop with hydrocarbons in the pipes are presented. Only the results for an initial pressure of 135 bar are presented here, for the other initial pressures see Appendix A.

4.2.1 Main process

In figure 4.2 the discharge and suction pressures from the compressor when operating with hydrocarbons at an initial pressure of 135 bar is shown. As the compressor speed increases (seen in figure 3.1), the discharge pressure increases. Initially the suction pressure decreases as the compressor is speeding up, however as the system is in a closed loop the suction pressure is also increased since the recycled gas is at a higher pressure than in stagnant conditions due to temperature of the gas increasing (the mass of nitrogen in the system is the same).

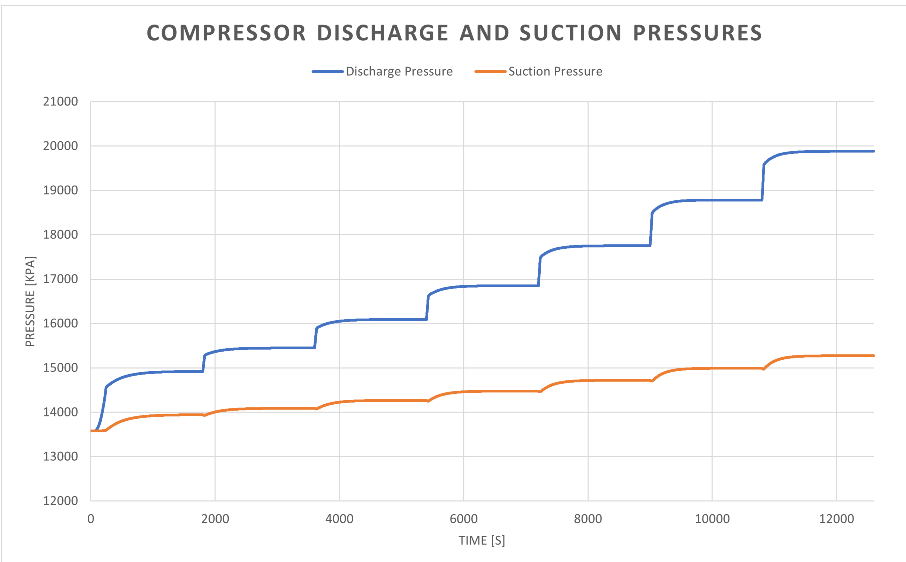


Figure 4.2: Suction and discharge pressures of the compressor. Hydrocarbons with initial pressure of 135 bar

Discharge pressure of the compressor when operating with nitrogen reaches comparable pressures to that when operating with hydrocarbons, see figures 4.2, 4.3. However the suction pressure is not increased as much for nitrogen. The compressor reaches maximum torque when the speed is commanded to ramp up to 5500 rpm, which means that the power required by the motor is higher when compared to hydrocarbons.

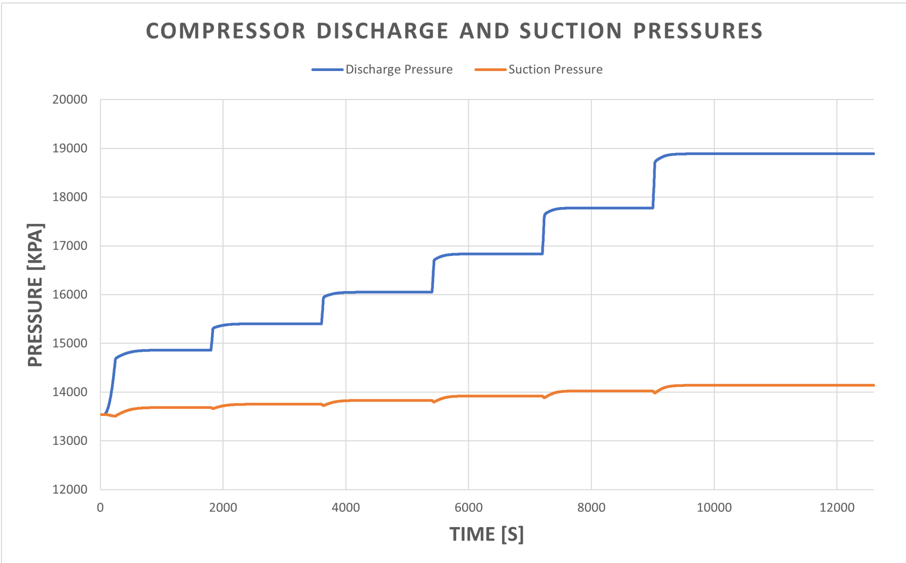


Figure 4.3: Suction and discharge pressures of the compressor. Nitrogen with initial pressure of 135 bar

Temperatures in the process increases as the compressor speed increases, which can be seen in figure 4.4. The highest temperature is seen at the discharge of the compressor and the lowest temperature is seen at the outlet of the inlet cooler. The temperature at the inlet of the inlet cooler is lower than at the discharge of the compressor. This is due to piping heat losses and due to the expansion of the flow over the anti-surge valve which will, as a side effect to reducing the pressure, reduce the temperature of the flow. The temperature is higher in the suction of the compressor compared to the exit of the inlet cooler as the temperature is read after the cooling gases are recycled.

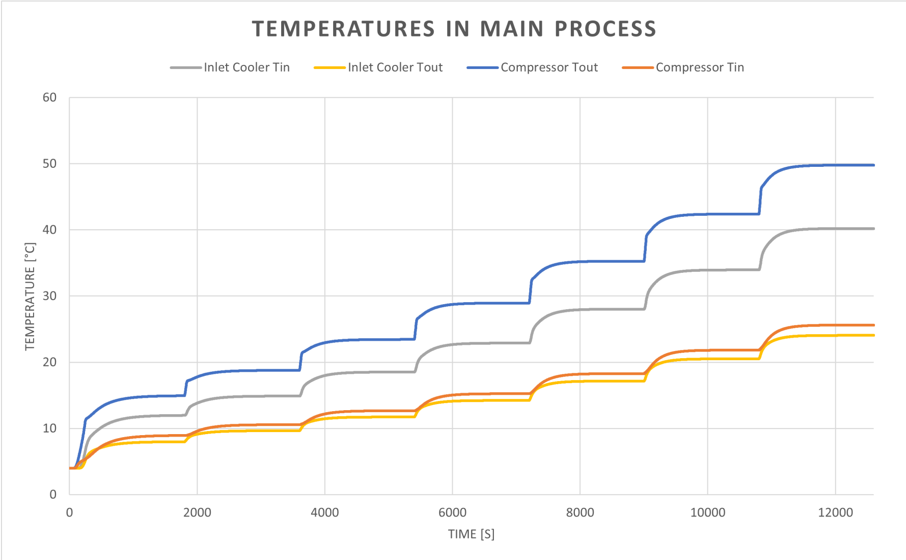


Figure 4.4: Temperatures throughout the process. Hydrocarbons with initial pressure of 135 bar.

In figure 4.5 the corresponding graph is seen for nitrogen. The temperatures in the discharge of the compressor are higher than for hydrocarbon operation whereas the temperatures in the discharge of the inlet cooler are lower.

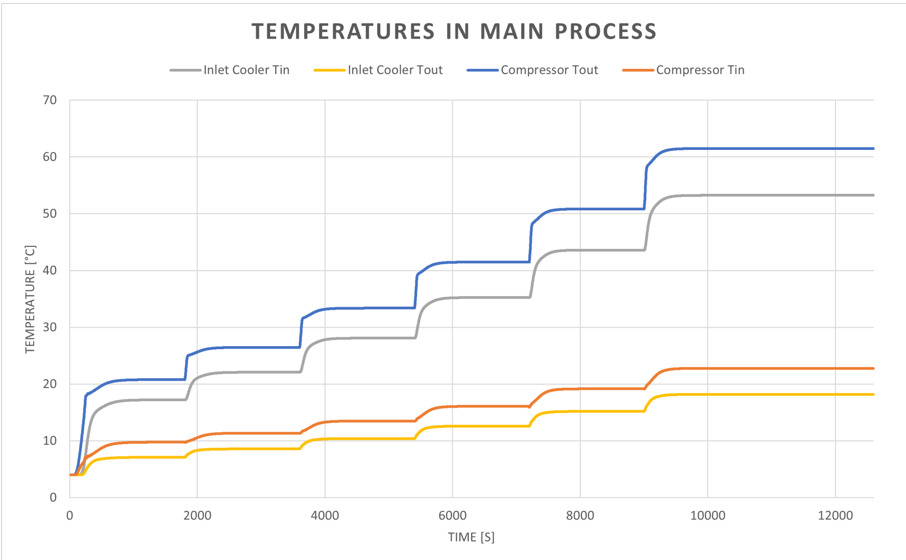
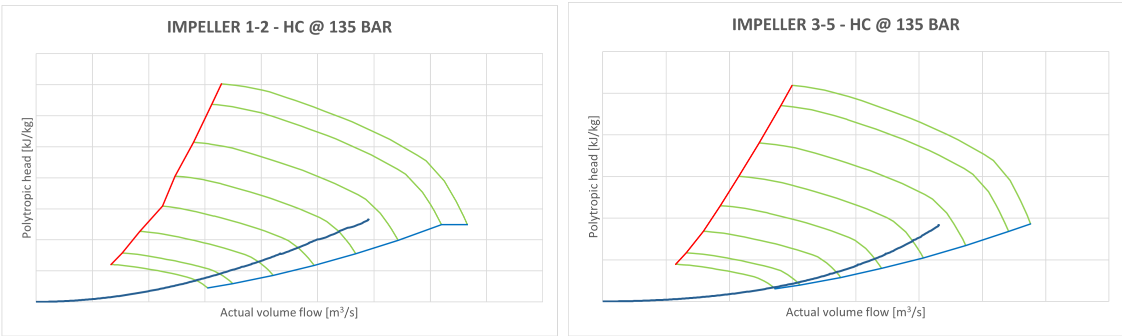


Figure 4.5: Temperatures throughout the process. Nitrogen with initial pressure of 135 bar

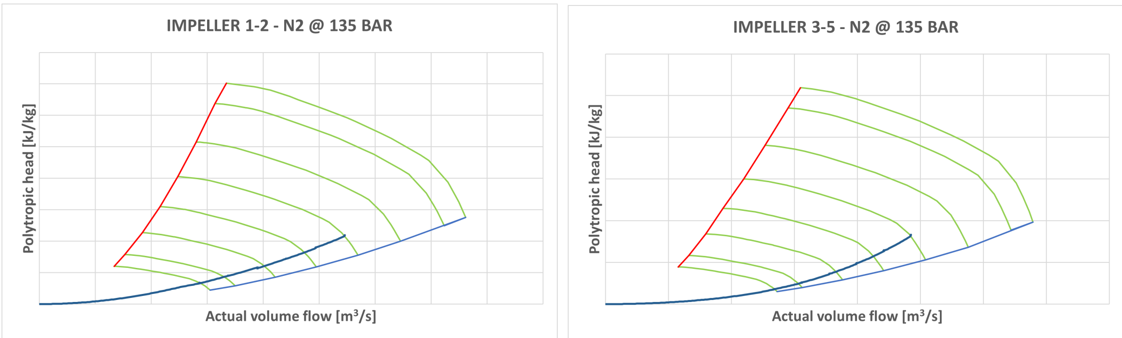
The compressor is operating close to the stonewall limit, as can be seen in figure 4.6. Operating close to the stonewall limit means that a lot of work is required to increase the pressure of the flow, as the flow is at the upper end of what the compressor can handle. Compressor operating points for nitrogen can be seen in figure 4.7, where the operating points are similar as to that of hydrocarbon operation.



(a) Impeller 1-2, before cooling gas extraction

(b) Impeller 3-5, after cooling gas extraction

Figure 4.6: Operating points on the compressor curves. Hydrocarbons with initial pressure of 135 bar



(a) Impeller 1-2, before cooling gas extraction

(b) Impeller 3-5, after cooling gas extraction

Figure 4.7: Operating points on the compressor curves. Nitrogen with initial pressure of 135 bar

In figure 4.8, the discharge pressure from the compressor is seen at different initial pressures for both nitrogen and hydrocarbon operation. As can be seen the discharge pressure is generally higher for nitrogen operation at the same compressor speed.

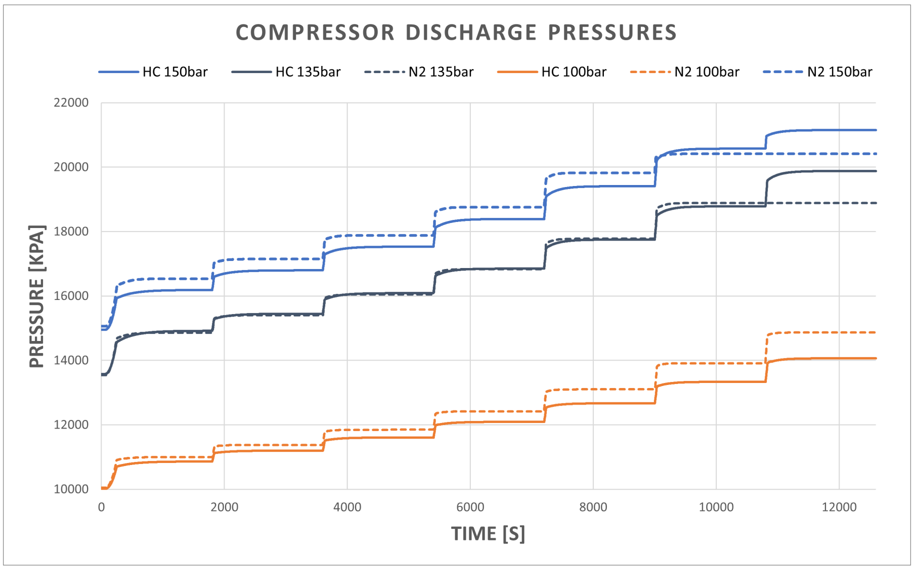


Figure 4.8: Comparison of discharge pressures for different process fluids and initial pressures

Figure 4.9 shows the power demand from the compressor at different initial pressures and speeds for nitrogen and hydrocarbon operation. The power demand is consistently higher for nitrogen operation at the same compressor speed and initial pressure.

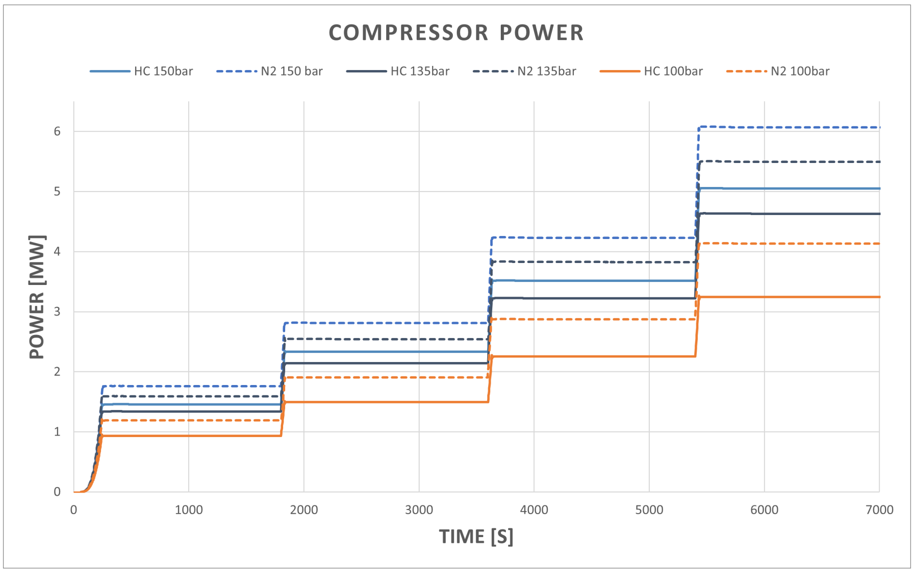


Figure 4.9: Comparison of compressor power for different process fluids and initial pressures

4.2.2 Cooling gas system

In figure 4.10 the temperatures across the cooling gas system are seen. The dashed line corresponds to the trip point of the cooling gas return temperature. In real life conditions exceeding this line would cause the compressor to trip, i.e. initiation of shutdown of the compressor to avoid motor damage. The temperature of the cooling gas out of the motor is not at the set-point of the temperature controller, see figure 2.5. This means that the cooling gas valve opening is selected by the controller calculating opening based on compressor speed. The heat that is required to be discharged from the motor is plotted on the right axis.

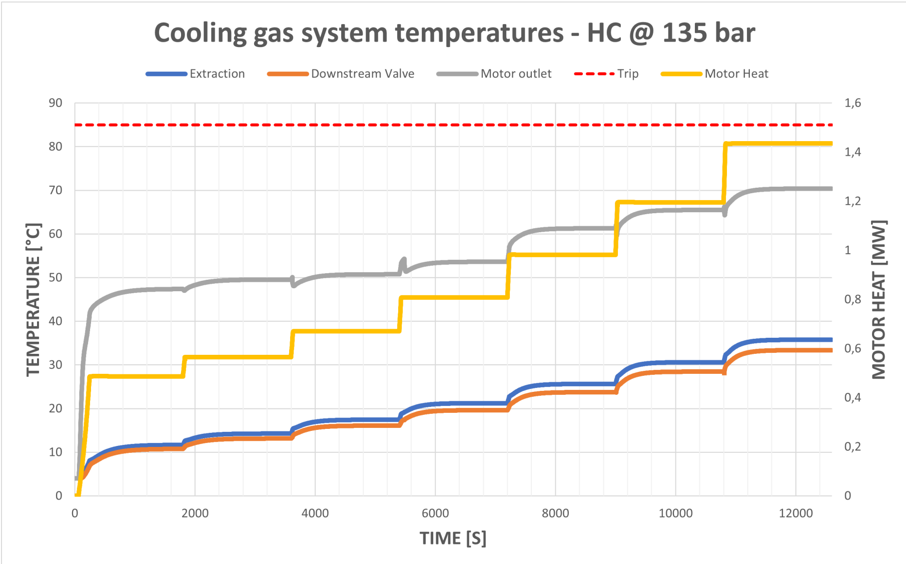


Figure 4.10: Temperatures across across the cooling gas system and required heat absorption from the motor. Hydrocarbons with initial pressure of 135 bar

In figure 4.11 the temperatures across the cooling gas system when operating with nitrogen are shown. As can be seen the maximum limit of the temperature of the gas exiting the motor is reached at 4500 rpm where it is operating steady. The temperature of the gas out of the motor reaches the temperature set-point of the temperature controller even at low speeds, see figure 2.5. This indicates that a larger opening of the cooling gas valve is required to cool the motor sufficiently with nitrogen. At similar speeds the temperature of the extracted cooling gas is higher for nitrogen operation.

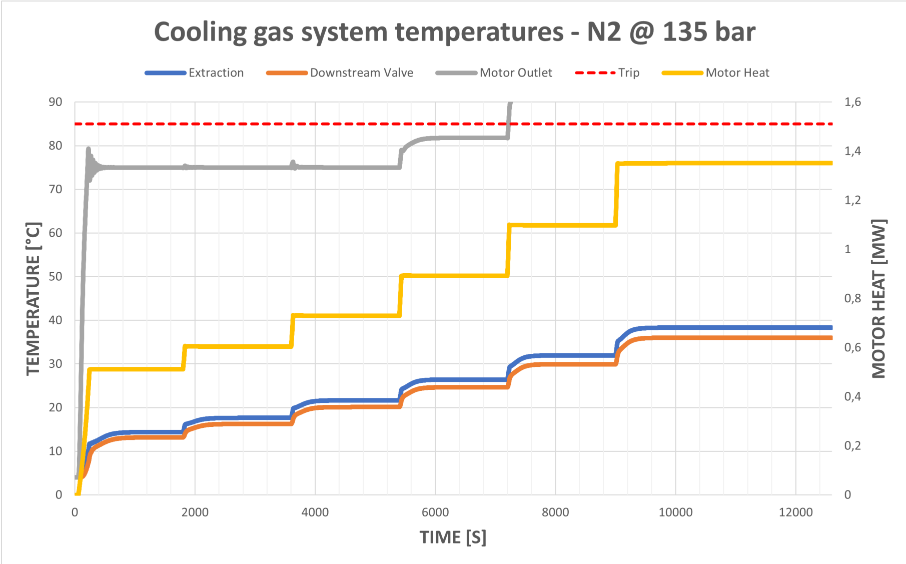


Figure 4.11: Temperatures across the cooling gas system and required heat absorption from the motor. Nitrogen with initial pressure of 135 bar

In figure 4.12, a comparison of the cooling gas mass flows is seen for different initial pressures for both nitrogen and hydrocarbons. The figure only presents massflows at 3000-4000 rpm. The required massflow in nitrogen operation is approximately twice the massflow in hydrocarbon operation.

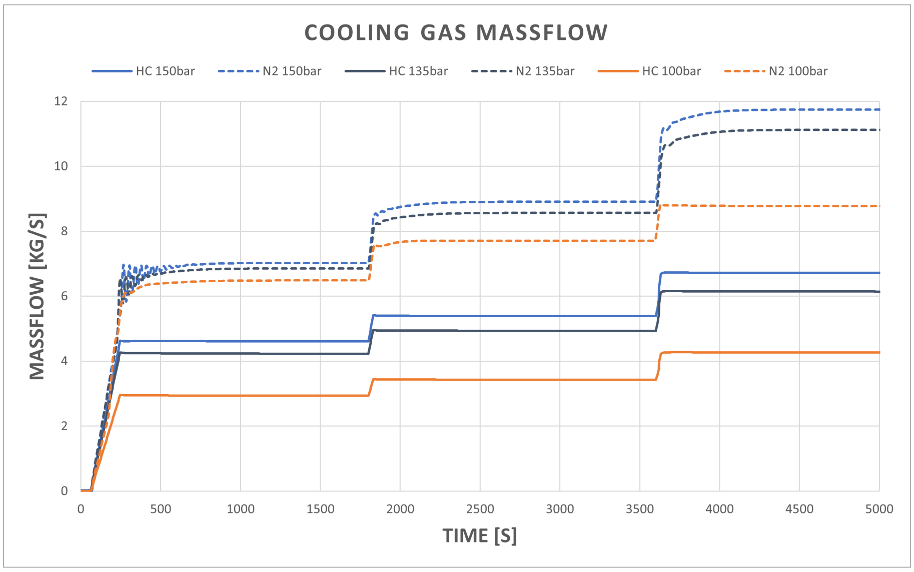


Figure 4.12: Comparison of the cooling gas mass flows for different process fluids and initial pressures

For a better comparison of the cooling gas massflows, a simulation with hydrocarbon operation where the opening of the cooling gas valve is only selected by the temperature controller was done. In figure 4.13 below, the cooling gas massflow at

135 bar initial pressure is seen. The lines correspond to operating with nitrogen, hydrocarbon and hydrocarbon including the change in cooling gas valve controls logic. With this change the cooling gas mass flow is almost 3 times higher for nitrogen operation.

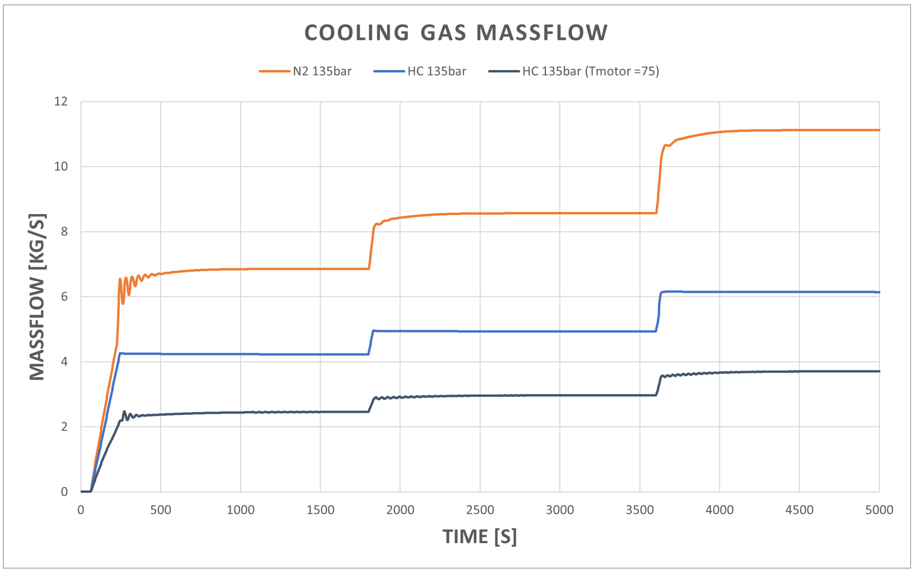
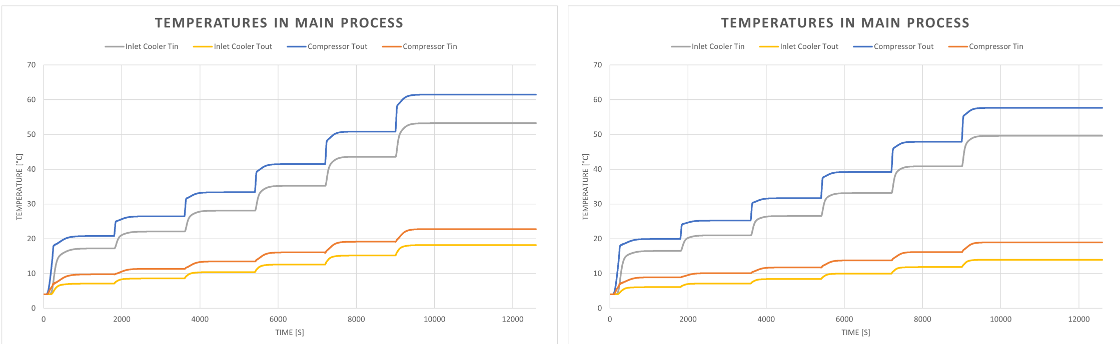


Figure 4.13: Cooling gas massflows for 135 bar initial pressure. Including simulation where massflow is dictated by temperature controller.

4.2.3 Impact of OHTC reduction

A simulation with nitrogen was also run without altering the OHTC of the inlet cooler, to investigate what impacts that change had on the temperatures in the process. In the figure below a comparison of the process temperatures with and without the OHTC reduction from the CFD analysis is shown. The temperatures are higher when the OHTC reduction is active.



(a) With OHTC reduction   **(b)** Without OHTC reduction

Figure 4.14: Process temperatures for a simulation of nitrogen as the process fluid with 135 bar as initial pressure. Comparison of the temperatures throughout the process with and without OHTC reduction from CFD analysis.

4.3 Closing the anti-surge valve

Here results are presented from the simulation where the anti-surge valve is ramped closed. As previously mentioned a fictional controller is set-up such that the power demand for the compressor is kept constant by changing the set speed of the compressor. The simulations were run with nitrogen as the process fluid with an initial pressure of 135 bar. At the start of the result data the compressor is operating at constant speed.

In figure 4.15 below, the suction and discharge pressures of the compressor can be seen. The discharge pressure is increased as the anti-surge valve is closed. The suction pressure is decreased as the discharge pressure is increased.

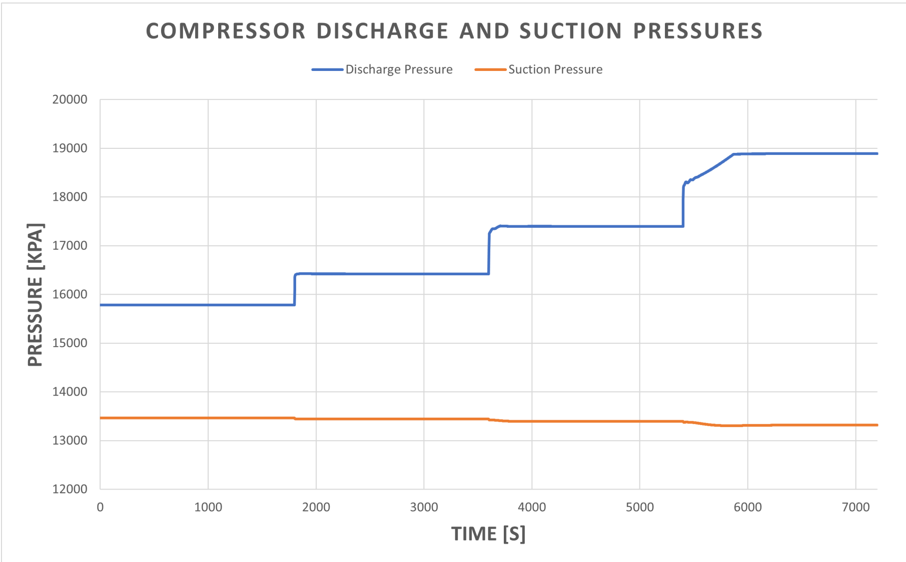


Figure 4.15: Change in discharge and suction pressure of the compressor as the anti-surge valve is successively closed

Temperatures in the process also change as the anti-surge valve is ramped closed, which can be seen in figure 4.16 below. As the anti-surge valve closes the discharge temperature of the compressor increases. The temperature out of the inlet cooler decreases, while the suction temperature of the compressor slightly increases.

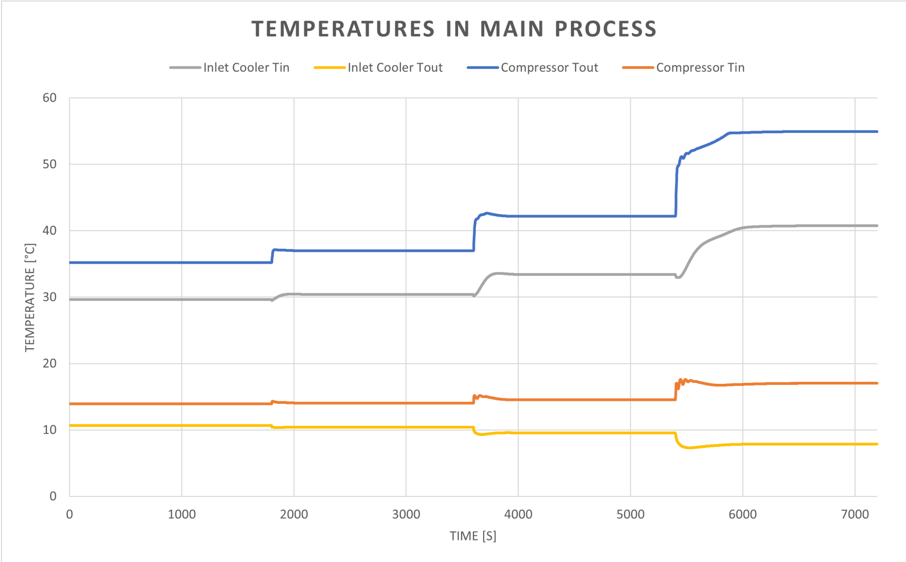
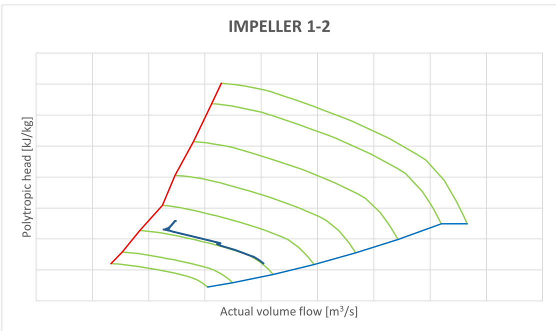
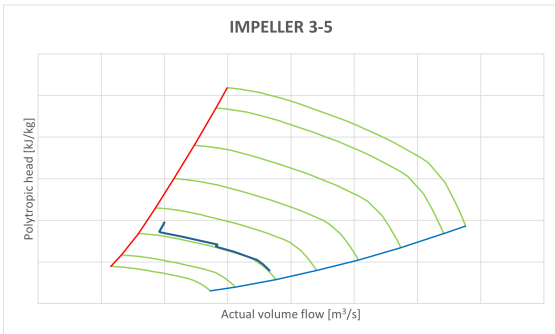


Figure 4.16: Change in temperatures in the process as the anti-surge valve is successively closed.

The compressor operating point will differ. The operating point is initially close to the stonewall line and the more the anti-surge valve is closed the closer the operating point moves to the compressor surge line, seen in figure 4.17 below. Compressor speed increases which is due to the fictional controller keeping the same power demand for the compressor.



(a) Impeller 1-2, before cooling gas extraction



(b) Impeller 3-5, after cooling gas extraction

Figure 4.17: Operating points on the compressor curves. Closing the anti-surge valve with constant compressor power

Temperatures in the cooling gas system are presented below in figure 4.18. The temperature of the cooling gas out of the motor is constant at the temperature set-point, as well as the heat from the motor which is also constant since the power output from the motor is kept constant. The temperatures in the cooling gas loop before the motor increases as the anti-surge valve closes. The "notches" in the power output are due to the controller not immediately being able to keep constant power as the flow is choked and can be disregarded.

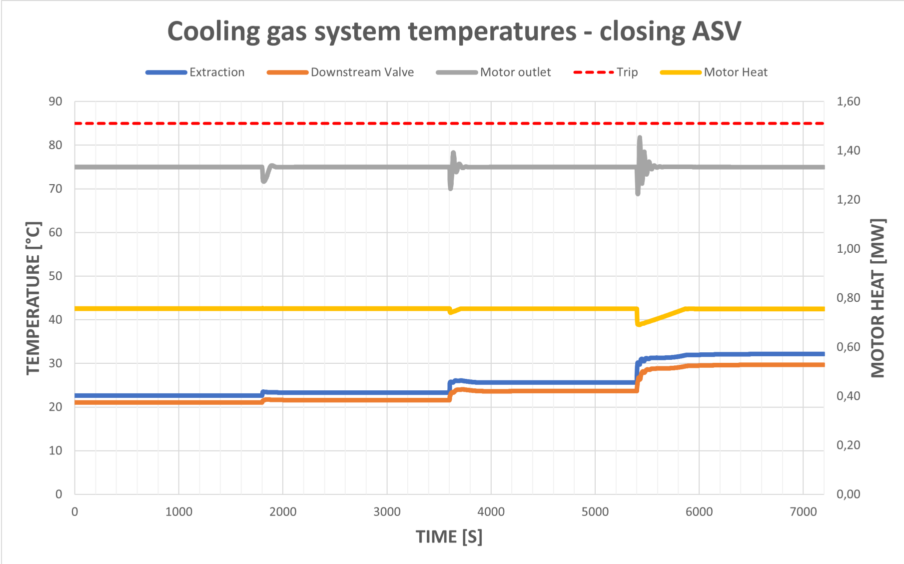


Figure 4.18: Change in temperatures in the cooling gas system as the anti-surge valve is successively closed.

Figure 4.19 shows the massflow through the cooling gas system, as well as the opening of the cooling gas valve. As the anti-surge valve closes the cooling gas massflow is increased, likely due to the increase in cooling gas extraction temperature. Interestingly, the opening of the cooling gas valve decreases as the anti-surge valve is closed despite the mass flow over the valve increasing.

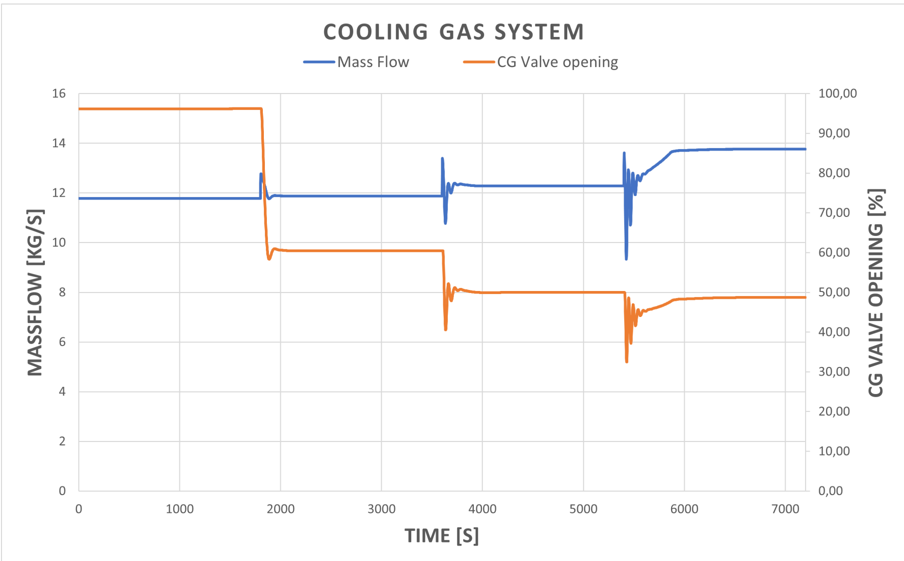


Figure 4.19: Change in massflow in the cooling gas system as the anti-surge valve is successively ramped closed.

5 Discussion

This chapter discusses the impact of nitrogen on the process equipment within the closed loop, when comparing with hydrocarbon operation. This is done by looking at how the results obtained relate to the theory, explaining why the results are seen and the implication for the available compressor operating envelope for nitrogen. The discussion begins with an analysis of the findings from the examination of the inlet cooler. Next, discussion around the results from simulations with the anti-surge valve fully open, with compressor speed variations, along with the conclusions that can be drawn from these simulations. Lastly, discussion about the results obtained from simulations where the anti-surge valve is ramped closed and what effects increased pressure has on the process system.

5.1 Inlet cooler

It was theorized that the overall heat transfer coefficient of the cooler will decrease when using nitrogen, based on the difference in fluid properties of nitrogen and methane from table 2.1. This reduction is mainly due to the effects of lower heat capacity which will decrease the actual temperature of the nitrogen compared to natural gas. While a low temperature is beneficial, the absolute amount of transferred energy will be decreased. This was supported by the CFD simulation that was done on the inlet cooler with nitrogen as the process fluid, which is seen in table 4.1 where the OHTC is decreased when nitrogen is used as the process fluid.

The effect of this on the process will be that the heat discharged by the inlet cooler will decrease. While the temperature out of the cooler will be lower for nitrogen, the heat out of the motor will remain approximately the same. This causes issues in the heat balance of the system, see equation 2.11. Less heat discharged from the cooler will mean that more heat is accumulated in the system, assuming that the heat flows into the system are unchanged.

Therefore the effectiveness of the inlet cooler is directly impacting the available operating points of the compressor during recycle operation, as a higher effectiveness of the cooler would lead to lower temperature cooling gas.

More work needs to be done to estimate what the difference in OHTC will be for other operating points along the cooler envelope for nitrogen. Since this is outside of the scope of this work, a simple reduction in the OHTC (as seen in table 4.1) is deemed enough. A comparison of what effect reducing the OHTC has can be seen in figure 4.14. Unsurprisingly, the temperatures throughout the process are increased with the OHTC reduction. This has adverse effects on the cooling of the motor as the gas extracted to the cooling gas loop will be at an elevated temperature.

5.2 Compressor

For both hydrocarbons and nitrogen, the compressor is operating close to the stonewall limit curve which can be seen in figures 4.6 and 4.7. This is due to the anti-surge valve being in fully open position which means that the flow through the compressor is not choked. The operating point on the compressor curve will be approximately the same, as the volume flow over the compressor will be similar. The massflow will be different due to the differences in density. In this condition the compressor will reach maximum power or maximum torque before reaching maximum speed as the larger flow through the compressor requires larger work. For nitrogen the compressor requires more power for the same initial pressure conditions, see figure 4.9. This is likely due to nitrogen having higher density than natural gas, therefore causing a larger massflow through the compressor. Higher power demand from the compressor with nitrogen leads to two negative effects for the commissioning activities with nitrogen: larger cooling demand from the motor and smaller operating envelope for the compressor (since maximum speed or torque will be reached at lower speeds for nitrogen compared to natural gas).

An increased power demand for nitrogen compared to natural gas, will not only increase the cooling demand from the motor but also increase the amount of heat stored in the system. From the heat balance (equation 2.11) the terms adding heat to the system, compressor and motor heat, will increase and the terms removing heat from the system, inlet cooler, will decrease. This will effect the cooling gas system, since more heat in the system means that there is a lower threshold until the maximum allowed temperature of the motor is reached.

In general, the discharge pressure of the compressor is higher for operation with nitrogen compared to hydrocarbons, see figure 4.8. This difference can be explained by equation 2.6. While speed and power/head is not perfectly comparable, the operating points at the compressor curves are fairly similar, see figures 4.6 and 4.7. Assuming that the same head is given at the same compressor speed for both fluids, an increase in molecular weight must lead to an increase in discharge pressure if the head is to remain the same. The discharge temperature is also higher for nitrogen operation, see figures 4.4 and 4.5. This corresponds with the literature review that a lower heat capacity ratio/specific heat capacity leads to higher discharge temperatures.

Of note is that the simulations showed that, at 135 bar initial pressure, the discharge pressure for nitrogen is very similar to the discharge pressure of hydrocarbons. For commissioning activities this is favorable as the pressure data yielded from these activities can be expected in actual operation, for example when it is required to operate the station in full recycle.

The suction temperature is higher in nitrogen operation (at the same initial pressure and speed) which can be seen in figure 4.4 and 4.5. Suction temperature is higher due to the recycling of cooling gas from the motor. This increases the amount of power required by the compressor, shown in equation 2.6, as well as increasing the amount of cooling gas required since the extracted cooling gas will be at a higher temperature.

5.3 Cooling gas system

Massflow through the cooling gas loop is different for the process fluids investigated, as can be seen in figure 4.12. Approximately double the massflow is required for nitrogen operation. Noteworthy is also that the temperature of the cooling gas exiting the motor is at 75°C or above for nitrogen (see figure 4.10) and below 75°C for hydrocarbon operation (see figure 4.11). Due to this another simulation was done where the cooling gas valve opening is dictated only by the temperature controller, see figure 2.5. The resulting graph can be seen in figure 4.13. The massflow is between 2.8 to 3 times higher for nitrogen operation compared to hydrocarbon. Since the specific heat capacity of methane is about 2.7 times greater than nitrogen (with larger hydrocarbons having lower C_p than methane) the differences in nitrogen operation is not only attributed to the differing specific heat capacity of nitrogen, however the largest factor impacting the differences in required amount of cooling gas is the specific heat capacities.

When the anti-surge valve is fully open the compressor will be operating close to the stonewall limit. For operation with hydrocarbons as the process fluid this yields no problem for the cooling of the motor, since the specific heat capacity of natural gas is high enough allowing the temperature of the cooling gas reaching the motor to be low enough in order to cool the motor adequately, see figure 4.4. For nitrogen however, looking at figure 4.5, operating close to the stonewall limit will mean that the compressor is requiring high power whilst increasing the temperature of the process fluid to a higher temperature than for hydrocarbons.

Increasing the initial pressure will lead to a higher pressure of the extracted cooling gas. This will translate into several positive effects for the cooling of the motor, which is increasing the margin until a critical temperature is reached in the motor. This can be seen in figures A.8, 4.10 and A.16. In these figures the cooling gas valve is opened the same amount (at corresponding simulation times), since the temperature of the gas out of the motor is below 75°C (see figure 2.5). With increased initial pressure the amount of heat that is required to be discharged from the motor is increased, however the temperature of the gas exiting the motor is lower. The increased pressure will mean that a higher massflow can be extracted at the same volume flow, since the density will be higher (see equation 2.10). According to this equation, if the pressure drop is increased the volume flow must increase. A higher pressure drop will also yield a larger temperature decrease, since the cooling gas is cooled by the Joule-Thomson effect during the cooling gas extraction. However the temperature of the gas before expansion will be higher since the compressor is requiring more power at elevated pressures, due to the increased massflow.

Operating close to the stonewall limit curve, i.e. recycle operation with a fully open anti-surge valve, therefore limits the speed at which the compressor can operate, due to the pressure of the gas being lower. Thus causing the motor cooling to be the limiting factor to running the compressor at high speeds for nitrogen operation.

5.4 Anti-surge valve

When closing the anti-surge valve the compressor operating point moves towards the left hand side of the compressor characteristic curve, closer to the surge line (see figure 4.17). This is due to the anti-surge valve choking the flow, causing a lower volume flow over the compressor.

The simulations also show what effects moving away from the stonewall limit curve has on the cooling gas system. When the anti-surge valve closes the discharge pressure of the compressor increases, due to the decreased flow through the compressor as the flow is choked. Decreased flow means that a higher head is given to the flow per unit of mass, which translates to a higher pressure. This has the positive effect of increasing the available pressure drop over the cooling gas system, yielding lower temperatures due to the J-T effect as well as a larger possible mass flow.

In figure 4.19 it can be seen that the massflow through the cooling gas loop is slightly increased as the anti-surge valve is closed, which correlates with the slightly increased cooling gas extraction temperature seen in figure 4.18 (since higher temperature gas in the cooling gas extraction means that a higher massflow of gas is required to cool the motor). Even though the cooling gas mass flow is increased the opening of the cooling gas valve is decreased when the anti-surge valve is increased. The reason being the higher pressure of gas causing increased pressure drop available over the cooling gas loop. Therefore the cooling gas system is positively affected by increased pressures in the cooling gas extraction, regardless if this increased pressure comes from a higher initial pressure or choked flow through the compressor.

As the compressor power is kept constant during these simulations, the increase in cooling gas massflow reveals that the heat discharged by the inlet cooler is reduced and more heat is accumulated by the system. This is explained by the reduced massflow in the system, limiting how much heat is able to be cooled by the inlet cooler. Increasing the pressure in the cooling gas system therefore allows more heat to be stored in the system before the cooling gas system is unable to cool the motor adequately.

Allowing the anti-surge valve to be closed while performing commissioning activities will allow compressor operation across a much larger range of the compressor operating curve. This will include operation at higher speeds as well as at lower volume flows closer to the surge line. The higher speeds will be enabled due to the increased effectiveness of the cooling gas system, while the lower volume flows are enabled by the choking of the flow from the anti-surge valve. Of course as the compressor speed limitation at fully open anti-surge valve is low, it is unlikely that the highest speeds on the compressor envelope can be reached. However the maximum speed limit for nitrogen operation can be increased by allowing the anti-surge valve to close.

6
Conclusion

In this chapter, conclusions from the results are drawn. Recommendations are given for how to perform commissioning activities on the compressor station specifically and similar systems generally.

6.1 Thermodynamics

The difference in thermodynamic properties of nitrogen and natural gas, mainly specific heat capacity and density, give rise to many differences in how the process system behaves with the respective fluids. Most often the limiting factor in recycle operation is the ability to cool the motor.

6.2 Compressor

The discharge pressure from the compressor will be higher for nitrogen at the same operating point in the compressor performance curve (same volume flow and speed). The temperature of streams in the process is higher for nitrogen operation due to the reduced heat capacity causing higher temperatures at the same power/heat output of the compressor. Disregarding the cooling of the motor, nitrogen operation is limited by the compressor reaching max torque or power at a lower speed than for natural gas operation.

6.3 Cooling gas system

The cooling gas system which cools the compressor motor using process gas, is an important part of the system in recycle operation. For nitrogen as the process gas, the motor will be much harder to cool. This is due to the lower specific heat capacity of nitrogen meaning that a higher flow of gas is needed to cool the motor. While nitrogen does have higher density than natural gas, the increased mass flow due to the density difference will not be enough. With the system being designed with natural gas in mind, the equipment will not be able to extract enough cooling gas due to pipe sizing and valve sizing in order to be able run the compressor across the entire compressor envelope. The cooling gas system is also restricted by the thermodynamic properties of nitrogen, as when the cooling gas is expanded and subsequently cooled by the Joule-Thomson effect the temperature will be higher than for natural gas.

6.4 Inlet Cooler

The inlet cooler has its effectiveness reduced with nitrogen operation. Due to the lower specific heat capacity of nitrogen, the amount of heat discharged from the inlet cooler is reduced compared to natural gas operation. This causes an increase in the amount of heat stored in the system as the compressor power demand is largely independent of process fluid, leading to increased temperatures throughout the system.

It should be noted that the inlet cooler is not perfectly modeled for nitrogen operation. The cooler performance at all operating points on the compressor envelope has not been investigated. However it is unlikely that this will lead to any significant change as the most limiting factor is the design of the cooling gas system.

6.5 Commissioning recommendations

If commissioning a subsea compression station with nitrogen, great care needs to be taken if a wide range of operating points across the compressor envelope are to be achieved. Depending on how the process system is designed, operating in recycle with nitrogen at too high compressor speed could cause extensive damage to the components. For the investigated system the limiting factor to running across all compressor speeds with nitrogen is the inability to cool the motor. A remedy could be having a larger cooling gas valve/piping in the cooling gas system, however having an over-sized valve for regular production could cause issues. Such as a more difficult to control process in low flow conditions or too much flow if the valve is a Fail Open valve (valve opens if signal malfunction) and the valve actuator loses signal.

A safety margin should be set in place on the compressor speed with nitrogen operation where the compressor speed will have to be limited (due to the limitations of the cooling gas system) as a slight increase in compressor power might push the motor temperature over the edge and cause catastrophic damage.

Based on these conclusions, the likely available operating points for the compressor during commissioning can be seen in figure 6.1. For nitrogen the available operating points are limited by the cooling gas system. By opening the anti-surge valve, increasing the pressure of the extracted cooling gas and shifting operating point towards surge line, the compressor speed and power can be increased slightly.

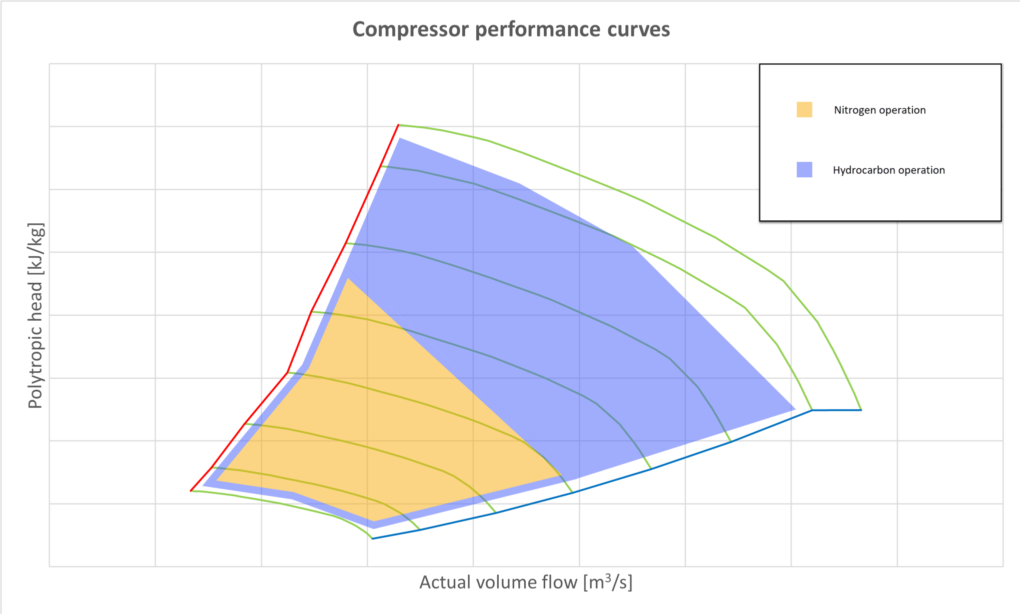


Figure 6.1: Approximate available operating points for the compressor in full recycle operation

For safety reasons, to avoid surge conditions, a limit should be placed on how much the anti-surge valve is allowed to be closed during commissioning activities.

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A

Appendix A

A.1 Initial pressure 100 bara

A.1.1 Nitrogen

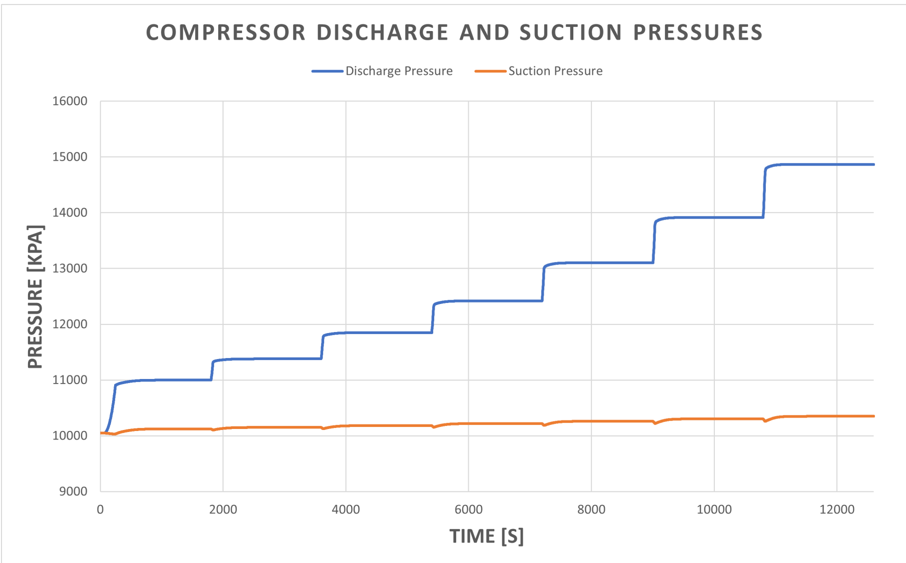


Figure A.1: Suction and discharge pressures of the compressor. Nitrogen with initial pressure of 100 bar.

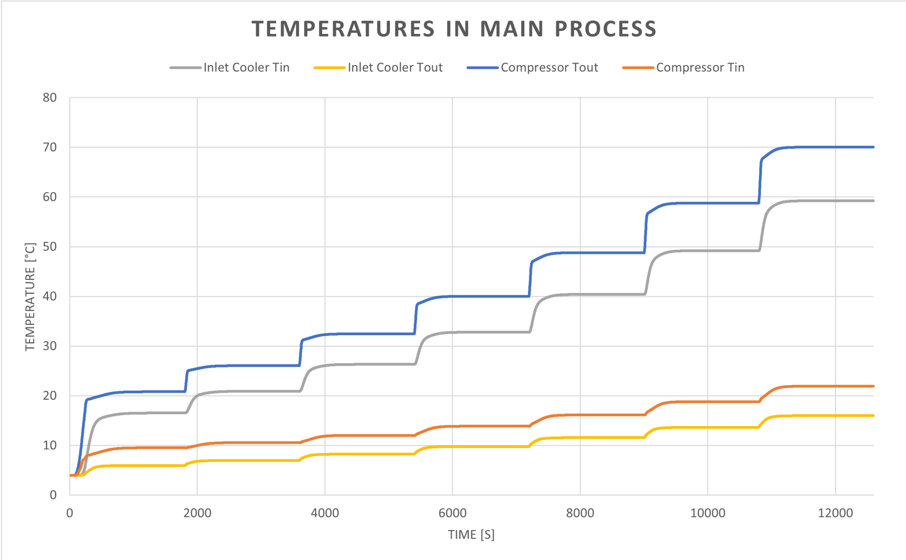
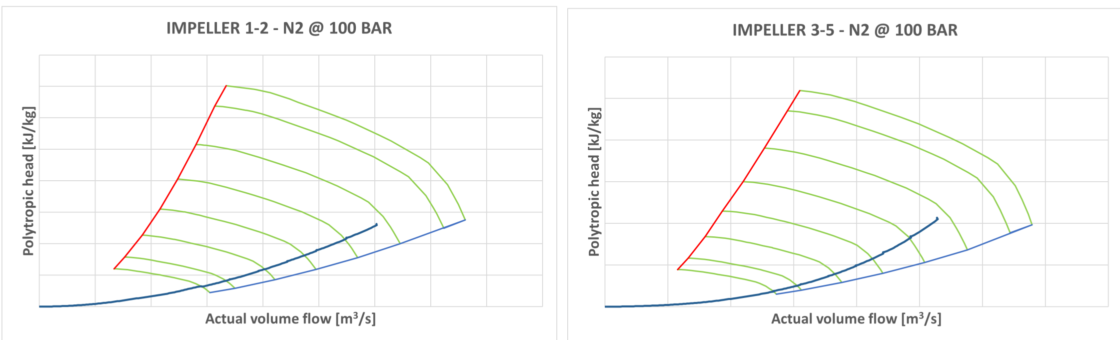


Figure A.2: Temperatures throughout the process. Nitrogen with initial pressure of 100 bar.



(a) Impeller 1-2, before cooling gas extraction

(b) Impeller 3-5, after cooling gas extraction

Figure A.3: Operating points on the compressor curves. Nitrogen with initial pressure of 100 bar.

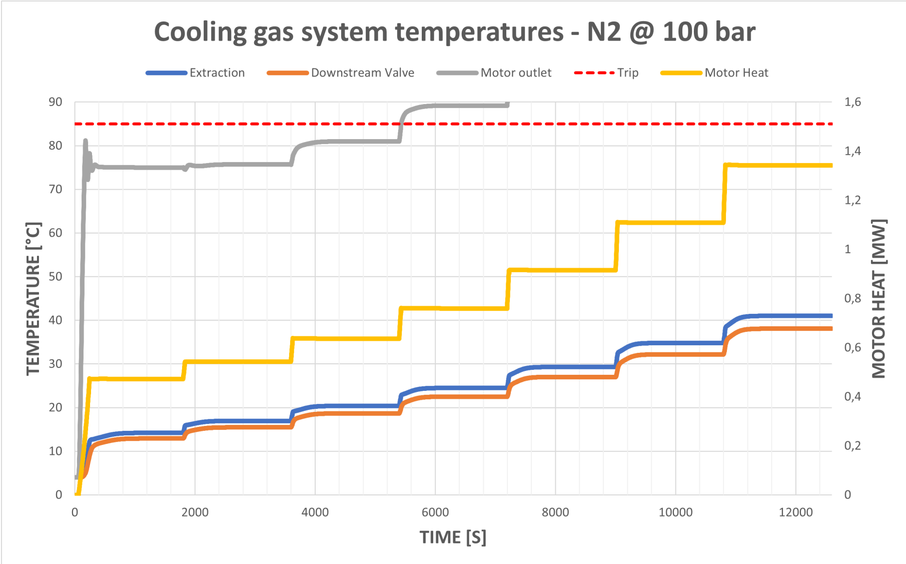


Figure A.4: Temperatures across across the cooling gas system and required heat absorption from the motor. Nitrogen with initial pressure of 100 bar.

A.1.2 Hydrocarbons

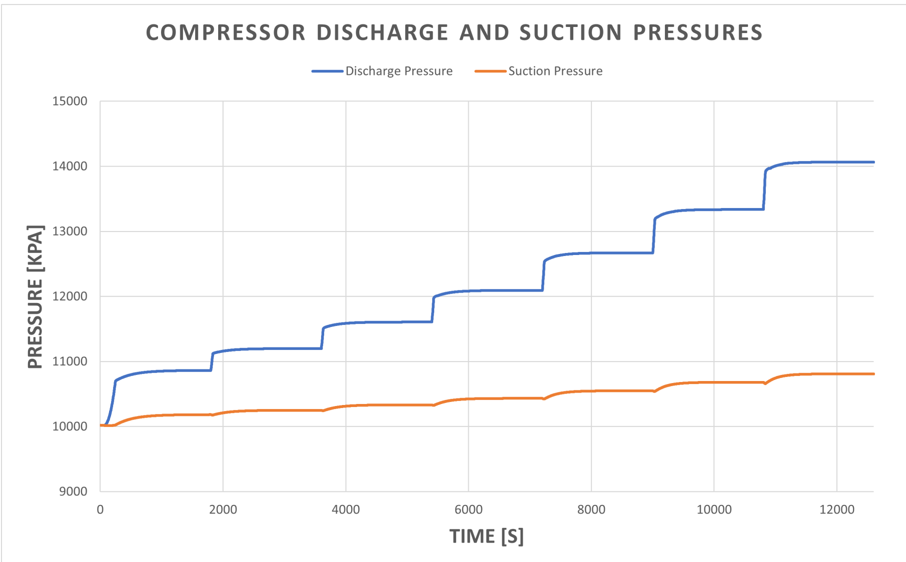


Figure A.5: Suction and discharge pressures of the compressor. Hydrocarbons with initial pressure of 100 bar.

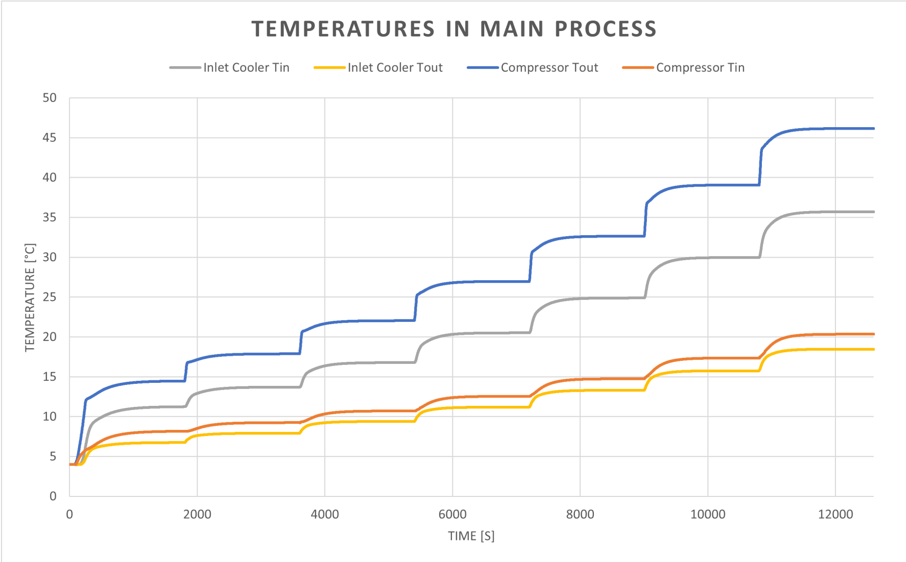
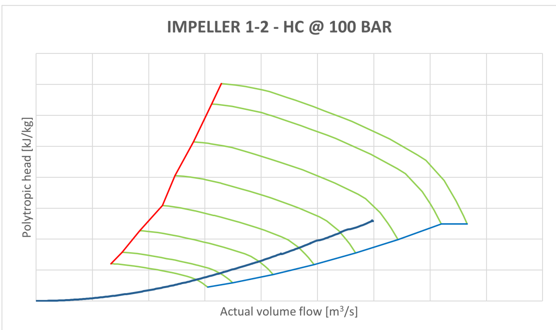
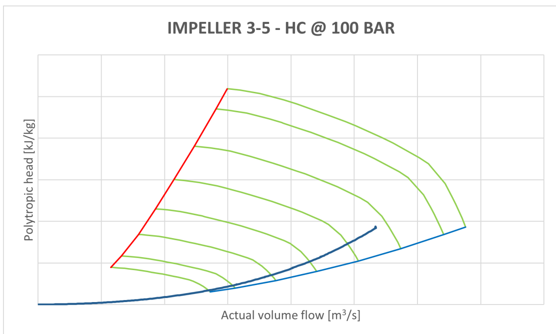


Figure A.6: Temperatures throughout the process. Hydrocarbons with initial pressure of 100 bar.



(a) Impeller 1-2, before cooling gas extraction



(b) Impeller 3-5, after cooling gas extraction

Figure A.7: Operating points on the compressor curves. Hydrocarbons with initial pressure of 100 bar.

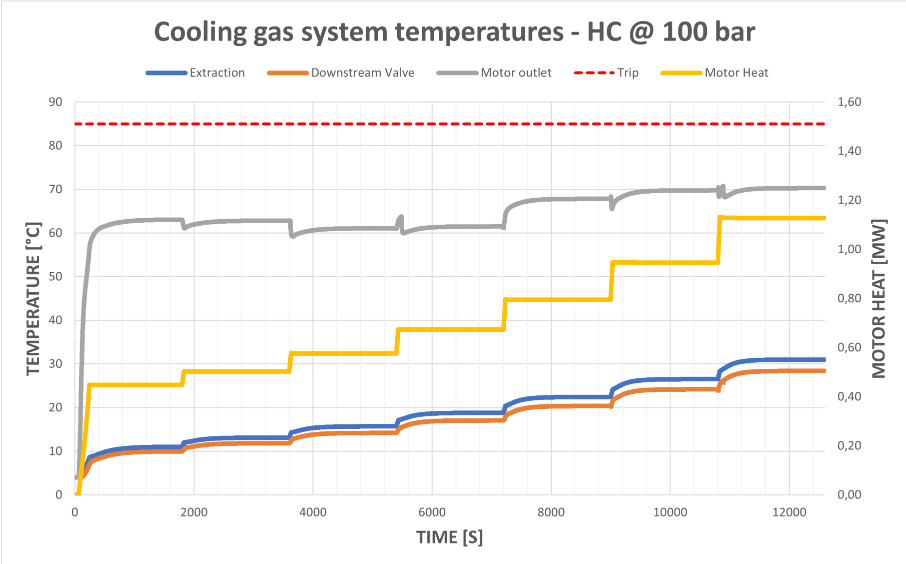


Figure A.8: Temperatures across across the cooling gas system and required heat absorption from the motor. Hydrocarbons with initial pressure of 100 bar.

A.2 Initial pressure 150 bara

Corresponding figures from results for initial pressure of 150 bar presented below.

A.2.1 Nitrogen

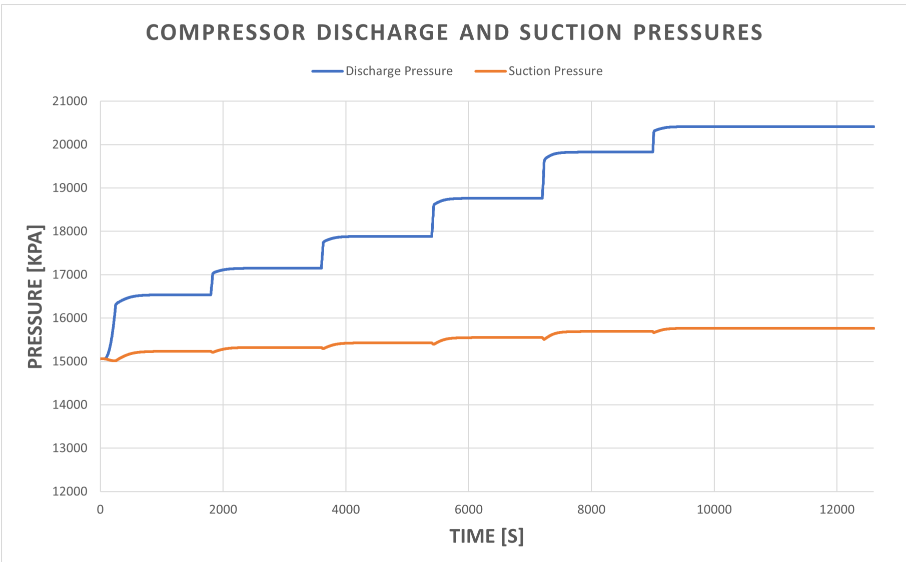


Figure A.9: Suction and discharge pressures of the compressor. Nitrogen with initial pressure of 150 bar.

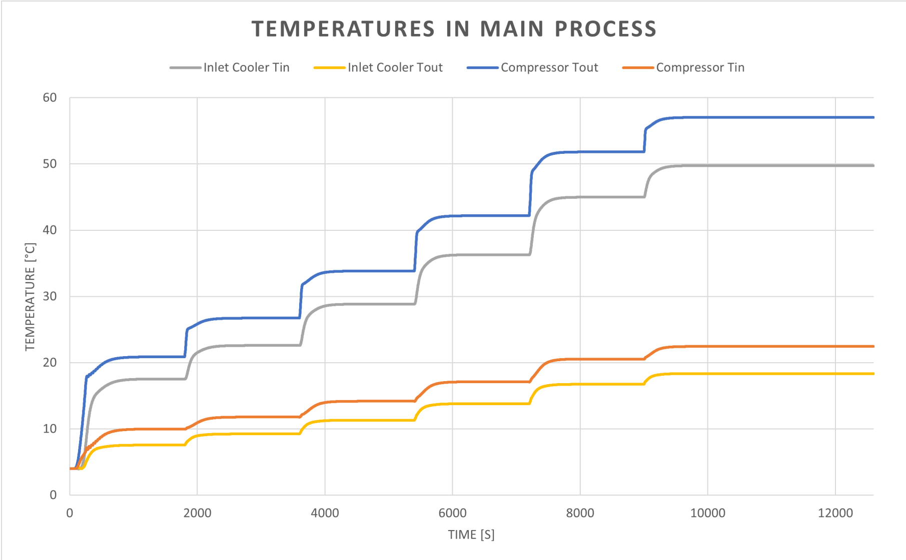
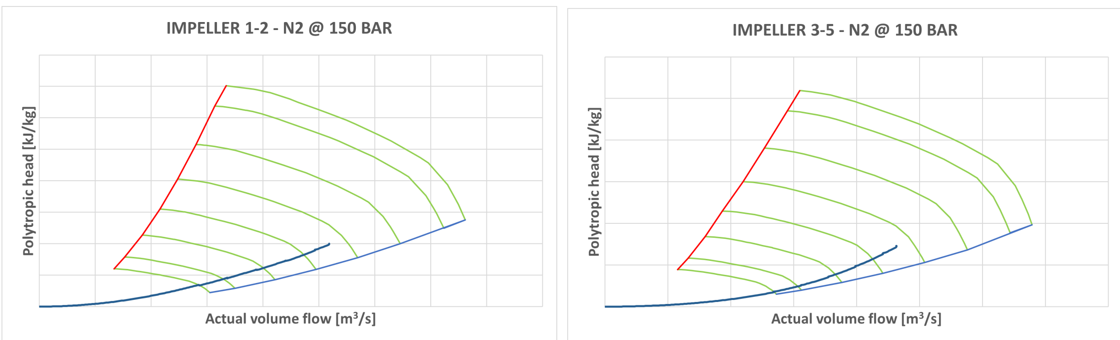


Figure A.10: Temperatures throughout the process. Nitrogen with initial pressure of 150 bar.



(a) Impeller 1-2, before cooling gas extraction

(b) Impeller 3-5, after cooling gas extraction

Figure A.11: Operating points on the compressor curves. Nitrogen with initial pressure of 150 bar.

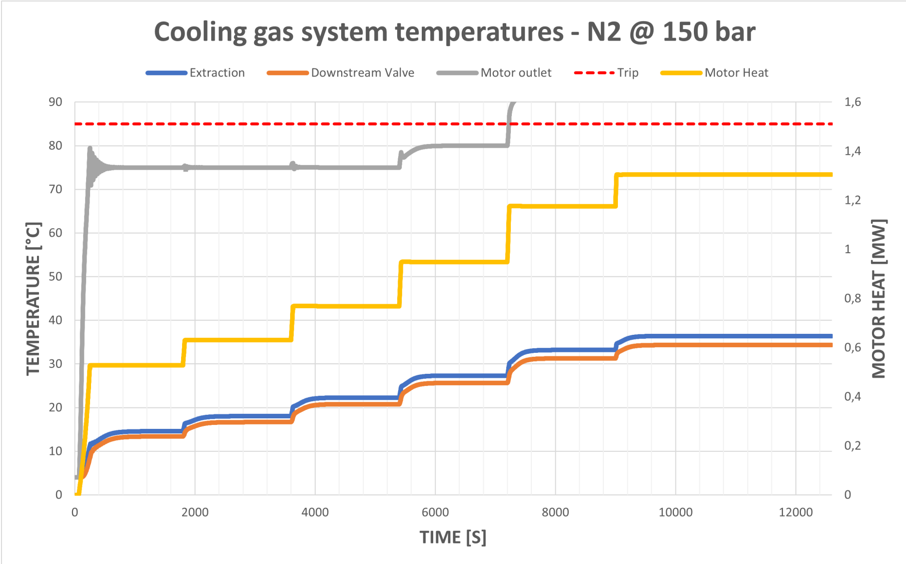


Figure A.12: Temperatures across across the cooling gas system and required heat absorption from the motor. Nitrogen with initial pressure of 150 bar.

A.2.2 Hydrocarbons

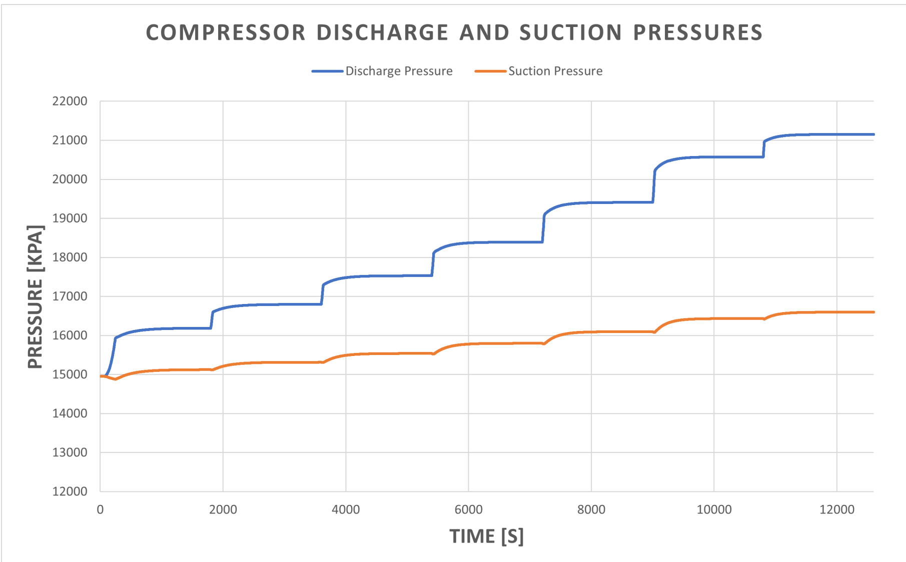


Figure A.13: Suction and discharge pressures of the compressor. Hydrocarbons with initial pressure of 150 bar.

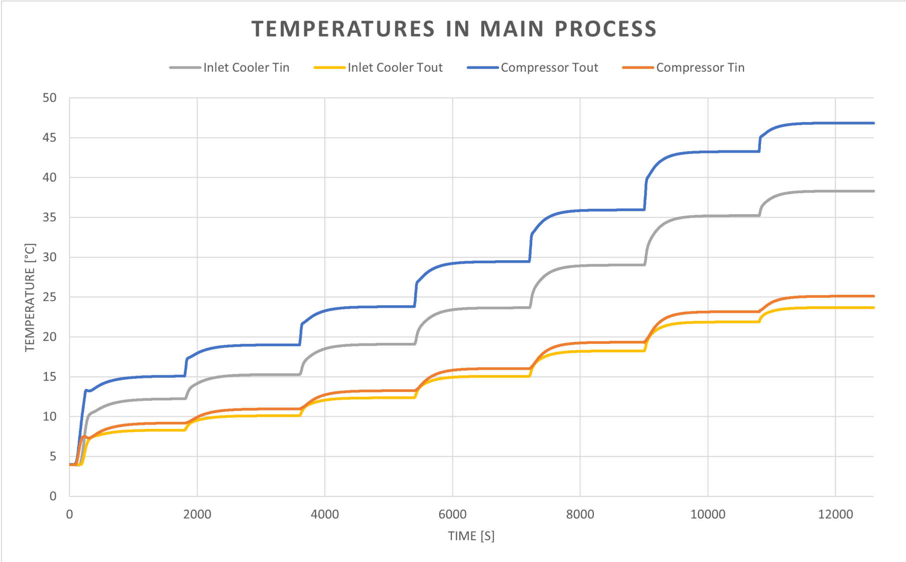
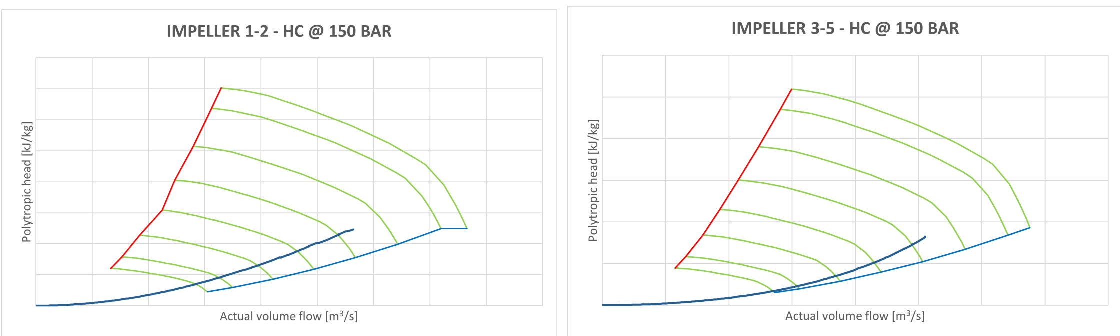


Figure A.14: Temperatures throughout the process. Hydrocarbons with initial pressure of 150 bar.



(a) Impeller 1-2, before cooling gas extraction

(b) Impeller 3-5, after cooling gas extraction

Figure A.15: Operating points on the compressor curves. Hydrocarbons with initial pressure of 150 bar.

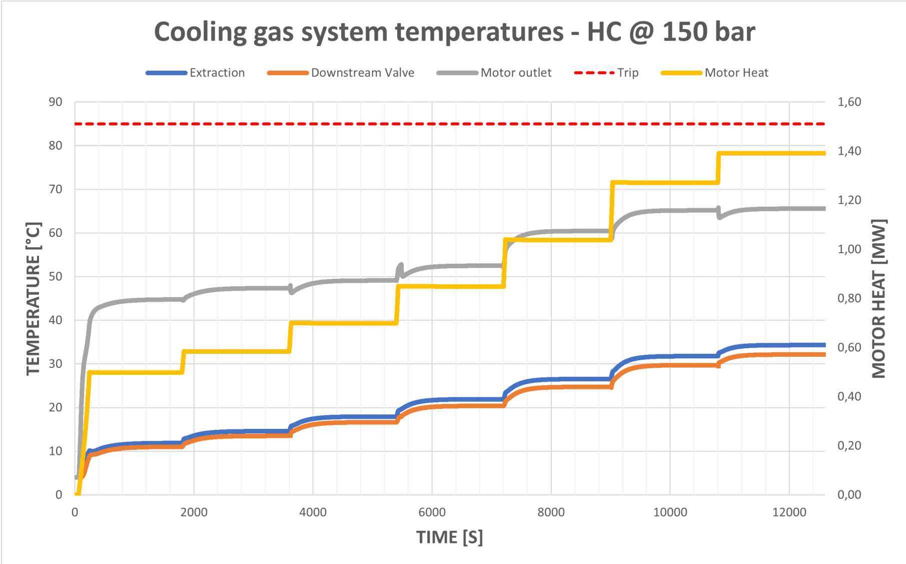


Figure A.16: Temperatures across across the cooling gas system and required heat absorption from the motor. Hydrocarbons with initial pressure of 150 bar.

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