NTNU
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Kompresjon av fakkelgass

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Master i produktutvikling og produksjon
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Norges teknisk-naturvitenskapelige universitet
Institutt for energi- og prosessteknikk

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MASTEROPPGAVE

for

Student Mari Masdal

Våren 2015

Kompresjon av fakkelgass

Flare gas compression

Bakgrunn og målsetting

Mellom 20 – 40 % av faklingen på olje-/gassplattformer skyldes kontinuerlig fakling, mens den resterende andelen er knyttet til enkelthendelser for å ivareta sikkerhet og operasjonelle hensyn. Kontinuerlig fakling er de siste årene blitt redusert på enkelte felt som følge av tekniske tiltak som for eksempel bruk av nitrogen som spyle- og dekkgass og forbedrete glykol-regenereringssystem. I tillegg er det utviklet ny teknologi for gjenvinning av fakkelgass. Ved å gjenvinne gass som kontinuerlig ville gått til fakkel, er det mulig å redusere faklingsvolumet.

Oppgaven dreier seg om å vurdere installasjon av et system med rekompresjon av fakkelgass (Flare Gas Recompressor) på Ekofisk Kompleks (EkoJ). Dette har vært prøvd to ganger tidligere, uten at det har lyktes helt. ConocoPhilipps har tidligere erfaring med design av kompressor for fakkelgass, og denne oppgaven vil bygge på dette.

Oppgaven bearbeides ut fra følgende punkter

1) Finn data på hva som er normale mengder og spenn på variasjon av sammensetning.
2) Gjøre rede for teknologi som finnes og benyttes for rekompresjon av naturgass, med fokus på fakkelgassanvendelser. Gjør rede for teknologileverandører.
3) Sett opp designkriterier for et system med kompresjon av fakkelgass.
4) Med basis i spesifikke data om mengder og sammensetninger; utfør design av et system med rekompresjon av fakkelgass (fra atmosfæretrykk til 12 bar).
5) Gjør rede for gevinst i form av reduserte utslipp av forurensende gasser, som konsekvens av rekompresjonssytemet.

" - "

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Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

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☐ Arbeid i laboratorium (vannkraftlaboratoriet, strømningsteknisk, varmeteknisk)
☒ Feltarbeid (besøk hos ConocoPhillips, Stavanger)

NTNU, Institutt for energi- og prosessteknikk, 9. januar 2015

Olav Bolland
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Medveileder(e): Clive Wilson, ConocoPhillips

Abstract

Recovery of flare gas on offshore installations is today, in Norway, required on all new installations. However, not all the old ones have one. ConocoPhillips has on Ekofisk, Norway's first producing field from 1971, tried to install a system two times earlier. Neither of them have managed to deal with the conditions at hand. A high pressure ratio and danger of condensation, together with limited floor space available offshore, makes it hard to find a system that will work. It has to be able to compress the flare gas from atmospheric pressure to 12 barg.

First, the design conditions for the potential system needed to be determined. Research into the operating conditions for the previous attempts has been used together with information on the conditions at Ekofisk from 2014. In addition, the reasons for the failure of the two first attempts were investigated.

All available flare gas recovery technology has been checked into, but it was found that there have not been any large breakthroughs here in the last years. Different suppliers were contacted to see if they had any equipment that could be used for the conditions at Ekofisk, or if they had any recommendations for what would work. From former research done by ConocoPhillips, the problem of this thesis boiled down to finding the correct type of compressor. In the review of flare gas recovery systems, the potential compressors that can be used for flare gas recovery is found. Through contact with suppliers and literature review, some of the alternatives could be disregarded. However, they might have been able to work, but the other alternatives were better in some regards. In the end, three potential compressors were chosen: the liquid ring compressor, the dry screw compressor and the oil-flooded screw compressor.

The liquid ring compressor and the dry screw compressor were simulated in PRO/II, and it was found that the dry screw compressor requires both less power and less heat duty for the heat exchangers, due to the higher compressor efficiency. However, from information from the suppliers, the initial cost of dry screw compressor is remarkably higher.

Two different design flow rates for the compressor were used in the simulations, to see how it affected the compressor consumption and heat duties of the required coolers. As expected, the higher flowrate yielded both higher power consumption and heat duties for both systems. However, more saved costs in connection with fees for emission to air and higher income due to recovery of the gas was present for the higher flowrate. In the end, the lower flowrate is recommended, since for the higher flowrate, 84 % of the total flaring would have been recovered. The lower flowrate is seen as an optimal balance between recovery and energy use.

Based on the results from the simulations in PRO/II, economical evaluations and input from suppliers, the final choice of a flare gas recovery system is: the liquid ring compressor system. It is the most used type of compressor in flare gas recovery in the world and it has a good reputation. Most importantly, there is no danger of compressor breakdown if condensation takes place. This decision has not taken into account maintenance costs of the compressors and operations costs of the systems as a whole. This information may change the outcome of the choice upon further investigation by ConocoPhillips.

Sammendrag

Gjenvinning av fakkelgass er i Norge i dag påkrevd på alle nye offshore installasjoner, men ikke alle de eldre installasjonene har det. ConocoPhillips har på Ekofisk, Norges første produserende felt fra 1971, prøvd å installere et gjenvinningssystem to ganger tidligere. Ingen av systemene klarte å håndtere forholdene på Ekofisk. En høy trykkrate og fare for kondensasjon, i tillegg til lite tilgjengelig gulvareal offshore, gjør det vanskelig å finne et system som vil fungere. Det må kunne komprimere fakkelgassen fra atmosfæretrykk til 12 barg.

Først må designkriterier for det potensielle systemet bestemmes. Disse ble funnet med basis fra de tidligere forsøkene på fakkelgassgjenvinning, sammen med info om forholdene på Ekofisk gjennom hele 2014. I tillegg ble grunnene til at de forrige forsøkene ikke fungerte som de skulle undersøkt.

All tilgjengelig teknologi for fakkelgassgjenvinning ble utforsket. Ingen store gjennombrudd for ny teknologi var å finne i de senere år. Forskjellige leverandører ble kontaktet for å se om de hadde noe utstyr som kunne brukes på Ekofisk eller om de hadde noen anbefalinger for hva som kunne fungere. Fra tidligere undersøkelser gjort av ConocoPhillips for å finne det ideelle gjenvinningssystemet ble problemet snevret inn til å finne den korrekte typen kompressor. I vurderingen av fakkelgassgjenvinningssystemer finnes også en oversikt over de potensielle kompressorene som kan bli brukt. Kontakt med leverandører og analyse av tilgjengelig litteratur førte til at noen av alternativene kunne sløyfes. De eliminerte alternativene kunne fungert, men de resterende var bedre i noen henseender. Til slutt ble tre alternativer valgt: væske-ring kompressor, tørr skruekompressor og olje-injisert skruekompressor.

Væske-ring kompressoren og den tørre skruekompressoren ble simulert i PRO/II. Det ble funnet at den tørre skruekompressoren krevde mindre kraft for å opereres og de medfølgende varmevekslerne trengte mindre varme. En grunn til dette kan være den høyere kompressoreffektiviteten. På den andre siden gir informasjon fra leverandørene at kjøpsprisen på den tørre skruekompressoren er betraktelig høyere.

To forskjellige volumstrømmer for kompressoren ble brukt i simuleringene for å se hvordan de påvirket kompressorkraften og nødvendig varme for begge systemene. Mer innsparinger i forbindelse med reduserte avgifter for utslipp til luft og høyere profitt på grunn av gjenvinning av gassen er tilstede for den høyere raten. Til slutt falt valget på den lavere raten etter som den høye innebar gjenvinning av omtrent 84 % av den totale faklingen. Den lavere volumstrømmen har den beste balansen mellom energibruk og gjenvinning.

Basert på resultater fra simuleringer i PRO/II, økonomiske evalueringer og input fra leverandører, ble det endelige anbefalte gjenvinningssystemet: væske-ring kompressor systemet. Det er den mest brukte kompressortypen i fakkelgassgjenvinning i verden og har et godt rykte på seg. Viktigst er det at det ikke er noen fare for kompressorsammenbrudd dersom kondensasjon finner sted. Vedlikeholdskostnader til kompressorene eller operasjonskostnader for hele systemet ble ikke tatt med i vurderingen. Denne informasjonen kan endre utfallet av valget ved videre undersøkelser.

Preface

The work in this thesis has been performed at the Norwegian University of Science and Technology (NTNU) over a period from January to June 2015.

My supervisors throughout this project have been Olav Bolland at NTNU and Clive Wilson at ConocoPhillips, whom I both thank for good guidance and for giving me the opportunity to carry out this project. Not only have I learned a lot about compressors, but I have also learned a lot regarding writing a bigger report and doing research through contact with suppliers to find a concept that would work. To obtain relevant information from the suppliers were more time consuming than originally thought. This experience will be helpful in the future.

I will also like to express special thanks to Steinar Duvold at ConocoPhillips for explaining the work done regarding this problem earlier and discussing what alternatives were most promising. Others contributing to the work are the representatives of the different suppliers that were contacted, and I am very grateful for their contribution as well.

Trondheim, 10th June, 2015

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Abbreviations

API = American Petroleum Institute

BDV = Blowdown Valve

FGR = Flare Gas Recovery

FPSO = Floating Production, Storage and Offloading

HP = High Pressure

HAZOP = Hazard and Operability

KO Drum = Knock Out Drum

LP = Low Pressure

NCS = Norwegian Continental Shelf

NGL = Natural Gas Liquids

PSV = Pressure Safety Valve

PV = Pressure Valve

VOC = Volatile Organic Compounds

VRU = Vapor Recovery unit

1. Introduction

1.1 Background

About 20-40 % of hydrocarbon vapor released to atmosphere on oil and gas platforms originates from continuous flow from compressor seals, glycol regeneration and produced water flash back. The remaining part is related to single events to ensure safety and for operational considerations. Continuous hydrocarbon vapor has the last couple of years been reduced on some installations due to technical measures such as use of nitrogen as purge and blanket gas and improved glycol-regeneration system. In addition, new technology for recovery of flare gas is constantly being developed. By recovering the gas, it is possible to reduce the flaring, thus reducing both emissions and costs in form of various fees.

ConocoPhillips has tried to install such a system two times earlier without them being able to live up the expectations. A system based on using an oil-flooded screw compressor was tried in 1997, and a reciprocating piston compressor in 2002. Due to the fact that there have been previous attempts, everything is in place for a new try.

There exist many possible solutions for recovery of flare gas. The challenge is to find a system that can handle high pressure ratio, the varying composition, the given flare gas flowrate and the possible problem of condensation through a compressor or similar equipment.

1.2 Objective

The main goal is to design one or several flare gas recovery systems that will be able to recover the flare gas that is continuously flared at the Ekofisk Complex. The system(s) needs to able to compress the flare gas from atmospheric to 12 barg, handle variations in composition, etc.

1.3 Scope of the Thesis

Investigation will be conducted to find possible designs or solutions for recovering the flare gas at Ekofisk. Design conditions for the system needs to be determined and different suppliers of compressors or flare gas recovery units will be contacted to see if they have some possible alternatives. The suggested systems will be evaluated among other things based on simulations in PRO/II. Initial costs of the systems will contribute to some degree. However, the total costs of running the systems is not within the scope of this thesis.

1.4 Definitions

Expressions used in this report include terms like flaring, venting, combustion and destruction efficiency and nmVOCs. Definitions are found below:

Flaring: is controlled burning of natural gas produced in association with routine oil and gas production

Venting: is controlled release of unburned gases into the atmosphere

Combustion efficiency: is a measure of the proportion of original hydrocarbons that are completely burned and converted to CO_2 and water vapor.

Destruction efficiency: is a measure of the proportion of original hydrocarbons that are completely or partially burned, and form CO and CO_2. The destruction efficiency is always greater than the combustion efficiency.

nmVOCs: volatile organic compounds (VOCs) except methane are called non-methane VOCs. These components evaporate from crude oil.

1.5 Organization of Dissertation

This thesis is divided into 7 chapters. Each chapter is summarized below:

Ch. 1: Introduction. The background and scope of the thesis are defined.

Ch. 2: Review of Flare Gas Recovery Systems. This part first explains why a flare system is present on offshore facilities. Further, the different types of flare gas recovery systems that exist is investigated both offshore and for other applications. More information on the offshore alternatives are given through details on compression methods both in general and for flare gas recovery purposes. The chapter ends with info on suppliers of flare gas recovery systems or compressors.

Ch. 3: Flare Gas System at Ekofisk. Focus is set on the specific conditions at Ekofisk. The structure of the flare gas system at the Ekofisk Complex is explained and information on the contributors to the continuous flaring is given. In the end, ConocoPhillips' previous attempts on flare gas recovery are presented.

Ch. 4: Design Criteria for the Flare Gas Recovery System. The design criteria for a flare gas recovery system at the Ekofisk Complex is obtained through data from 2014. The parameters focused on are suction temperature, suction and discharge pressure, flowrate and composition of the flare gas.

Ch. 5: Choosing a Flare Gas Recovery System for the Ekofisk Complex. Based on communication with suppliers and information from Chapter 2, the compression alternatives are reduced to three. These are among other things evaluated through simulations in PRO/II.

Ch. 6: Consequences of installing a flare gas recovery system at Ekofisk. In this chapter the benefits of installing a flare gas recovery system at Ekofisk is highlighted, both in form of reduced emissions and reduced costs due to fees. The value of the previously flared gas will also no longer be lost but contribute to the overall production on the field.

Ch. 7: Conclusion. This final chapter summarizes the thesis and gives recommendations for future work.

2. Review of Flare Gas Recovery Systems

2.1 Introduction

This chapter starts with a brief introduction to the purpose of the flare gas system at offshore installations, in Section 2.2.1, which further leads to why a flare gas recovery system is needed. Emissions due to flaring are highlighted in Section 2.2.3 and fees for these emissions are given in Section 2.2.4. Different alternatives for reducing the flaring is proposed in Section 2.2.5 and Section 2.2.6.

In Section 2.2.7, other forms of flare gas recovery systems are presented, for instance for refineries where the conditions are somewhat different from offshore.

In Section 2.3, different compression methods for re-compression of the flare gas are mentioned. Pros and cons for the different types are presented. In the end of the chapter, in Section 2.3.3, some suppliers of compressors and flare gas recovery units are listed.

2.2 Flare Gas Recovery

2.2.1 Flare Gas System

On any oil and gas process plant, flare systems play an essential role. Offshore processing of oil and gas involve large volumes of hydrocarbons at high pressures. Consequently, these systems represent an inherent risk for personnel, environment and assets. Risk of fire or explosions are reduced by flaring and venting when gas cannot be stored or used commercially. The flare system serve as one of the last layers of protection for the plant, to relieve pressure in a safe manner when overpressure occurs.

Gas to be flared may come from different sources, such as:

- Surplus gas that cannot be supplied commercially to customers
- Gas leaking through valves connected to the flare system
- Vapor from storage tanks being filled
- From process upsets, equipment maintenance or changeover
- From a depressurization of the facility if there is a need to rapidly reduce the pressure to prevent catastrophic situations

There are two kinds of flaring of interest: flaring during an emergency situation and flaring during normal operation. Safety is the most important aspect during emergency flaring. Large flows of gases, up to more than 500 000 kg/h, must be burned. Waste gases generated during normal operation together with planned maintenance of equipment often involve a substantial lower rate of gas. The flowrate and composition may vary a lot and the flare should be able to safely release and destroy the waste gas and at the same time minimize emissions. (1)

Releases to the flare system comes from systems operating at different pressures and temperatures, thus a practical and cost effective flare gas system design demands more than one system. The different categories can be separated intro three:

- HP flare system – operates at a relatively high backpressure, which leads to minimizing piping and equipment size. A pressure of at least 10 barg must be maintained by systems discharging to the HP flare system. Operation at sonic velocity, significant pressure drop and good emissivity characteristics are specified in the HP flare tip to minimize radiation intensity.
- LP flare system – receives discharges from processes operating at low pressure, which cannot be handled by the HP flare system. Selection of appropriate piping sizes together with a subsonic open pipe flare, incurring minimal pressure drop, result in the flare system backpressure being minimized.
- Vent system – receives discharges from equipment that cannot handle backpressures above 0,07 barg. They are either combusted or "cold" vented to the atmosphere. In many production facilities both kinds may be found.

A combination of the HP and LP flare systems may be possible as well. (2)

Gas may come from relief valves and other overpressure protection devices like Pressure Safety Valves (PSVs), Rupture discs, Blowdown Valves (BDVs) or Pressure Control Valves (PVs). These are situated on or near the equipment being exposed to high pressures. In addition, they have to be located at high points in the process systems to minimize liquid carry-over and ensure free drainage into the flare system. From these relief sources, the gas is routed through flare headers to a knock out drum. The knock out drum is used to reduce the gas velocity and to allow liquid or liquid drops to "fall out". Then, the liquid free gas can go up in the flare stack and be safely burned in the flare tip. It can be dangerous with liquids present here as it can yield burning rain released to sea or standby vessels. (3)

In cold climates, some precautions need to be taken to avoid formation of ice or hydrates causing potential blockages in the flare system. Some preventive measures to be taken may be using knock out drum heaters, insulation and heat tracing of the flare headers, avoid mixing low temperature gas with high temperature gas or liquid, use cold flare headers for the coldest gases, etc. In addition, flare and vent headers shall be routed to the knock out drum without pockets and shall be sloped to allow free drainage. (2)

2.2.2 Flaring in Norway

In Section 2.2.2, all info is obtained from Ref. (4).

The total amount of flaring in 2011 was respectively 337 million Sm^3 offshore (938 000 tCO_2) and 203 000 tons onshore (396 000 tCO_2) in Norway.

Since the 1970s, Norway has had regulation of flaring associated with exploration and production of oil and gas. Flaring that is not of safety reasons is prohibited by the Petroleum legislation (Petroleum act §4-4), unless the Petroleum and Energy Ministry (OED) approves otherwise. The authorities regulate flaring by OED issuing flaring permits in the annual production licenses. The level of flaring in Norway is low compared with other oil and gas producing countries. The long-lasting, predictable and strict regulation of flaring has undoubtedly contributed to this. In 1991, the CO_2 tax regime was implemented, more on this in Section 2.2.4. As a result, a series of measures to reduce continuous flaring were carried out by developing and adopting new technology; for instance flare gas recovery and extinguished flare tip that ignites only when required.

Earlier, until around 1940, it was usual to emit the gas unburned into the atmosphere. When this trend gradually started to change there was a growing need to improve burner design, ignition systems and other accessories. A supplier industry for flare technology was then established. Because of the irregularity in operation and need for depressurization, the flare typically has to operate over a broad span of operating conditions; from maximum to very low quantities of gas. Effort is being made by the flare vendors to develop new technology to be able to flare gas in a safe and environmentally sensitive manner. Over the last 60 years, from an environmental perspective, several technologies have been developed with focus on achieving a high combustion efficiency and smoke free operation.

For newer installations, flare gas recovery and extinguished flare tip are regulatory requirement and is implemented in the original design. For many of the older installations, steps are taken to achieve the same. However, limited profitability and minimal environmental benefits are challenges that oppose further action.

A report was written in connection with the Environmental Department's ("Miljødirektoratet") project: "The flare project 2012", with purpose to map key issues related to flaring and emission to air from oil and gas related businesses in Norway. Carbon Limits AS together with Combustion Resources Inc. (Utah, USA) conducted the project and wrote the report. The basis for the analysis and recommendations in the study was collected through a survey. Questionnaires were sent out to onshore and offshore installations, to 66 businesses operating 114 flares, and follow-up calls were conducted with representatives from the businesses. Six different suppliers of flare technology were also contacted.

In this project, the Norwegian enterprises were asked to classify the sources for flaring in 2011. This proved to be hard, but the enterprises managed to send in estimates for 81 of the flares. The results are plotted in Figure 1. The figure shows a snapshot of the situation at one specific moment and cannot be used to draw clear conclusions. It can however be used to give indications on where there are areas of improvements to reduce flaring even further. The rough estimates interpret that about 80 % of the flaring offshore is due to unforeseen/not-planned happenings and operation disturbances. The continuous flaring consist of about 20 % and is mainly related to four sources (the four columns to the left in the Figure 1): use of pilot gas and purge/blanket gas, and flashing from produced water system and from glycol regeneration.

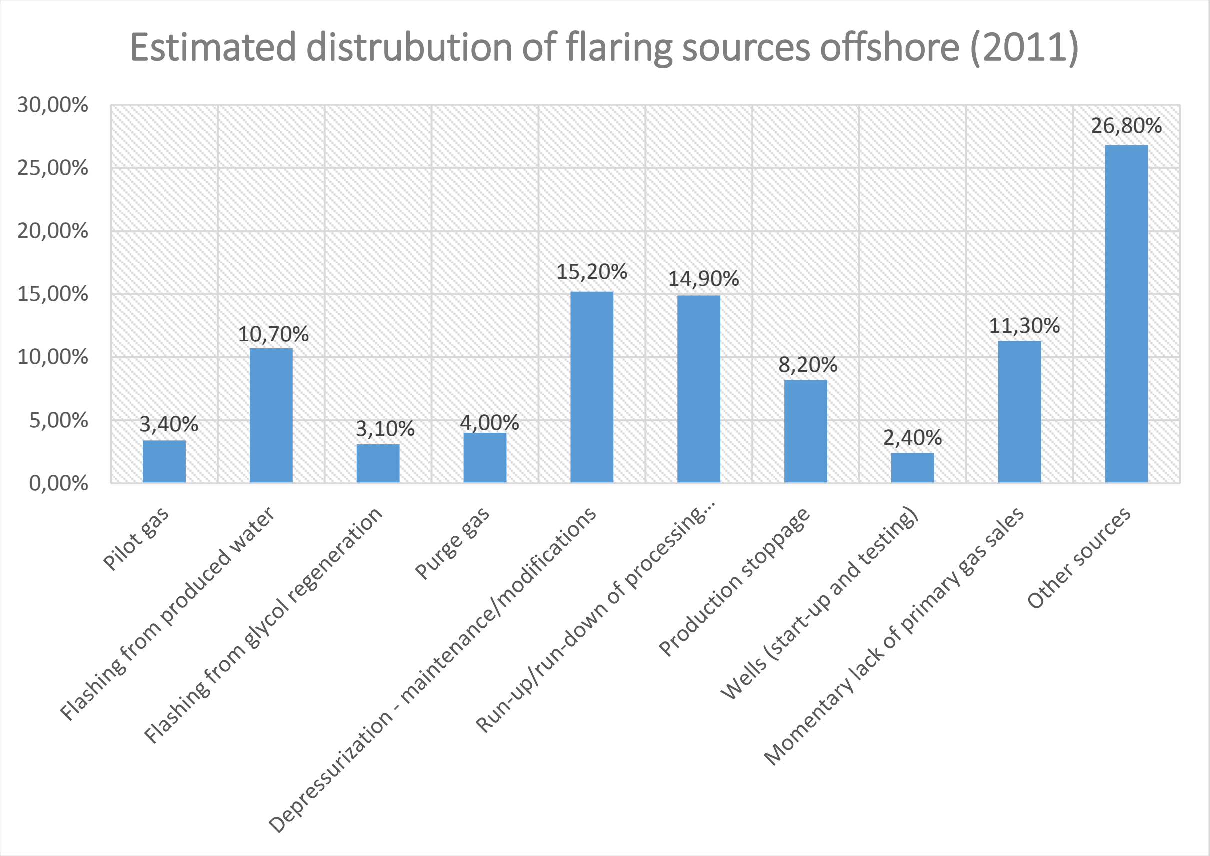

Figure 1: Estimated distribution of flaring sources offshore in 2011, from «The flare project 2012» (4)

Knowing the sources of the continuous flaring make it easier to find the best possible way to recover the lost gas. The “other sources” category is suspected to be connected to insufficient registration of flaring incidents and their cause. These flaring volumes would in reality be distributed on the other sources, thus contributing to change the snapshot presented above.

Continuous flaring contribute only to a limited part of the total flaring. The report recommends considering measures to recover flare gas if it has not been done in a long time. Especially if flashing from the produced water system or glycol regeneration are main contributors to the flaring. This is also valid for installations where a great part of the flaring comes from the use of hydrocarbon gas as purge gas. However, the project team understands that some measures in many relations will not be carried out at older installations due to technical limitations or low profitability.

2.2.3 Atmospheric Emissions due to Flaring

In Section 2.2.3, all info is obtained from Ref. (4).

Flaring of natural gas result in emissions of a number of different components, thus it is an important source to air pollution. When it comes to amount and potential influence, the most important emission components are CO_2, Nitrogen Oxides (NO_x) Volatile Organic Compounds (VOCs), CO, SO_2 and particles.

Measuring emissions is a challenging task, thus flare emissions have historically not been a parameter of interest. One reason for this is because flaring usually take place out in the open and there is no combustion chamber or similar to extract measurements from. Other contributing factors that make measuring hard are the variations in weather conditions, gas flowrate and composition. The performance of the flare may for example be very dependent on wind.

The combustion process in a flare is complex and typically consist of an uncontrolled flame open to external influence. Amount of emissions of different pollutive components depend on a number of physical and chemical reactions through conservation of mass, momentum and energy. These are again affected by gas composition, flare rate, design of flare gas system and external influences. Important concepts when looking into combustion of natural gas is combustion efficiency and destruction efficiency.

Gases with low density and with a high-energy content will in general achieve a better combustion. The flame temperature is directly related to the reaction rate, thus the flame temperature will increase for higher combustion efficiencies. A flare tip with a big diameter will yield a low combustion efficiency near the flame center due to low oxygen levels there. A high gas velocity will in general increase the intermixture of air and result in an increased combustion efficiency. Increasing the combustion efficiency can also be done through designing the flare tip with a special geometry to improve the mixing of gas and air.

The wind will only influence the combustion efficiency when the velocity is larger than about 10 m/s. Then the flame will be “ripped apart” yielding a lower combustion efficiency.

To summarize, in Table 1 a row of parameters is listed at the top. Increasing these parameters will have an impact on the combustion efficiency given by either an upward pointing arrow representing an increase, a downward pointing arrow representing a decrease or a question mark representing inconclusive.

Parameter:	Flame temp.	Gas density	Energy content	Velocity in flare tip	Diameter	Turbulent mixing	Cross wind
Combustion efficiency:	↑	↓	↑	↑	?	↑	↓?

Table 1: Increasing the parameters will have the following influence on the combustion efficiency, (4)

The major component of natural gas is methane. Flaring produces mainly carbon dioxide emissions, while venting results in mainly methane emissions. Both carbon dioxide and methane are known as greenhouse gases. The effects of methane and carbon dioxide are different when it comes to the global warming potential. A kilogram of methane is estimated to have twenty-one times the effect than that of a kilogram of carbon dioxide when looking on a period for over one hundred years. Thus, flaring will be preferred in the case of flaring or cold venting the same amount of natural gas. In addition, it’s preferable to have a high combustion efficiency yielding a greater emission of CO_2 than other components.

About 1,3 million tons of CO_2 was emitted from flaring in 2011, representing 10,9 % of CO_2-emission on the Norwegian Continental Shelf. Emission of CO_2 from flaring is directly coupled to combustion efficiency and gas composition. When having complete combustion, all the carbon is converted to CO_2. Emission of CO_2 is in itself undesirable, but from a safety and economic perspective, it's a goal to have an effective combustion and to limit emissions of other unwanted components. For instance, a reduction in emissions of CH_4, nmVOC and CO will result in an increase in CO_2 emissions.

Emissions of Nitrogen Oxides (NO_x) and Sulphur Dioxide increase the risk of respiratory pains and contribute to acidification and damage to materials. If the NO_x is also mixed with sunlight and VOC, it can contribute to the formation of tropospheric ozone. The Sulphur Dioxide may also acidify earth and water, and the emission is directly related to the content of Sulphur (H_2S) in the flare gas.

Incomplete combustion contribute to emission of among other things VOCs, CO and particles. Emission of methane and non-methane VOCs (nmVOCs) depend on the share of methane and hydrocarbons in general present in the gas. The nmVOCs can be carcinogenic and contribute to formation of tropospheric ozone. Carbon monoxide is one of the most important pollutants associated with incomplete combustion, and if measured it can help finding the combustion efficiency when flaring. The CO has health-related consequences, and also contribute to formation of tropospheric ozone.

A summary of the most important emission components and their potential influence can be found in Table 2.

Emission Component	**Potential Influence**
CO	- health-related consequences - contribute to the formation of tropospheric ozone
NO_x	- increase the risk of respiratory pains and contribute to acidification and damage to materials - if mixed with sunlight and VOC, it can contribute to the formation of tropospheric ozone
SO_2	- increase the risk of respiratory pains and contribute to acidification and damage to materials - may acidify earth and water
nmVOCs	- can be cardiogenic and contribute to the formation of tropospheric ozone

Table 2: A summary of emission components from flaring and their potential influence

"Soot" is often a term used to describe emission of particles, and consist of "Black carbon" and "Organic carbon". It's a result from incomplete combustion. Emission into the air has a significance for local air quality, it affects the climate and contribute to transport of among other things environmental poison over large distances. The knowledge about this sort of emissions is rather limited and research is being done on this. From US EPA (2002) (as cited in (4)) it's found that all hydrocarbons heavier than methane will involve sooting or carbon deposit. James G. Seebold wrote in an article (as cited in (4): Combustion Efficiency of Industrial Flares. 2012) that: "data actually suggest that for the best combustion efficiency, you should run the flare at least slightly smoking all the time". Thus, a "smokeless" flare does not guarantee a highest possible combustion efficiency.

The issue of climate change is complex and there are many uncertainties that need to be resolved before being able to understand it completely. However, to avoid unnecessary emissions into the atmosphere make sense. A practical way to reduce these therefore need to be found. (1)

2.2.4 Fees for Emissions to Air from Flare

ConocoPhillips informs that there are three fees for emissions to air from flare. They are the CO_2-tax, the quota system and the NO_x-tax.

CO_2-tax

The CO_2 tax was introduced in Norway in 1991. The CO_2-tax is one of the most important instruments in the climate policy. More than 80 % of climate emissions in Norway is today covered by CO_2-taxes or the European quota system. It's about putting a price tag on the CO_2-emissions, were the Norwegian Parliament determines the tax-level. In 2015, for petroleum activity, the CO_2-tax is set to 1,00 NOK/Sm^3 flared gas. (5) (6)

Quota system

A climate quota is a permission to emit a certain amount of climate gases within a given amount of time. In a national quota system, the authorities determine an upper limit for emission of climate gases for businesses with duty to surrender allowances. Then, the Government sells or distributes quotas, which are securities conferring the right to emit a limited amount of climate gases. The purpose of a quota system for climate gases is to limit emissions. It is necessary for Norway to reduce it's contribution to global climate change and to fulfill the commitments in international agreements. Private and governmental businesses both may be required to trade quotas. Thus, they need to have emission quotas corresponding to the amount of own emissions of CO_2 and other climate gases. The quotas can be bought and sold on a level with other securities. The companies' emissions are reported to the authorities. It is ensured that the companies report correctly and that nobody emits more than their quota. If connected to an international quota market, foreign quotas are made available for Norwegian companies, in addition to Norwegian quotas being able to be sold abroad.

The authorities set a limit on amount of emissions. It is the different companies' job to stay within these limits. Usually, most will try to seek out the solution with the lowest cost. If reducing emissions with low costs is possible, then that would be most profitable. However, if there is more to earn by continuing to emit, the companies can buy quotas from each other. The price on the quotas is determined by the market. (7)

NOx-tax

From the Gothenburg protocol from 1999, Norway committed to reducing emissions of nitrogen oxides (NO_x) to a maximum amount of 156 000 tons per year from 2010. In 2006, the emissions of NO_x was 194 500 tons. Hence, to meet the emission commitment the yearly emissions had to be reduced by 38 500 tons by 2010. The Norwegian Government introduced a NO_x-tax of 15 kr per kg emission from January 1st 2007, to encourage reductions in emissions. This tax concerns larger fishing vessels and other ships, larger motors, boilers and turbines in the industry and flares on offshore and onshore installations. (8)

In 2015, the NO_x-tax is set to 19,19 NOK/kg emission of NO_x.

2.2.5 Reduction of Continuous Flaring

The report in connection with the “Flare Project 2012” highlights that in some cases, it would be unwise to implement certain measures to reduce the continuous flaring. It can have negative effects for other environmental objectives. A higher fuel consumption may be required and the emission of methane may increase if the combustion efficiency reduces. This is dependent on installation specific conditions and need to be taken into account when evaluating what measure should be taken. (4)

The report go thoroughly into two main groups to reduce flaring and emissions to air. The first group addresses measures to reduce the amount of gas being flared while the second focuses on changing the combustion conditions in the flare and reduce emissions of certain components. These two groups are further divided into subcategories, shown in Table 3.

Type of measure:		**Subcategory:**
Reduce amount of gas being flared	Technical measures	Technical measures to improve the regularity
		(Increased) flare gas recovery
		Different measures to reduce the amount of gas sent to the flare
	Operational measures	Improving procedures and flaring strategy
		Training of personnel
	Change the flare design	Measures connected to pilot burners
		Reduced use of hydrocarbons as purge/blanket gas
		Other measures connected to flare design
Changing combustion conditions and reduce emissions of certain comp.	Technical measures	Select a flare system to optimize combustion
	Operational measures	Control the use of assistance medium

Table 3: Measures to reduce flaring and emissions to air

In Table 3, the different colors have different purposes. The yellow markings represent measures to reduce non-continuous flaring, the blue: measures to reduce continuous flaring and the green: measures to improve the combustion conditions.

Further, focus is set on the blue subcategories concerning reduction of continuous flaring. The first one deals with flare gas recovery. This can be installed with or without an extinguished flare tip. These solutions have been used in Norway since the 1990s, both offshore and onshore. More on how a flare gas recovery system works in Section 2.2.6. The report have a table shown in Table 4 showing technical and economic conditions coupled to flare gas recovery and extinguished flare tip.

Effect on Flare rate:	**Barriers:**	**Capital expenditure (CAPEX):**	**Operational expenditure (OPEX):**	**Benefit:**
0,1 to 6 million Sm^3/year per flare	Safety Cost-benefit (lifetime) Operational challenges (small and variable amounts)	20 to 300 million NOK	1 to 1,5 million NOK/year Operation of equipment (and possibly use of pellets for ignition)	The value of gas (that is not flared) Reduced costs connected to emissions

Table 4: Technical and economic conditions coupled to flare gas recovery and extinguished flare tip

Measures connected to pilot burners is the second subcategory. There are in general three ways to reduce flaring using pilot burners:

- Replacing to a new type of pilot burner(s), i.e. with a more fuel effective design
- Reduce the amount of pilot burners in operation
- (Re)install pilot burner(s)

Pilot burners have traditionally played a central role when it comes to ignition systems for flares. It is a small burner operating continuously and provides energy to ignite and light the flared gases. From the report, one can understand that with a new pilot burner design, it’s possible to reduce the fuel needed by up to 85% and still be able to nurture the flare. An evaluation to install pilot burners should be conducted if it does not exist on a plant. The lack of a good functioning pilot burner may result in unburned hydrocarbons and/or toxic gases being released directly into the atmosphere. (9)

Reduced use of natural gas as purge gas is the last subcategory. On several older plants, hydrocarbon gas is used as purge gas. In these cases there are two measures that can be conducted:

- Installation of equipment for reduced use of purge gas
- Transition to use of Nitrogen (N_2) as purge gas

It is required at offshore installations to purge the flare headers to prevent oxygen ingress, thus avoiding the formation of explosive mixtures inside the headers. In worst case explosions may take place if ignited. To prevent air ingress, a positive pressure should be maintained in the flare headers. This is done by injecting the purge gas (either fuel gas or nitrogen) at different locations in the systems.

The use of fuel gas as purge gas result in environmental emissions. However, replacing with use of nitrogen will eliminate these.

If installing a flare gas recovery system, using nitrogen as purge gas will no longer be necessary. This is because the purge gas will be recovered and sent back to the process, and it’s therefore preferable that it’s maintained as natural gas. However, if implementing a flare gas recovery system has a significantly longer pay back time than changing the purge gas from fuel gas to nitrogen, the nitrogen purge should be considered instead. (10)

2.2.6 Flare Gas Recovery Systems

In Section 2.2.6 and 2.2.6.1, all info is obtained from Ref. (11).

Minimizing flaring might seem easy, but it can be hard to isolate the flare gas (or safety release) system from the rest of the facility to allow Flare Gas Recovery. In many cases, large and specialized projects are carried through to solve this. One of the main challenges is that it can be uneconomical to recover the gas for different reasons at older plants.

Strategies for minimizing flaring can be grouped into two categories: *plant practice* and *new equipment*. *Plant practices* include using existing equipment to control the process that leak gas into the waste-header. This may be done by making sure that the equipment is properly maintained or by investigating what waste gases are produced under what conditions such that these can be avoided. *New equipment* involve adding equipment to reduce the amount of gas going to the flare. Redesigning plant processes by recycling gases back into the processes or by using alternative technology are examples to minimize the production of waste gas. Flare Gas Recovery Units (FGRUs) can capture waste gases going to the flare, such that it can be used in the plant or for sale.

Following evaluations of data and location, focus should be set on reducing the continuous flowrates. Flaring reductions can be done by making improvements to the facility:

- Reduce purge rates in the flare header
- Reduce the continuous purge rate
- Replace pressure safety valves (PSVs) and control valves that are leaking to the flare header

The last flaring mitigation proposal above suggest upgrading PSV's and control valves. There is often a large number of these valves present in a facility, and it may be uneconomical to upgrade all of them. Thus under some circumstances, it may be more practical to install a flare gas recovery unit.

The best suitable flare gas recovery system depend on numerous factors. The units producing the gases to the flare gas system should be evaluated, the flow rate and composition should be monitored and an investigation of the existing flare gas system should be conducted to find opportunities for reusing the flare gas. Several techniques for flare gas recovery exist today.

Flare gas recovery systems may be designed for both HP and LP flare systems, and their aim is to recover hydrocarbon gas and return it to the main process. The gas should be taken from the flare gas system downstream of the knock out drum. Recommended flare gas recovery systems from Norsok P-100 are: (2)

- Raising the operation pressure in the flare system to such an extent that the gas can be returned directly into the process
- Installing a re-compressor or ejector

The integrity of the flare system should not be jeopardized by a flare gas recovery system. If, for whatever reason, the flare gas recovery system doesn't work, the flare gas system should be able to function as normal.

2.2.6.1 The main components of a flare gas recovery unit (FGRU) system

The main components in a flare gas recovery unit is shown in Figure 2.

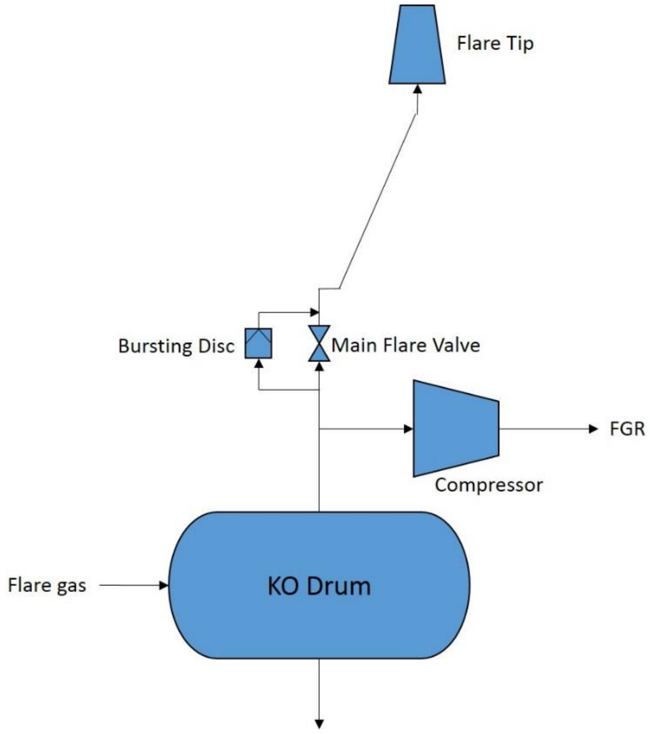

Figure 2: Main components in a flare gas recovery unit

The *Compressor*: compresses the flare gas from a low to a high pressure. This enables the gas to be used elsewhere in the plant as pilot gas, assist gas, etc. A single stage compressor may be sufficient or adequate enough for smaller FGRUs, but for the larger systems, multiple stages of compressors are needed.

The *Control System*: handles the turndown, which ensures that the suction pressure, the pressure in the flare header, remains at an approximately constant level, as the flare gas rates entering an FGRU can vary over time. Normally, a FGRU will include several different instruments that are monitored by the control system. To ensure that the flare gas recovery unit is operating within its envelope at all times, the control system makes constant alterations to the different system settings.

The *Flare Valve* & *Bursting disc*: are installed on the stack and work to isolate the flare stack from the flare gas recovery system. The valve is a fail open, quick opening shut off valve and it’s only opened during emergencies or during other abnormal situations. Also, the bursting disc bypasses the valve, to ensure that the flare system is inherently safe. Thus, the bursting disc works as a secondary protection to ensure proper depressurization during emergencies. In addition, there is a valve on the recovery line connecting the flare gas recovery system with the main process that is closed when gas is being flared. High pressure (Pressure Alarm High (PAH)) in the knock out drum or vent drum shall open the flare valve such that gas can be flared if the pressure gets too high.

Auxiliary Equipment: can be supplied depending on the specific application of the FGRU. Such equipment can be:

- Suction scrubbers: remove liquid droplets present in the incoming flare gas
- Coolers: are used for cooling of recycled service liquids or for interstage cooling or aftercooling of flare gases. The heat exchangers are air-cooled or cooling medium cooled shell-and-tube heat exchangers.
- Separator systems: are used to separate lube oil or working fluid from recovered flare gas in respectively liquid ring compressors and oil injected screw compressors
- Pumps: may be used for transporting lube oil in oil injected screw compressors or for emptying separator vessels for water or condensate
- Noise enclosures: may be installed to reduce the overall noise level from the compressors and/or the motors to adhere to working environment requirements
- Vibration monitoring systems: are used to ensure reliable and safe operation of rotating eqipment

2.2.6.2 Advantages to Installing a FGRU

There are several advantages to implementing Flare Gas Recovery: (12)

- *Improved Public Relations*: almost constant burning of gasses in a flare may trouble many people, thus installing a flare gas recovery system may yield near zero flaring and eliminate complaints. This is particularly valid onshore where the flaring is more visible.
- *Reduced Plant Fuel Gas Consumption* or *Increased Product Sales*: recovered flare gas may for example be used in the plant fuel system to balance out purchased fuel or it can be used to produce electricity
- *Reduce Green House Gas Emissions from the Facility*: installing a flare gas recovery unit yields recovered flare gas as fuel gas and eliminates emissions from the previously purchased fuel
- *Reduced Flaring Light, Noise* and *Odor*
- *Reduced Steam* or *Electricity Consumption for the Flare*: to achieve smokeless flaring many plants need supplemental energy in the form of steam or air injection. When installing a flare gas recovery unit this energy is reduced to a minimum
- *Extended Flare Tip Life*: the flare tip is not designed for continuous flaring of small gas flows. This result in a much smaller flame closer to the flare tip and can cause damage over time

2.2.6.3 Basic Processes in a FGRU

Compression and physical separation are the basic processes used in flare gas recovery systems (12). Many factors should be evaluated when choosing the compressor that is most suited for flare gas recovery. These include process requirements, efficiency, maintenance requirements and dependability. In addition, the choice will affect the initial cost of the flare gas recovery unit, the physical size and operating and maintenance expenses. (13) Several compression technologies are available and typical technologies used in flare gas recovery systems are:

- Dry Screw Compressors
- Oil injected Screw Compressors
- Sliding Vane Compressors
- Reciprocating Compressors
- Liquid Ring Compressors
- Ejectors

The pressure condition in the flare header decides how the operation of the FGRU is carried out. The operation rate for the compressor is established through monitoring the suction pressure. The compressor maintains the flare gas line pressure balance. (13)

The typical way to compress the flare gas is by using compressors. However, in some cases a simpler and more cost effective device may replace the compressor to some degree: the ejector. (14) The compressor often have higher initial, operation and maintenance cost, in addition to a higher floor space requirement and a higher demand for power. See Section 2.3 for more details on the compressor technologies.

2.2.7 Flare Gas Recovery in Other Applications

There have not been conducted many studies or reports on optimizing flare gas recovery offshore. Most of the literature on this is found through catalogues from different suppliers of such equipment. However, some investigation into larger facilities such as refineries or other onshore plants have been conducted. Due to their substantial larger capacity demands and other different conditions, there is a larger range of different flare gas recovery systems available.

Comparing offshore and onshore installations, they have the same technical challenges. However, there are space and weight restrictions and limited access to utilities offshore. This also affect the choice of flare technology since the logistics associated with installing, maintaining and replacing flare tips are more challenging and expensive offshore. Flare solutions with a long lifetime is chosen over solutions that give better performance in other areas, for instance optimal combustion efficiency or low emissions.

Volatile organic compounds (VOC) recovery is another form of vapor recovery within shipping tranpsort. Even though VOC recovery is not directly coupled to flare gas recovery, it is a way of recovering hydrocarbons during the transportation of oil in tanks. This way one can avoid venting VOCs out to the atmosphere. See Section 2.2.7.2.

2.2.7.1 FGR in Refineries

In addition to the compression method explained in Section 2.2.6.3, using a compressor or ejector, other options for flare gas recovery are available in refineries. These include Gas-to-liquid production (GTL), generation of electricity, flare gas used as fuel gas or application of solid oxide fuel cell.

<u>Gas-to-liquid technology (GTL)</u>

Flare gas (FG) is, through GTL technology, converted into longer-chained hydrocarbons and can be used in for instance gasoline or diesel fuel. The conversion from gas to liquid is done either directly or by synthetic gas as an intermediate step: using a Fisher Tropsch (FT) or Mobil process. In the FT process the flare gas is first, through partial oxidation or steam reforming (or a combination), converted into hydrogen and carbon monoxide (synthesis gas). Then, the syngas chemically react over an iron or cobalt catalyst, thus resulting in liquid hydrocarbons and other by-products (15). In the Mobil process the natural gas is also converted to syngas, however, further to methanol and in the end polymerized into alkenes using a zeolite catalyst. (Wise and Silvestri, 1976 as cited in (16)).

Generation of electricity

Generation of electricity through a gas turbine power plant is another method for flare gas recovery. Typical components involved are a compressor, a combustion chamber, a gas turbine and a generator generating the electricity. An increasing number of such power plants are found around the world and they produce high power outputs at high efficiencies and low emissions. The Brayton cycle generate electricity or mechanical power from flare gas in a very efficient way. (15)

Fuel gas

The flare gas can be fed as fuel to process heaters and steam generators to achieve high pressure and temperature steam. Thus, one can save costs on fuel gas from external sources. (17)

Application of solid oxide fuel cell for flare gas recovery

In (18), a new approach towards flare gas recovery using solid oxide fuel cell (SOFC) was evaluated. Further, this was tested on the Asalouyeh gas processing plant in Iran. By using SOFC, there is no pre-reforming of the flare gas; it’s fed directly into the cell. Fuel cells convert the chemical energy of fuel to electricity and are classified as power-generation systems. Compared to other types of cells, the SOFC is more efficient (Petruzzi et al., 2003, as cited (18)). Recycling the anode outlet gas is done to achieve required amount of steam.

The SOFC consists of two porous electrodes separated by a nonporous oxide ion-conducting ceramic electrolyte. The operating temperature of the SOFC lies around 600-1000°C, the feed is a gas mixture consisting of among other things hydrogen and the oxidant is oxygen from air (Stambouli and Traversa, 2002 as cited in (18)). Various fuel types may be used due to the high operation temperature (Yuan and Sunden, 2005 as cited in (18)).

The Ni/Zr ceramic-metallic anodes enables, through appropriate catalytic properties, power generation and may also be used as catalyst for the steam reforming and shift reactions (Dicks, 1998; Clarke et al., 1997; Xu and Froment, 1989; Georges et al., 2006 as cited in (18)). A significant problem with the internal steam reforming is carbon deposition on the Ni-anode. This can lead to both catalyst deactivation and reduction of cell performance and lifetime. To counteract this a high steam/carbon ration is used. However, this is an unattractive action because dilution of fuel by steam leads to a lower electrical efficiency (Ahmed and Foger, 2000 as cited in (18)).

Real cases

Looking at a case-study from the Asaluoyeh gas refinery in Iran, it was found from Ref. (15) that the compression method with injection into pipelines was an effective and the most economical way of flare gas recovery. The Asaluoyeh gas refinery had a flare gas flow rate of about 420 624 m3/h. For refineries with a lower amount of flare gas than this, the rate of return for investment increment of power plants and GTL become more and more uneconomical. The GTL method was found to have a lower rate of return than the compression method, but on the other hand, it had a higher annual profit. Thus, the GTL technology is in Ref. (15) recommended for refineries with high capital investment.

Applying SOFC technology to the Asaluoyeh refinery generates approximately 1200 MW electrical energy in addition to reducing the greenhouse gas emissions from 1700 kg/s to 68 kg/s. The total capital investment of SOFC is found to be, through economical evaluations, much lower than other no-flaring suggestions. Thus, SOFC technology is more effective and more economical. (18)

2.2.7.2 Volatile Organic Compounds (VOC) Recovery Systems

In Section 2.2.7.2, all info is obtained from Ref. (19).

Disregarding methane, volatile organic compounds (VOCs) are referred to as nmVOCs (non methane VOC). The nmVOCs can evaporate from crude oil. Contributors to a significant amount of emissions of nmVOCs are:

- Storage, loading and unloading of oil offshore
- Floating Storage and Offloading Vessel (FSOs)
- Floating Production, Storage and Offloading Vessel (FPSOs)
- Onshore storage tanks and terminals
- Shuttle tankers

By installing VOC recovery units on each of these applications, it’s possible to capture and recover nmVOCs. The emissions can be reduced by more than 90% on storage ships.

There are two approaches to VOC recovery:

- Active vapor recovery unit (VRU) systems usually consist of a compression step, followed by condensation, absorption and/or adsorption.
- Passive VRU systems may use nmVOC as blanket gas for storage vessels during vapor-balanced loading/unloading

Active VRU technology captures nmVOC-evaporation from the crude oil. This is done by specially designed process equipment during storage, loading and unloading operations. The active recovery systems are categorized into three: compression-condensation, absorption and adsorption.

Compression-condensation technology is done through compressing and cooling down to a temperature were the VOCs condense. The condensed nmVOC is stored in a separate tank, thus avoiding emissions.

Absorption involves the VOCs being absorbed in an absorption tower, in a high boiling solvent at low temperature. Further, desorption takes place by heating the solvent. This results in a desorbed gas with high concentration of VOC that is to be condensed. Sometimes it may become necessary to use a refrigerated condensing system to be able to meet emission standards from the condenser vents.

Adsorption is based on separation of fractions of hydrocarbons from inert gases. The nmVOCs can be separated from the inert gases through for instance using an active coal filter. However, VOCs are usually adsorbed in activated carbon. Upon saturation of the bed, the gases are switched to another bed and the VOC is desorbed by heating the first bed. The gas that comes out is both concentrated and condensed. To meet emission standards, also here refrigeration systems might be needed.

Vapor recovery units (VRUs) can be installed on onshore oil storage tanks to recover emissions of nmVOCs from tanks. Hydrocarbon vapors are drawn out from the tank under low pressure and further routed to a separator suction scrubber to separate out condensed liquids. Discharging from the scrubber, vapors flow through a compressor providing the low-pressure suction. In the end, the vapors are metered and removed from the system for pipeline sale or fuel supply onsite.

Passive VRU technology is developed as an alternative to the active technology since it is often large, complicated and expensive to install and operate. Two passive approaches to VRU technology is found through using a hydrocarbon gas as blanket gas or using KVOC technology.

Using the *hydrocarbon gas as blanket gas* on FPSO vessels instead of inert gases may reduce nmVOC emissions, together with integration with the existing production plant for oil and gas. The hydrocarbons from the storage vessel mix with the inert gas when used as blanket gas, thus the hydrocarbons are vented to the atmosphere together with the inert gases. However, when using hydrocarbon gas as blanket gas the venting can be eliminated. When the vessel is being offloaded, the hydrocarbon gas is taken from the production process to the storage part of the vessel to act as blanket gas.

KVOC technology is developed by Knutsen OAS Shipping. One of the key features of this technology is that flashing is prevented by keeping the pressure at the oil's true vapor pressure or higher during the entire loading period. This way, the nmVOC emissions that evaporate from loading of crude oil can be reduced. It is simpler and significantly less expensive to install than active technologies.

2.2.7.3 Other ways to Recover Flare Gas: Microturbines

Microturbines are small turbines fired by gas and may burn natural gas that otherwise would be flared. They produce electricity that can either be sold or used to provide power for industry purposes, for instance compression, pumping or to run some other kind of gas processing equipment. (20)

Microturbines usually consist of a compressor, combustor, turbine, alternator, recuperator and generator, thus a power generator driven by a small scale gas turbine. Large gas turbines or reciprocating engines are used at sites that require multi megawatts (such as for refineries), while microturbines are better suited at smaller and more dispersed sites. (21)

Microturbines belong to a relatively new distributed generation technology used for stationary energy generation applications. One of the biggest suppliers of such technology is Capstone and they claim to account for about 80% of all microturbines sold. (22)

Advantages of microturbines compared to other technologies of the same purpose are: (21)

- A small number of moving parts
- Compact size and lightweight
- Greater efficiency, can reach greater than 80 % if waste heat recovery is included
- Lower emissions
- Lower electricity costs

- Opportunities to utilize waste fuels
- Expected low operations and maintenance costs

This alternative does not completely eliminate the emissions from continuous flaring. However, you get the bonus of producing both heat and electricity on a relatively small scale.

Capstone mentions an example where a Capstone microturbine was installed on a BP Offshore Platform in the Gulf of Mexico. In this case, the issue was not only to recover value from the flare gas, but also to provide a reliable power source. The microturbine ran on onsite unprocessed wellhead gas, providing a power source. Capstone also has running microturbines on other offshore platforms in the Gulf of Mexico, Gulf of Alaska, Bay of Campeche, the North Sea, Mediterranean Sea and South China Sea.

2.3 Compression Methods

To increase the pressure of a compressible fluid, a compressor is a device that might be used. The inlet pressures may range from vacuum to high positive pressures, while the discharge pressures can be any value between sub atmospheric up to hundreds of bar. The compressor type, together with its configuration, yields a relation between the inlet and discharge pressure. The working fluid through the compressor may be any compressible fluid with a wide range of molecular weight, in either gas or vapor phase. (23)

2.3.1 All Compressors

The compression mode may divide the different types of compressors into two main groups: compressors with intermittent and compressors with continuous compression mode. In the former, the mode of compression is cyclic. A given amount of gas enter the compressor, is acted upon and exit before the cycle is repeated. In the other case, the gas moves through the compressor without interruptions. (23) Further details on these two groups follow in Section 2.3.1.1 and Section 2.3.1.2.

2.3.1.1 Intermittent Mode Compressors

Compressors with intermittent compressor modes are also known as positive displacement compressors. There are two types of positive displacement compressors: reciprocating and rotary.

Reciprocating Compressors

The *piston compressor* is probably the most commonly used compressor. A reciprocating motion is transferred to a piston that can move inside a cylinder. A quantity of gas enter the cylinder through the inlet valve or valves where the piston’s displacing action compresses the gas and exit though the discharge valve or valves. These valves also prevent the gas from flowing back into the cylinder when starting a new cycle. The piston compressor is well suited for high pressure service. (23) The principle of how the piston compressor works can be seen in Figure 3.

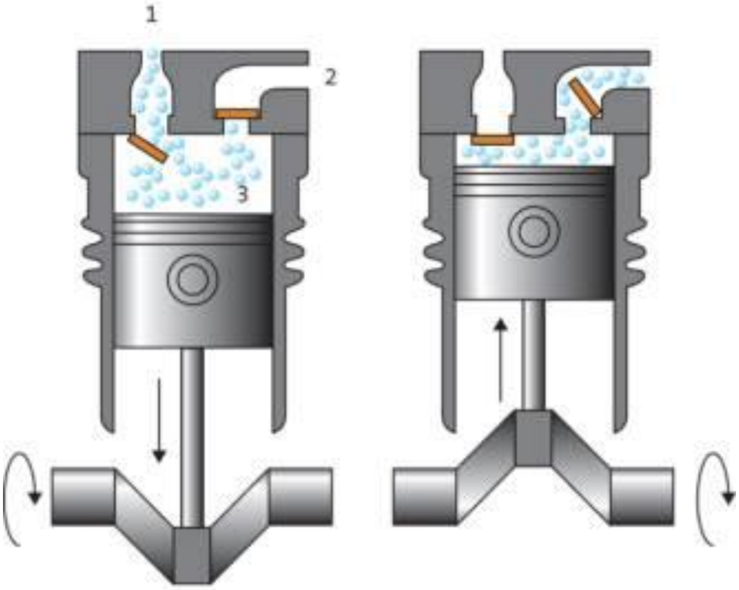

Figure 3: Operation of a piston compressor, 1: intake valve, 2: outlet valve, 3: gas gathered before compression, http://cbs.grundfos.com/au-nz/lexica/AC_Reciprocating_compressor.html#-, 19/5-15

The *diaphragm compressor* is mainly used when having low flowrates, but is also capable of handling high pressures. It resembles the piston compressor, only the piston in this case move a volume of hydraulic oil instead of gas. The oil is used to bend a set of diaphragms up and down, thus compressing the gas. The diaphragm compressor is particularly used when little or no leakage is tolerable. Using only static seals enables compression without gas leaking through dynamic seals. (24) In Figure 4, a typical diaphragm compressor is shown.

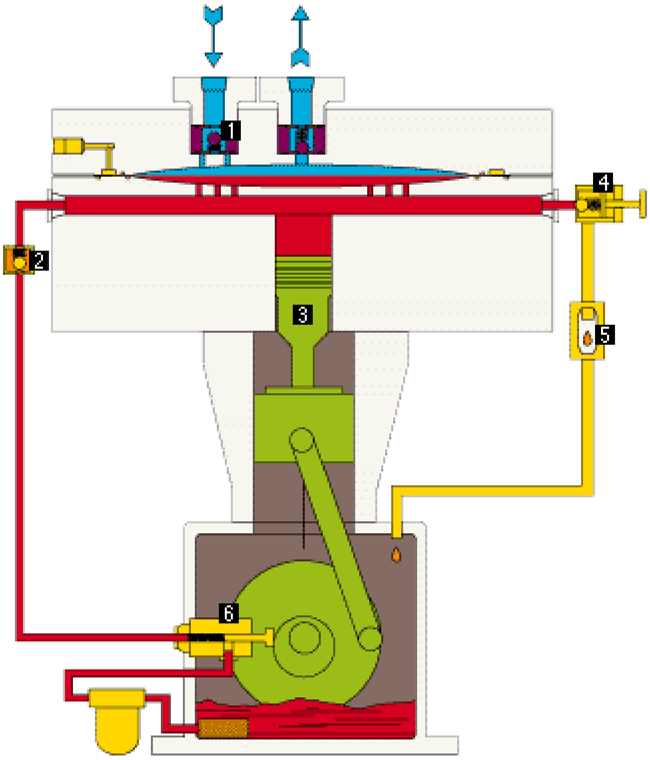

Figure 4: Diaphragm Compressor, http://www.sundyne.com/Products/Compressors/Legacy-Brands/PPI-Pressure-Products-Industries/How-Diaphragm-Reciprocating-Compressors-Work, 19/5-15

Rotary Compressors

For rotary compressors, increase of pressure take place as one or two rotating shafts create chambers that decrease in size from inlet to outlet. Rotary compressors may be divided into four large groups: screw compressors, rotary piston compressors, sliding vane compressors and liquid ring compressors. (25)

The *screw compressor* consist of two screws rotating in opposite directions. One of the screws has a concave inlet while the other has convex. The former receive power from an external source and transmit the power to the other screw. Process gas is sucked into the inlet while the screws are rotating. The interconnecting screws have a rotary motion responsible for compressing the gas. The flow path through the compressor is axial and start as the gas enter at the top, travel around the outside of the screws and exit at the bottom through the discharge port. There is no contact between the two screws. For the oil-injected screw compressors, lubrication oil is injected to reduce the temperature rise throughout the compressor and to aid sealing the suction and discharge ports. When exiting the compressor, the oil needs to be separated from the gas and recycled after, if necessary, filtering and cooling. Oil-free compressors may be used when oil contamination must be avoided and the compression is done entirely through the action of the screws. However, they have usually lower pressure and volume flow capability. (26) The principle of how the screw compressor works is shown in Figure 5.

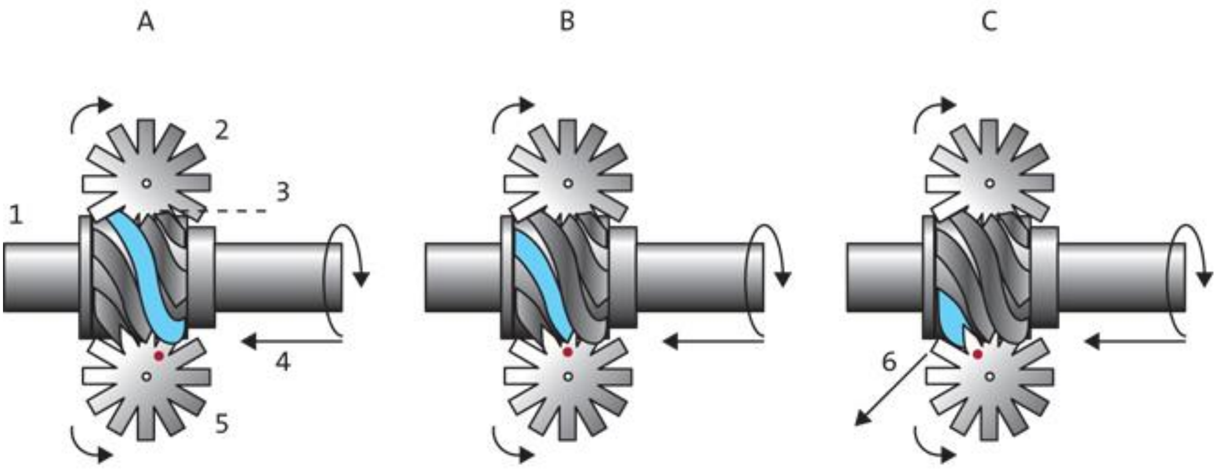

Figure 5: Operation of a screw compressor, A: Suction, B: Compression, C: Discharge, [*http://www.cbs.grundfos.com/middle-east/lexica/AC_Screw_compressor.html#-*](http://www.cbs.grundfos.com/middle-east/lexica/AC_Screw_compressor.html#-)*, 19/5-15*

The *rotary piston* (or rotary lobe or roots) *compressor* has two lobe-shaped rotors that intermesh and rotate in opposite directions. When the lobe pair cross the inlet port, gas get trapped between an open area between the lobes. Instead of the gas being compressed as it moves toward the discharge port, it is compressed externally as the gas is pumped against back-pressure. Four pulses of gas is delivered by one turn of the lobes. This compressor is a low-pressure machine. (23) In Figure 6, a twin rotary lobe compressor is shown.

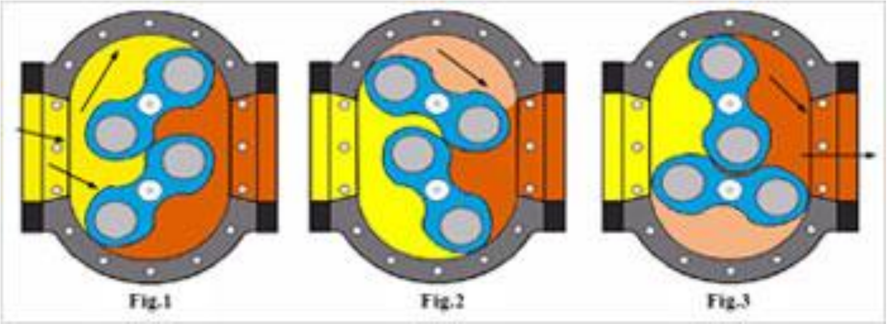

Figure 6: Twin Lobe Rotary Compressor, [*http://www.everestblowers.com/working-principle.html*](http://www.everestblowers.com/working-principle.html)*, 19/5-15*

The *sliding vane* (or rotary vane) *compressor* is composed of a single rotating shaft. The rotor is eccentrically located inside the casing and there are sliding vanes in the rotor that are free to move in and out within the slots. When the rotor start to rotate, gas is trapped between a pair of vanes as they pass the inlet port. Circumferentially compression take place as the vane pair and gas is moved toward the discharge port. The vanes need to be lubricated externally. A typical sliding vane compressor is shown in Figure 7.

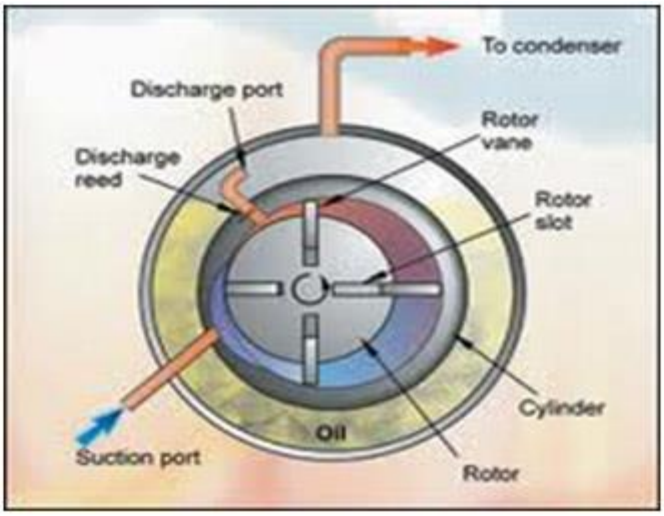

Figure 7: Sliding vane compressor, *http://www.lubewhiz.in/compressors_compressor_lubrication.html, 19/5-15*

Liquid ring compressors are oil free and without valves. A liquid called “seal liquid” is filled in the casing up to the rotor centerline. A conical distributor is fixed to the front cover of the compressor and is the inlet for the process gas. Impeller rotation when starting up the compressor make the seal liquid centrifuge and distribute along the inner wall in a double eccentricity shape. There are two suction ports and two discharge ports in the distributor where each of them is placed opposite to the other. Starting up with the first quarter of turning, gas is sucked through the two suction ports. In the second quarter, the gas is compressed and exit through the discharge ports. Repeating of the cycle happens in the third and fourth quarters. The gas and liquid need to be separated in a separator after discharge and the seal liquid is sent through a cooler and then back again to the compressor. The seal liquid may be any liquid, for example water, that does not react with the process gas. An advantage with this type of positive displacement compressor is that the only wear parts are the mechanical seal and the bearings, thus their efficiency will hold for a long time. (27) The principle of how the liquid ring compressor works in shown in Figure 8.

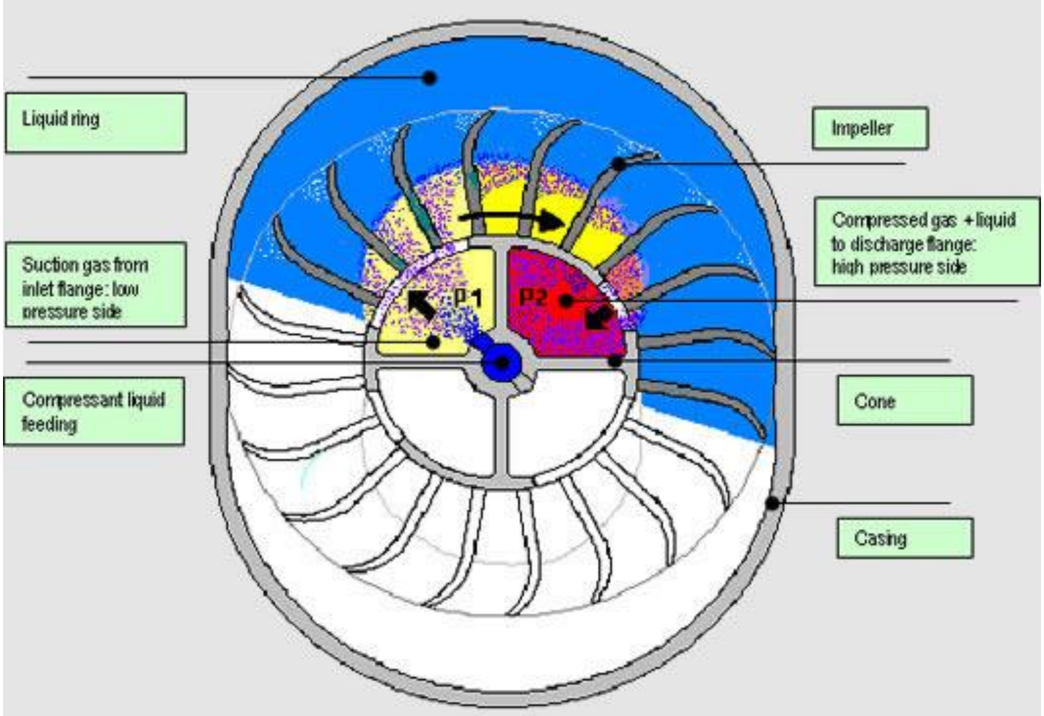

Figure 8: Liquid ring compressor, *http://www.garo.it/inglese/Compressori%20Anello%20liquido/Principio_di_funzionamento_compressore.htm, 19/5-15*

2.3.1.2 Continuous Mode Compressors

There are two main types of continuous-mode compressors: ejector and dynamic.

<u>Dynamic compressors</u>

Dynamic compressors can further be divided into axial compressors and centrifugal compressors.

Axial compressors accelerate the gas flow using blades mounted on a rotating shaft and then increase the pressure when passing the stationary blades connected to the compressor casing. The flow through the compressor is parallel to the axis of rotation. They are used when having very high flowrates and moderate pressure drops. (25) (28) In Figure 9, an axial compressor is shown.

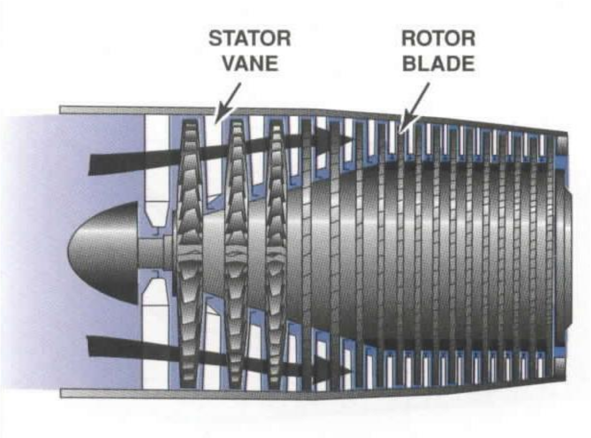

Figure 9: Axial flow compressor, http://ffden-2.phys.uaf.edu/212_fall2003.web.dir/Oliver_Fleshman/turbinesandcompressors.html, 19/5-15

The *centrifugal compressor*, as the axial compressor, achieve compression of the process gas using rotating impellers to exert inertial forces as acceleration, deceleration and turning to the gas. One or more stages make up the centrifugal compressor. A stage consist of a rotating impeller and a stationary diffuser. In most cases, the gas enter the centrifugal compressor horizontal with the rotating shaft and then change direction when flowing past the impeller. When exiting the impeller the gas move through the diffuser or the flow decelerator. The impellers do work on the gas and energy is added as the flow is accelerated. Velocity energy is converted into pressure energy by the stationary components. The flow through the centrifugal compressor is turned perpendicular to the axis of rotation. (26) (28) This can be seen in Figure 10.

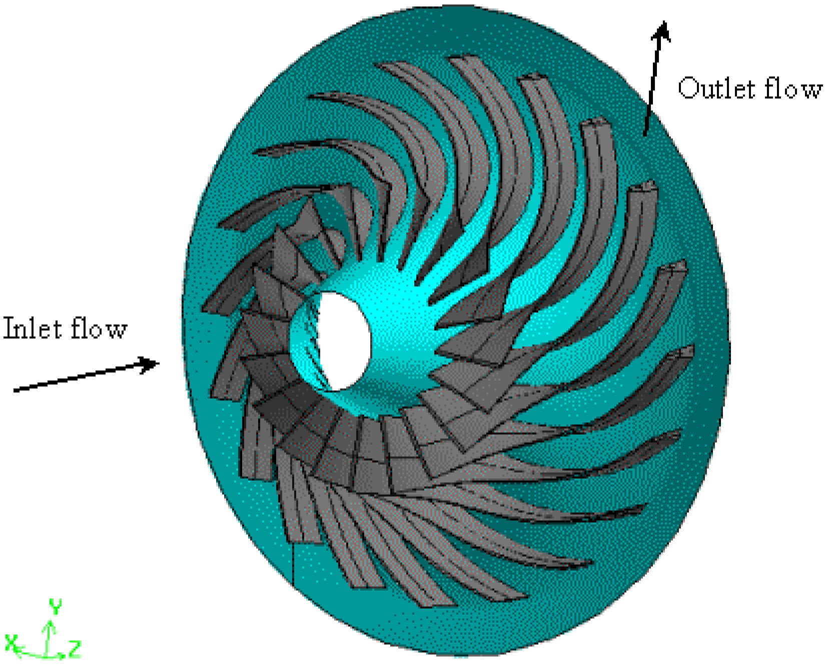

Figure 10: Centrifugal compressor, https://www.sharcnet.ca/Software/Gambit/html/tutorial_guide/tg09.htm, 20/5-15

Ejector

Info in this section is obtained from Ref. (14), (23) and (29).

There are no moving parts in the ejector and it is used mainly due to that feature. It is not as efficient as most of the mechanical compressors. However, the simplicity of the ejector make it reliable and with low maintenance costs.

A so-called motive fluid is used to operate the ejector. The motive fluid is accelerated through a nozzle section and into the suction chamber, or mixing chamber, where the gas to be compressed is added and entrained by the motive fluid. Further, the mixture move on to a diffuser where the high velocity gas is transformed to an increase in pressure through deceleration of the velocity. The ejector is based on Bernoulli's principle that states that when the fluid velocity decrease, its pressure increase and vice versa. The velocity of the HP motive fluid increase in the converging nozzle to go from high static pressure to velocity pressure. After mixing with the LP side fluid, the diverging diffuser reduce the velocity and increase the pressure. The principle of this is shown in Figure 11.

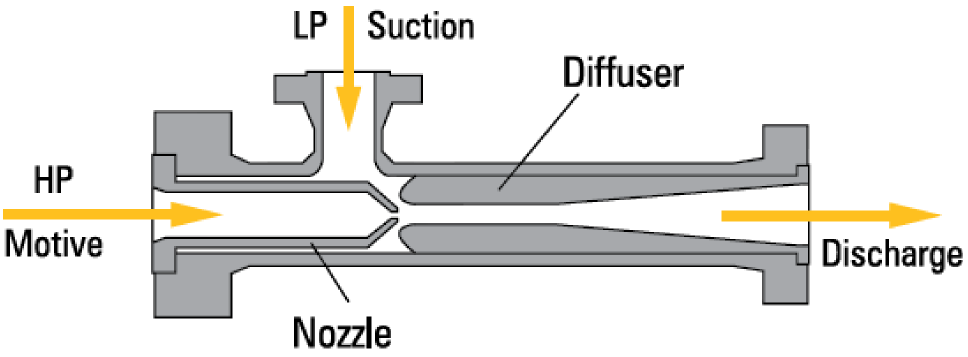

Figure 11: Principle of the ejector, *http://www.transvac.co.uk/pdf/Flare_Gas_Recovery_&_Zero_Flare_Solutions.pdf, 28/4-15*

The motive fluid may be either gas or liquid. In one single stage, the gas-motivated ejector can yield a compression of 7:1, while the liquid driven can yield a compression of up to 90:1. A secondary ejector may be added to boost up the pressure of the single-stage gas-motivated one, thus the system is called a multi-ejector solution. This way the ejectors are connected in series and the total flow from the first stage ejector become the LP flow for the 2nd stage ejector. This is shown in Figure 12.

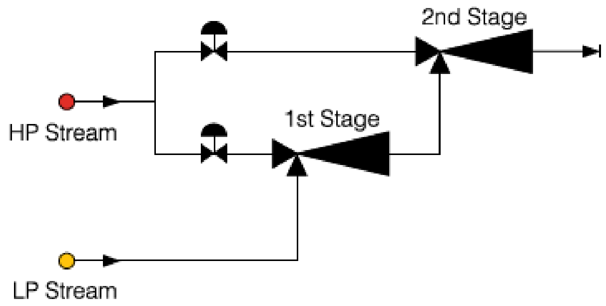

Figure 12: Multi-ejector solution, *http://www.transvac.co.uk/pdf/Flare_Gas_Recovery_&_Zero_Flare_Solutions.pdf, 28/4-15*

2.3.2 Compressors in Flare Gas Recovery

In flare gas applications, compressors should be able to deal with wide swings in mole weight and solids or liquids entrained in the gas stream. From Ref. (30) and (11), it's clear that positive displacement machines, in addition to the ejector, are most suitable for flare gas recovery as they can handle changes in the gas composition. Pros and cons regarding the different relevant types of intermittent mode compressors follow below:

Sliding vane compressors work best in low-pressure clean gas applications. The vanes may be prevented from sliding back and forth in the rotor slots if liquid or dust is present in the gas stream. Oil for lubrication is needed continuously and jacket-cooling is required. Frequent inspections may be required but they are often minor and easy to handle. Initial costs are low. Advantages and disadvantages regarding the sliding vane compressor are listed in Table 5.

Pros	**Cons**
Small floor space	Typically limited to 150 psig (=10,34 barg) in discharge pressure
Low cost	A compressor housing of cast/nodular iron may cause fire risk
System turndown is available	Small continuous oil usage
	Demanding specifications or material requirements from customers are hard to meet

Table 5: Pros and cons regarding the use of a sliding vane compressor in flare gas recovery

Liquid ring compressors are well suited for wet gas, dirty gas applications and are most common in Flare Gas Recovery Units. The liquid, often water, absorbs heat through the compressor, and the gas is maintained at a low temperature. A variety of materials for the compressor enables it to handle different types of gases. There is a high power demand to maintain the liquid ring in proper motion during all operating conditions, thus the compressors are not very energy efficient. In addition, the liquid used needs to be treated.

Special measures may have to be taken in cold climates when it comes to water availability. Advantages and disadvantages regarding the liquid ring compressor are listed in Table 6.

Pros	**Cons**
Liquid slugs and dirty gases are handled well	Typically limited to 150 psig (=10,34 barg) in discharge pressure
A wide range of gas compositions and temperatures can be handled	Operates at single speed
Low noise and vibration levels (due to low-speed operation)	Water is required for operation
Low heat of compression	
Technology proven to work well in Flare Gas Recovery Unit applications	

Table 6: Pros and cons regarding the use of a liquid ring compressor I flare gas recovery

Reciprocating piston compressors are very efficient machines. They can handle both high compression ratios and high discharge pressures. The components most sensitive to solids or liquids entrained in the gas are the valves and piston rings. Also, gases that may polymerize in an accelerated manner are not handled well by these. Advantages and disadvantages regarding the reciprocating piston compressor are listed in Table 7.

Pros	**Cons**
High discharge pressure are available	Large size
High volumetric flows are available	High noise and vibration levels
	Frequent maintenance is required
	High heat of compression and a significant auxiliary equipment is required

Table 7: Pros and cons regarding the use of a reciprocating piston compressor in flare gas recovery

Oil-flooded screw compressors are simple machines and don’t require heavy foundations. High compression ratios can be reached in a single stage and good efficiency levels are achieved. A challenge is that oil may react with the gas and the gas will be scrubbed of its contaminants. Further, the lubricating properties of the oil may be lost, acid could form and a gel like substance may develop sometimes. Thus, precautions regarding too frequent oil changes, maintenance and repairs must be taken. Advantages and disadvantages regarding the oil-flooded screw compressor is listed in Table 8.

Pros	**Cons**
Water is not required	The lube oil can be contaminated by the flare gas
High discharge pressures are available	High cost to replace oil
An internal slide valve in the compressor enables it to turndown to about 20 % capacity	Liquids present in the compressor can cause premature bearing or rotor failure
	Medium-speed operation (3000-5000 rpm) yields medium noise and vibration levels (higher than for liquid ring compressors)

Table 8: Pros and cons regarding the use of an oil-flooded screw compressor in flare gas recovery

Oil-free screw compressors have a higher investment cost than the other rotary compressors. However, they can handle wide swings in gas composition and since they are oil-free; the gas cannot contaminate the oil. No special foundations are required. Liquid injection may be required occasionally to remove substances that may stick to the rotor or casing to avoid accumulation in inlet or discharge channels. Advantages and disadvantages regarding the oil-free screw compressor is listed in Table 9.

Pros	**Cons**
High discharge pressures are available	High noise and vibration levels due to high-speed operation (7000-9000 rpm)
Compressors can be set together to achieve multiple stages, thus even higher discharge pressures are possible	High heat of compression, thus intercooling between stages is needed to reach the higher discharge pressures
Some entrained liquid can be handled	High cost
Dirty gases are handled	
To conserve power usage it can be turned down to 70-75 % of max. capacity	
Water is not required	
Additional turndown through recycle line	

Table 9: Pros and cons regarding the use of an oil-free screw compressor in flare gas recovery

2.3.3 Suppliers

Below follows some different suppliers of either compressors or flare gas recovery systems as a whole, which were contacted throughout this thesis. It varies from supplier to supplier if they produce the compressor themselves or if they act on behalf of several compressor-producers, thus offering several types of compressor types.

Gardner Denver and Gardner Denver Nash

Info on Gardner Denver and Gardner Denver Nash is obtained from Ref. (31), (32), (33) and (34).

Gardner Denver was founded in 1859 and is a global supplier of high-quality industrial equipment, technologies and services. They have offices in 33 countries and have a wide and diverse customer range through a group of well-known brands. Among several industries, Gardner Denver deliver products to the automotive, chemical, electric power, marine, oil and gas and industrial businesses in general.

The Nash Engineering Company was founded in 1905 in Connecticut, USA and became the leading in producing liquid ring vacuum pumps.

On the other side of the Atlantic, Siemens-Schuckert applied for the liquid ring patent in 1903 and they too started to manufacture liquid ring pumps. These pumps got an excellent reputation and went under the brand name “elmo”. In 2000, elmo vacuum technology was founded when Siemens went out of the liquid ring pump and compressor business. Nash Engineering merged with elmo vacuum technology in 2002 and became nash_elmo. Gardner Denver Nash was established as a result of an acquisition of nash_elmo by Gardner Denver Inc. in 2004.

Today, Gardner Denver Nash provide improved global service and technical support for liquid ring vacuum pumps, compressors and engineered systems delivered by Nash. Industries served by Gardner Denver Nash are mining, power, paper, chemical, petroleum, food, environmental, and wastewater treatment.

Within oil and gas, Gardner Denver Nash has experience from flare gas recovery and offer liquid ring compressors for this task. Using these eliminates, according to Gardner Denver, the need for downstream scrubbers and after condensers, because the liquid ring compressor cleans and cools the gas as it is compressed. Gardner Denver Nash recommends using either HP or NAB compressors for recovery of fuel gas and condensing hydrocarbons.

Howden Ltd.

Info on Howden Ltd. is obtained from Ref. (35), (36), (37), and (38).

James Howden, at an age of 22, formed his own consulting engineering business in Glasgow, Scotland in 1854. In 1862, the first Howden engineering work was built and engines and boilers for ships were constructed here.

In the 1930’s, Howden Compressors Ltd pioneered the first commercial rotary twin compressor in the world. Today, they design and manufacture rotary screw compressors of both oil-injected and oil-free types. According to themselves, Howden Compressors Ltd offer the largest most versatile range of screw compressors of both types that can be used for a variety of demanding gas compression and refrigeration duties.

The different industries that Howden Compressors Ltd provide compressors for are chemical, emission control, industrial processes, iron & steel, midstream oil & gas, petrochemical, power generation, refineries, refrigeration and upstream oil & gas. Within upstream oil and gas, Howden Compressors Ltd have some experience delivering compressors for flare gas recovery.

In Glasgow, bare-shaft compressor units are supplied globally from the manufacturing plant here. About 35000 screw compressor units have been supplied worldwide by Howden Compressors Ltd over the years. These screw compressors serve the refrigeration and process gas handling markets. In addition to a variety of different applications, they also serve as supplying units to boost the fuel gas pressure in gas turbines.

Zeeco

Info on Zeeco is obtained from Ref. (39), (40) and (41).

Zeeco was formed in 1979 and began its operations with only a handful of employees in a rented facility in Tulsa, Oklahoma. This is also where Zeeco has its headquarters today. Initially, the company focused on oil and gas production equipment, in addition to manufacturing machined parts for the aerospace industry. Today, Zeeco engineers the lowest emission combustion equipment available.

Zeeco has 20 locations around the world serving practically all continents. They have more than 1300 employees and agents and the largest product research and test facility on the planet. Within next-generation combustion equipment and advanced environmental systems, Zeeco is leading in both the design, engineering and manufacturing. The equipment can be found in industries such as refining, power, production, biogas, LNG pulp and paper, pharmaceutical and numerous others. Products than can be delivered by Zeeco are burners, flares, incinerators & thermal oxidizers, combustion rentals, vapor control, aftermarket products & services and products & scanners.

The staff members in Zeeco have experience within the design, fabrication and installation of Flare Gas Recovery Systems. All available compressor technologies such as liquid ring, sliding vane, dry screw, flooded screw, reciprocating, etc. can be used. Zeeco offer different services for flare gas recovery. They can evaluate the existing flare system, size the potential Flare Gas Recovery Systems, design the liquid seal drum and recommend the proper integration of the recovery system into the existing flare gas system.

Gas Compressors Ltd., GCL Fabrications Ltd

Gas Compressors Ltd is obtained from Ref. (42) and (43).

Gas Compressor Ltd (GCL) was established in 2000 as an independent compressor packaging company. GCL deliver equipment worldwide for use within oil and gas, water, power generation, landfill, petrochemical and renewable industries. They specialize in designing, manufacturing and commissioning large or medium gas compressors, booster and blower packages. According to themselves, they are flexible and not tied to a specific compressor technology, sub-vendor or compressor manufacturer. The most appropriate type of machine is supplied for every projects. Anything from turnkey solutions to minimum scope can be delivered by GCL. Designing, building and testing of the products all take place at the factory in England.

The different types of compressor packages offered by GCL are the rotary vane, screw, centrifugal and reciprocating. The units can operate with pressures from vacuum to hundreds of bars and with flowrates ranging from 10 m3/h to 100 000 m3/h.

Common applications for the compressors are gas recycle, sour gas, wellhead, pipeline gas, boil off gas, vapor recovery, gas storage, associated gas and fuel gas boosting for gas turbines and gas engines.

When it comes to flare gas recovery, GCL claim that the rotary vane or screw compressor is best suited. Hence, it’s evident that GCL has some experience with delivering compressors for flare gas recovery purposes.

K.LUND Offshore

Info on K.LUND Offshore is obtained from Ref. (44) and (45).

Since 1984, K.LUND Offshore has delivered compressors and air dryers to nearly 50 platforms in the North Sea. Their main office is located in Sola, Norway where they manufacture compressors, winches, air dryers, HPU and air hoists according to the different oil companies’ specifications. The compressor packages with own design of air dryers are specially designed for the oil and gas industry. For the North Sea, this means, in addition to company requirements, with regard to NORSOK. Engineering, purchase and testing are all done at the premises in Sola.

K.LUND Offshore produce gas compressors to handle VOC gas. The compressor systems are designed, constructed and manufactured entirely according to project-specific requirements. All types of compressors are delivered, either centrifugal, oil-free screw, oil-lubricated screw or piston. According to K.LUND, their strength is to supply gas compressors where standard industrial compressors do not meet the requirements.

Wärtsilä and Wärtsilä Hamworthy

Info on Wärtsilä and Wärtsilä Hamworthy is obtained from Ref. (46), (47), (48), (49), (50), (51) and (52).

Wärtsilä was established in 1834 and have today approximately 17700 employees in nearly 70 countries worldwide. They are globally leading when it comes to complete lifecycle power solutions for energy and marine markets. Wärtsilä maximizes the environmental and economic performance of vessels and power plants. This is done through emphasizing technological innovation and total efficiency.

The Hamworthy business was founded in 1914 in Poole Quay in Dorset, UK. A good reputation within the marine engineering business quickly established. In January 2012, Wärtsilä acquired Hamworthy. Hamworthy’s high technology products and systems was a valuable addition to Wärtsilä’s offerings.

Wärtsilä Hamworthy is globally a market-leading company. They provide specialized equipment and services to marine, oil & gas and other industrial sectors. The two key markets are marine and oil & gas. The marine markets mainly consist of deliveries to specialized ship types such as oil and gas carriers and cruise ships. However, the entire merchant fleet is supplied with a wide range of equipment and services. In the oil & gas market, the delivered systems direct issues of process efficiency and environmental indulgence at production facilities.

The flare gas recovery systems offered by Wärtsilä eliminate the continuous flaring and will be designed to meet customer specific requirements. The flare gas recovery technology operates on several offshore and land based installations and has proved to be successful during several years of operation according to Wärtsilä. Due to Wärtsilä's experience, professional workmanship in design, installation and commissioning is ensured.

Wärtsilä have previously delivered a flare gas recovery system based on compressing with an ejector to Eldfisk II, 2/7S operated by ConocoPhillips. In addition solutions using a liquid ring compressor and screw compressor were delivered to respectively Mongstad (operated by Statoil) and Troll C (operated by Norsk Hydro). All three locations in Norway.

MAN

Info on MAN is obtained from Ref. (53).

The MAN group has more than 250 years of industrial experience, being established in 1758. The company can be divided into four Strategic Business Units: Engines & Marine Systems, Power Plants, Turbomachinery and After Sales care. The head office is located in Augsburg, Germany.

The business unit called Turbomachinery has a product range consisting of a wide range of compressors, expanders, gas and steam turbines. The types of compressors offered by MAN are: axial, centrifugal, pipeline, highspeed oil-free (HOFIM), integrally geared, isothermal and process gas screw compressors. The process gas screw compressors can either be oil-free or oil-injected.

MPR

Info on MPR is obtained from Ref. (54).

The Swiss engineers that invented the sliding vane technology established MPR Industries in 1921. In 2012, MPR Industries entered the Pumps Division of the Moret Industries Group and became a subsidiary of Ensival Moret. Air and gas handling equipment are MPR Industries' responsibility within the Ensival Moret Division. In Paris, France, they have a commercial office and manufacturing facilities.

MPR Industries have experience from more than 90 years of designing and manufacturing rotary machines for air and gas applications. Industrial applications have been a specialty and today compressors, vacuum pumps and blowers are the main products being supplied. A great variety of needs in the different industries may be satisfied by the wide range of products MPR Industries are providing.

Both liquid ring and sliding vane compression technology is offered by MPR Industries.

Transvac

Info on Transvac is obtained from Ref. (55), (56) and (57).

Transvac Systems Limited was established in 1973 and provide ejector solutions. It is a privately owned company and they both design and manufacture the ejectors. To ensure maximum operating efficiency, all the products delivered by Transvac are designed to satisfy the process and mechanical requirements of all applications.

In the petroleum industry, Transvac has delivered hundreds of ejectors that have proven to operate successfully. Transvac has experience from different areas within the petroleum business where for instance ejectors are delivered for boosting production, flare gas recovery or subsea processing. Transvac can deliver for gas, liquid, steam or multiphase fluids both individual ejectors and complete ejector packages.

Process and mechanical design, supply of raw materials, manufacturing, scheduling and testing do all take place within Transvac' four walls, they have full in-house control. The materials of construction offered are among others Hastelloy, Graphite, PTFE (Polytetrafluoroethylene), Duplex, Titanium, etc.

3. Flare Gas System at Ekofisk

This chapter focuses on Ekofisk in particular. In Section 3.1, some information about ConocoPhillips and the Ekofisk Complex in general is provided. Further, in Section 3.2, the structure of the flare system is explained and the main contributors to the continuous flaring are highlighted in Section 3.3.

In Section 3.4, the previous attempts on installing flare gas recovery systems are presented and the reasons for why they failed are given. The chapter ends with explaining how much work that has been done during recent years when it comes to flare gas recovery.

Most of the information from this chapter is from ConocoPhillips' internal pages and are not available to the public. This information comes from mainly system descriptions of the flare system and the systems contributing to the flaring. In addition, information from the previous attempts on flare gas recovery is found through old internal reports and work done during the projects.

3.1 The Ekofisk Complex

ConocoPhillips is the world's largest independent exploration and production (E&P) company, based on proved reserves and production of liquids and natural gas. ConocoPhillips has headquarters in Houston, Texas (USA), has operations in 27 countries and about 19000 employees. In Norway, it's one of the largest foreign operators on the Norwegian Continental Shelf (NCS). The company is operator on the fields in the Greater Ekofisk Area with a 35,112 % interest in Ekofisk, Eldfisk and Embla. On the Tor field they have 30,658 % interest. Table 10 shows how Ekofisk is distributed between the different companies involved.

Company	**Share**
Total E&P Norway AS	39,90 %
ConocoPhillips Scandinavia AS	35,11 %
ENI Norway AS	12,39 %
Statoil Petroleum AS	7,60 %
Petoro AS	5,00 %

Table 10: A list of the companies that have a share in Ekofisk and how big the shares

ConocoPhillips also has non-operated assets, such as Heidrun, Visund, Oseberg, Troll, Grane and Alvheim. In Norway their headquarters lie in Tanager, just outside Stavanger. In 2013, the net production in Norway was approximately 118500 barrels of oil equivalent per day including non-operated assets. (58)

Ekofisk was Norway's first producing field with production starting in 1971. It is one of the largest on the NCS and produces both oil and gas. The reservoir covers an area of 10x5 kilometres, 3000 metres below sea level, and is of chalk.

The Ekofisk Complex make up all the installations that are connected with bridges on the central Ekofisk field. From 2014 the Complex comprises nine platforms and bridge supports, see Figure 13, and it has been developed in stages. Since it was established, the Complex has been upgraded and modernized numerous times. Production from fields nearby is transported via the Ekofisk Complex to receiving gas terminal in Emden, Germany and oil terminal in Teesside, UK.

Figure 13: The Ekofisk Complex, http://www.conocophillips.no/PublishingImages/Ekofisk_Complex_Press-Photo3.jpg, 5/5-15

The Ekofisk Complex comprises the platforms listed in Table 11. (59)

Platform	**Type/function**
Ekofisk 2/4 A(lfa)	Wellhead platform 3,1 km south of the Ekofisk complex Shut down in September 2013
Ekofisk 2/4 B(ravo)	Wellhead platform 2,3 km north of the Ekofisk complex
Ekofisk 2/4 C(harlie)	Wellhead – and gas injection platform
Ekofisk 2/4 H(otel)	Accommodation platform
Ekofisk 2/4 K(ilo)	Water injection platform
Ekofisk 2/4 Q(uarters)	Accommodation platform Shut down in the summer of 2014
Ekofisk 2/4 X	Wellhead platform
Ekofisk 2/4 M	Wellhead – and processing platform
Ekofisk 2/4 J	Main processing platform at the Ekofisk field
Ekofisk 2/4 VA	A seabed unit for water injection
Ekofisk 2/4 VB	A seabed unit for water injection
Ekofisk 2/4 L(ima)	Accommodation and field center
Ekofisk 2/4 Z(ulu)	Wellhead platform

Table 11: The Ekofisk Complex comprises by the listed platforms

The Greater Ekofisk Area is shown in Figure 14.

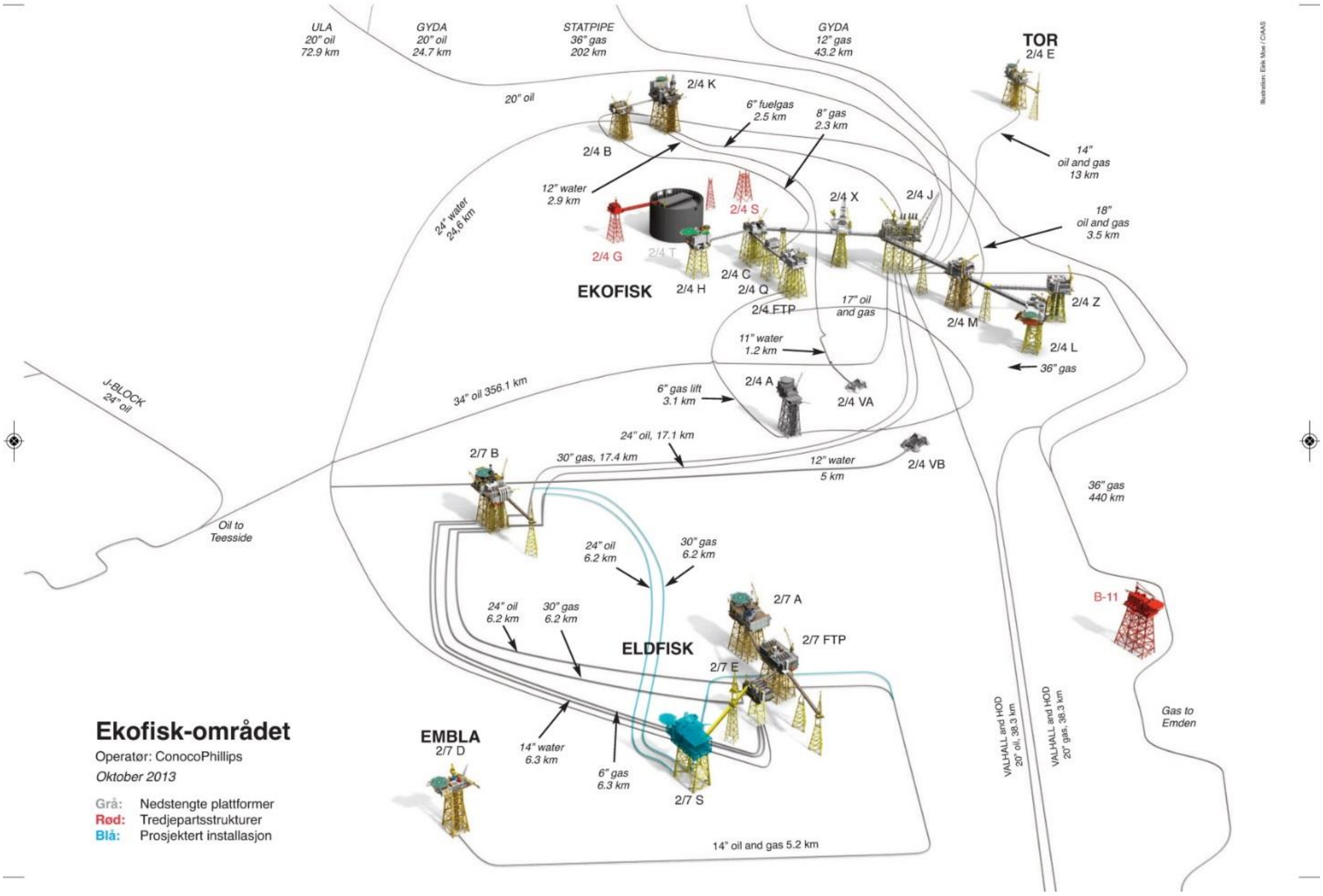

Figure 14: The Greater Ekofisk Area with the Ekofisk Complex up to the right, http://www.conocophillips.no/PublishingImages/Ekofisk-KART-CMYK.jpg, 5/5-15

Ekofisk 2/4 J is the center for all production in the Greater Ekofisk Area. It is connected to Ekofisk 2/4 M to the south via gangways and the same with Ekofisk 2/4 X to the west. Oil and gas from Eldfisk, Embla and Tor is also routed through Ekofisk 2/4 J. Other fields connected to Ekofisk 2/4 J is the BP operated fields: Ula, Valhall and Hod, and the Talisman operated field: Gyda. Ekofisk 2/4 J is a processing and transportation platform, thus the oil and gas are processed and pressurized here before being shipped in export lines. (60)

The Ekofisk South development project from 2013 contribute to continued production towards 2050. This consisted of the building of three new platforms; Ekofisk 2/4 L, Ekofisk 2/4 Z and the integrated platform Eldfisk 2/7 S. Also the building of Ekofisk 2/4 VB, a subsea installation for water injection, and modifications on existing platforms and infrastructure was part of the project.

3.2 Flare Gas System at the Ekofisk Complex

The flare gas system is combined for the platforms 2/4 J, 2/4 X, 2/4 C, 2/4 Z and 2/4 M. It is connected to equipment pressurized under normal operation.

Nitrogen is supplied to purge the flare system during operation to avoid oxygen ingress. It can also be used to flush equipment when performing maintenance to remove hydrocarbons. The nitrogen is vented out through the flare/vent system.

By emissions from the process, the flare system receives gas and liquid that is further lead through headers to the high pressure knock out drum (KO drum) at EKO J. All pipes leading to the drum have a downwards slope of at least 1:100. This is necessary to prevent accumulation of liquid in the pipes since this can affect the capacity of the system during larger emissions. All liquid droplets larger than 600 micron are removed from the gas in the KO Drum. The headers from 2/4 X and 2/4 M are also connected to the drum. Downstream of the drum, the flare system has a flare header with fiscal metering and a burner, High Pressure Flare Tip, for the High Pressure (HP) flare. The structure of the flare system at the Ekofisk Complex is shown in Figure 15.

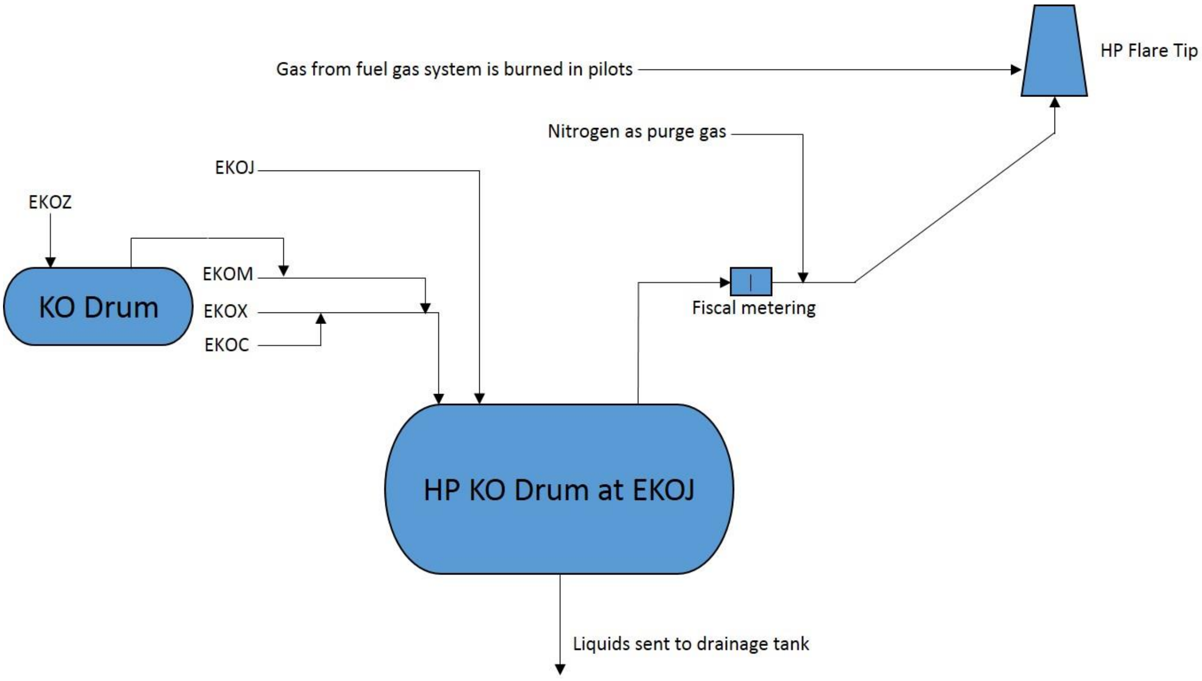

Figure 15: Flare system at the Ekofisk Complex

The HP Flare Tip consist of several discharge lines: one big and eight small ones. The outer part of the discharge lines are pointed away from the platform. Together with a high pressure (4 barg at maximum rate of flare gas) and many discharge lines, a short and stable flame is obtained which also minimize the radiation at the platform. There are three pilot burners in continuous operation and they make sure that when experiencing gaseous emissions the big flare will ignite. Every pilot flame is kept under surveillance from the control room via cameras. The pilots are ignited manually using a signal pistol. Gas from the fuel gas system is normally burned in the pilots, or from propane in reserve.

At EKO Z, gas and/or liquid is lead to the Flare KO Drum here for separation. EKOZ has its own KO Drum because of long distance to EKOJ, and since it has an upward slope towards EKOM. This ensures that there are no liquids that can cause slugging, freezing, etc. The gas from the drum is routed to EKO J HP KO Drum, via a bridge connection to EKO M and further to EKO J.

The system at EKO M consist of three gathering pipes. Pipes are connected to these from the EKO Z HP flare system and to BDVs and PSVs from the following systems:

- Produced water
- Test separator
- HP separator and oil cooler
- Gas lift and production manifolds
- EKO A & EKO B export gas pipelines
- EKO Z HP Flare

At EKO C the system receives gas and liquid from safety valves and manual blowdown valves at the production manifolds and from closed drainage. The gas and liquid are further separated in a scrubber and the gas is lead in a header via EKO X to EKO J.

The system at EKO X consists of manifolds and work as a connection for the header going from EKO C to EKO J. (3)

3.3 Contributors to Continuous Flaring

The reason for the continuous flaring at the Ekofisk Complex is mainly due to gas from C-Tour flash tank at EKO J and flash tank at EKO M, both connected to the produced water systems at respective platforms. In addition, leakages from valves connected to the flare system contributes. This is primarily from Pressure Control Valves (PCVs), but also from Blowdown Valves (BDVs).

<u>Produced water system</u>

The purpose of the produced water system, located at EKO J, is to remove oil from produced water originating from HP-, LP- and test separators, in addition to produced water from EKO M. Contaminated water from open drain is treated in a separate part of the system. Purified produced water is lead to sea. Separated oil is lead back to the oil process. (61)

The system has two separate treatment systems: the C-Tour and the Back-up system. The C-Tour system consists of pressure rise and injection pumps, mixers, hydro cyclones, a flash tank and a condensate separator. The Back-up system consists of a hydro cyclone package, a flash gas tank, two centrifuges and a pump package.

In 2008, C-Tour was installed at EKO J. The purpose was to cleanse all produced water from Ekofisk according to the best technology possible and discharge the water through one overall drain. Partly treated water from conventional systems at EKO J and EKO M is further processed in C-Tour.

Condensate (NGL) is added to the HP and LP water streams after the water has gone through a pressure increase using pumps. Further, the water streams are combined and the condensate can be mixed in. To ensure optimal operation, the addition of condensate is continuously controlled by monitoring oil in water content. The pressure is also controlled to minimize the energy use.

NGL has the property of making the particles in the produced water gather, thus making separation easier. Then, the hydrocarbon drops can be removed from the water in hydro cyclones. The produced water is further lead to the C-Tour flash tank for degassing. The pressure in the flash tank will normally lie around 1,5 barg, the same as the flare gas pressure. From here, produced water will be routed to sea, gas to the flare system and recovered oil to treatment in the C-Tour facility.

When the flare is burning with a smoky flame heavier hydrocarbons are burning. The smoke indicates, since the C-Tour system is the main contributor to the continuous flaring, that the hydro cyclones needs to be washed as the heavier hydrocarbons are accumulating and thus can’t be removed. Ta bort?

Prior to installing the C-tour system the molecular weight was significantly lower, which can be seen from ConocoPhillips’ previous attempts on installing a flare gas compressor (see Section 3.4). A reason for the increase in molecular weight after implementing C-Tour is the fact that condensate is added to the water and not fully removed in the hydro cyclones. (59)

3.4 Previous Attempts on Flare Gas Recovery

ConocoPhillips has previously tried to implement a flare gas recovery system two times on the Ekofisk Complex. Both a screw compressor and a reciprocating piston compressor have been tested. More on why they were not able to live up the expectations is explained in Section 3.4.1 and 3.4.2.

In addition, in 2006-2008, a study was performed on possible solutions for flare gas recovery. Further details on this can be found in Section 3.4.3.

Section 3.4.4 explains what have been done recently on the subject.

3.4.1 In 1997: Oil-flooded Screw Compressor

First, in 1997, a single-screw positive displacement rotary compressor driven by an electric motor was installed at the Ekofisk Complex. It was delivered as a skid-mounted package and consisted of the compressor, a motor driver, oil separator, oil cooler, control system, piping and some other components.

From the KO Drum exit, the gas was routed to the compressor and oil was injected into the gas steam. The oil and gas mixture discharged from the compressor and went into the discharge separator. Here, the oil was removed, collected and re-injected. The system was protected from excessive gas pressure by a relief valve on the separator. Upon exiting the separator, the gas was further delivered back into the main process on the plant, into the LP-separator.

A continuous flow of cold, filtered oil was supplied to the compressor by an injection system. From the discharge separator, the oil went via a temperature control valve, an air cooler and an oil filter before returning to the compressor.

The problem was that the heavier components in the flare gas (NGL) got absorbed into the lubrication oil. This resulted in thinner oil, in addition to the auto-ignition temperature being lowered, and a higher vapor pressure being obtained. After about 48 hours, the compressor package broke down and it was impossible to use.

The operating conditions in Table 12 laid the basis for the first attempt:

Inlet Pressure (Bar A)	2
Inlet Temperature (C)	50
Relative Humidity (%WT)	100
Molecular Weight	21,3
CP/CV (K1)	1,25
Compressibility (Z1)	0,996
Inlet Volume (m3/h)	457
Density at T & P at Suction (kg/m3)	1,597
Discharge Pressure (Bar A)	12
Discharge Temperature (C)	73,6
CP/CV (K2)	1,19
Compressibility (Z2)	0,999
KW required (All losses incl.)	79
Speed (RPM)	3600

Table 12: Operating conditions for the flare gas screw compressor installed in 1997

3.4.2 In 2002: Reciprocating Piston Compressor

Secondly, in 2002, a reciprocating piston compressor was chosen. This resulted in problems with internal gas leakage. Due to a misunderstanding between the supplier and ConocoPhillips, single mechanical seals were chosen. Single seals are used for compressors with lower sealing pressures and where a small gas leakage is tolerable. Leakages of hydrocarbons is unfavorable in the petrochemical industry, thus a sealing system that prevents product gas from escaping to the surroundings should have been used instead. When, during commissioning, the problems with the single mechanical seals were discovered, the project ended. Thus, this compressor was never commissioned offshore. Since the skid was so compact, there was also no opportunity to rebuild it.

The compressor was a 2-stage, non-lubricated, V-type reciprocating compressor. The operating conditions used in this case are shown in Table 13:

Item no.	**Proc. 1**	**Proc. 2**
Stage	Stage 1	Stage 2
Molecular Weight	21,41	21,46
Cp/Cv (K) @ 65°C or 0°C	1,26	1,26
Temperature [°C]	50	63
Compressibility (Zs)	0,995345	0,989758
Press bara @ cyl. flange	5,36	12,11
Press bara @ pul. supp. outlet	5,30	12
kg/h capacity specified	730 wet	712 wet
m^3_n/h (1013mbar & 0°C)	764	744
Inlet Pressure, bar a @cylinder flanges	1,97	5,16
Discharge Pressure, bar a @cylinder flanges	5,36	12,11
RPM: rated/max allow	740/1000	

Table 13: Operating conditions for the flare gas piston compressor from 2002

3.4.3 Study by Aibel Gas Technology in 2006-2008

Over a period from 2006-2008, Aibel Gas Technology (AGT) carried out a study to find a new concept for flare gas recovery at the Ekofisk Complex. In 2006, during the initial phase of the study, the most promising solution was to use a liquid ring compressor. However, in a HAZOP-report from 2007, conducted by Aibel AS, it was found that the liquid ring compressor would not be able to yield a satisfactory discharge pressure. Thus, the project was forced to leave the liquid ring compressor concept.

In 2008, an oil-injected screw compressor type was chosen. The same type of compressor as in 1997. One significant difference between this compressor and the previous one was the addition of dew-point control to avoid condensation of gas in the lube oil.

Condensate build-up in the lube oil was a problem when installing an oil-injected screw compressor 10 years earlier. Thus, a good dew point control was needed. The pressure increases through the compressor, and the discharge temperature needs to be kept above the dew point at the discharge pressure. Condensate dilution of the lube oil results in reduced lubricating effect and the compressor will eventually break down.

In 2008, the maximum flare gas temperature was found to be 20°C. Since the discharge dew point of the compressor is dependent on inlet temperature, this would be monitored and the compressor would shut down at 40°C.

The discharge dew point was calculated through process simulations at the maximum suction temperature of 40°C. It was found to be 80°C. To ensure a good margin to the gas dew point, the compressor discharge temperature should hold a temperature of at least 15°C above. With a discharge pressure of 12,5 barg, the exit temperature would be controlled at approximately 95°C. The compressor would shut down at low discharge temperatures.

The lube oil system was equipped with a heater to maintain at temperature above the gas dew point, to avoid condensation when the compressor was not in use.

A suction scrubber would be installed to protect the compressor against any unlikely liquid formation. The lube oil should be especially chosen to suit the specific operating conditions, but should be monitored such that it is replaced before it is degraded.

After these studies were finished, ConocoPhillips decided not go through with any of the two mentioned concepts above.

3.4.4 Further Work done on implementing a Flare Gas Recovery Unit

After the study conducted by Aibel Gas Technology in 2006-2008, there has not been done anything on the subject until 2014. Then, one process engineer and a mechanical engineer at ConocoPhillips resumed the work on finding a flare gas recovery system for the Ekofisk Complex. They were in contact with a couple of suppliers regarding using a liquid ring compressor, an ejector, an oil-free screw compressor or an oil-flooded screw compressor with dew point control. This research did not result in any clear conclusions and further investigations was therefore needed. Hence, this thesis.

4. Design Criteria for the Flare Gas Recovery System

When contacting suppliers there were some information that was crucial for them to know to be able to say anything on what type of compressor or system to recommend. The most important design criteria were suction pressure, discharge pressure, suction temperature, flow rate and composition of the flare gas. In addition, most of the suppliers wanted to know if there were any special standards to be applied and they were interested in the available floor space offshore.

In the following chapter, design criteria for a flare gas compression system at Ekofisk can be found. Focus is set on determining the parameters mentioned above.

The chapter ends with a comparison between the operating conditions from the previous attempts on flare gas recovery and the new ones suggested here.

The design criteria from this chapter is mostly based on the progress of the different parameters throughout 2014. These charts are obtained through a program used by ConocoPhillips called PI Process Book that displays both current and, as in this case, historical data from Ekofisk.

4.1 Inlet Temperature

With basis in the temperature progress from 2014 shown in Figure 16, the minimum and maximum temperature were respectively 2°C and 28°C, with an average of approximately 11,5°C.

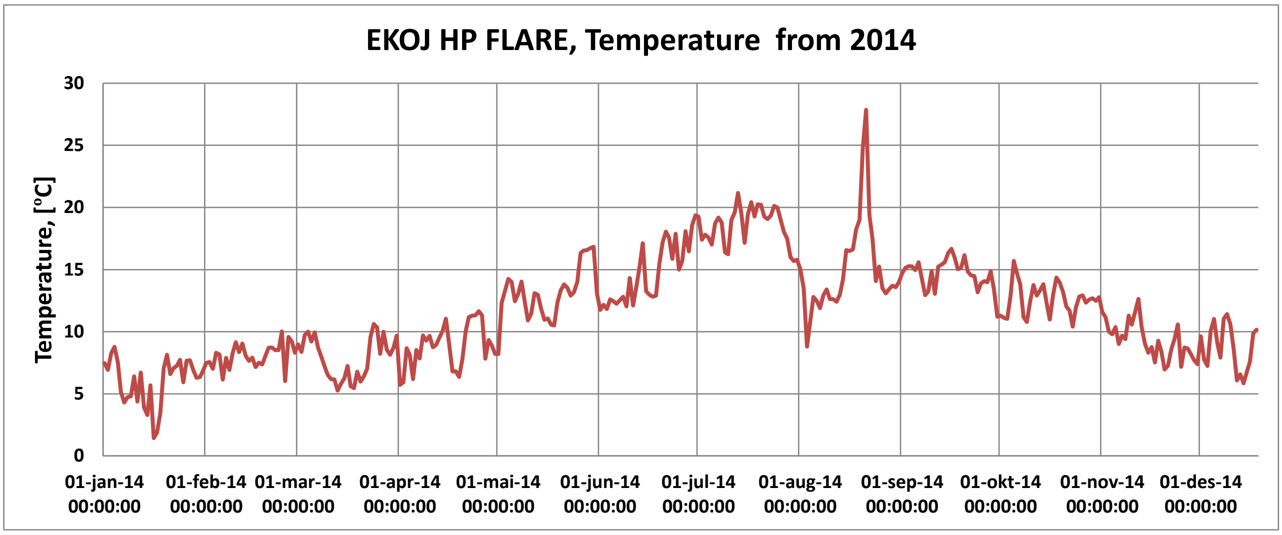

Figure 16: Variations in temperature of the flare gas from day to day in 2014

From Figure 16 it's evident that the temperature of the flare gas is dependent on the ambient temperature. Thus, instead of choosing one temperature, based on an average value, a minimum and maximum are chosen. Thus, one gets a roughly impression of how the most extreme temperatures possible for the system would influence power and duty requirements for a flare gas recovery system. The minimum temperature are therefore set to 2°C and the maximum to 30°C.

4.2 Pressure

Two pressures need to be determined for the recovery system: the pressure that enters the system and the required discharge pressure.

4.2.1 Suction Pressure

ConocoPhillips informs that the suction pressure to the compressor equals 1 barg.

4.2.2 Discharge Pressure

The discharge pressure from the recovery system is required to match the pressure of the point where it is reinjected into the main process. In the previous attempts on installing flare gas recovery systems the gas was routed to the Low Pressure (LP) Separator. The pressure variations in the LP separator from 2014 is shown in Figure 17.

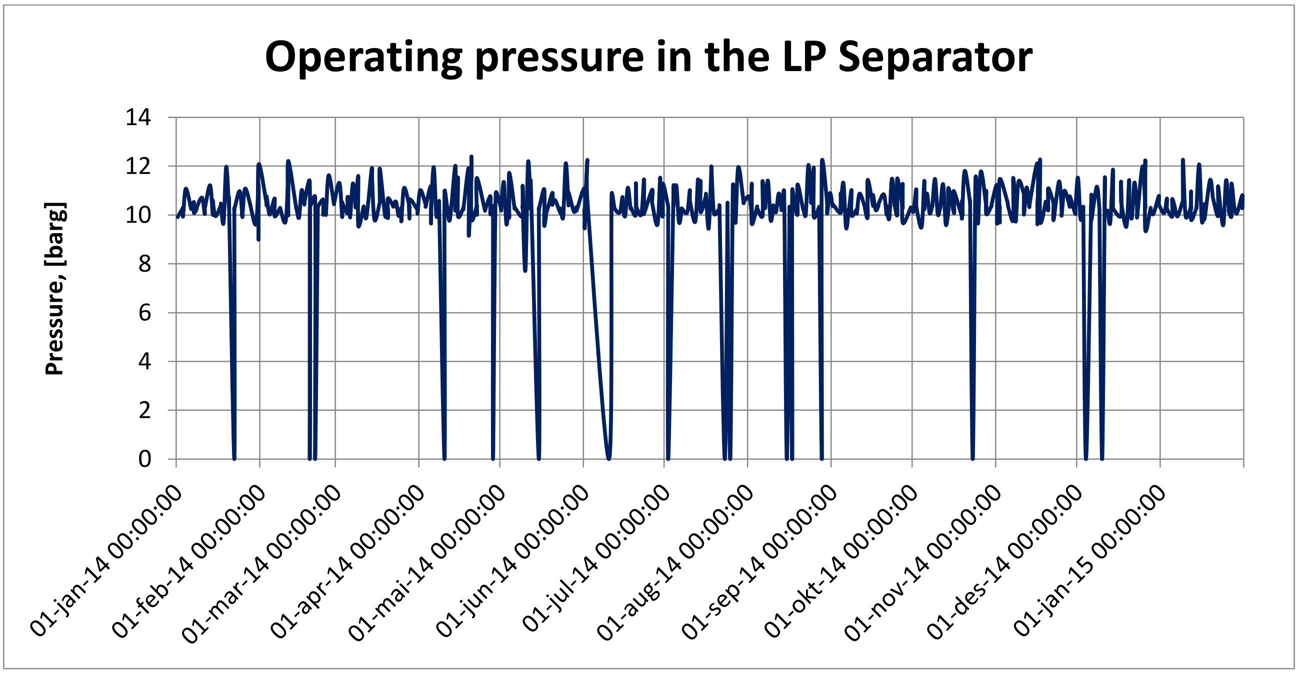

Figure 17: Pressure variations in the LP Separator from 2014

From Figure 17 one can see that the maximum pressure in the LP Separator is approximately 12 barg and it's thus the pressure that is required to discharge from the recovery system.

The high compression ratio, from 1 barg to 12 barg, can be a problem together with the low flow rate of flare gas. ConocoPhillips informs that an option to injecting the gas into the LP separator after compression is to inject it into the LP flash scrubber that operates at a slightly lower average pressure, thus reducing the compression ratio a little. The pressure variations in the LP Flash Scrubber is shown in Figure 18.

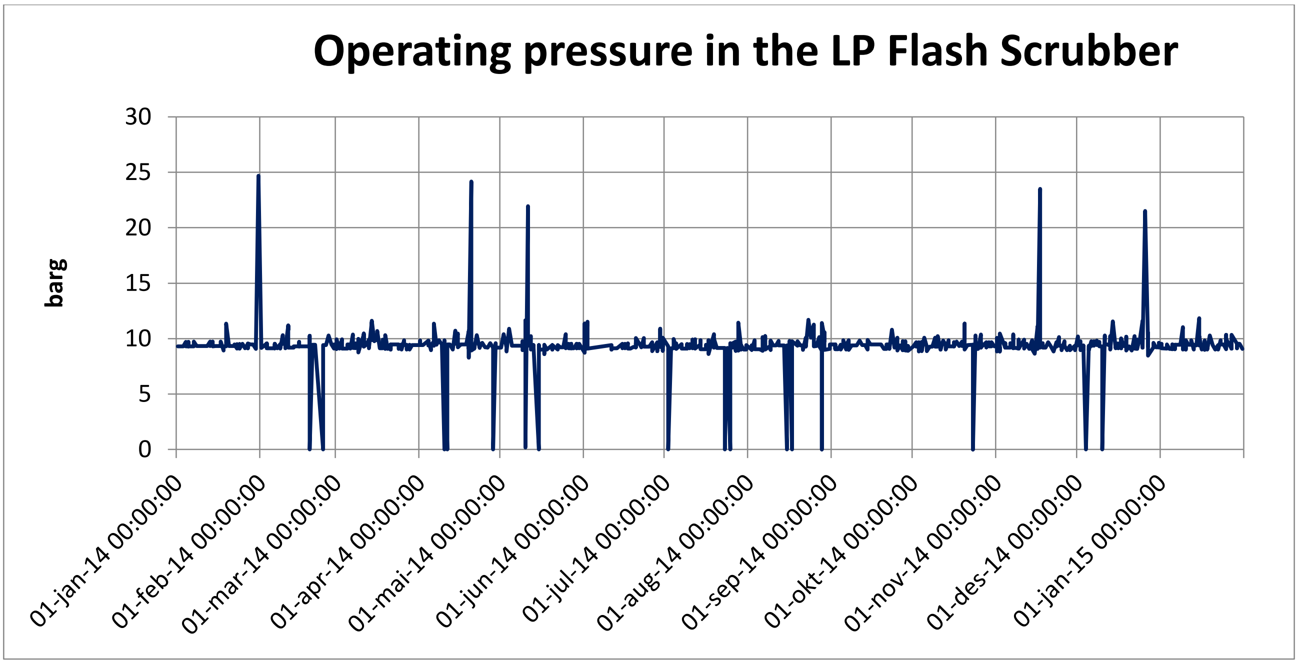

Figure 18: Pressure variations in the LP Flash Scrubber from 2014

Information from ConocoPhillips yields that an advantage with this is that the LP Flash Scrubber is situated on the same floor and just nearby where the new flare gas recovery unit is supposed to be. This may be more convenient as the LP separator is situated on another floor. However, ConocoPhillips informs that an advantage with the LP separator is that it is a bigger system that has fewer variations in pressure.

Comparing the average of the operating pressure of the LP Separator to the LP Flash Scrubber yields a difference of about 1 bar. The main difference when comparing Figure 17 to Figure 18 is that the pressure in the LP Flash Scrubber has some quite high pressure peaks. This happens when both flash compressors, downstream of the scrubber, stop. Then there will normally be quite an amount of gas going to flare, thus a potential flare gas compressor will not be operative. The peaks in pressure will therefore not be paid attention to when determining the discharge pressure of the flare compressor.

Disregarding the peaks of pressure in the LP Flash Scrubber, there are still some variations in pressure. Even though the average here is lower, the pressure reaches 12 barg numerous of times. Thus, independent of if the gas is routed to the LP Separator or the LP Flash Scrubber, the system should be able to deliver a compressed gas with a pressure of 12 barg.

4.3 Composition of the Flare Gas

The variations in molecular weight throughout 2014 is shown in Figure 19. It ranges between 21 and 33 kg/kmole, with an average of 28 kg/kmole.

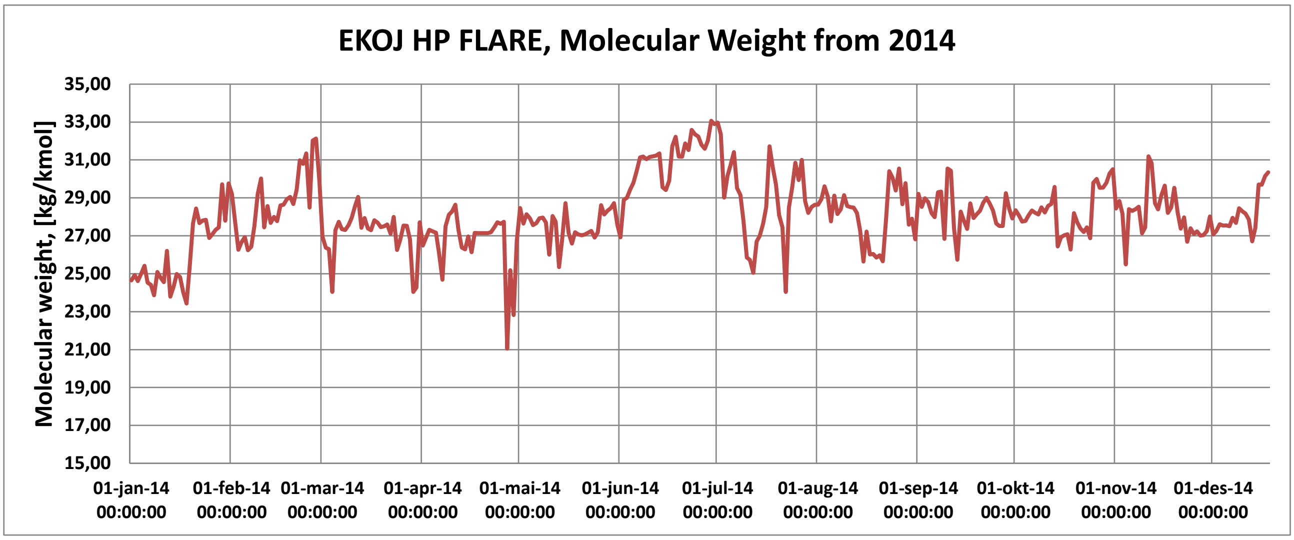

Figure 19: Variations in molecular weight of the flare gas from day to day in 2014

Initially, the plan was to take a sample of the flare gas and get a composition from this. However, this proved to be hard to get hold of, thus a fictional composition was made up based on previous compositions and the average molecular weight from 2014. The resulting composition is shown in Table 14 with a molecular weight of 27,1778 kg/kmole.

Component	Molecular weight, [kg/kmole]	Mole Fractions, [%]
Methane	16,043	56,50
Ethane	30,07	18,15
Propane	44,097	13,70
i-Butane	58,124	2,27
n-Butane	58,124	4,54
i-Pentane	72,151	0,41
n-Pentane	72,151	0,53
n-Hexane	86,17536	0,92
H_20	18,015	0,3
CO_2	44,01	2,38
Nitrogen	28,013	0,3

Table 14: Assumed composition of the flare gas

The flare gas is assumed clear of liquid droplets before entering the compressor, thus there is not much water present in the fictional composition. Most of it is supposed to be removed in the high-pressure knock out drum. To make sure that there is only vapor present, the dew point of the flare gas at 1 barg is about -1°C. The temperatures of the flare gas never went below this in 2014, hence there were, in theory, never liquids present initially (with this composition).

The phase envelope for the composition in Table 14 is given in Figure 20 with suction pressure and the minimum and maximum suction temperatures marked in red.

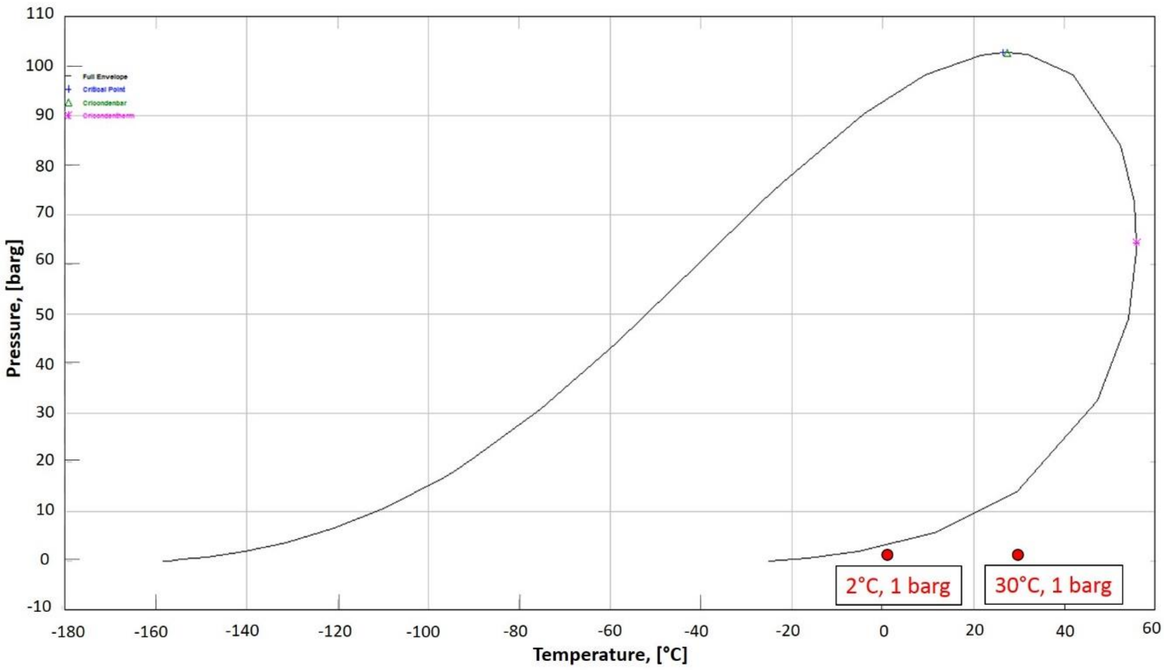

Figure 20: Phase envelope of fictional composition of the flare gas with suction pressure and minimum and maximum suction temperatures marked

Figure 20 shows that the conditions for flare gas recovery at Ekofisk are situated in the lower right corner of the figure, in the vapor region outside the graph. Hence, for this composition, there are never liquid droplets at the inlet of the flare gas compressor.

4.4 Design Flowrate

In 1997, the flare gas recovery system was designed for a flowrate of 457 Sm^3/h. In the study done by Aibel Gas Technology in 2006 a flowrate of 1250 Sm^3/h was used. Thus, the flowrate more than doubled over these 10 years.

When evaluating which flowrate to base the design of this system on, the different flow rates from 2014 shown in Figure 21 was used.

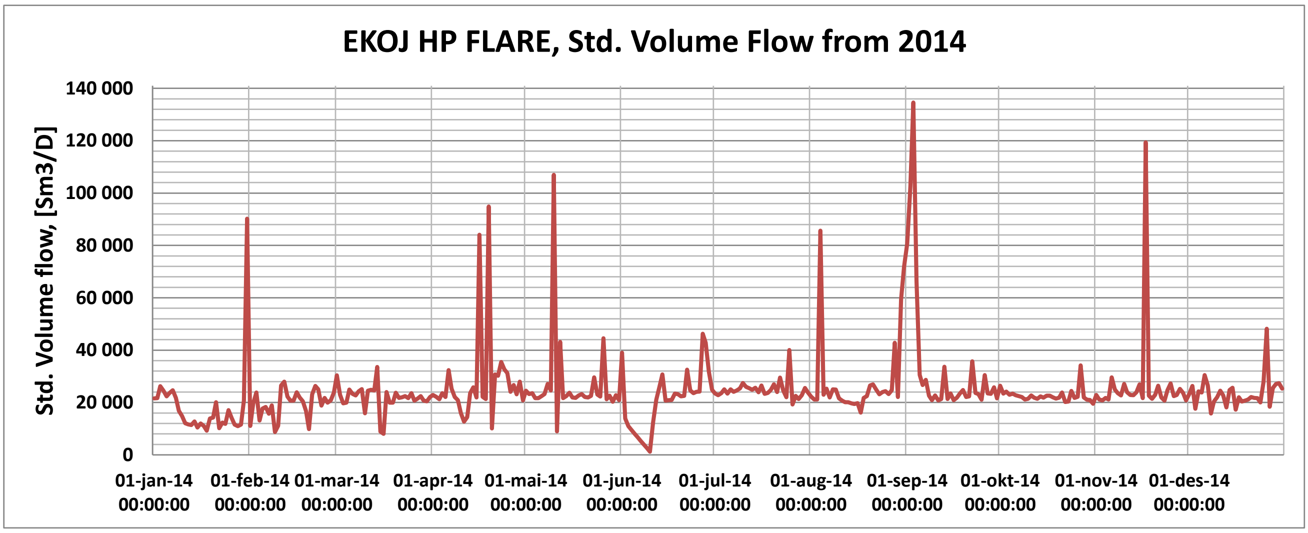

Figure 21: Variations in std. volume flow of the flare gas from day to day in 2014

The peaks in flowrate from Figure 21 are to be flared anyway, independent of a flare gas recovery system. Disregarding these peaks, the average flowrate in 2014 was 23124,9 Sm^3/d. This corresponds to 963,54 Sm^3/h. ConocoPhillips does not think that the flow rate will increase substantially in the future. The main contributor to flaring, the produced water system, is not expected to increase its contribution. Thus, there is no need to take account for an increase of the flowrate. It is expected that it will stay fairly the same as it is now.

If the flowrate is larger than the design flow rate, the gas will be sent to flare. Thus, when deciding on which flowrate to choose, choosing a higher flowrate might result in less flare gas being sent to the flare stack. However, the compressor may require more power and more cooling to handle the increased flow rate. One therefore need to compare the benefits of flaring a little less versus the cost of a slightly bigger compressor and the influence on auxiliary equipment.

The flow varies a lot and a comparison of setting the design flowrate equal to 1000Sm^3/h or 1500 Sm^3/h follows in Chapter 5.

4.5 Standards to be applied at Ekofisk

ConocoPhillips demands that the standards in NORSOK shall be applied for the flare gas recovery system.

In the petroleum industry, International and European standards lay the basis for all activity. In Norway, there are, due to climate conditions and Norwegian safety framework, a requirement for own standards, or additions/supplements to the International and European ones. The NORSOK standards are developed to support the international standards with Norwegian knowledge. The originator is the Norwegian petroleum industry and the standards are generated to ensure sufficient safety, value adding and cost effectiveness for both future and existing developments in the petroleum industry in Norway. (62)

4.6 Available Floor Space

ConocoPhillips informs that the available area for the compressor is 3,5m x 7m x 2,5m.

4.7 Summary

In Table 15 a summary of the design criteria chosen for the flare gas recovery system can be found.

Inlet Temperature, [°C]	2 / 30
Inlet Pressure, [barg]	1
Inlet Volume Flow, [Sm^3/h]	1000 / 1500
Molecular Weight, [kg/kmole]	27,1778
Discharge Pressure, [barg]	12
Available Floor Space, [m]	3,5 x 7 x 2,5

Table 15: Summary of design criteria for the flare gas recovery system at the Ekofisk Complex

4.8 Changes in Operating Conditions over the years at Ekofisk

From 1997 to 2015, there have been some changes in operating conditions for a potential flare gas recovery system at Ekofisk. These are shown in Table 16.

Parameter:	**1997**	**2002**	**2008**	**2015**
Flare gas pressure, [bara]	2	1,97	2	2
Molecular weight, [kg/kmole]	21,3	21,41	23,5	Average: 28
Volume flow, [Sm^3/h]	457	764 m3/h (at 1013 mbar & 0°C)	1250	1000/1500
Flare gas temperature, [°C]	50	50	20, max. 40	Ambient, max. 30

Table 16: Changes in operating conditions over the years at Ekofisk for a potential flare gas recovery system

Comparing the different operating conditions from Table 16 with each other follows below. If the oil-flooded screw compressor from 1997 had been able to work, if the NGL wouldn’t have dissolved in the lube oil, it still wouldn’t have been able to handle the almost doubling of volume flow in 2008. ConocoPhillips informs that the reason for this jump in volume flow is, among other things, due to additions of new platforms to the Ekofisk Complex.

The molecular weight did not change much from 1998 to 2008 where it went from 21,3 to 23,5 kg/kmole. However, from 2008 to 2015 the average molecular weight jumped to 28 kg/kmole. This is partly due to installing C-Tour in the produced water system. More info in Section 3.3.

As for the temperature of the flare gas, it was initially thought that this would be high, the same as from where the flare gas originated. However, thorough research resulted in a temperature approximately the same as ambient. This is the reason for the change in temperature.

The suction pressure of a potential compressor has been approximately the same all the time.

5. Selecting a Flare Gas Recovery System for the Ekofisk Complex

The basis for choosing a flare gas recovery system lay primarily with the suppliers that were contacted throughout the thesis. First, when contacting them, a general mail explaining roughly the situation at Ekofisk was sent out to several suppliers. Some was quick on responding and asking for more details, and some never replied. In the end, nine suppliers contributed with an opinion on what would be the best solution for Ekofisk, with six different alternatives or compressor types. Information about the suppliers were given in Section 2.3.3.

In this chapter, the different alternatives for flare gas recovery systems at Ekofisk are explained. Prior to this, there is an attempt on stating the reason why some of the options have been disregarded, in Section 5.1.

System designs and simulations of these can be found in Section 5.2 and 5.3. Information on the program used for the simulations is given in Section 5.3.1.

This chapter reflect that a great part of the information provided by the suppliers is confidential. Some places in the text there will therefore be anonymized information, especially in Section 5.1.1.

5.1 Evaluations of the Different Options Available

From Section 2.2.5, different methods were suggested for reducing the continuous flaring. Three measures were proposed in connection with the “Flare Project 2012”. They were:

- (Increased) flare gas recovery
- Changing the flare design
    - Measures connected to pilot burners
    - Reduced use of hydrocarbons as purge/blanket gas

Since the pilot burners work satisfactory and nitrogen is already used as purge gas, the flare gas recovery system is the only alternative left to reduce the continuous flaring at the Ekofisk Complex. In addition, because the main contributor to the flaring is flashing from the produced water system, implementing flare gas recovery is recommended in Ref. (4) to be evaluated.

The different compressors or equipment to compress the flare gas proposed by the contacted suppliers were:

- The liquid ring compressor
- The sliding vane compressor
- The reciprocating compressor
- The oil-free screw compressor
- The oil-injected screw compressor
- Ejector

As expected, none of the suppliers suggested using the continuous mode compressors: axial or centrifugal compressors. The flowrate at Ekofisk is much lower than the high flowrates that are suitable for the axial compressor, and the centrifugal compressor cannot handle well the variations in molecular weight that are present. The reciprocating diaphragm compressor is also not an alternative due to operating at a lower flowrate than present at Ekofisk, and the rotary piston is a low-pressure machine. Thus, neither of the mentioned compressors are further evaluated for flare gas recovery at Ekofisk.

The flare gas recovery methods used in other applications, as mentioned in Section 2.2.7, are mostly not applicable at Ekofisk. Either the methods used are designed for much higher flowrates, as for refineries, or they are too advanced, thus resulting in a too big and too heavy construction. When asked, Zeeco was skeptical to applying a VOC recovery system for flare gas recovery. They were not sure if it was fitted for offshore use. However, there were no clear arguments to contradict it, except the higher maintenance demand required that could be avoided by choosing a flare gas recovery unit designed for offshore use. Hence, no further investigation was conducted to look into alternative solutions.

There are advantages and disadvantages with all the six suggestions above. They will all be able to do the job; one just has to be willing to invest in the necessary auxiliary equipment. Some of the alternatives need more of this than the others, thus to find a flare gas recovery system design, different factors need to be taken into account to limit the alternatives. This can for instance be if it’s able to handle liquid droplets. More about this later in the section.

Since the location of the flare gas recovery system is going to be on an offshore platform, there will be area and weight limitations for the recovery system. It is therefore a goal to find a compressor skid that take up a small deck space. In addition, the initial cost of the compressor is of some importance, as well as maintenance and operation cost. Not all the suppliers could provide the floor space of the different compressors at this early stage in the investigations. This is therefore not evaluated further for the possible alternatives. The suppliers also disagreed on which of the compressors that would demand the least maintenance, etc. Hence, it was hard to base a decision on this particular information as well. Further research should therefore be conducted with respect to these two factors in the future.

Condensation in the compressor

Condensation of liquid and dissolution of the heavier components in the lube oil made the oil-injected screw compressor from 1997 break down. Thus, if there is lube oil in direct contact with the gas to be compressed, one needs to be sure that this does not happen again. For compressors where the lube oil has a cooling purpose in addition to lubricating the compressor, this problem might arise. It is the case for both the oil-injected screw and the sliding vane compressor. In both compressor types, the lube oil is injected directly into the compression chamber and mix with the flare gas. For the sliding vane compressor the “flooded lubrication” work to both cool and to minimize vane wear (63). If one of the above mentioned compressors are to be used, preventive measures against dilution of the lube oil need to be taken, such as introducing dew point control of the flare gas (64).

Another important demand connected to liquids present in the compressor, in addition to problems with the flare gas dissolving in the lube oil, is if the compressor is able to handle it. The majority of the compressor types are designed to handle only gas and are highly sensitive to liquids in the suction stream. This is the case for the reciprocating compressor, the sliding vane compressor and the oil-injected screw compressor. Undesirable liquids, being incompressible, does not behave in the same manner as gases when reducing the volume to get a higher pressure. This can yield very damaging results to the compressors and make them useless. Thus, sufficient auxiliary equipment is needed to ensure that the gas stream is free of all liquids when entering the compressor types mentioned above. A properly designed inlet scrubber is often the solution to this problem. However, to avoid the extra equipment, there do exist some compressor types that are designed to handle some liquid entrainment: the liquid ring compressor and some types of screw compressors. On the other hand, they might have the need for auxiliary equipment in other regards. The liquid ring compressor for instance need a system to separate out and recirculate the operating liquid.

Discharge pressure

The most important requirement for the compressor is that it has to be able to compress the flare gas up to 13 bara to be able to be injected into the LP Separator or the LP Flash Scrubber at Ekofisk. Both reciprocating and screw compressors can achieve quite high discharge pressures and will not have a problem reaching 13 bara. From the compressor chart in Figure 22 one can see that both the liquid ring compressor and the sliding vane compressor have operating areas with discharge pressures just below the one at Ekofisk, marked by the red arrows and circle.

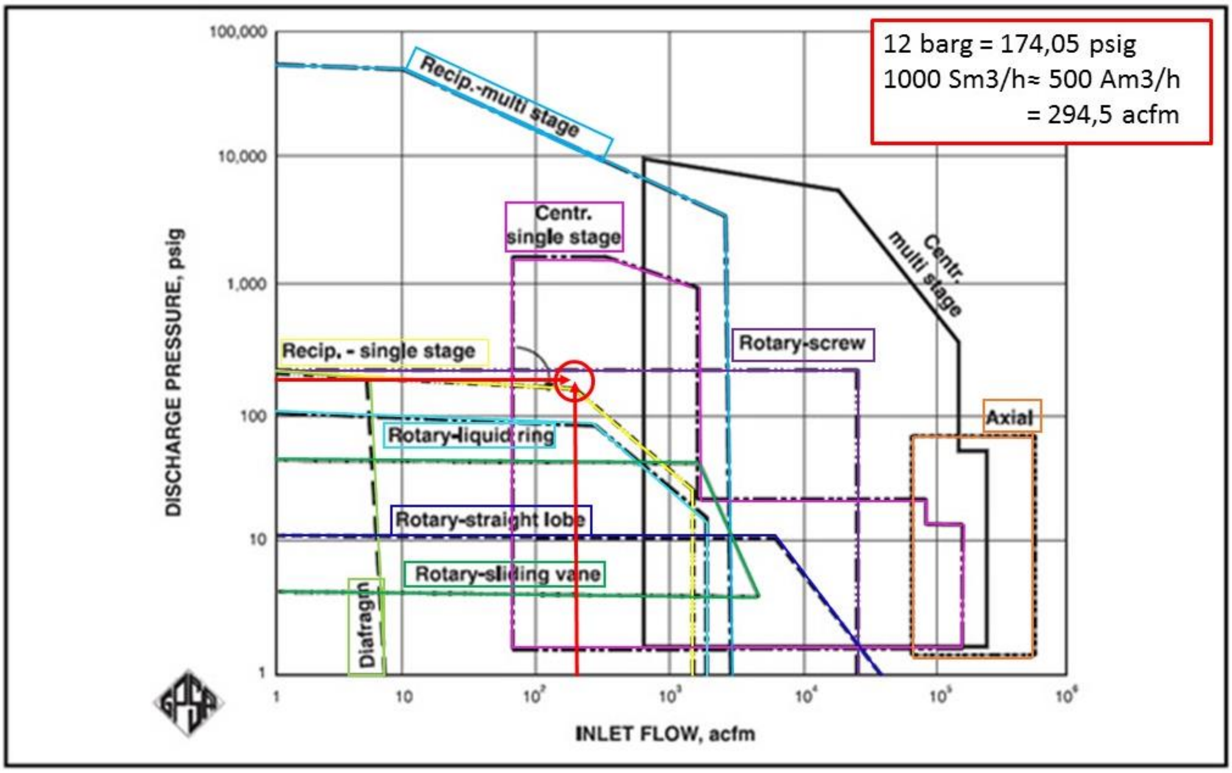

Figure 22: Compressor chart, https://hiramada.wordpress.com/2011/10/09/rotating-equipment-design-basis-general-guideline-part-1-of-2/, 12/3-15

This chart and the information on it are a guideline to help eliminate some types of compressors. The boundaries are not as rigid as is implied. The fact that the liquid ring and sliding vane compressor does not match completely with the discharge pressure and inlet flow at Ekofisk does therefore not matter too much. However, it can shed lights on why some suppliers disagreed on if both the two compressors were able to achieve the required discharge pressure or not.

Cooling the compressors

Cooling of the flare gas in connection with compressors may be done through mixing the gas with a cooling medium such as lube oil or water, or it has to be done externally through auxiliary equipment. As mentioned earlier, for the sliding-vane compressor and the oil-injected screw compressor, the flare gas is cooled through mixing it with lube oil. For the liquid ring compressor it's done through mixing with operating liquid, often water. In the case of oil-free screw compressors or reciprocating compressors, the cooling has to be done by an external source. At Ekofisk, cooling through heat exchangers is done by heat exchanging with seawater.

5.1.1 Initial Costs

A general trend in the oil business today is focus on budget reductions. When contacting the different suppliers of compressors and flare gas recovery systems, ConocoPhillips was therefore interested in getting budget quotations on the different alternatives. For a student with little experience from interpreting quotations, it's hard to base a decision on this. However, a small impression may be gained on how the prices vary from compressor type to compressor type. In addition, what is included in the different packages that are offered, such as maintenance services or auxiliary equipment, may be different. The prices must therefore only work as guidelines.

Not all of the suppliers contacted were able to give a budget quotation, only the following were able to give an approximation: Zeeco, Gas Compressors Ltd., Howden, Gardner Denver, MAN and MPR. These six companies came up with eight budget quotations for eight different systems, three of them from the previous work done in 2014. The different types of compressors are listed in Table 17 with an accompanying percentage of the most expensive alternative. The suppliers are named from A-F, to anonymize them, and where attached number is present if the supplier has offered more than one compressor type.

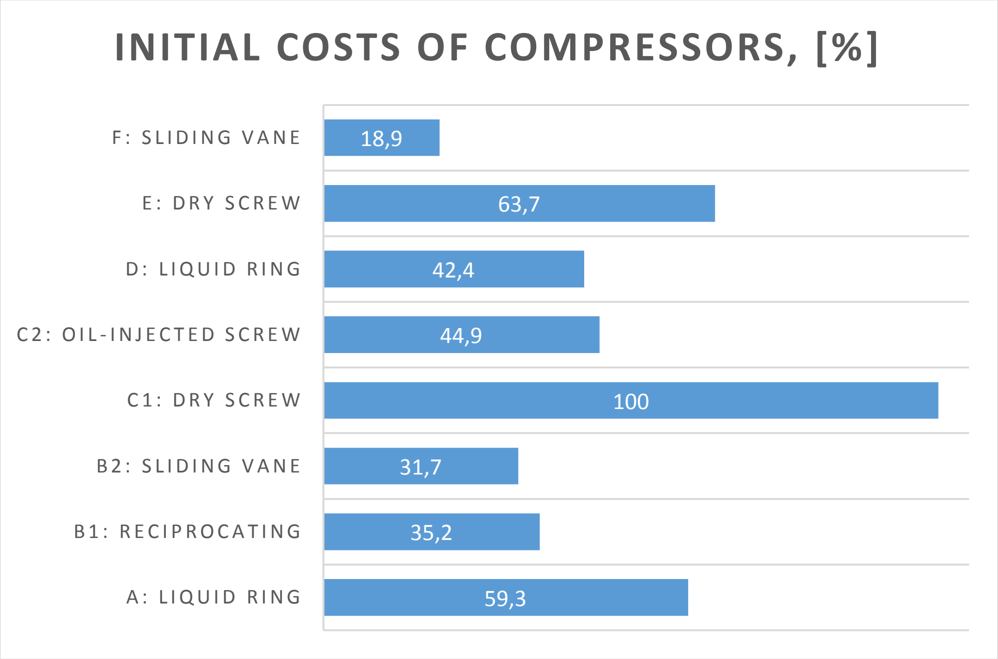

Table 17: Initial costs of the different compressors in [%] with respect to the most expensive alternative for suppliers A-F

From Table 17, the two most expensive alternatives were the oil-free screw compressors. The most expensive is from the work done in 2014, delivered by supplier C, and the second most expensive dry screw compressor has about 36 % lower costs, delivered by supplier E. Hence, there is quite a big gap in price within the same compressor type. After the dry screw comes one of the liquid ring compressors from supplier A. The liquid ring compressor has about 7 % lower initial costs than the second most expensive dry screw compressor. Further, the prices of the oil-injected screw from supplier C and the second liquid ring compressor from supplier D are quite similar. After the liquid ring compressor, the reciprocating compressor from supplier B has even 17 % lower costs. The last two remaining compressors are of sliding vane type. The more expensive of the two delivered by supplier B and the second by supplier F. Comparing the most expensive dry screw compressor with the sliding-vane compressor with lowest costs yields a difference of 81 %, which is quite a big gap.

To summarize, looking at only the initial costs of the compressors, it’s no doubt that the sliding vane compressor is the alternative with lowest initial costs while the oil-free screw compressor is the most expensive. The liquid ring, oil-injected screw and reciprocating are spread evenly in between, with the liquid ring being in the more expensive range and the reciprocating on the opposite side. These prices only take into account the cost of buying the different systems, not the costs related to operating them.

5.1.2 Reciprocating Compressor

The reciprocating compressor handles well high discharge pressures and will have no problem compressing the gas to 13 bara. The gas to be compressed does not flow continuously through the reciprocating compressor, it’s intermittent, and it exerts alternating forces on support and foundation. In addition, pulses are produced in the gas stream, which can be reduced by pulsation dampeners. One of the suppliers contacted informed that if a reciprocating compressor were to be used, it has to be of “boxer type”, which means that the arrangement of cylinders are in-line. It also needs to be an API618 machine. (65)(66)

Intercoolers and after coolers are needed for reciprocating compressors to remove heat that is generated when the gas is compressed. They may be fitted with moisture separators to remove condense from the gas stream and to enable water and oil to be drained through each separator. In addition, the removal of heat is important to achieve efficient compression. When the gas is compressed, the temperature increases and the volume expands. This will again result in that an increase of work is needed to compress the gas. Thus, the power requirement will be reduced through multistage reciprocating compressors with intercoolers. On the other hand, this form of cooling the gas may lead to a heavier construction, which is not desirable when the location of the compressor is offshore. (67)(68)

A substantial amount of auxiliary equipment is needed if the reciprocating compressor were to be used for flare gas recovery. An inlet scrubber, intercooler and after cooler is needed and vibrations and pulsations should be prevented. Noise enclosure should be included as well. This will result in a heavy construction, thus the reciprocating compressor is not further evaluated for flare gas recompression at Ekofisk.

5.1.3 Sliding Vane Compressor

There are some uncertainties regarding if the sliding vane compressor is able to compress the flare gas to a pressure of 12 barg. MPR offers both liquid ring and sliding vane compressors. The compressor type they recommended for flare gas recovery at Ekofisk was the sliding vane compressor. When they were asked why they choose one over the other they said that the liquid ring compressor would not be able to get a high enough discharge pressure. On the other hand, GCL only recommended the sliding vane compressor when the discharge pressure was lowered to 11 barg for injection into the LP Flash Scrubber instead of LP Separator. As previously mentioned, the average pressure in the flash scrubber was slightly lower than in the separator. However, as was evident from the pressure variation diagrams, the pressure in the LP Flash Scrubber varied a lot and it would be preferable if the selected compressor would be able to compress up to 12 barg independent of injection point. It is therefore questionable if the sliding vane compressor can handle the required discharge pressure.

The sliding vane compressor is sensitive to liquids and an inlet scrubber is needed. Other auxiliary equipment needed is for instance a system for the lube oil. Since the sliding vane compressor operates best when compressing a clean gas with a low-pressure discharge it may not be the perfect fit at Ekofisk. Also, the fact that there is no API-standards for this compressor is a disadvantage. It is not disqualified, but a lot of further work, investigations and testing needs to be done for it to be accepted (30). Hence, the sliding vane compressor is also further not an alternative.

5.1.4 Ejector

In 2014, there were contact between ConocoPhillips and Transvac regarding the use of an ejector in a flare gas recovery system. Then, three different concepts of ejectors were proposed:

- Liquid-driven ejector
- One-stage, gas-driven ejector
- Two-stage, gas-driven ejector

At Ekofisk, if using gas, it would be taken from the gas lift compressor. This would reduce the gas available for lifting the wells. If using the liquid-driven ejector, the R&D director in Transvac, Gary Short, proposes in an article from 2013 that for instance injection water can be used. (69)

The initial suggestion was to use a two-stage, gas-driven ejector. However, the suction pressure was set too low at this point. Thus, increasing the suction pressure to the correct value of 1 barg made it possible to use a reduced motive gas flow rate and enabling one-stage instead. Even less motive fluid flow rate is needed if using liquid instead of gas. The disadvantage with using liquid as motive fluid is that it is required that pressurized liquid is available. In addition, extra equipment is often needed.

When ConocoPhillips evaluated these alternatives in 2014, the most relevant one was the one-stage gas-driven ejector. A presentation to management in 2014 of the concept with a one-stage ejector vs. a compressor resulted in a compressor being more promising due to the high motive gas consumption for an ejector. As management in ConocoPhillips dismissed the ejector in 2014, and there has not been any major breakthroughs in the technology since then, or changes at Ekofisk, the ejector is not an alternative during this thesis either. Hence, further, full focus is set on finding the best type of compressor.

5.1.5 Summary

So far, the alternatives that have been disqualified are the reciprocating compressor, the sliding vane compressor and the ejector. A summary of some of the reasons the two compressors are not considered further is listed in Table 18. The ejector is not shown here because the management in ConocoPhillips have already decided that it will not work at Ekofisk.

Type of compressor	**Available pressure ratio**	**Ability to handle liquids**	**Need for auxiliary equipment**	**Area (floor space) & weight**	**Noise**	**Price**	**Other**
Reciprocating compressor	High	No	- Inlet scrubber - Intercooling - After cooling	Heavy and take up a lot of floor space	High noise and vibration levels	Neither high or low	- Frequent maintenance is required
Sliding vane compressor	Questionable if high enough, typically a limited discharge pressure of 150 psi (=10,34 bar)	No	- Inlet scrubber - System for lube oil	Small floor space	No particular problem	The one with lowest costs	- Follow no standards, no API - Works best in low-pressure clean gas applications

Table 18: Summary of the compressors disqualified

5.2 System Design

In theory, all the compressors that have been evaluated in this thesis could have worked at Ekofisk as long as there would have been unlimited of space for the compressor skid and unlimited of money to invest in necessary auxiliary equipment. However, since these restrictions are present, together with the disadvantages mentioned in Section 5.1, the alternatives that are left are the liquid ring compressor, the dry screw compressor and the oil-injected screw compressor. In the following sections, different designs for the different compressor types are elaborated.

5.2.1 Liquid Ring Compressor System Design

A flare gas recovery system based on the liquid ring compressor is most common on offshore facilities. The main advantage with this compressor is the fact that it can handle liquid droplets present in the flare gas and does not need any equipment prior to the compressor inlet. A disadvantage is the low efficiency of the compressor.

When communicating with different suppliers, there were some disagreements on if the compressor is able to compress up to a pressure of 13 bara at the given flow rate. In the study conducted by Aibel Gas Technology in 2006 the liquid ring compressor was proposed as the main alternative. However, in 2008, it was concluded that the liquid ring compressor wouldn't manage to get the high discharge pressure. The same type and model of liquid ring compressor evaluated in the study in 2006 was proposed both in 2014 and during this project. In 2014, when the supplier was asked some follow-up questions regarding the compressor and it's ability to handle the conditions of the flare gas at Ekofisk, they were vague and in some cases avoided or did not answer at all. ConocoPhillips therefore got a bit skeptical. In the end, when contacting the same supplier in relation to this thesis, it was concluded that the initially suggested liquid ring compressor would have too high capacity for the conditions at hand. Aibel Gas Technology was therefore correct when rejecting this in 2008. However, a new liquid ring compressor was suggested with the correct capacity, and it's therefore an alternative for flare gas recovery in this thesis.

The flare gas recovery system based on using a liquid ring compressor is shown in Figure 23. It consist of, in addition to the compressor itself, two subsystems: one for recycle of flare gas (the green arrows) and one for recirculation of operating liquid (the red arrows). The recycle system consist of a recycle control valve and a seawater cooler to reduce the pressure and temperature and control the flowrate that pass through recycle (more info on the recycle loop is found in Section 5.2.4.2).

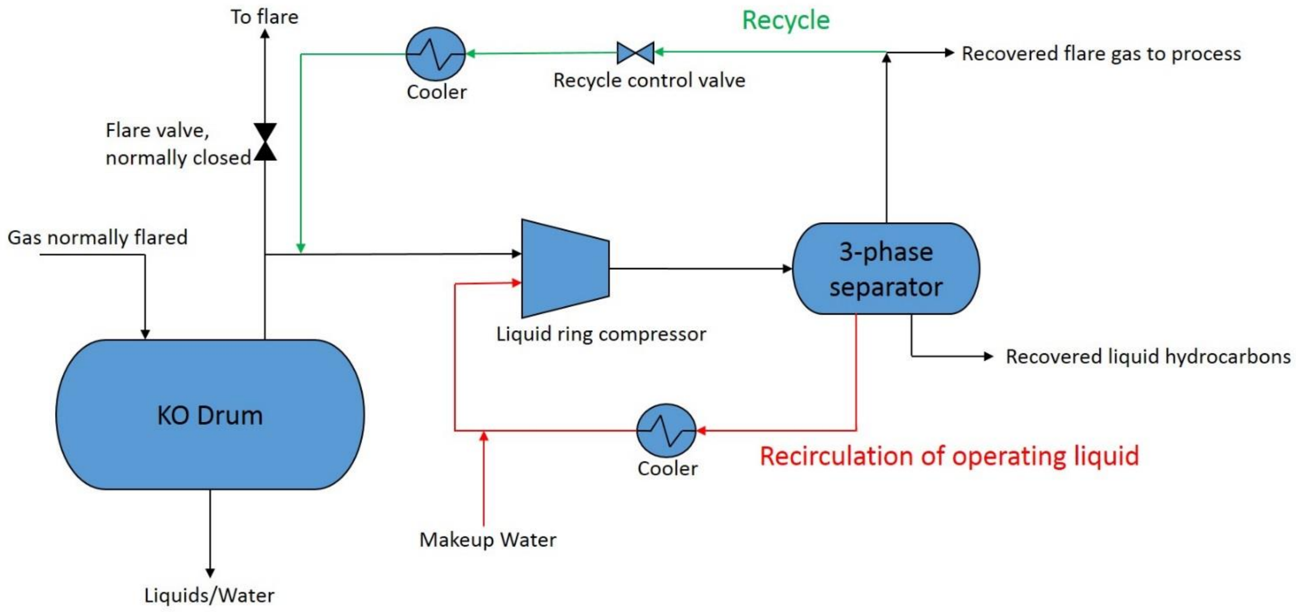

Figure 23: Flare Gas Recovery System design based on using a liquid ring compressor

Discharging from the high-pressure knock out drum, the flare gas is routed directly to the liquid ring compressor. Inside the compressor, the flare gas is mixed with the operating liquid of the system that both cools and compresses the gas. The operating liquid used is water with glycol to prevent freezing. However, when simulating this system in Section 5.3 the operating liquid was simplified to just containing water.

After the compressor discharge, the mix of gas and liquids enter a three-phase separator. The separator has three main tasks:

1. To separate the recovered flare gas from the operating liquid and the condensed hydrocarbons
2. To return flare gases and liquids to the main process
3. To re-circulate the operating liquid back to the liquid ring compressor

The gas phase discharging from the three-phase separator is fed directly into the main process. Some gas will be routed through the recycle loop to maintain correct flow through the compressor, while the rest will be returned to the main process. The temperature rise of the recovered flare gas through the compressor is minimal due to the operating liquid absorbing heat. Hence, there is no need for an after cooler for the gas.

As mentioned above, most of the heat of compression got absorbed into the operating liquid, and a heat exchanger is needed to remove the heat from the liquid. Once cooled, the operating liquid is returned to the liquid ring compressor. Since the operating pressure of the separator is so much higher than the suction pressure of the compressor, there is no need to pump the operating liquid.

To ensure that the quality of the operating liquid is satisfactorily, liquid-bleed and make-up capabilities are present. The liquid can then be removed if being contaminated or to prevent acid build up. (13)

5.2.2 Dry Screw Compressor System Design

The dry screw compressor handles well wide swings in molecular weight and gas composition, and it’s able to handle contaminants in the gas to be compressed. In the oil-free screw compressor there is no need for lubrication since the rotors neither come in contact with the compressor housing or each other. The pressure ratio of the compressor is limited by the temperature rise from intake to discharge, thus the oil-free screw compressors are often built with several stages with intercoolers and after cooler. (70)

A flare gas recovery design based on a dry screw compressor is shown in Figure 24 and consist of, in addition to the compressor itself, one subsystem: the recycle of compressed flare gas. The dry screw compressor runs at constant speed. It can operate at variable pressure ratio, discharge pressure over suction pressure (P2/P1), as long as it is within the design range. Due to the constant speed of the compressor, one should have a recycle based on the P2/P1 ratio such that a constant discharge pressure is obtained for varying flow rate (71). The recycle system is the same for the liquid ring compressor system.

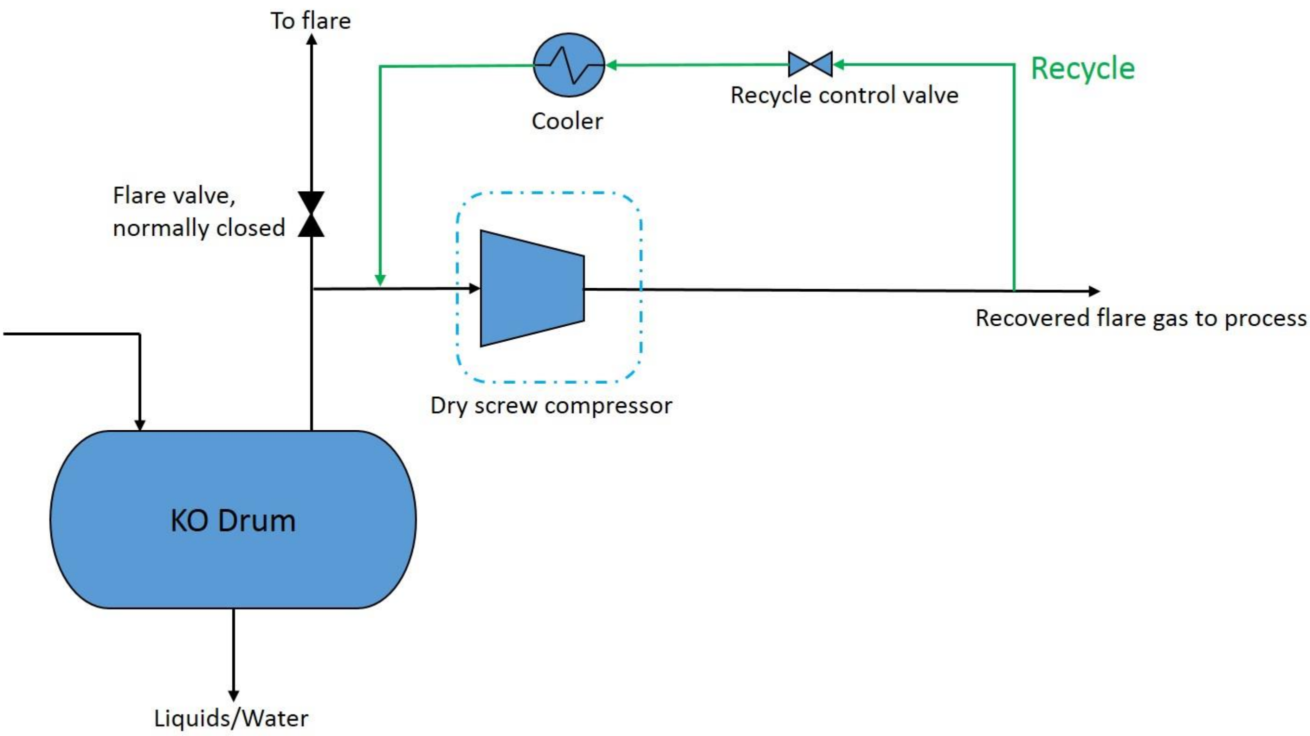

Figure 24: Flare Gas Recovery Design based on using a dry screw compressor

As for all other flare gas recovery systems suggested, the flare gas discharges from the high pressure knock out drum at EKOJ and is routed to the compressor inlet. In Figure 24, the compressor is encircled by a blue quadrate. This is because there are two alternatives for this part, which will be explained in more detail below.

The limitations of the oil-free screw compressor are primarily due to temperature. Typically, the maximum discharge temperature of the dry screw compressor is around 260°C. The pressure ratio limitations are also related to temperature. If the suction temperature increases, the discharge temperature does as well. The pressure ratio therefore needs to be decreased if the suction temperature is increased. In addition, the molecular weight affect the available compression ratio. A gas with a low molecular weight require a compressor operating at high speed, thus resulting in a lower compression ratio. This is more relevant for clean-gas operation.

The flare gas compression at Ekofisk, through using a dry screw compressor, needs to undergo two stages. Depending on how the pressure ratio is distributed, two alternatives for the compressor configuration can be found. These are shown in Figure 25.

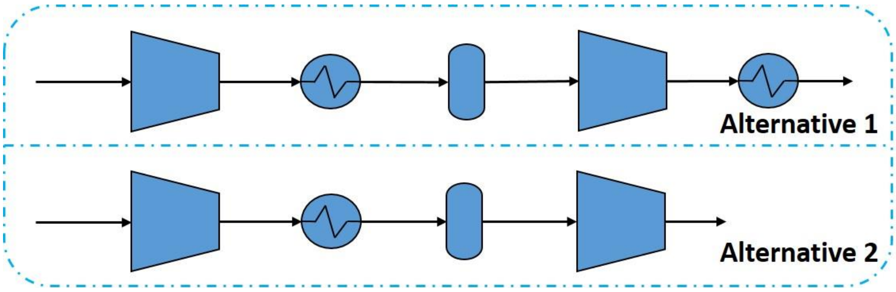

Figure 25: Two alternatives for the dry screw compressor depending on the pressure ratio for the two compression stages

First looking at what the two alternatives in Figure 25 have in common. Since there is no lube oil or water that cools the gas through the compressor, an intercooler is needed. Condensation may occur through this cooler and a small scrubber is placed downstream to get rid of these liquids, just as a precaution. Further, the liquid free flare gas enter the second compressor stage and is compressed to the pressure dictated by the downstream process.

The main difference between the two alternatives is the need for after cooling in Alternative 1. Here the discharge temperature is too high for direct re-injection of compressed flare gas into the main process at Ekofisk. ConocoPhillips informs that it should not exceed 100°C. The pressure ratios over the two compression stages in Alternative 1 are the same, 4,14, while in Alternative 2 the gas if first compressed from 1 to 6 barg and secondly from 5 to 12 barg. Through both the intercoolers and the after cooler there are, as mentioned earlier, a pressure loss of 1 barg. This results in that the discharge pressure of Alternative 1 has to be set to 13 barg instead of 12 barg and a slightly higher power need is expected.

5.2.2.1 Extra equipment needed, but not crucial for the system

Since screw compressors don't have suction or discharge valves (as the reciprocating compressor does), it's normal to think that the gas flow continuously through the compressor without any pulsations. However, Standard 619 5th edition (as cited in (72)) informs that the flow through the screw compressor system is not steady, but moves in a series of flow pulses. If the compressor is operating near the design conditions, pulsations are minimized. If it however operates at off-design, the pulsation levels may increase considerably.

Silencer are auxiliary equipment that are often needed when designing systems with a dry screw compressor. They are installed to reduce the pulsations in the piping and consequently high-frequency vibrations and possible failures. The dry screw compressor has inherent high noise levels due to vibrations of the compressor (high rotational speed) and the gearbox. These ambient noise levels may be reduced to some extent by installing silencers. The type of silencers that are normally used are expansion and/or absorption type in combination or separately. In (73), it is found that a combination of absorption and expansion type silencers is most effective when looking at noise reduction. In addition to the silencers, one can add a noise enclosure covering the compressor and the gearbox. In hot climates, this can cause problems with too high temperatures within the enclosure, but the North Sea rarely have temperatures above 20°C, hence it is not expected to be a problem at Ekofisk.

An inlet and outlet silencer will be installed on both compression stages. Since this is not crucial for making the flare gas recovery system work, it is not a part of the system overview in Figure 24, but it will be present to reduce noise and pulsations in the piping. A noise enclosure enclosing the compressor and gearbox should also be present. These components, even though not crucial for making the system work, will affect the area of the recovery system.

5.2.3 Oil-injected Screw Compressor System Design

ConocoPhillips urged the oil-injected screw compressor to still be an alternative in spite of the outcome in 1997. However, this time, it should include dew point control, as explained in Section 3.4.3. Such flare gas recovery systems have been tried out on other offshore platforms in the North Sea, and ConocoPhillips has so far not heard anything negative about them.

The layout of the simplified flare gas recovery system with dew point control can be seen in Figure 26. It involves only the main components of the flare gas recovery system, there will be additional equipment that is not present in the figure. Simulating the system proved to be hard as no composition of a lube oil was available. However, a simulation of this sort of system was carried out during the study in 2008, and it was shown to work.

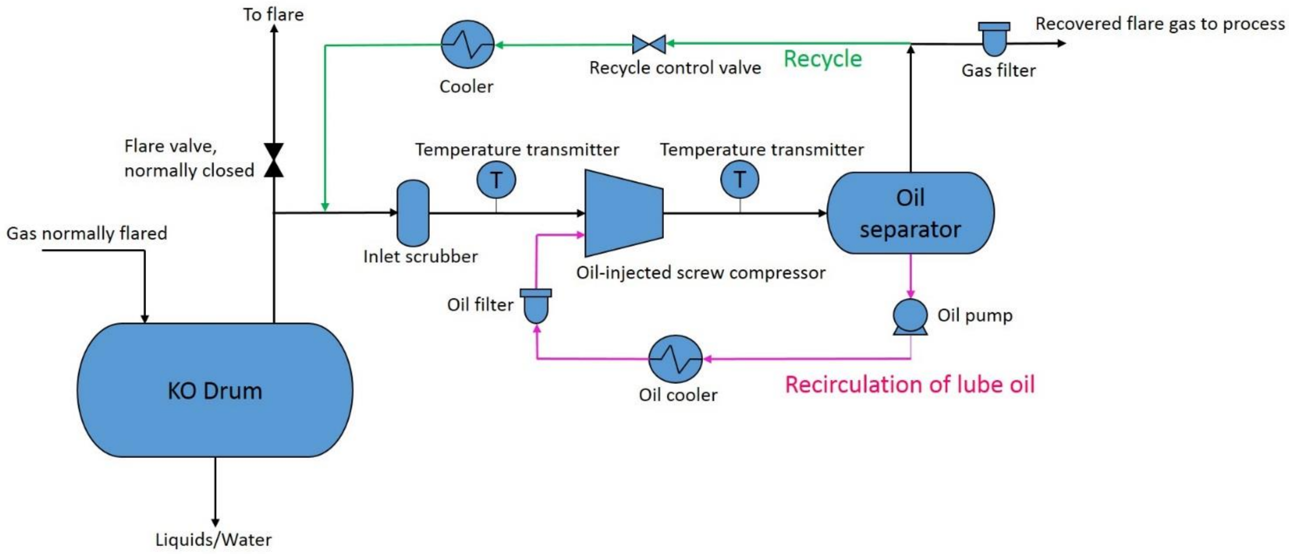

Figure 26: Flare Gas Recovery Design based on using an oil-injected screw compressor

To avoid liquid condensation that may dissolve in the lube oil, the outlet temperature should be maintained at least 15°C above the discharge dew point temperature. At a discharge pressure of 12 barg the dew point temperature of the flare gas is found to equal 28°C through PRO/II simulations (info on PRO/II in Section 5.3.1). Hence, the discharge temperature should always stay above 43°C. Safety devices must be in place to shut down the compressor at low discharge temperature. The compressor should also be shut down if the inlet temperature exceeds 30°C.

The system will, as with the liquid ring compressor system, have two recirculation loops: one for recycle of flare gas and one for recycle of lube oil. The recycle loop has the same configuration as for the two other systems. Upon discharge from the knock out drum, the flare gas enter an inlet scrubber. As mentioned earlier, the oil-flooded screw compressor is sensitive to liquid droplets present in the gas, thus extra precaution is taken by making sure that as much liquid as possible is removed in the scrubber prior to the compressor inlet. Monitoring the suction temperature of the flare gas follows the discharge from the inlet scrubber. Further, the dry gas enter the screw compressor together with the lube oil; due to the cooling effect of the lube oil, the compression is possible in just one stage. A compressed mix of flare gas and lube oil discharges from the compressor were the temperature is monitored and ensured to be at least 43°C such that the flare gas doesn't condense. In the oil separator, the gas is separated from the oil. The compressed gas is either recycled, same as in the other two systems, with injection prior to the inlet scrubber, or it can go through a gas filter before re-injection into the main process. The filter ensures that all oil is gone.

The oil lubrication system mainly consist of an oil pump, oil cooler and oil filter. The oil pump draws lube oil from the oil separator, which is at compressor discharge pressure: 12 barg. Then, the oil is routed through a sea water cooled oil cooler. In addition, the oil pass through an oil filter for cleaning following the cooling. Hence, the clean and cooled oil can re-enter the compressor.

As mentioned in the previous section, dry screw compressors often need silencers installed upstream and downstream of the compressor. The oil-injected screw compressors, however, does not need that. The oil separator downstream of the compressor is not only used for removal of oil from the gas, but can also attenuate and/or amplify the pulsation generated by the compressor. (72)

5.2.4 Things in common for all the Systems

The heat exchangers used in the recovery systems and the recycle loop is the same for all the systems. Information about these is therefore summarized below.

5.2.4.1 Heat exchangers

ConocoPhillips informs that all the heat exchangers used in connection with flare gas recovery are seawater coolers. Process gas is being cooled by seawater at a temperature of 11°C and a pressure of 7-8 barg. The cooler shall be designed such that the seawater outlet temperature does not exceed 40°C. This requirement should be maintained by regulating the flow rate of seawater to get the process gas outlet temperature wanted.

5.2.4.2 Recycle loop

All the systems require a recycle loop to handle a flare gas rate that varies. This way, compressed flare gas is routed back to the inlet of the compressor such that a constant flow rate and constant pressure ratio over the compressor is maintained. For this to be done some form of recycle control needs to be installed on the loop. Simplified, this can be a recycle control valve that regulate how much of the recovered flare gas that should be routed back to the compressor suction. In addition a cooler should be present. The temperature at the compressor discharge is quite much higher than at the inlet. Since the flow rates being dealt with here are so small, the temperature of the recovered gas from the loop can therefore influence the temperature of the gas to be compressed. This may change the performance of the compressor, which is undesirable. A cooler should therefore be installed on the recovery loop to yield a similar temperature as the main flare gas flow. In addition, the pressure of the recovered flare gas is quite much higher than suction pressure. The valve controlling the recycle will also take care of this pressure reduction.

5.2.5 Summary

Different system designs have been presented for the different compressor types: liquid ring compressor, dry screw compressor and the oil-injected screw compressor. The main components in the design are shown, but there will be a lot more that is not present in the figures. There are quite an amount of difference in required auxiliary equipment and further evaluations between the proposed systems above leads to the simulations, in Section 5.3.

5.3 Simulations

In the following section, the different alternatives are simulated to find heat duties for the coolers and power demands for the compressors. There were not enough info on the alternative concerning the oil-injected screw compressor, thus it was not possible to simulate it in this thesis. However, thorough investigation by ConocoPhillips, both in 2008 and in 2014, proves that it is a strong alternative. This section in the report will therefore focus on comparing the liquid ring compressor to the oil-free screw compressor.

First, there is a short introduction to the program used for the simulations in Section 5.3.1, and then details on how the simulations were carried out, together with the results, follows.

5.3.1 SimSci PRO/II

PRO/II is a process simulation program that can optimize the plant performance by improving both process design and operational analysis, in addition to carrying out engineering studies. A great variety of thermodynamic models is offered to suit practically all industries. PRO/II is designed to perform rigorous heat and material balance calculations for many different chemical processes. Both capital and operating costs are decreased since PRO/II is cost effective. (74)

In this thesis, PRO/II is used to simulate the proposed flare gas recovery system designs. By doing this one can find out if condensation occurs through the compressor and under what conditions it does. The power and duties needed by the compressors and the heat exchangers can be approximated, in addition to changes in these due to altering design and inlet conditions to the compressor.

The Soave – Redlich – Kwong (SRK) equation of state is used in the simulations. Together with the Peng – Robinson (PR) equation of state, they are perhaps the two most widely used cubic equations of state in refinery and gas processing industry, especially for prediction of vapor – liquid equilibria for systems with nonpolar components. (75)

5.3.2 Compressor Efficiencies

An important difference between the liquid ring compressor and the dry screw compressor is the efficiency. The liquid ring compressor is known for having a lower efficiency, while the screw compressor has a slightly better one. In Ref. (76), a rule of thumb was found to estimate the efficiency for the compressors. Rotary compressors have efficiencies of 70-78%, except the liquid types which have about 50%. In the simulation conducted during this thesis the efficiency of the dry screw compressor was therefore set to 74% and the efficiency of the liquid ring compressor was set to 50%.

5.3.3 Simulating the Recycle Loop

The recycle loop was not simulated together with the rest of the flare gas recovery system in PRO/II. To find the duty of the heat exchanger to cool the compressed flare gas down to suction temperature of the compressor, the configuration in Figure 27 was used in PRO/II. Here the compressed flare gas is first routed through a valve to reduce the pressure down to 2 barg. Further, it's cooled in a seawater heat exchanger to reduce the temperature, and due to pressure loss through the cooler the outlet pressure gets the correct suction pressure of 1 barg.

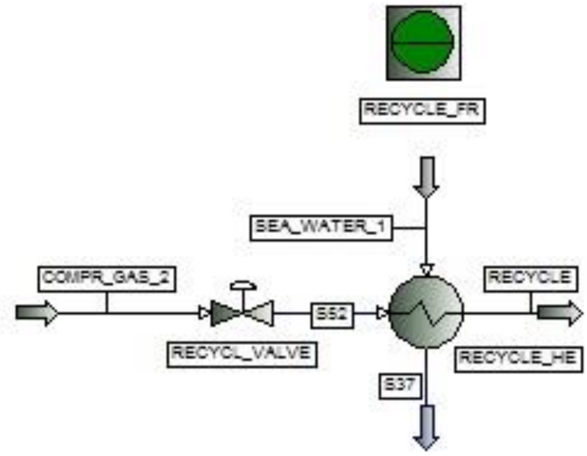

Figure 27: Recycle system in PRO/II, valid for all the different flare gas recovery systems

The controller in the top of the figure controls the flow rate of seawater such that the outlet temperature of the seawater does not exceed 40°C, but is still able to yield the correct outlet temperature of the recycled flare gas. The duty of the heat exchanger is found through Eqn. 1:

$$Q_{recycle} = \dot{m}_{compr\_gas\_2} * (h_{S52} - h_{recycle}) \qquad (1)$$

When simulating the recycle loop, the outlet temperature of the cooler varied together with the suction temperature of the compressors: either 2°C or 30°C. In addition, as the flowrate into the compressor was changed from 1000 to 1500 Sm^3/h the flowrate in the recycle also changed. Based on the flowrates from 2014, a maximum rate for recycle was found for the two design flowrates for the compressor. Thus, the maximum duty for the heat exchanger could be found. For a design flowrate of 1000 Sm^3/h the maximum recycle rate needed is 665,04 Sm^3/h and for a design flowrate of 1500 Sm^3/h the maximum recycle rate needed is 1165,04 Sm^3/h. All recycle heat duties given in this thesis are therefore maximum heat duties.

5.3.4 Simulating the Liquid Ring Compressor System

When simulating with respect to a liquid ring compressor certain simplifications were made. First of all, as mentioned before, the operating liquid is set to consisting only of water. Secondly, since the compressor is the main problem with finding a system that works, this is the focus of the simulations. Hence, the recirculation of operating liquid and the recycle of compressed flare gas have not been simulated together with the compressor part. However, they have been simulated separately to find the duties of the heat exchangers. The recycle loop configuration in PRO/II has already been shown in Figure 27. The model of the liquid ring compressor itself in PRO/II is shown in Figure 28.

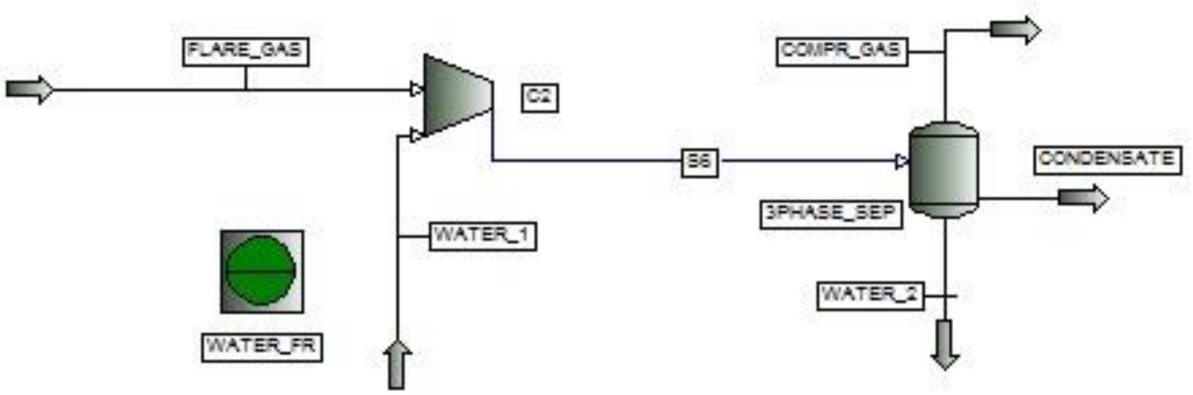

Figure 28: Liquid ring compressor in PRO/II

From Figure 28, the liquid ring compressor system in PRO/II consist of the compressor and the 3-phase separator. The controller controls the supply (flowrate) of water into the compressor, such that the discharge temperature reads 50°C. The operating liquid is potable water, and it is assumed to have the same conditions as the seawater in the coolers, 11°C and 7 barg. From the simulations, the power needed for the compressor to run can be found.

The model of the recirculation of operating fluid in PRO/II is shown in Figure 29.

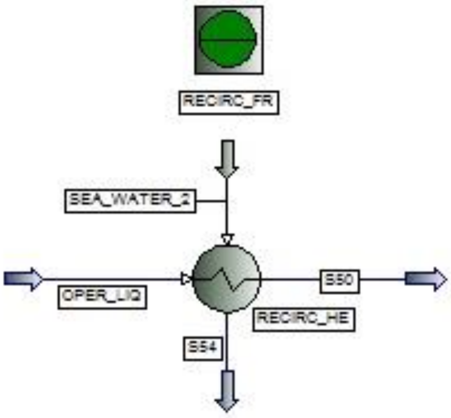

Figure 29: Recirculation of operating liquid in PRO/II

The recirculation of operating liquid from Figure 29 shows only the heat exchanger used for cooling. A controller regulates the sea water supply in the same way as for the recycle loop, such that the outlet temperature equals 40°C. The duty of the heat exchanger is found through Eqn. 2:

$$Q_{recirculation} = \dot{m}_{oper\_liq} * (h_{oper_{liq}} - h_{S50}) \tag{2}$$

5.3.5 Simulating the Dry Screw System

When simulating the dry screw compressor design the recycle loop is still modeled as shown in Figure 27. The model of Alternative 1 in PRO/II is shown Figure 30.

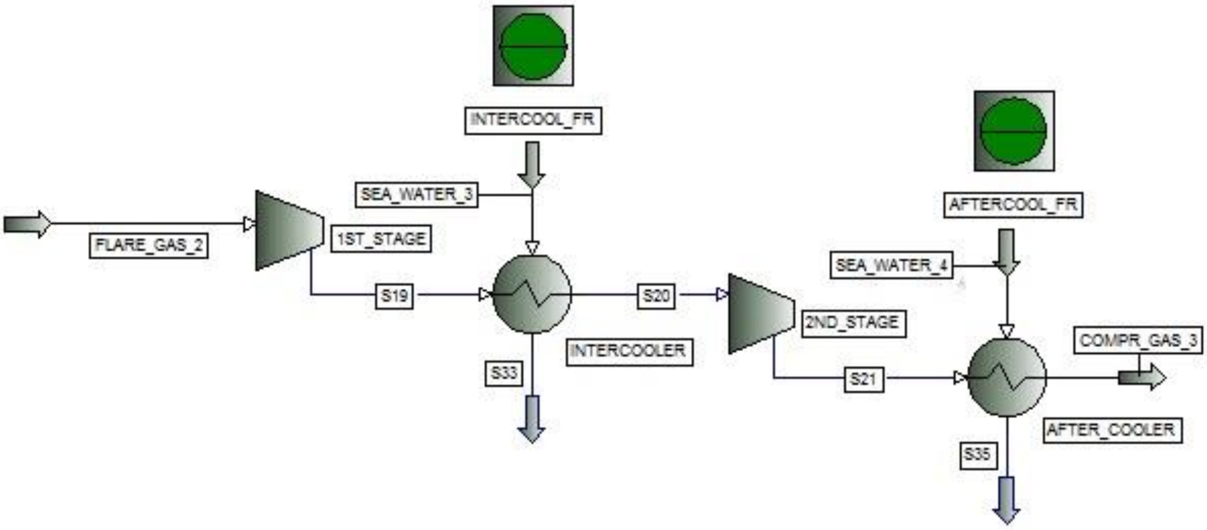

Figure 30: Alternative 1 for dry screw compressor in PRO/II

Alternative 1 for flare gas recompression using a dry screw compressor in PRO/II consists of two compression stages and two coolers: one intercooler and one after cooler. The scrubbers shown in Figure 25 are not included in the PRO/II models since no condensation take place. More on this in Section 5.3.6.3.

In the same way as before, the flowrate of seawater through the heat exchangers is controlled such that the outlet seawater temperature does not exceed 40°C. The flare gas outlet temperature of the intercooler is set to be 30°C and the flare gas outlet temperature of the after cooler is set to be 50°C. The power need of the compression stages can be found directly from PRO/II, while the heat duties of the heat exchangers can be found from Eqn. (3) and Eqn. (4):

$$Q_{intercooler} = \dot{m}_{flare_{gas_2}} * (h_{S19} - h_{S20}) \tag{3}$$

$$Q_{after\_cooler} = \dot{m}_{flare_{gas_2}} * \left(h_{S21} - h_{compr\_gas\_3}\right) \tag{4}$$

The model of Alternative 2 in PRO/II is shown in Figure 31.

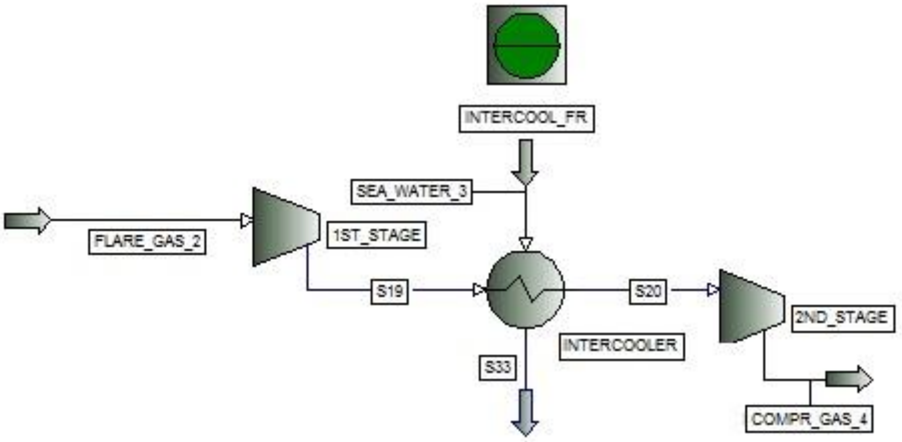

Figure 31: Alternative 2 for dry screw compressor in PRO/II

Alternative 2 is identical to Alternative 1, except for the pressure ratios over the compression stages and the lack of an after cooler. The heat duty of the intercooler is found in the same way as for Alternative 1, through using Eqn. (3).

5.3.6 Results from the Simulations

5.3.6.1 Discharge compositions of compressed flare gas

In Table 19, the molar compositions of the compressed gases ready for re-injection are listed for respectively the liquid ring compressor and the dry screw compressor.

Component	**Molar Composition [%], Liquid Ring**	**Molar Composition [%], Dry Screw compressor**
Methane	56,14	56,50
Ethane	18,04	18,15
Propane	13,61	13,70
i-Butane	2,26	2,27
n-Butane	4,51	4,54
i-Pentane	0,40746	0,41
n-Pentane	0,5266	0,53
n-Hexane	0,91435	0,92
H20	0,96788	0,3
CO_2	2,33	2,38
Nitrogen	0,29817	0,3

Table 19: Molar compositions of the compressed gas ready for re-injection into main process for the liquid ring compressor and the dry screw compressor

For the liquid ring compressor, the composition is taken from the separator exit. For the dry screw compressor, the composition is taken from the discharge from the 2nd compression stage. As can be seen from Table 19 the compositions from the outlet of the two different compressors varies. The gas discharging from the 3-phase separator in the liquid ring system is saturated with water, thus having a slightly bigger amount of water present: 0,97 % vs 0,3 % for the dry screw compressor. However, the gas discharging from the dry screw is the same as the initial composition and has a slightly bigger amount of all the remaining components in the flare gas, except water. The liquid ring discharge molecular weight has become slightly lower with 27,1112 kg/kmole vs the initial 27,1778 kg/kmole. This is due to some liquid water and condensate taken out in the 3-phase separator. Thus, for the liquid ring compressor, the outlet temperature from the separator equals the dew point temperature. The dew point temperature of the compressed flare gas at dry screw compressor outlet is 28,03°C when outlet pressure is 12 barg and 29,291°C at 13 barg.

5.3.6.2 Results from liquid ring compressor simulations

For the liquid ring compressor there were four different cases that were simulated: two inlet temperatures and two flow rates. Figure 32 shows the results from using an inlet temperature of 2°C with both design flowrates for the compressor, shown by purple for 1000 Sm^3/h and orange for 1500 Sm^3/h.

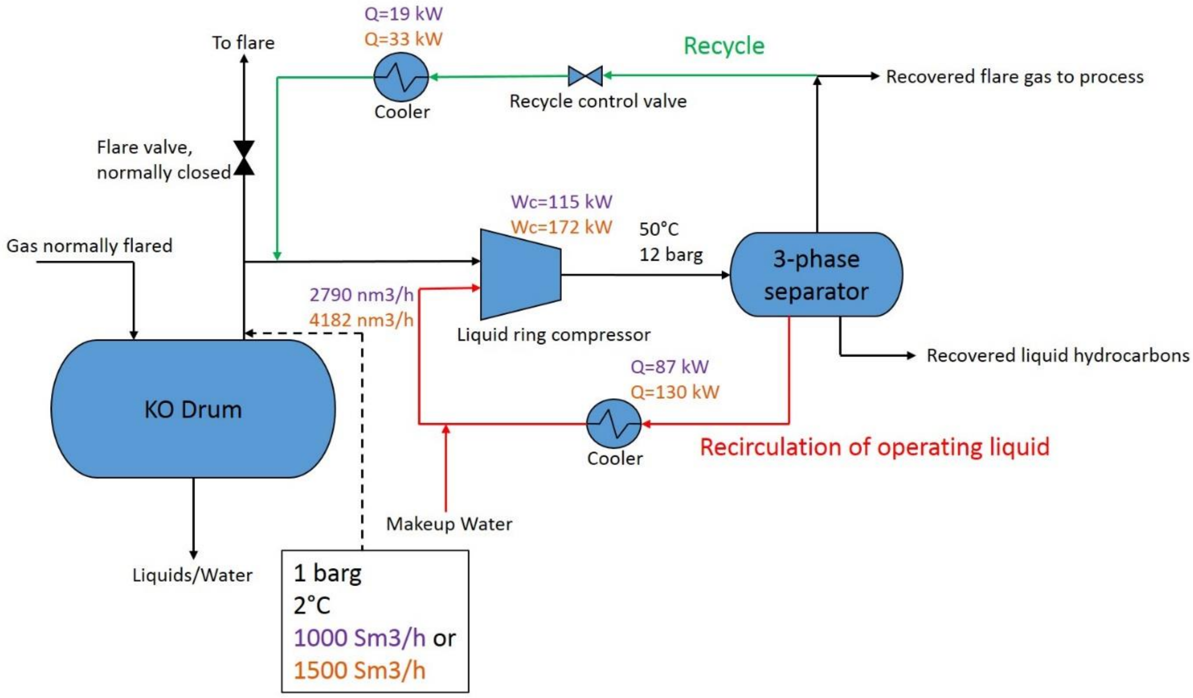

Figure 32: Liquid ring compressor system with heat exchanger duties and compressor power need for inlet temp. of 2°C

From Figure 32, as expected, for a higher design flowrate for the compressor, the duties for the heat exchanger and the compressor power-need increases.

In Figure 33, the results for an inlet temperature of 30°C is shown.

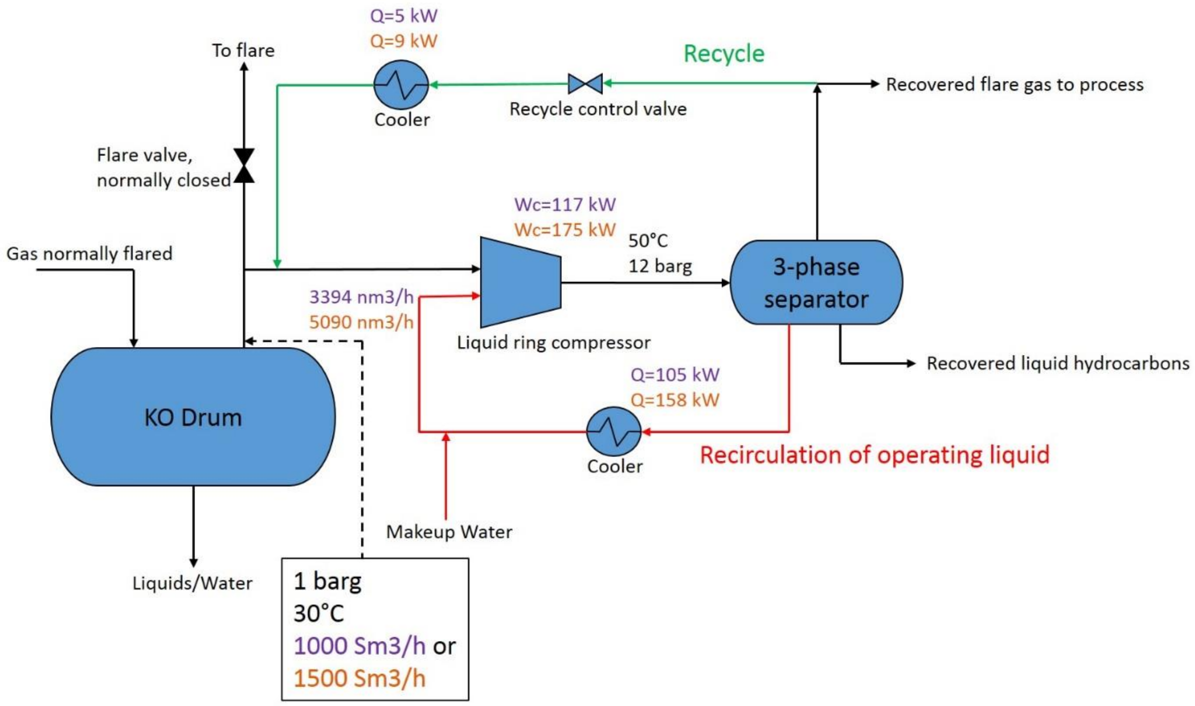

Figure 33: Liquid ring compressor system with heat exchanger duties and compressor power need for inlet temp. of 30°C

Figure 33 shows the same trend as Figure 32 for increasing compressor design flowrate. Comparing the two temperatures yields little difference in power need for the compressor, which is good when the temperature of the flare varies as much as it does. The duties of the recycle and recirculation cooler, however, vary some more. The recycle cooler heat duty is larger for the minimum inlet temperature while the recirculation cooler is larger for the maximum inlet temperature. This is one of the reasons both maximum and minimum suction temperatures are simulated, to find the maximum heat duties the coolers should be able to handle. The temperature will most likely not go below 2°C or exceed 30°C. The results from the simulations can also be seen in Table 20.

LIQUID RING COMPRESSOR	**INLET TEMP. = 2°C**		**INLET TEMP. = 30°C**	
Compressor design flowrate	**1000 Sm^3/h**	**1500 Sm^3/h**	**1000 Sm^3/h**	**1500 Sm^3/h**
Power need compressor, [kW]	115	172	117	175
Duty of recycle cooler, [kW]	19	33	5	9
Duty of recirculation cooler, [kW]	87	130	105	158

Table 20: Power need of compressor and duties of recycle and recirculation coolers for the liquid ring compressor system for varying inlet temp. and compressor design flowrate

Changing the flowrate from 1500 Sm^3/h to 1000 Sm^3/h yields a reduction of about 33 %. A similar reduction is found for the compressor power and for the duty of the recirculation cooler. The recycle cooler, on the other hand, reduced it’s duty with about 43 % which is the same as when the recycle rate is reduced from 1165 to 665 Sm^3/h. Thus, the change in flowrate is approximately proportional with the power consumption of the compressor and the duty of the recirculation cooler, and the flowrate in the recycle with the heat duty of the recycle cooler.

5.3.6.2.1 Recycle loop in the liquid ring compressor design

In the recycle loop for the liquid ring compressor, the recovered flare gas condenses through the heat exchanger when cooling to an outlet temperature of 2°C, to match the suction temperature of the compressor. At a maximum temperature of 30°C, there is no condensation. Because liquid hydrocarbons may be removed in the three-phase separator, there is not installed a scrubber upstream of compressor suction.

The liquid condensation in the recycle happens for temperatures below 18°C. At Ekofisk, the ambient temperature is below this most of the year.

As mentioned earlier, when the flare gas is mixed with water in the liquid ring compressor and later separated in the three-phase separator, the composition of the flare gas has changed. The flare gas is saturated with water and the water content has increased from 0,3 to 0,97. Thus, the phase envelope in Figure 20 is no longer valid for the compressed flare gas.

5.3.6.3 Results from dry screw simulations

Simulating both alternatives for the dry screw compressor in PRO/II yielded eight different cases: two alternatives for dry screw compressor configuration, two inlet temperatures and two compressor design flowrates. Inserting the values for the heat duties of the coolers and power need for the dry screw compressors into the flow sheets yield Figure 34 and Figure 35 for Alternative 1 for respectively an inlet temperature of 2°C and 30°C. In the same way as before does the purple numbers represent a compressor design flowrate of 1000 Sm^3/h and orange numbers represent 1500 Sm^3/h.

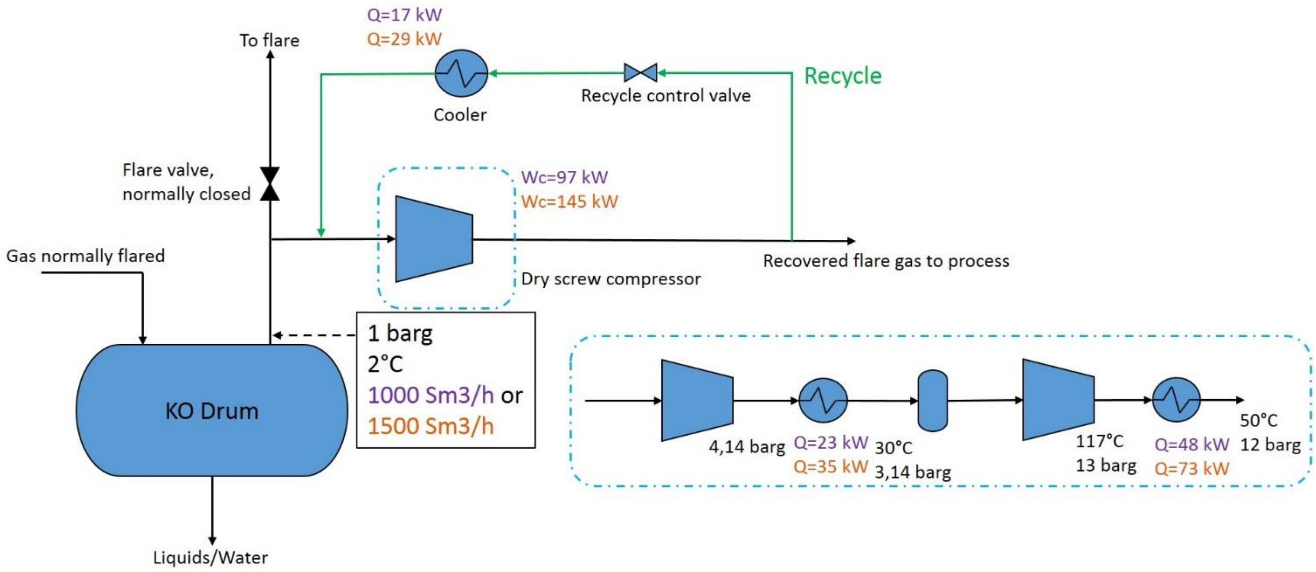

Figure 34: Alternative 1 for dry screw compressor system with heat exchanger duties and compressor power need for inlet temp. of 2°C

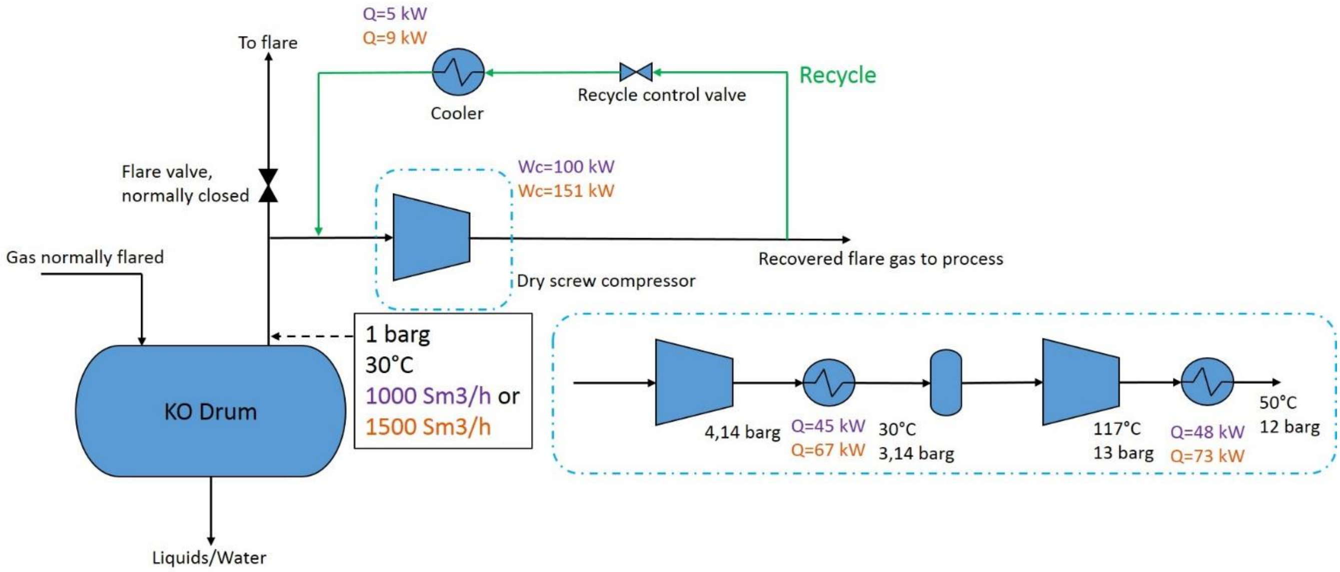

Figure 35: Alternative 1 for dry screw compressor system with heat exchanger duties and compressor power need for inlet temp. of 30°C

From Figure 34 and Figure 35, changing the suction temperature does not affect the compressor consumption very much, as with the liquid ring compressor. However, the heat duties of the intercooler and recycle cooler is affected more. Also here, similarities can be drawn to the liquid ring compressor system where the maximum heat duty for the recycle cooler is found for the minimum suction temperature. Maximum heat duty of the intercooler is, on the other hand, found for the maximum suction temperature. The heat duty of the after cooler is unchanged.

Figure 36 and Figure 37 show the results for Alternative 2 for respectively an inlet temperature of 2°C and 30°C.

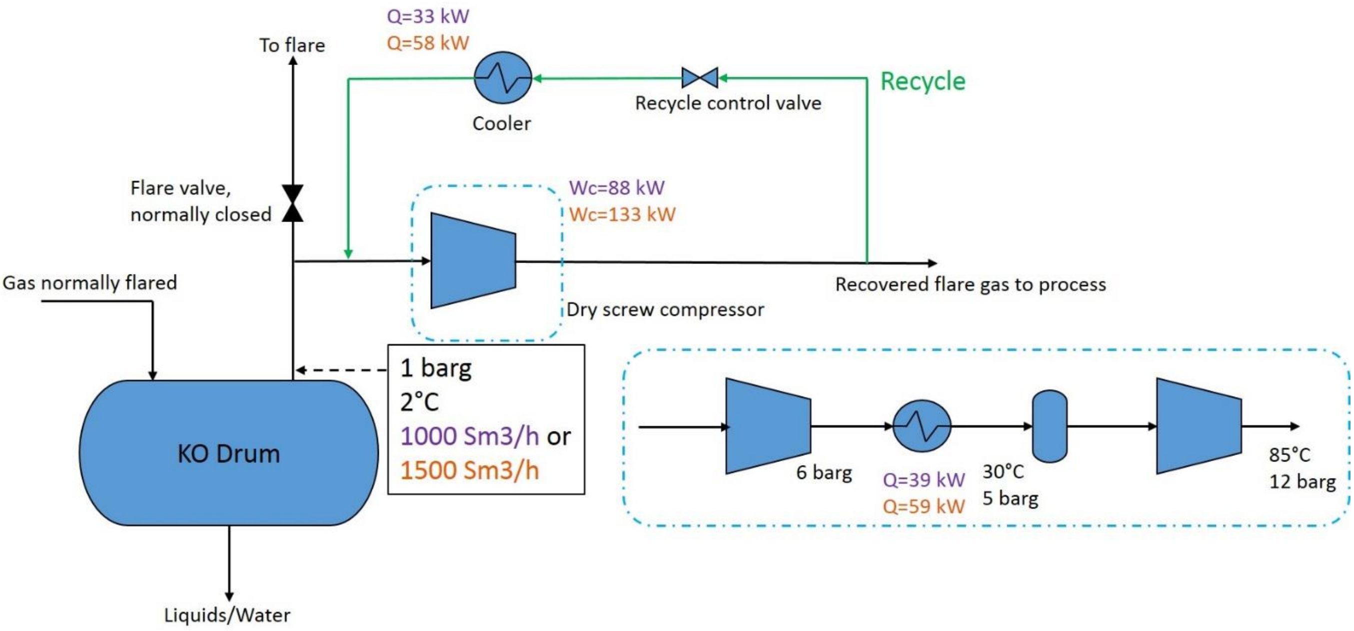

Figure 36: Alternative 2 for dry screw compressor system with heat exchanger duties and compressor power need for inlet temp. of 2°C

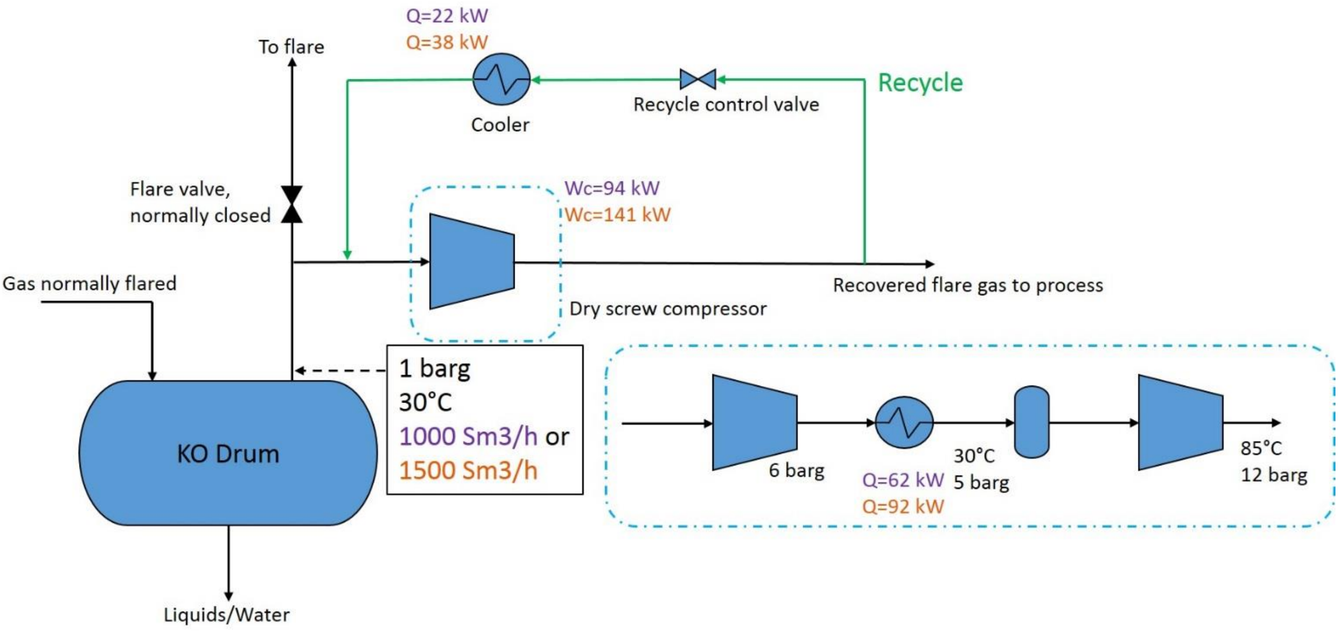

Figure 37: Alternative 2 for dry screw compressor system with heat exchanger duties and compressor power need for inlet temp. of 30°C

From Figure 36 and Figure 37, the same tendency as for Alternative 1 is found for varying suction temperatures.

Similar as for the liquid ring system, changing the design flowrate of the compressor from 1500 Sm^3/h to 1000 Sm^3/h, for both alternatives, yields about 33 % in reduction of flowrate. Approximately the same reduction is found for the heat duties of the intercoolers and after coolers. However, for the recycle, there is, as for the liquid ring compressor, a reduction of about 42 % as the recycle rate changes with a similar amount. It is important to remember that the recycle heat duties normally will be much lower, as these are for the maximum rate of recycle the system should be able to handle.

In Table 21 and Table 22 summaries of the duties for the heat exchangers and the power need for the compressors can be found.

DRY SCREW, Alternative 1	**INLET TEMP. = 2°C**		**INLET TEMP. = 30°C**	
Compressor design flowrate	**1000 Sm^3/h**	**1500 Sm^3/h**	**1000 Sm^3/h**	**1500 Sm^3/h**
Power need compressor, [kW]	97	145	100	151
Duty of recycle cooler, [kW]	17	29	5	9
Duty of intercooler, [kW]	23	35	45	67
Duty of after cooler, [kW]	48	73	48	73

Table 21: Summary of heat duties for coolers and power needs for the dry screw compressor for Alternative 1

DRY SCREW, Alternative 2	**INLET TEMP. = 2°C**		**INLET TEMP. = 30°C**	
Compressor design flowrate	**1000 Sm^3/h**	**1500 Sm^3/h**	**1000 Sm^3/h**	**1500 Sm^3/h**
Power need compressor, [kW]	88	133	94	141
Duty of recycle cooler, [kW]	33	58	22	38
Duty of intercooler, [kW]	39	59	62	92

Table 22: Summary of heat duties for coolers and power needs for the dry screw compressor for Alternative 2

Comparing Alternative 1 to Alternative 2, the power need for the two compression stages are bigger for Alternative 1. This was expected as the gas is compressed to 13 barg in this case compared to 12 barg for Alternative 2. In addition, there will be more in heat duty for Alternative 1 as there are both an intercooler and an after cooler here. However, the heat duty for the recycle cooler is less for Alternative 1 than Alternative 2 due to the after cooler cooling down to a lower temperature than discharge temperature from 2nd compression stage in Alt. 2.

In contrast to using a liquid ring compressor, the composition of flare gas does not change when using a dry screw compressor. It is never in contact with any other fluids. In Figure 38 the phase envelope of the initial composition of the flare gas is shown and the different operating conditions of the dry screw compressor are marked in the right, lower corner.

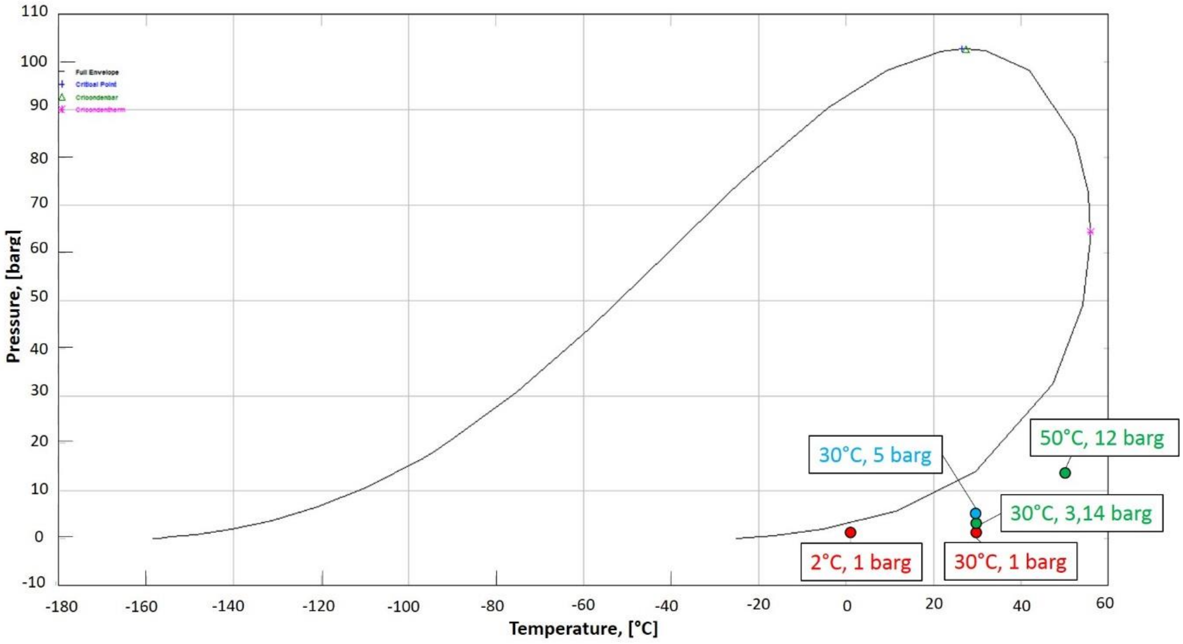

Figure 38: Phase envelope of initial flare gas composition with different operating conditions for the dry screw compressor marked

From Figure 38 it’s evident that there will be no condensation of the flare gas under the operating conditions evaluated. The red marks are for the two inlet conditions to the compressor, thus all other inlet conditions will lie between these two points. The green marks are for Alternative 1: the point with the lowest temperature and pressure representing the discharge from the intercooler and the point for the highest temperature and pressure representing the discharge from the after cooler. The blue mark represents the discharge from the intercooler for Alternative 2. The discharge from the second compression stage lies to the right of the figure.

One must keep in mind that this is only one composition, with basis in the average molecular weight from the whole year of 2014. There is no guarantee that there will be no condensation for other compositions when the molecular weight varies between 21 and 33 kg/kmole. This is also why there is an inter-stage scrubber, even though for the modeled composition, there is no condensation. In addition, from the simulations, there were no liquid condensation in the recycle loop for any of the cases.

5.3.6.4 Summary of simulation results

In Table 23, all the results from the simulations are gathered. Total cooling duty required for the system and power need is listed for the different flow rates and inlet temperatures.

		INLET TEMP. = 2°C		**INLET TEMP. = 30°C**	
Compressor design flowrate		**1000 Sm³/h**	**1500 Sm³/h**	**1000 Sm³/h**	**1500 Sm³/h**
Liquid ring	Power need, [kW]	115	172	117	175
	Total cooling duty, [kW]	106	163	110	167
Dry screw, Alt. 1	Power need, [kW]	97	145	100	151
	Total cooling duty, [kW]	88	137	98	149
Dry screw, Alt. 2	Power need, [kW]	88	133	94	141
	Total cooling duty, [kW]	72	117	84	130

Table 23: Total cooling duties and power need required for the different systems for varying flowrates and inlet temperatures

Comparing the three different systems: the liquid ring compressor and the two alternatives for the dry screw compressor, show that the liquid ring has both a higher power demand and a higher total cooling duty. Thus, even though the initial cost of the dry screw compressor is higher, it may cost more to operate the liquid ring compressor. See Section 5.3.6.5 for input on this. Out of the two screw compressors, Alternative 2 demands the least of both power and total heat duty.

From Table 23, it can be seen that changing the design flowrate of the compressor will have an effect on the power demand and the total heat duty of the coolers of all proposed systems. Changing the suction temperature, however, has little effect. Normally, the compression work is proportional with the suction temperature, but this was not clear for this case. For the liquid ring compressor this may be due to the suction temperature being the temperature of both the flare gas and the operating liquid. It was previously mentioned that maximum and minimum suction temperature resulted in different minimums and maximums for the various coolers. The total heat duty does however not change that much.

5.3.6.5 Power costs for the different compressors

ConocoPhillips informs that the generators used to operate the potential compressor has a fuel gas consumption of 0,32 Sm^3/kWh. From Ref. (77), the average price on gas was 2,23 NOK/Sm^3 in 2014. Multiplying these with each other yields 0,7136 NOK/kWh. In Table 24 the resulting costs of running the different compressors is shown over the duration of a year. The compressor power need from Table 23 where multiplied by amount of hours in a year and further multiplied with 0,7136 NOK/kWh. One must keep in mind that this is a simplification to give an idea of how the cost of operating only the compressor will vary. There will for instance be losses between the generator and the compressor.

	INLET TEMP. = 2°C		**INLET TEMP. = 30°C**	
	1000 Sm^3/h	**1500 Sm^3/h**	**1000 Sm^3/h**	**1500 Sm^3/h**
Liquid ring	718 881 NOK	1 075 195 NOK	731 383 NOK	1 093 949 NOK
Dry screw, Alt. 1	606 360 NOK	906 415 NOK	625 114 NOK	943 922 NOK
Dry screw, Alt. 2	550 100 NOK	831 401 NOK	587 607 NOK	881 410 NOK

Table 24: Costs of running the different compressors over the duration of a year

From Table 24, as expected, the cost of running the liquid ring compressor is the highest followed by the dry screw Alt. 1 and dry screw Alt. 2 with the lowest cost. Changing the inlet temperature does not have a significant effect on the costs. However, changing the flowrate yields about 300 000 NOK more in operation costs within the specific compressor type. The difference between the compressors varies from 100 000 NOK to 250 000 NOK for the same flowrates and inlet temperatures.

If only taking into account the simplified operating costs of the compressors above, the dry screw Alternative 2 is the most favorable alternative.

5.4 Comparing the Different Systems

From the results from the simulations in the previous section, it was evident that the liquid ring compressor demands both more power for the compressor, due to the lower compressor efficiency, and more heat duty for the heat exchangers. However, it will have a lower initial cost than the dry screw compressor. There were not conducted any simulations on the oil-flooded screw compressor, and it’s therefore difficult to compare this with the simulations from the two other compressor types. This should therefore be investigated further.

Ref. (72) informs that the available pressure ratios and discharge pressures of the oil-flooded screw compressor are in general considerably higher than for dry screw compressors. Since oil needs to be moved through the system in oil-flooded screw compressors, the power consumption is often higher as well. How much greater is hard to say without conducting simulations.

A comparison of some selected parameters between the different designs is shown in Table 25.

Type of compressor	**Available pressure ratio**	**Able to handle liquids**	**Need for auxiliary equipment**	**Power consumption**	**Price**	**Other**
Liquid ring compressor	Enough, but with low margin for higher pressure ratios	Yes	- System for operating liquid - 3-phase separator -Recycle	High	Third most expensive	- Works well in flare gas recovery - Operates at single speed - Not very energy efficient
Dry screw compressor	High	Some	- Intercooling - Possibly after cooling - Recycle	Less than liquid ring	Most expensive	- Danger of the skid being too big - Silencers and noise enclosures to prevent vibrations and high noise levels
Oil-injected screw compressor	High	No	- Inlet scrubber - Dew point control - Separator - System for lube oil - Recycle	Higher than dry screw	Second most expensive	- Turndown is available - Danger of the lube oil being contaminated by the flare gas

Table 25: Comparing the different relevant compressors that can be used at Ekofisk

If recommending a system based on the work done in this project, the liquid ring compressor would be the final choice. The fact that it is the most commonly used compressor in flare gas recovery in the world talks in its favor. It has a good reputation and was recommended by three of the suppliers that were contacted, and most importantly, it will not be affected by liquid condensation. Even though the compressor is not that energy efficient, it is more important that the compressor is able to withstand the conditions at Ekofisk and be able to fulfill its job. The operating costs from Section 5.3.6.5 are somewhat larger for the liquid ring than the alternatives for the dry screw compressor. However, the initial costs from Section 5.1.1 yielded the most expensive liquid ring compressor to be approximately 60 % of the price of the most expensive dry screw compressor. The calculations gave some ideal of the differences, however, calculations that are more accurate needs to be conducted to give a better comparison.

Datasheets of the different compressors suggested by the suppliers were received, but due to it being confidential information, they cannot be shown in this thesis. To analyze the datasheets and compare them is beyond the scope. Thus, this is up to ConocoPhillips. In addition, special expertise and experience with the different types of compressors are preferable when looking at maintenance and operation costs of the system as a whole. This may change the outcome of the chosen system, but due to lack of information, it does not contribute to the choice in this thesis.

6. Consequences of Installing a Flare Gas Recovery System at Ekofisk

If installing a flare gas recovery system at the Ekofisk Complex, ConocoPhillips will gain several benefits. Not only in the form of reduced costs, but also as a more eco-friendly company emitting less.

Some advantages to installing a flare gas recovery system has already been mentioned in Section 2.2.6.2. Below follows some calculations on how much reduction in flaring is possible with the proposed designs from Ch. 5. The resulting reduced costs in form of less fees is calculated in Section 6.2 and in addition, the increased income due to recovering the value of the gas instead of "wasting" it in the flare is found in Section 6.3.

6.1 Reduced Emissions if Implementing a Flare Gas Recovery System

In 2014, the amount of flare gas burned in the flare at EKOJ during the whole year was 8 977 631 Sm^3. This corresponds to an average of about 748 136 Sm^3/month.

Depending on the design rate for the chosen compressor the saved costs can be calculated. Whenever the flare gas flow rate is larger than the design rate it will be sent directly to the flare. However, if it is less the recovered gas will go through recycle.

Out of all the 365 days in 2014, 244 of them had an average flowrate below 1000 Sm^3/h. Thus, the flare gas could have been recovered 244 days out of 365. If increasing the design flow rate to 1500 Sm^3/h even 96 more days of flaring could have been avoided, resulting in 25 days of flaring in total in 2014. These extra 96 days have a flow rate above 1000 Sm^3/h, thus it's a considerable amount of flare gas that will not be burned and emitted.

Looking at how much gas in total in 2014 that could have been recovered for the two possible design rates of 1000 Sm^3/h and 1500 Sm^3/h, yields respectively 4 937 380 Sm^3/year and 7 513 872 Sm^3/year. In other words, for the design flowrate of 1000 Sm^3/h: 55 % of the flare gas from 2014 could have been recovered, while for 1500 Sm^3/h: 84 %.

6.2 Reduced Costs in form of Fees

In Section 2.2.4, it was informed that there are especially three fees related to emission to air from flaring: the CO_2-tax, the quota system and the NO_x-tax. Below follows an estimation on how much expenses ConocoPhillips have related to these fees and how much they can save if installing a flare gas recovery system with a design flow rate of 1000 Sm^3/h or 1500 Sm^3/h.

Prior to starting the calculations, emission factors are needed to estimate how much CO_2 and NO_x is actually being emitted from the burned flare gas. The Norwegian Oil and Gas Association (NOROG) recommends the following emission factor for flaring, see Table 26: (4)

Component	Emission Factor
CO_2	3,73 kg/Sm^3
NO_x	0,0014 kg/Sm^3

Table 26: NOROG's recommended emission factors for flaring, for CO_2 and NO_x

In Table 27 the calculations of the different fees and total expenses can be found.

	Price	Price for flaring at Ekofisk Complex
CO_2-tax	0,98 NOK/Sm^3 flared gas (in 2014)	$8\,977\,631\ Sm^3 * 0{,}98\frac{NOK}{Sm^3} = 8\,798\,079\ NOK$
Quota	7,1 Euro/ton CO_2 & 8,63 NOK/Euro (March 2015)	$\frac{8\,977\,631\ Sm^3 * 3{,}73\ kg/Sm^3}{1000\ kg/ton} * \left(7{,}1\frac{Euro}{ton} * 8{,}63\frac{NOK}{Euro}\right) = 2\,051\,822\ NOK$
NO_x-tax	17,33 NOK/kg emission of NO_x (in 2014)	$8\,977\,631\ Sm^3 * 0{,}0014\frac{kg}{Sm^3} * 17{,}33\frac{NOK}{kg} = 217\,816\ NOK$
In total:		$\mathbf{11\,067\,717\ NOK}$

Table 27: Price of CO_2-tax, quotas and NO_x-tax at the Ekofisk Complex

From Table 27 the total annual costs for emitting to air from flare in 2014 is 11 067 717 NOK. The CO_2-tax constitute almost 80 % of the total costs. The NO_x-tax is rather small compared to the others, about 2 % of the total, thus it's the CO_2-tax together with the quota-expenses that dominate the total costs. It is important to remember that if installing a flare gas recovery system at the Ekofisk Complex not all of the above costs will disappear. The flow rate used to calculate the costs includes both the necessary flaring and the continuous flaring. The flare gas recovery system will only eliminate the costs connected to the continuous flaring.

Estimating by using the same method as above and with the recovered flare gas per year from Section 6.1, the saved costs from 2014 can be seen in Table 28.

Design rate FGR	Recovered flare gas per year (in 2014)	Saved costs	Difference
1000 Sm^3/h	4 937 380 Sm^3/year	6 086 854 NOK	3 178 326 NOK
1500 Sm^3/h	7 513 872 Sm^3/year	9 265 180 NOK	

Table 28: Saved costs by recovering flare gas instead of flaring it for possible design flow rates of 1000 Sm^3/h and 1500 Sm^3/h

Going from a design flowrate of 1000 Sm^3/h to 1500 Sm^3/h yields a difference in reduced cost of 3 178 326 NOK. If only considering these costs, a design flow rate of 1500 Sm^3/h seems more favorable.

Using the emission factors from Table 26 and the annual recovered flare gas in 2014 from Table 28 yields, in Table 29, how much the emission of CO_2 and NO_x can be reduced for the two design flowrates.

Design rate FGR	Recovered CO_2, [ton]	Recovered NO_x, [ton]
1000 Sm^3/h	18416	7
1500 Sm^3/h	28027	11

Table 29: Reduction in emission of CO_2 and NO_x for the two design flowrates in 2014

6.3 Increased Income

ConocoPhillips informs that the value of the flare gas is the same as the gas that is to be sold. As mentioned in Section 5.3.6.5, the average price on the gas was 2,23 NOK/Sm^3 in 2014.

Recovering the flare gas instead of burning it in the flare will yield increased income. Based on the two design rates for the flare gas recovery system and the average gas price from 2014, Table 30 shows how much ConocoPhillips would gain in increased income in value of the recovered gas from 2014.

Design rate FGR	Recovered flare gas per year (in 2014)	Increased income	Difference
1000 Sm^3/h	4 937 380 Sm^3/year	11 010 357,4 NOK	5 745 577,2 NOK
1500 Sm^3/h	7 513 872 Sm^3/year	16 755 934,6 NOK	

Table 30: Increased income by recovering flare gas instead of flaring it for possible design flow rates of 1000 Sm^3/h and 1500 Sm^3/h in 2014

Table 30 shows that ConocoPhillips' income can be increased by respectively 11 million and 16,8 million NOK for design flow rates of 1000 and 1500 Sm^3/h. Also in this case, the higher flowrate seems most attractive.

6.4 Summary

If combining the values from the reduced costs with the increased income, Table 31 shows the total possible gain from 2014.

Design rate FGR	Saved costs	Increased income	Total
1000 Sm^3/h	6 086 854 NOK	11 010 357,4 NOK	17 097 211,4 NOK
1500 Sm^3/h	9 265 180 NOK	16 755 934,6 NOK	26 021 114,6 NOK

Table 31: Total gain from installing a flare gas recovery unit using values from 2014

From Table 31, the higher flow rate seems most favorable with almost 9 million NOK more in total gain. However, as seen in Chapter 5, increasing the flow rate result in both a higher compressor consumption and heat duties for the coolers. Evaluating these up against each other therefore needs to be done. In addition, the costs of running the systems needs to be taken into account, together with maintenance costs. An intermediate flowrate should be investigated as well.

If recommending one of the flowrates, 1000 Sm^3/h would have been chosen, even though there would have been a higher total gain for the higher flowrate. The continuous flaring was assumed to account for about 20-40 % of the total flaring at the Ekofisk Complex. Recovery of about 84 % for the case with 1500 Sm^3/h therefore seems to be a bit much. The higher flowrate might have started to recover gas that is supposed to be flared.

7. Conclusion

7.1 Summary of Thesis

The work performed in this thesis can be separated into four main parts:

1. In Chapter 2, a review of existing flare gas recovery technology is found, both for offshore facilities and for other applications. Since using compressors is most frequent offshore a separate section focusing on the possible compressor types is present. In addition, different suppliers of flare gas recovery systems is included
2. Chapter 3 and Chapter 4 focuses on the Ekofisk Complex. In Chapter 3, there is information about what have been done at Ekofisk previously to implement flare gas recovery and how the flare system is structured today. Further, in Chapter 4, the design conditions for a potential recovery system at the Ekofisk Complex is chosen based on data from 2014 and the previously attempts
3. In Chapter 5, the different possible alternatives are evaluated and designs for flare gas recovery systems are found. There are three different systems based on using either a liquid ring compressor, the dry screw compressor or the oil-injeceted screw compressor. Contact with suppliers lay the basis for this choice. The liquid ring compressor and the dry screw compressor are further evaluated through simulations in PRO/II
4. Chapter 6 focuses on the consequences of installing a flare gas recovery system at Ekofisk. Reduced emissions, reduced costs and increased income are calculated

7.2 Conclusions

These are the conclusions of this thesis work:

- Three possible flare gas re-compressors are found to satisfy the conditions at Ekofisk: the liquid ring compressor, the dry screw compressor and the oil-flooded screw compressor
- The final choice for a flare gas recovery system at Ekofisk is the liquid ring compressor. It is the most used compressor in flare gas recovery in the world and it has a good reputation. Most importantly is the fact that it will not be affected by condensation of the flare gas
- Through contact with suppliers it's found that the initial cost of the dry screw compressor is the highest. The lowest costs are found for the sliding vane compressor. In between these, the reciprocating compressor, the oil-injected screw compressor and liquid ring compressor is spread. The liquid ring towards the dry screw and the reciprocating towards the sliding vane
- The liquid ring compressor has the highest power demand and highest heat duties for the heat exchangers, due to lower compressor efficiency, compared to the dry screw compressor. Thus, the operation costs of the compressor itself, calculated through a simplified calculation, will be higher for the liquid ring compressor
- Changing the design flow rate of the compressor from 1000 to 1500 Sm^3/h results in being able to recover respectively 55 or 84 % of the flaring from 2014. However, going from 1500 to 1000, will also yield 33 % less power consumption for the

compressor. The heat duties of the coolers in the recycle will decrease with 43 % while the remaining coolers will also decrease with 33 %

- Changing the suction temperature of the compressor has some effect on power demand for the compressor and total heat duty for the system, a little increase for higher suction temperature. However, the effect is bigger for changing the flowrate
- ConocoPhillips paid in 2014 approximately 11 million NOK in fees (CO_2-tax, the quota system and the NO_x-tax) for atmospheric discharge. Through installing a flare gas recovery system a cost reduction of 6 or 9 million NOK can be acheived and an increased income of 11 or 17 million NOK can be yielded by setting the design rate of the compressor equal to respectively 1000 or 1500 Sm^3/h
- The reduction in emissions of CO_2 and NO_x is for a design flowrate of 1000 Sm3/h respectively 18416 and 7 tons and for 1500 Sm3/h: 28027 and 11 tons
- A design flowrate of 1000 Sm^3/h is recommended. The higher flowrate meant recovering about 84 % of the total flaring and this may include recovery of gas that should be sent to flare and not be recovered. The lower flowrate is seen as an optimal balance between recovery and energy use

7.3 Recommendations for Future Work

Recommendations on future work on finding the ideal flare gas recovery system at Ekofisk:

- Do more accurate simulations with:
  - a correct composition of the flare gas, not the fictional one used in this thesis
  - real compressor efficiencies, proved by the compressor suppliers
- Evaluate further the design flowrate of the recovery system. A flowrate of for instance 1250 Sm^3/h should be tested
- Simulate the oil-injected screw compressor
- Investigate further if the footprint of the systems satisfies the requirement at EKO J by developing a simplified layout of the skid with support systems
- Received datasheets from the suppliers should be evaluated by experienced personnel at ConocoPhillips
- Further multidiscipline feasibility- and concept studies should verify solutions proposed in this thesis; type of compressor, operational frame conditions, etc.
- Basis for final recommendation of flare gas recovery system at Ekofisk is to fulfill right level of maturity within ConocoPhillips, both within technical solutions and requirements for execution containing both initial investment cost and total cost in the operation phase

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