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Evaluation of production processes for LNG in arctic climate

Terje Borlaug

Natural Gas Technology

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Supervisor:	Arne Olav Fredheim, EPT
Co-supervisor:	Jostein Pettersen, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

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MASTEROPPGAVE

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Evaluering av produksjonsprosesser for LNG i arktisk klima
Evaluation of production processes for LNG in arctic climate

Bakgrunn

De fleste av verdens LNG-produksjonsanlegg er lokalisert i temperert klima med høy og stabil luft- og kjølevannstemperatur. For LNG-utbygginger i arktisk klima står en overfor et mye lavere temperaturnivå, i tillegg til mye større variasjon i lufttemperatur gjennom året. På Kola-halvøya kan for eksempel lufttemperaturen godt variere fra -30°C på vinteren til +30°C på sommeren. Dette gir store utfordringer både for design av kjøleprosessen, men også svært varierende kraftproduksjon fra gassturbiner eller gass/dampturbinsystemer som driver kjølekompressorene.

En viktig utfordring en står overfor når luft benyttes som kjølemedium er det store driftsområdet for kompressoren(e) i forkjølingsanlegget, særlig hvis propan brukes som kuldemedium i dette trinnet. Det er behov for en god forståelse av konsekvensene ved bruk av andre kuldemedier i forkjøling og hovedkjøling. I prosjektoppgaven ble det etablert simuleringsmodeller for C3-MR og C2-MR. Disse har vært benyttet til prosessdesign og simulering av prosess responser ved varierende luft temperaturer.

Mål

Oppgaven går ut på vurdering og simulering av prosesser for produksjon av LNG i arktisk klima. Det fokuseres på prosesser som benytter rene kuldemedier i alle kretser. Målet er å gjennomføre analyser og valg av kjølemedium og driverløsning for en kaskadeprosess for å kunne maksimere produksjon og kapasitet på årsbasis.

Oppgaven bearbeides ut fra følgende punkter:

1. Etablering av Hysys modell for en optimalisert kaskadeprosess (Optimized cascade) basert på drift i kaldt klima. Modellen skal benytte rigorøs simulering av kompressorer (kompressorkurver) og varmevekslere (UA modeller) i alle kretser.

2. Vurdere av forskjellige metoder for kjøling av prosessen, for eksempel bruk av luft, vann, sekundær vannkrets eller kombinasjoner av disse. Vurderingene skal knyttes mot den etablerte kaskadeprosess.

3. Vurdere optimale driver løsninger for kaskadeprosesser i kaldt klima med tanke på maksimering av effektivitet i anlegget.

4. Gjennomføre design av prosess samt de viktigste utstyrsenheter med valgt driverløsning og kjølemedium. Designpunktet for prosess velges slik at kapasitet og effektivitet mak-

simeres på årsbasis. Etablerte data fra prosjektoppgaven for års-variasjon i luft og vanntemperatur benyttes.

" - "

Senest 14 dager etter utlevering av oppgaven skal kandidaten levere/sende instituttet en detaljert fremdrift- og eventuelt forsøksplan for oppgaven til evaluering og eventuelt diskusjon med faglig ansvarlig/veiledere. Detaljer ved eventuell utførelse av dataprogrammer skal avtales nærmere i samråd med faglig ansvarlig.

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.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og eventuelt figurnummer.

Det forutsettes at kandidaten tar initiativ til og holder nødvendig kontakt med faglærer og veileder(e). Kandidaten skal rette seg etter de reglementer og retningslinjer som gjelder ved alle (andre) fagmiljøer som kandidaten har kontakt med gjennom sin utførelse av oppgaven, samt etter eventuelle pålegg fra Institutt for energi- og prosessteknikk.

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Ett -1 komplett eksemplar av originalbesvarelsen av oppgaven skal innleveres til samme adressat som den ble utlevert fra. Det skal medfølge et konsentrert sammendrag på maksimalt én maskinskrevet side med dobbel linjeavstand med forfatternavn og oppgavetittel for evt. referering i tidsskrifter).

Til Instituttet innleveres to - 2 komplette kopier av besvarelsen. Ytterligere kopier til eventuelle medveiledere/oppgavegivere skal avtales med, og eventuelt leveres direkte til de respektive. Til instituttet innleveres også en komplett kopi (inkl. konsentrerte sammendrag) på CD-ROM i Word-format eller tilsvarende.

NTNU, Institutt for energi- og prosessteknikk, 17. januar 2011

Olav Bolland
Instituttleder

Arne O. Fredheim
Faglig ansvarlig/veileder

Medveileder
Jostein Pettersen

Preface

This Master Thesis is written at the Norwegian University of Science and Technology, Department of Energy and Process Engineering, in the topic Industrial energy and process technology.

Basic knowledge in LNG production is required and some knowledge in Aspen HYSYS® is also advantageous.

I would like to thank my supervisors Arne Olav Fredheim and Jostein Pettersen for useful advises and guidance. I would also like to thank Eugene Uthaug (the department computer system manager) for letting me borrow a computer when my computer crashed.

Terje Borlaug, 16.06.2011

Summary

Most of nowadays base load LNG plants are localized in the area around equator, with stable warm air and cooling water temperature. For new LNG developments in arctic areas there are several features that differ them from plants operating further south. In this work a ConocoPhillips Optimized Cascade LNG process model has been established in HYSYS® and evaluated. The evaluation focus on the driver configuration and cooling method used in order to optimize process efficiency and capacity of the plant for operation in cold climate. Simulations with air cooling and water cooling have been done. Each cooling method has been evaluated for an aero derivative gas turbine compressor driver, an industrial heavy duty gas turbine compressor driver, and an electric compressor driver configuration. Yearly temperature statistics from Kola has been used. The air cooled simulations have a design temperature of 20°C and the water cooled simulations have a design temperature of 4°C seawater temperature and an air temperature of 5°C. The air cooled cases are not close to design operation the entire year. The aero derivative driver configuration will have problems operating at high air temperatures and a higher design temperature is needed. The heavy duty gas turbine driver configurations have limitation in speed variation and this leads to low process efficiency at low temperatures. The electrical driver configuration will not have problems operating. The results show that air cooling is not the desired cooling method because of lower production variation and lower process efficiency. The water cooled cases are close to design conditions the entire year; hence it has the highest flexibility when it comes to production variation and highest process efficiency. The aero derivative driver configuration varies most throughout the year with lowest production in the summer. The heavy duty gas turbine driver configuration has a lower variation in production. The power delivered to the electrical motors will not be affected by air temperature which lead to high process efficiency and stable production plateau throughout the year.

Sammendrag

De fleste av verdens LNG - produksjonsanlegg er lokalisert i temperert klima med høy og stabil luft og kjølevannstemperatur. For LNG – utbygginger i arktisk klima står en ovenfor et mye lavere temperaturnivå, i tillegg til mye større variasjon i lufttemperatur gjennom året. En ConocoPhillips Optimalisert Kaskade LNG - prosessmodell er blitt etablert og evaluert for drift i kaldt klima. Kompressordrivere og kjølemetode er evaluert slik at kapasitet og effektivitet i anlegget maksimeres på årsbasis. Simuleringsprogrammet HYSYS® er brukt i evalueringen. Simuleringer med både luftkjøling og sjøvannskjøling er gjort. Hver kjølemetode er evaluert for tre forskjellige kompressordriverløsninger, industriell rammeturbin, aeroderivert gassturbin og elektrisk driverløsning. Simuleringene er knyttet opp mot årlige temperaturstatistikk fra Kolahalvøya. Simuleringene med luftkjølt anlegg er gjort med en designtemperatur på 20 °C og vannkjølt anlegg har 4 °C vann og 5 °C luft. Luftkjølt anlegg generelt har lavere mulighet for produksjonsøkning og lavere effektivitet fordi anleggene må driftes utenfor design hele året. Luftkjølt anlegg med aeroderivert gassturbindriver får problemer med for lav produsert effekt i forhold til hva anlegget krever ved 30 °C. En høyere designtemperatur kan være aktuell men det fører til enda lavere effektivitet. Industriell rammeturbinløsningen har restriksjoner i turtallsområde og vil derfor oppnå en lavere effektivitet ved lave temperaturer enn aeroderivert og elektrisk løsning. De vannkjølte casene har generelt størst produksjonsfleksibilitet og høyest effektivitet fordi disse casene kan driftes nær design hele året. Aeroderivativ gassturbindriver har den største produksjonsvariasjonen med lavest produksjon ved høy temperaturer og samtidig lavest effektivitet. Industriell rammeturbindriverløsning har lavere produksjonsvariasjon, og høyere effektivitet. Elektrisk driverløsning med vannkjøling virker som den mest optimale løsningen, da denne løsningen ikke er avhengig av lufttemperatur og dermed kan holde en jevn produksjon og høy effektivitet gjennom året.

Nomenclature and Annotations

Expression	Meaning	Unit
LNG	Liquefied Natural Gas	
LPG	Liquid Petroleum Gases	
LP	Low pressure	
MP	Intermediate pressure	
HP	High pressure	
HHP	High, high pressure	
CRHX	Cold recovery heat exchanger	
MTPA	Million tons per annum	
TEG	Triethylene glycol	
U	Surface area heat transfer coefficient	[W/K m^2]
A	Area	[m^2]
Q	Cooling duty	[W],[kW] or [MW]
ΔT_{LM}	Logarithmic mean temperature difference	[°C]
m	Mass flow	[kg/s]
Δh	Enthalpy difference	[kJ/kg]
P	Pressure	[Bar]
n	Polytrophic exponent	
Z	Compressibility factor	
R	Ideal gas constant	[J/K mol]
T	Temperature	[K]
g	Gravitational constant	[m/s^2]
M	Molar weight	[kg/kmol]
H_p	Polytrophic head	[m]

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1 INTRODUCTION

Most of nowadays base load LNG plants are localized in the area of equator, with a constant warm air and cooling water temperature. For new LNG developments in arctic areas there are several features that differ them from plants operating further south. The average air and water temperature is low, typically around 4°C for seawater and around 0°C for air. The seasonal variations can be large with extreme air temperatures down to -30°C in the winter and up to 30°C in the summer.

The low average temperature is an advantage as it can enhance process efficiency. The large variations are challenging as they give large variation in condensing pressures, hence large variation in compressor speed and load.

This project aims to highlight and discuss challenges related to process design, driver selection and selection of cooling medium with regards to optimized production and process efficiency. The process technology in focus is the ConocoPhillips Optimized Cascade LNG process.

The simulation tool used is Aspen HYSYS®. Six different cases have been simulated. Three cases are simulated with an air cooled design at 20°C and three cases with water cooled design at 4°C water temperature and a air temperature of 5°C. Three different driver setups have been chosen for the two cooling systems; the aero derivative gas turbine GE LM6000, the heavy duty industrial gas turbine GE Frame 6B, and electrical motors, which are tailor-made for the specific production rate. The air cooled cases are simulated at the entire temperature range from -30°C to +30°C with a temperature step of 10°C. The water cooled cases are simulated with use of monthly average temperature statistics.

Compressor maps and UA-models are implemented in all circuits. Compressor regulation has been performed to keep the operating point of the compressors valid. The control methods used to keep the operating point of the compressors valid at the different temperatures are compressor recycling, varying of the condensing pressure and varying production.

This report contains a chapter introducing the basics of LNG and LNG production, and a description of the process in focus (The ConocoPhillips Optimized Cascade LNG process), followed by a chapter containing a discussion of the different aspects of LNG process design.

Then comes a chapter containing the description of the established model and information regarding the simulations, followed by a chapter containing the results from the simulations, a chapter discussing the results and a conclusion. Bibliography comes in the end. The Appendices contain all compressor maps with their operating points and tables containing the values for the compressor curves.

2 THEORY

This chapter contains a description of what Liquefied Natural Gas is, basic theory behind liquefaction of natural gas and a description of the process in focus, the ConocoPhillips Optimized Cascade LNG process.

2.1 BASIC FACTS ABOUT LNG

LNG is natural gas cooled down to liquid state, at approximately -163°C. This is done if there is a long distance between the gas field and existing infrastructure for transporting gas. When the natural gas is liquefied, 1 m^3 of LNG corresponds to 600 m^3 of natural gas in gaseous form. The LNG is transported in special built ships. This way of transporting is flexible, and costumers all over the world can be reached. When using pipelines one is bound to a specific geographically area where the pipeline is brought to shore and sale of the gas has to be done in this area.

Cooling of the natural gas is most commonly done by the principle of evaporative cooling. This means that the natural gas flows through a heat exchanger, and a refrigerant evaporates in the same heat exchanger to absorb heat from the natural gas. Rejection of heat is done by compression of the refrigerant and condensation against ambient temperature, either air, water or an indirect circuit where for instance glycol is cooled by seawater. After condensation the refrigerant is throttled to a lower pressure and then evaporated against the natural gas. A sketch of the basic principle of evaporative cooling is shown in Figure 1 (Pettersen 2009).

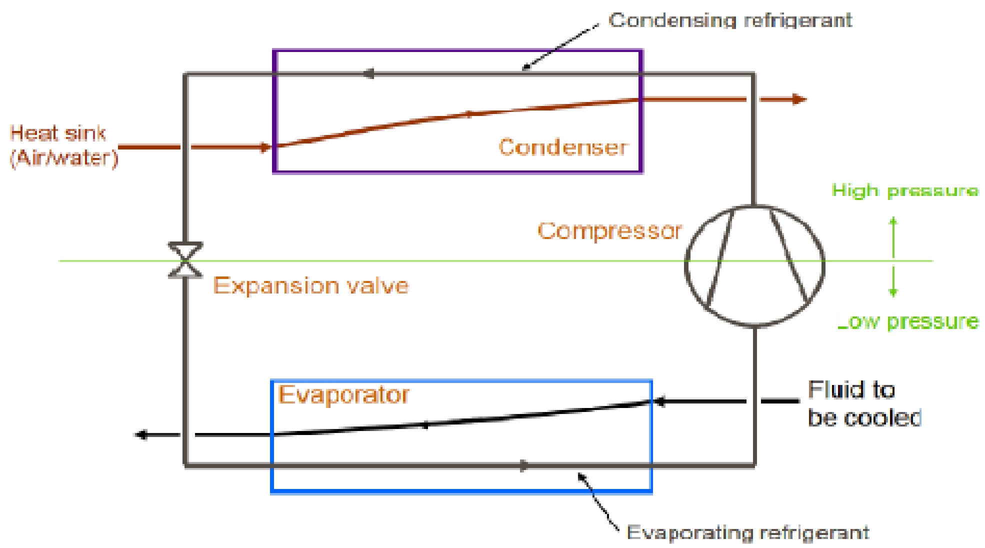

FIGURE 1 BASIC PRINCIPLE FOR EVAPORATIVE COOLING (PETTERSEN 2009)

In base load LNG plants hydrocarbons like propane, ethane, and methane are common refrigerants, because of their presence and availability for refrigerant makeup. Nitrogen can be also used as refrigerant. Ethylene is used in the ConocoPhillips Optimized Cascade LNG process due to its practical evaporation curve, which lies between ethane and methane, therefore matches the cooling curve of the natural gas. However ethylene has to be imported to the site. One requirement for choosing the refrigerants is their ability to evaporate above atmospheric pressure, so that risk of leakage of air into the system is removed. Low pressures will also lead to high volumetric flows, hence large compressors. The most commonly used refrigerants are shown in Figure 2 (Pettersen 2009).

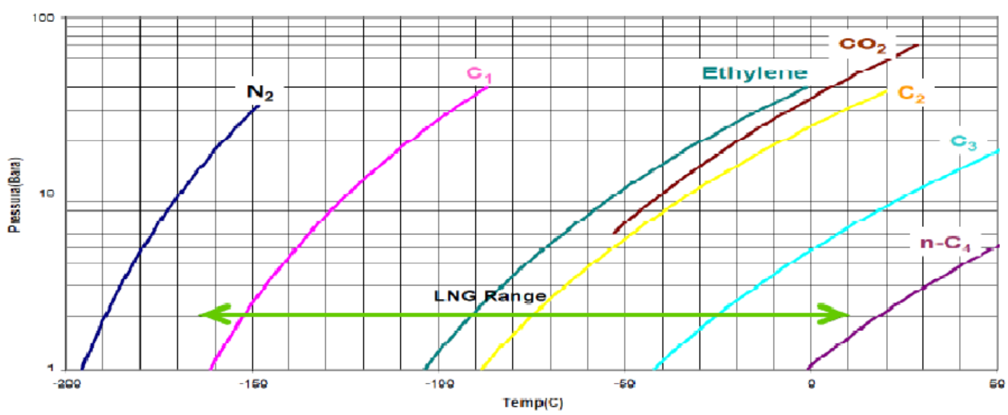

FIGURE 2 TYPICAL REFRIGERANTS FOR LNG PRODUCTION (PETTERSEN 2009)

The refrigerants can be either in pure form or a mixture of several of the components mentioned above. One parameter for obtaining high process efficiency is to maintain low temperature difference as possible between the condensing natural gas stream and the evaporating refrigerant. To obtain this small minimum temperature approach is done in different ways for pure refrigerant systems and mixed refrigerant systems. In a pure refrigerant system a low temperature difference between the refrigerants and the natural gas composite curve is obtained by using several pressure stages, hence, evaporate the refrigerant at different temperatures. In a mixed refrigerant system the composition of the refrigerant is the main tool for obtaining a minimum approach. By adjusting the composition, the refrigerant can evaporate with a gliding temperature profile, close to the natural gas cooling curve (Pettersen 2009).

2.2 Optimized Cascade LNG process

ConocoPhillips has patented this process technology. The patent is a development from the classic cascade LNG process which has been in commercial operation in Kenai, Alaska since the 1970's. The Optimized Cascade LNG process is built up by three circuits, a pre-cooling circuit using propane as refrigerant, a liquefaction circuit using ethylene as refrigerant and a sub-cooling circuit using a methane/flash gas mixture (ConocoPhillips 2011).

A simplified sketch of a classical cascade LNG process is shown in Figure 3. Propane cools the natural gas to approximately -32°C. The ethylene circuit cools it further and condenses the natural gas. The natural gas exits the ethylene circuit at approximately -96°C. The methane circuit sub-cools the natural gas to approximately -155°C before the LNG is throttled to atmospheric pressure at approximately -163°C (Pettersen 2009).

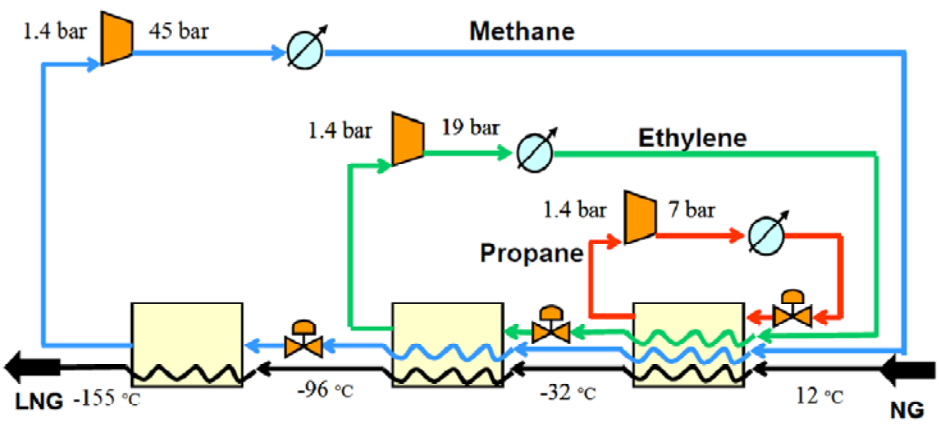

FIGURE 3 SIMPLIFIED SKETCH OF A CASCADED LNG PROCESS (PETTERSEN 2009)

A sketch of the Optimized Cascade LNG process is given in Figure 4. Pretreatment of gas like dehydration and sour gas removal are shown as one process stage in the start. It is also shown how the flash gas being brought back to the methane/flash gas circuit and used as refrigerant and plant fuel.

The Optimized Cascade LNG process utilizes a 2in1 concept where each circuit has two or more compressors with their individual driver. This is done to ensure that the plant can produce at a lower production rate, even when one or two drivers/compressors are not operating. This leads to high reliability and flexibility according to (ConocoPhillips 2011).

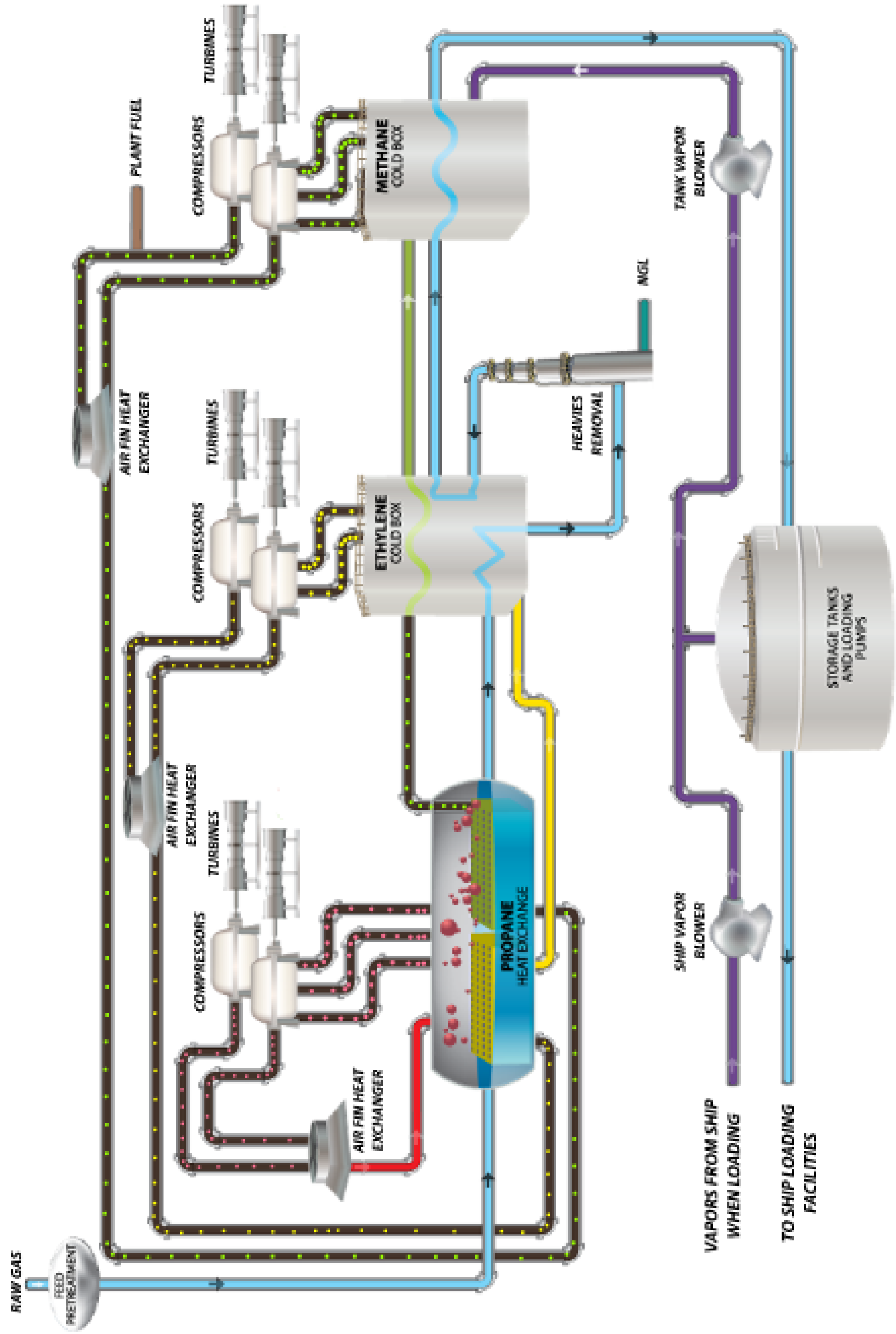

FIGURE 4 OPTIMIZED CASCADE LNG PROCESS (CONOCOPHILLIPS 2011)

As mentioned earlier it is important to obtain small temperature difference as possible between refrigerant and natural gas. Figure 5 and Figure 6 show typical composite curves for a classical cascade LNG process and an Optimized cascade LNG process (Ransbarger 2007). The main difference between the two processes is in the lower (right) part of the curve, methane/flash stage. In Figure 5, this stage represents the classical cascade that uses several pressure stages with methane as refrigerant to maintain a low temperature difference. The Optimized cascade shown in Figure 6, uses the flash gas mixture in the sub-cooling circuit and the mixture is evaporating with a gliding temperature profile. The flash gas mixture is mainly a mixture of nitrogen and methane. According to (Ransbarger 2007), a temperature difference of 16 °F for classical cascade and 12 °F for the Optimized cascade, hence 4°F difference between the two processes. Bear in mind that these numbers are estimates and not real life measurements.

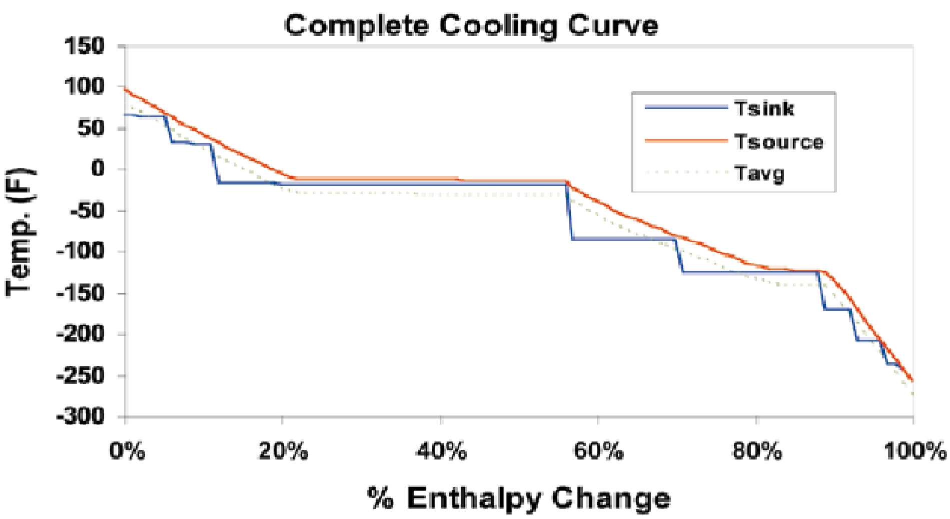

FIGURE 5 TYPICAL COOLING CURVE FOR CLASSICAL CASCADE (RANSBARGER 2007)

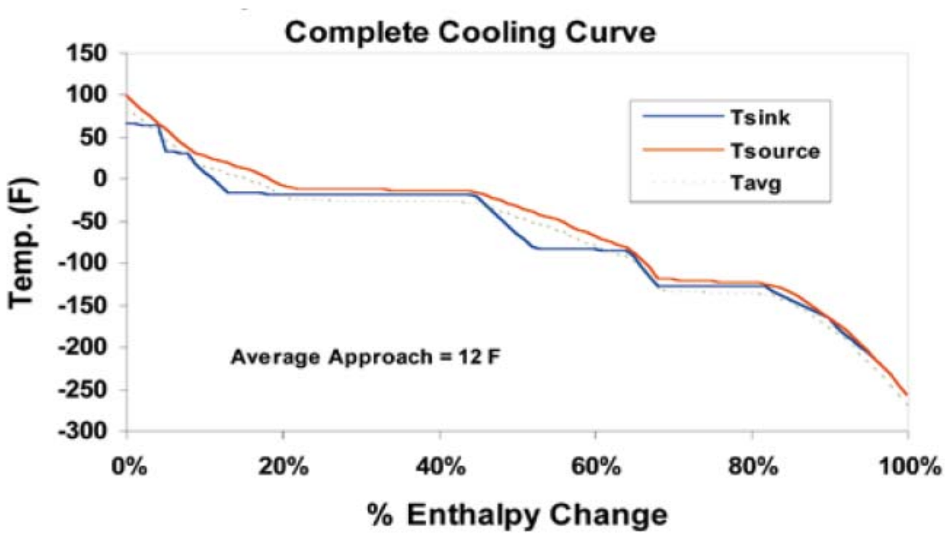

FIGURE 6 TYPICAL COOLING CURVE FOR OPTIMIZED CASCADE LNG PROCESS (RANSBARGER 2007)

One of the largest differences between Optimized Cascade LNG process and a classical cascade process is the use of cold recovery heat exchangers in the ethylene circuit and in the methane/flash circuit. These heat exchangers improve the process efficiency.

There are several driver solutions used nowadays. Some examples are;

Angola LNG Project utilizes two parallel GE Frame 6 driving the methane compressors and two parallel GE Frame 7 gas turbines driving the propane and ethylene compressors (Tsang, Larkin et al. 2009). The Atlantic LNG trains 2/3, Trinidad, utilizes six GE Frame 5D, two gas turbines in parallel for propane compressors, two gas turbines in parallel for the ethylene compressors and two gas turbines in parallel for the methane compressors (Hunter and Andress 2002). The Darwin LNG plant utilize six GE PGT25+, two on each circuit, as its compressor driver configuration(Meher-Homji, Yates et al. 2007). The driver configuration for the three examples is shown in Figure 7, Figure 8 and Figure 9.

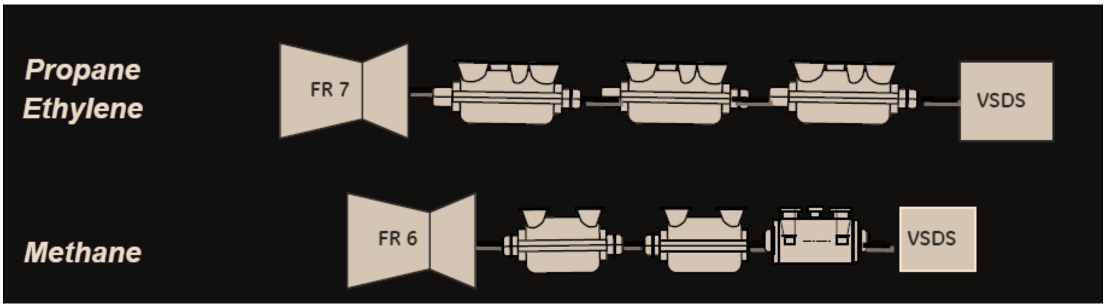

FIGURE 7 DRIVER CONFIGURATION ANGOLA LNG (ROCKWELL 2010)

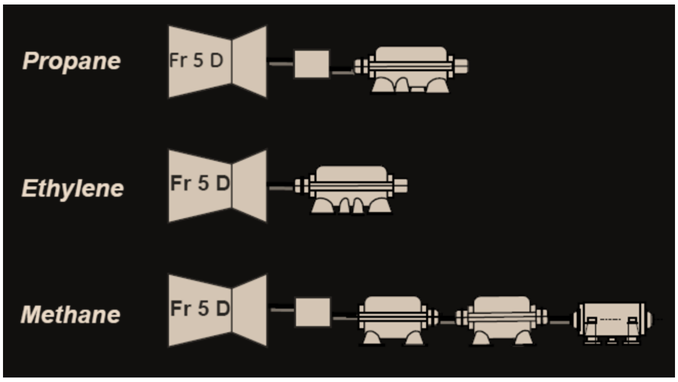

FIGURE 8 DRIVER CONFIGURATION ATLANTIC LNG TRAINS 2/3, TRINIDAD (ROCKWELL 2010)

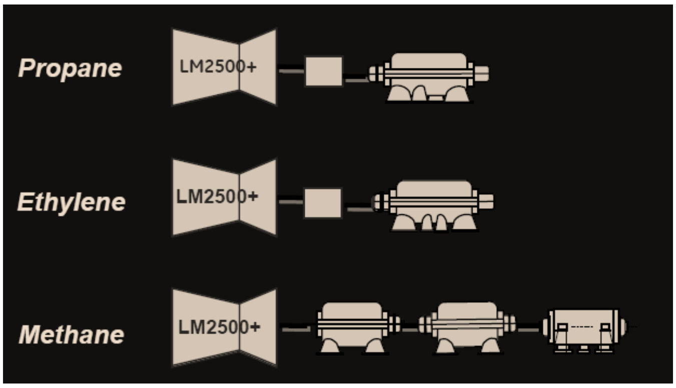

FIGURE 9 DRIVER CONFIGURATION DARWIN LNG (ROCKWELL 2010)

3 SELECTION OF COOLING SYSTEM AND DRIVER CONFIGURATION

In this chapter a general discussion of cooling system, driver configuration and design consideration is given. Consequences of using either air cooling, water cooling, indirect water cooling and/or a combination of indirect and direct water cooling, is discussed. The properties of the different gas turbines are highlighted. The discussions are related to the ConocoPhillips Optimized Cascade LNG process.

3.1 SELECTION OF COOLING SYSTEM

Deep seawater as coolant holds a stable temperature throughout the year and will vary in a typical arctic climate with 5-6 °C in a year (Pettersen 2010). The small seasonal temperature difference means that the production can be kept stable, and close to design. Water will have a minimum temperature of -1°C, normally 0°C, which means that during winter, colder air temperatures cannot be utilized.

Water cooled heat exchangers will have a small temperature difference between the seawater and the condensing/or warm refrigerant. A temperature difference around 5-6°C is a usual assumption (Fredheim 2010). If space saving is an important factor, a water cooled plant is preferable. In case of a leakage of water in to the heat exchanger and to the refrigerant, problems related to repairing the unit will arise, because of extremely compact design. The main seawater condenser at Hammerfest LNG during manufacturing (Fredheim 2010), can be seen in Figure 10.

FIGURE 10 WATER COOLED HEAT EXCHANGER (THOMAS 2007)

Fouling on the tube side has to be taken into consideration, and use of chemicals to remove fouling must be considered. This can lead to emissions of chemicals to sea which are not wanted. Seawater cooling leads to heating of seawater which may have environmental impact. There may be government restrictions on the temperature of heated, seawater, from the heat exchangers.

An indirect cooling system will work as a water cooled system, but with a larger temperature difference between the seawater and the refrigerant because of the use of one extra heat exchanger with additional temperature difference. An advantage is that the seawater and the rest of the process is separated, which leads to less use of expensive corrosion resistant materials and less chance of leakage of seawater into the refrigerant circuit.

In an arctic climate the ambient air temperature can vary greatly. Large temperature variations mean that the compressor and driver have to tolerate a large variation in condensing pressures and production volume. Varying air temperature also affects the output power of gas turbines.

An air cooled heat exchanger has a high temperature difference between the air and the refrigerant, typically 15°C - 20°C (Perry, Green et al. 1997). The temperature difference will result in lower process efficiency. The reason for the large temperature difference of air cooling compared to water cooling is the heat transfer coefficient of air is much lower than water. By looking at equation (1), one can realize that by doing the same cooling duty, Q, ΔT_{LM} and/or A, have to be larger when having a low U-value compared to a higher U-value.

$$Q = U \cdot A \cdot \Delta T_{LM} \tag{1}$$

An air cooled plant will use a large area, built up by a large number of smaller units in parallel. Because of simple design, and no/less need for expensive corrosion resistant materials, the maintenance is less problematic and less expensive. Maintenance cost is about 20-50 % of a water cooled plant (Perry, Green et al. 1997). CAPEX is lower for an air cooled plant than for a water cooled plant, which has to use corrosion resistant materials and piping for seawater transportation which is more expensive (Josten and Kennedy 2008). An air cooled LNG plant is shown in Figure 11 and shows that the air cooled heat exchangers occupies a large area.

FIGURE 11 AIR COOLED PLANT (CONOCOPHILLIPS 2010)

A graphical presentation of the yearly minimum and maximum extreme air temperatures and deep seawater temperature for Kola Peninsula in Russia is shown in Figure 12. With maximum air temperatures at above 30°C in the summer and minimum air temperatures below -30°C in the winter, the plant has to cope with extreme variation in compressor work.

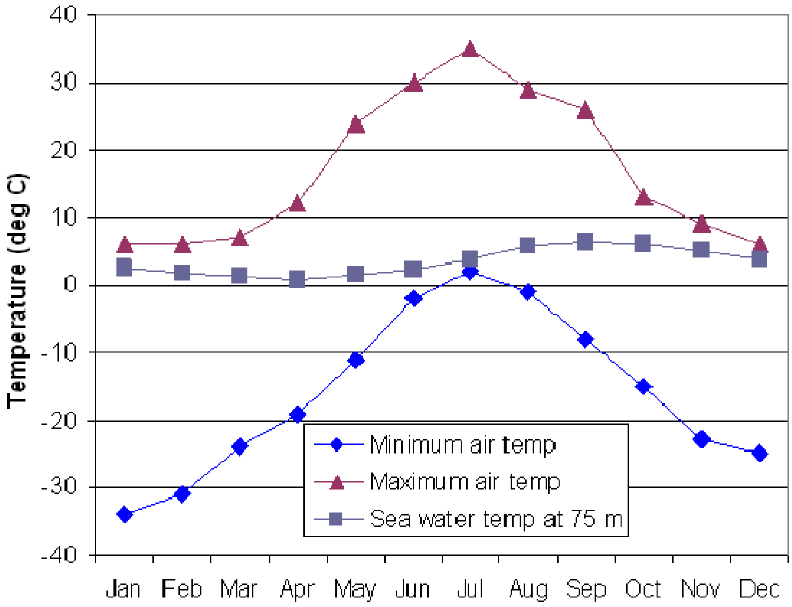

FIGURE 12 EXTREME AIR TEMPERATURES AND WATER TEMPERATURE (PETTERSEN 2010)

To be able to do a comparison between an air cooled plant and a water cooled plant, all simulations will be connected to temperature statistics from the Kola peninsula. Average monthly temperature statistics are shown in Table 1.

TABLE 1 MONTHLY TEMPERATURE STATISTICS FOR AIR AND DEEP WATER (PETTERSEN 2010)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Deepwater intake [°C]	2.7	1.9	1.0	1.1	1.7	2.5	3.7	4.7	5.6	6.0	5.2	3.9
Ambient air [°C]	-7.8	-8.5	-6.3	-2.1	2.4	7.5	11.2	10.8	6.9	1.5	-2.8	-5.8

If an air cooled solution is implemented, the large variation in temperature has to be taken into consideration. Moreover, extreme temperatures in both summer and winter have to be accounted for. In the optimized cascade LNG process the condensing temperature and pressure of propane in the pre-cooling circuit is determined by the cooling temperature of air or water. It is expected that the propane circuit is the circuit that is most affected by change in ambient temperature, because ethylene and flash/methane have a constant condensing pressure.

3.2 Driver configuration

The refrigerant compressors are responsible for a large part of the power consumption of a LNG plant, typically 40% (Hasan, Karimi et al. 2009). Having a flexible and efficient driver configuration can ease operation of the plant and lead to a more efficient plant. A compressor driver can either be an electrical motor, a gas turbine or a steam driven turbine. Gas turbines are the most common driver for existing LNG plants, but the interest for using electrical motors is increasing (Martinez, Meher-Homji et al. 2005). Electrical drives are in operation at Hammerfest LNG.(Thomas 2007).

There are two types of gas turbines; heavy duty gas turbines and aero-derivative gas turbines. The heavy duty gas turbine type such as GE Frame 6 and GE Frame 7 are constructed for flexible fuel composition, high reliability and large power output. Heavy duty gas turbines have low operational flexibility when it comes to speed control and a lower efficiency. Aero-derivative gas turbines such as GE LM6000 and GE LM2500 have a design based on jet engine, with high efficiency and large operational area when it comes to output power and speed control. Aero derivatives have low fuel composition flexibility. Operational changes have to be done on the machine for example, before changing from wet gas to dry gas fuel. Aero derivatives have a steeper loss of power output at increasing air temperature; approximately 1% decrease for every 1°C rise. Heavy duty industrial gas turbines lose approximately 0.7% per °C (Meher-Homji, Yates et al. 2007).

An overview of some of the most common gas turbine compressor drivers are shown in Table 2. Notice the difference in efficiency between the heavy duty gas turbines and the aero derivatives. The largest electrical motor built is approximately 65MW (Bakken 2010). An electrical drive has efficiency around 95% (Devold, Nestli et al. 2006).

TABLE 2 SELECTED INFORMATION FOR SOME COMMON GAS TURBINES (ROCKWELL 2010)

Turbine	Shaft	Power (kW)	Efficiency	Fuel Consumption Indexed	Scheduled Downtime
LM2500+	Dual	31364	41.1%	72	1.6%
LM6000	Dual	44740	42.6%	69	1.6%
Frame 5D	Dual	32580	29.4%	100	2.6%
Frame 6B	Single	43530	33.3%	88	4.4%
Frame 7E	Single	87300	33.0%	89	4.4%
Frame 9E	Single	130100	34.6%	85	4.6%

There are different options when discussing an electric driver configuration. The plant can import electricity from the electrical grid or have an onsite power plant. When importing from grid the driver efficiency on site will be in the range of above mentioned. If an onsite gas fired power plant is built, the efficiency of the gas turbines should be taken into consideration. According to (Wehrman, Roberts et al. 2011) a fuel efficiency of 35-36% for generation with aero derivative gas turbine, 27 – 29% with generation from an industrial heavy duty gas turbine and 22 – 30% with power generation from steam turbines. An integrated power plant will increase the overall investment.

An LNG plant has a need for heat. Amine CO_2 capture units need heat to separate the amine and CO_2, dehydration units using TEG need heat to separate water from TEG. If gas turbines are the selected driver configuration, exhaust heat from the gas turbines can be utilized to heat oil at different temperatures in a hot-oil system or heat water in a steam system and use this to supply the process heat. Burning of fuel, non-fossil or fossil to produce steam at different pressure levels can be done if there is no gas turbines presence on-site. Work done by (Tangås 2010) describes how process heat can be generated for electrical driven LNG plants utilizing electricity from the grid. The overall process efficiency of the plant will increase if heat from gas turbines exhaust are utilized.

The power curves for LM6000 and Frame 7 are shown in Figure 13. Here one can see the difference in power output, where the heavy duty gas turbine has a less steep power curve than aero derivatives.

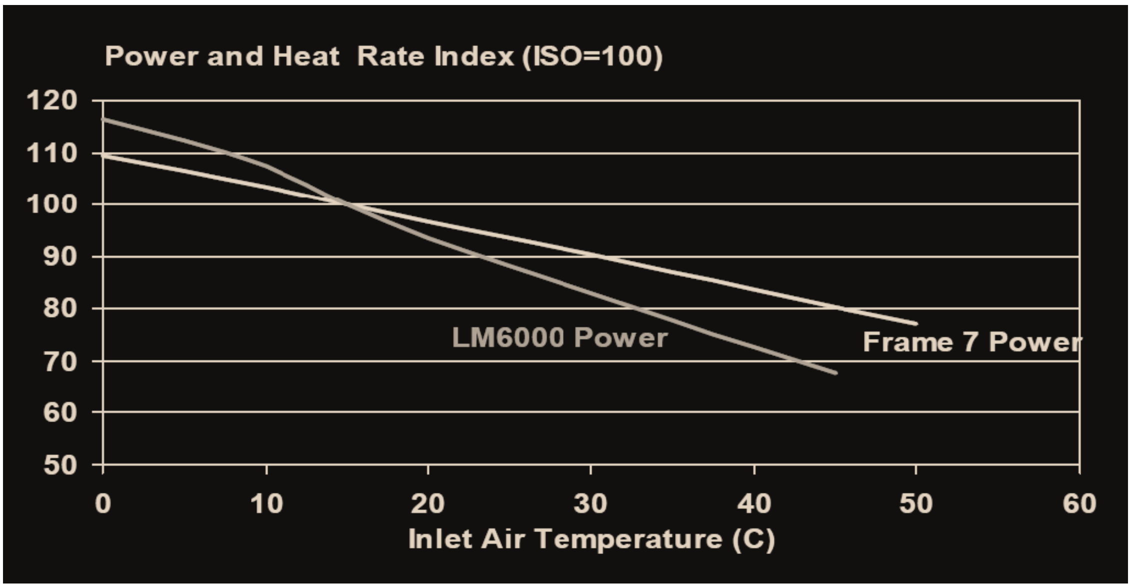

FIGURE 13 POWER RATE FOR LM6000 AND FRAME 7 (ROCKWELL 2010)

Speed control is important especially in arctic climate where the propane condensing pressure may vary considerably. An overview of the speed control possibilities for the most relevant drivers is shown in Table 3.

TABLE 3 SPEED CONTROL FOR RELEVANT DRIVERS (Pettersen 2010)

Driver	Minimum speed [% rpm]	Maximum speed [% rpm]
LM6000	50%	105%
LM2500	50%	105%
Frame 5	95%	102%
Frame 6	95%	102%
Frame 7	95%	102%
Electrical motor	50%	105%

The optimized driver configuration for a cascade LNG processes in an arctic climate has to be based on several aspects.

- Size
- efficiency
- Speed regulation
- Maintenance

The drivers should match the desired plant capacity. If too large gas turbines are used, the gas turbines have to operate on part load and as a consequence of that at lower efficiency. This is a parameter that is important no matter what kind of cooling system is chosen.

The efficiency tells us how much of the energy in the fuel the driver actually utilizes. High efficiency means lower fuel consumption. As seen in Table 2, LM6000 has a high efficiency. The higher efficiency of an aero derivative gas turbine can improve the plant overall thermal efficiency with more than 3% (Meher-Homji, Yates et al. 2007).

To have the possibility to control the speed of the gas turbine is an advantage especially in an air cooled plant. A system utilizing non – or low driver speed regulation, will be more difficult to operate and will have to operate at low efficiency more often throughout the year. A plant designed for a very low ambient temperature may have to stop operating at days with extremely high temperatures. The driver may not be able to operate at the speed the compressor needs to deliver the required condensing pressure in the process.

An aero derivative gas turbine can be replaced by a new one within 48 hours, versus 14 days or more for a heavy duty gas turbine (Meher-Homji, Yates et al. 2007). This will increase the plant availability. An electrical driven LNG plant requires less maintenance than a gas turbine driven compressor solution (Martinez, Meher-Homji et al. 2005).

3.3 Design premises

The LNG process design temperature is important for the process efficiency, capacity and capacity flexibility. The process should be designed according to the operating conditions. A poor design will lead to the process operation in off-design, and probably with a lower process efficiency.

When designing an air cooled LNG process, one important criterion is the requirement for the process to be able to operate at the entire temperature range. Satisfaction of this requirement is done by designing for a temperature high enough for the plant to handle extreme temperatures, but at the same time low as possible because of the low average temperature. The high design temperature will lead to the plant operating off-design some periods of the year, but it is necessary if the process is required to operate at the entire temperature span. One way to avoid operating in the warmest months is to put revision stops in the expected warmest months.

When designing a water cooled plant, there is no need to design for extreme temperatures because of the stable water temperature through the year. But one should take into consideration that the gas turbine driver power output is dependent on the air temperature that may vary, and experience both extremely low power output and the possibility for high power output.

3.4 Compressor regulation

Compressors and speed of compressors can be controlled in several ways. The type of regulation method to be chosen is based on simplicity, investment cost and operational costs. The most common ways of compressor regulation is;

- Regulating suction pressure
- Regulating discharge pressure
- Change recycle mass flow

- Direct speed regulation

(Øverli 1984) defines direct speed regulation as the most efficient way of going from one operating point to another. Throttling the suction pressure is the second most efficient way, throttling the discharge pressure comes third, and the least efficient way of controlling the compressor is recycling.

In this project, direct speed regulation, change of discharge pressure and recycling has been used to control the operating points of the compressors.

4 The simulation model

In this chapter the model is described. The restrictions in the model are also given.

The model is based on an improved version of the typical classical cascade process. The sketch used as a basis, is found in (Pettersen 2009) and is shown in Figure 14, Figure 15, Figure 16 and Figure 17. The process consists of a pre-cooling circuit using propane as refrigerant, a liquefaction circuit using ethylene as refrigerant and a sub-cooling circuit using the flash gas mixture as refrigerant.

This description of the model may not be how the process is in real life. There are not much open information available explaining how the process can be modeled. Air cooled condensers and heat exchangers are given a minimum temperature difference of 15 K, and water cooled condensers and heat exchangers are given a minimum temperature difference of 6K in design.

The propane circuit has three pressure stages, each with its own compressor. In real-life this will be one compressor casing or two parallel (or more) compressor casings with several pressure inlets. Three separate core in kettle heat exchangers cool the natural gas and the ethylene refrigerant to approximately -33 °C. All LNG heat exchangers are given a design temperature difference of 2K. Figure 14 shows a simple sketch of how the propane circuit is built up.

The propane refrigerant is compressed from LP to MP, then from MP to HP and from HP to HHP. After the HP compressor propane is condensed in an air or water cooled heat exchanger (CW1) before it is throttled down to a lower pressure through V1. The propane enters a separator (S1) and the gas goes back to the HP compressor. The liquid is split into two streams, where one of the streams goes through E1A (the first core in kettle heat exchanger) and evaporates to cool natural gas and ethylene. The evaporated stream goes into the HP compressor. The second stream is throttled down to a lower pressure though V2 before going into a separator (S2) and the gas goes back to the MP compressor. The liquid is split into two streams where one stream goes to E1B and is here evaporated to cool the natural gas and the ethylene before entering the MP compressor. The second stream is throttled to the lowest pressure level through V3 and goes into a separator (S3). The gas goes to the LP compressor, and the liquid goes to E1C were it is evaporated and cools the natural gas and condenses the ethylene at approximately -33°C.

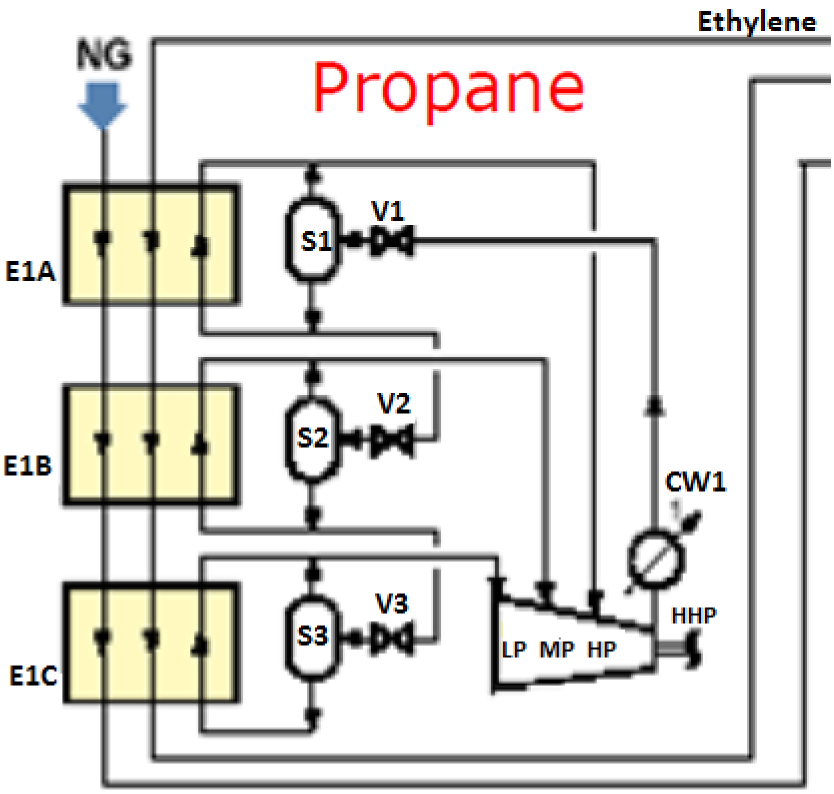

FIGURE 14 SIMPLE SKETCH OF THE PROPANE CIRCUIT

The setup of the ethylene circuit is quite similar to the propane circuit. The difference lies in the cold recovery heat exchangers. It has three pressure stages, each modeled as a separate compressor. As for the propane compressor, this will in real-life be one compressor casing or two (or more) compressor casings in parallel with several pressure inlets. Three separate core in kettle heat exchangers cool the natural gas and flash/methane to approximately -96°C. Figure 15 shows a simple sketch of the ethylene circuit.

The ethylene refrigerant is compressed from LP to MP and then to HP before the stream is cooled in an air/water cooled intercooler (CW2). After cooling the refrigerant is compressed to HHP. From the HP compressor the ethylene is cooled by an air/water cooled heat exchanger (CW3) and then condensed by the propane circuit. After condensation, ethylene goes through the first cold recovery heat exchanger (CRHX1) where it is cooled, and then throttled to a lower pressure through V4. After throttling the ethylene goes into a separator (S4), the gas goes back to CRHX1 before it enters the HP compressor. The liquid is split into two streams, where one stream goes directly to E2A (the first ethylene core in kettle heat exchanger), where it evaporates to partly condense the natural gas and cools the flash/methane stream. The stream then goes through CRHX2 and CRHX1 before it enters the MP compressor. The second stream goes into a new cold recovery heat exchanger (CRHX2) were it is cooled, before it is throttled to a lower pressure through V5. After throttling the ethylene goes into a separator (S5), the gas goes back to CRHX2 and then CRHX1 before it goes back to the MP compressor. The liquid is split into two streams where one stream goes directly to E2B where it evaporates to fully condense the natural gas and cool the methane/flash stream. The stream goes further to the CRHX2 and CRHX1 before entering the MP compressor. The second liquid stream goes into the third cold recovery heat exchanger (CRHX3) where it is cooled, before it is throttled to the lowest pressure through V6. After throttling the stream enters a separator (S6), and the gas goes back to CRHX3, then CRHX2 and CRHX1 before entering the LP compressor. The liquid goes to E2C were it evaporates to sub cool the liquefied natural gas and condense the methane/flash stream. The temperature is approximately -100 °C.

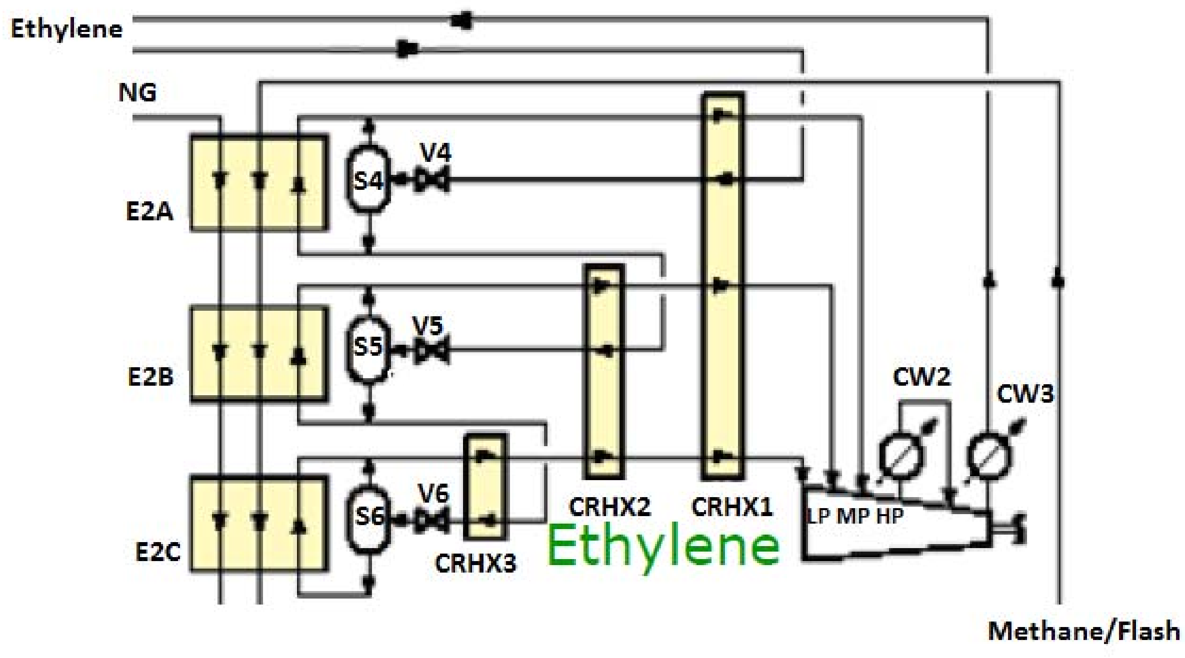

FIGURE 15 SIMPLE SKETCH OF THE ETHYLENE CIRCUIT, INCLUDING COLD RECOVERY HEAT EXCHANGERS

The methane circuit is built up in a different way. It has no separators, and utilizes a liquid expander in the HP stage of the system to recover work instead of a Joule-Thomson valve.

Similar to the propane and ethylene circuits the methane/flash circuit has one or two three stage compressors, which in the simulations is modeled as three separate compressors.

The LP compressor compresses the flash mix to the MP compressor which compresses the mixture further up. The flash mix is then cooled with an air/water cooled intercooler (CW4) before it enters the HP compressor and then a new air/water cooled heat exchanger (CW5). The flash mix goes through a cold recovery heat exchanger (CRHX4) where it is cooled and then through the ethylene circuit where it is cooled and finally condensed. A simple sketch of the methane/flash circuit is shown in Figure 16.

After condensation the stream is further sub cooled through three plate fin type heat exchangers E3A, E3B and E3C. For each heat exchanger parts of the flash stream is throttled and used as refrigerant for internal heat exchange. In the last heat exchanger (E3C), internal heat exchange is done by one individual stream, in the second heat exchanger (E3B); two streams will contribute to internal heat exchange, the one that is throttled to MP pressure level and the stream from the LP pressure level. The first heat exchanger (E3A) will have three streams contributing to the internal heat exchange; this includes two streams from lower pressure levels in addition to the stream that is throttled. Notice that after sub-cooling in the first plate fin heat exchanger the flash mix goes through the liquid turbine to recover work E1, and to achieve a lower temperature due to the fact that a liquid expander is an (near) isentropic process. After sub-cooling, the LNG is throttled to atmospheric pressure through a liquid expander and a Joule Thomson valve before the flash gas is separated.

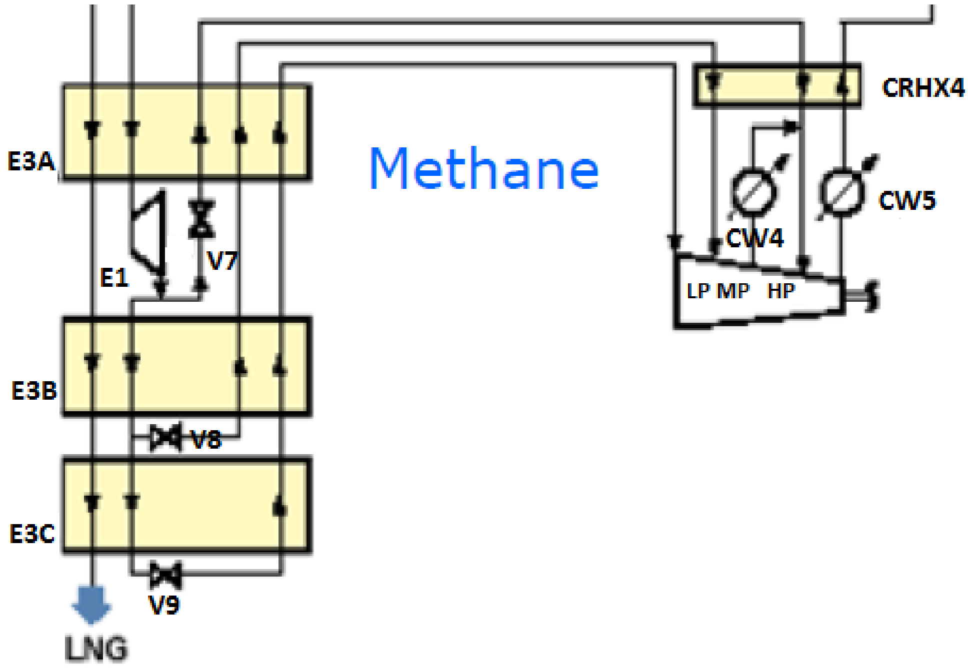

FIGURE 16 SKETCH OF FLASH/METHANE CIRCUIT

The split temperatures are shown in Table 4. The same split temperatures are used in all simulation cases.

TABLE 4 SPLIT TEMPERATURES

Heat exchanger	Temperature [°C]
After propane circuit	-32.54
After ethylene circuit	-96.32
After 1. Methane heat exchanger	-115
After 2. Methane heat exchanger	-135
After 3. Methane heat exchanger	-155

In the propane and ethylene circuit, the mass flow of refrigerant is calculated by HYSYS® through an energy balance. In the methane/flash gas circuit there are not enough known variables to make HYSYS® do the energy balance and therefore calculation of the mass flow of refrigerant has to be done manually. An energy balance over each heat exchanger in the methane/flash circuit has been done to calculate the mass flow through the respective heat exchangers. The calculated mass flows are then exported to the streams that are going through the heat exchangers.

The energy balances are shown in equation (2), (3) and (4). Where m_{NG} is the natural gas mass flow, Δh_{NG3} is the heat rejected by natural gas in E3C, Δh_{LP3} is the enthalpy change of the LP refrigerant and m_{LP} is mass flow of LP refrigerant.

Δh_{NG2} is the heat rejected by natural gas in the second heat exchanger, Δh_{LP2} is the change in enthalpy of LP refrigerant in E3B, Δh_{r2} is the heat rejected by the refrigerant stream in E3B, Δh_{MP2} is the enthalpy change of MP refrigerant in the E3B and m_{MP} is the mass flow of MP refrigerant.

Δh_{NG2} is the heat rejected by natural gas in the first heat exchanger, Δh_{MP1} is the change in enthalpy of LP refrigerant in E3A, Δh_{r1} is the heat rejected by the refrigerant stream in E3A, Δh_{LP1} is the enthalpy change of LP refrigerant in E3A, Δh_{HP1} is the enthalpy change of HP refrigerant in E3A and m_{HP} is the mass flow of HP refrigerant.

$$m_{LP} = \frac{m_{NG} \cdot \Delta h_{NG3}}{\Delta h_{LP3}} \quad (2)$$

$$m_{MP} = \frac{m_{LP} \cdot (\Delta h_{LP2} + \Delta h_{r2}) - m_{NG} \cdot \Delta h_{NG2}}{(\Delta h_{r2} - \Delta h_{MP2})} \quad (3)$$

$$m_{HP} = \frac{m_{MP} \cdot (\Delta h_{MP1} + \Delta h_{r1}) + m_{LP} \cdot (\Delta h_{LP1} + \Delta h_{r1}) - m_{NG} \cdot \Delta h_{NG1}}{(\Delta h_{r1} - \Delta h_{HP1})} \quad (4)$$

The pressures in the propane and ethylene circuit where found by using equation (5), (6), (7) and (8). Where P_r is the total pressure ratio, P_{HHP} is the highest pressure, P_{LP} is the lowest pressure, $P_{r\ stage}$ is the stage pressure ratio, P_{MP} is the lowest intermediate pressure and P_{HP} is the highest intermediate pressure. The methane/flash circuits used equation (5), (6), (7) and (8) as a starting point, and was later adjusted to fit the minimum approach specification of 3K in the heat exchangers.

$$P_r = \frac{P_{HHP}}{P_{LP}} \quad (5)$$

$$P_{r\,stage} = P_r^{\frac{1}{3}} \quad (6)$$

$$P_{MP} = P_{LP} \cdot P_{r\,stage} \quad (7)$$

$$P_{HP} = P_{LP} \cdot P_{r\,stage}^{\ 2} \quad (8)$$

An overall sketch of the process is shown in Figure 17. The HYSYS® model is shown in Figure 18.

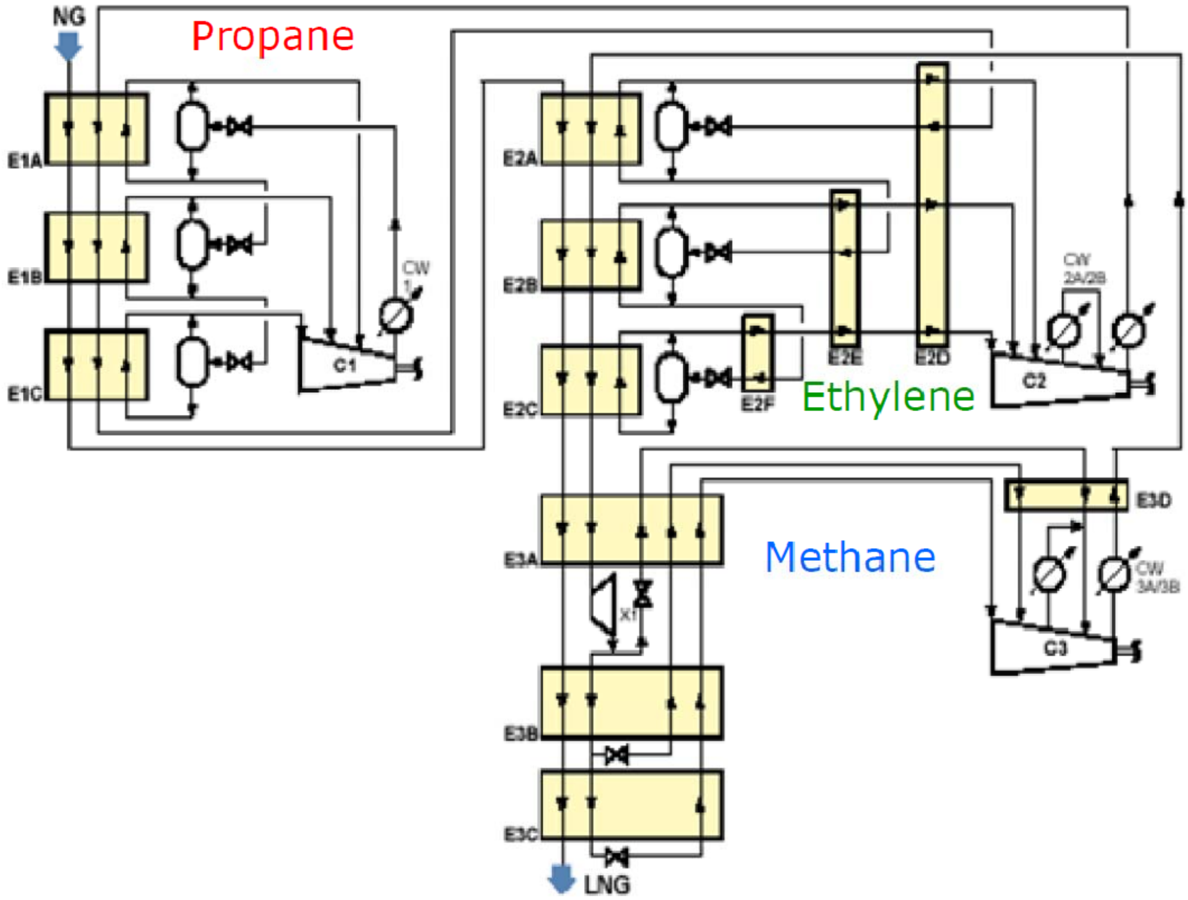

FIGURE 17 SKETCH OF THE PROCESS (PETTERSEN 2009)

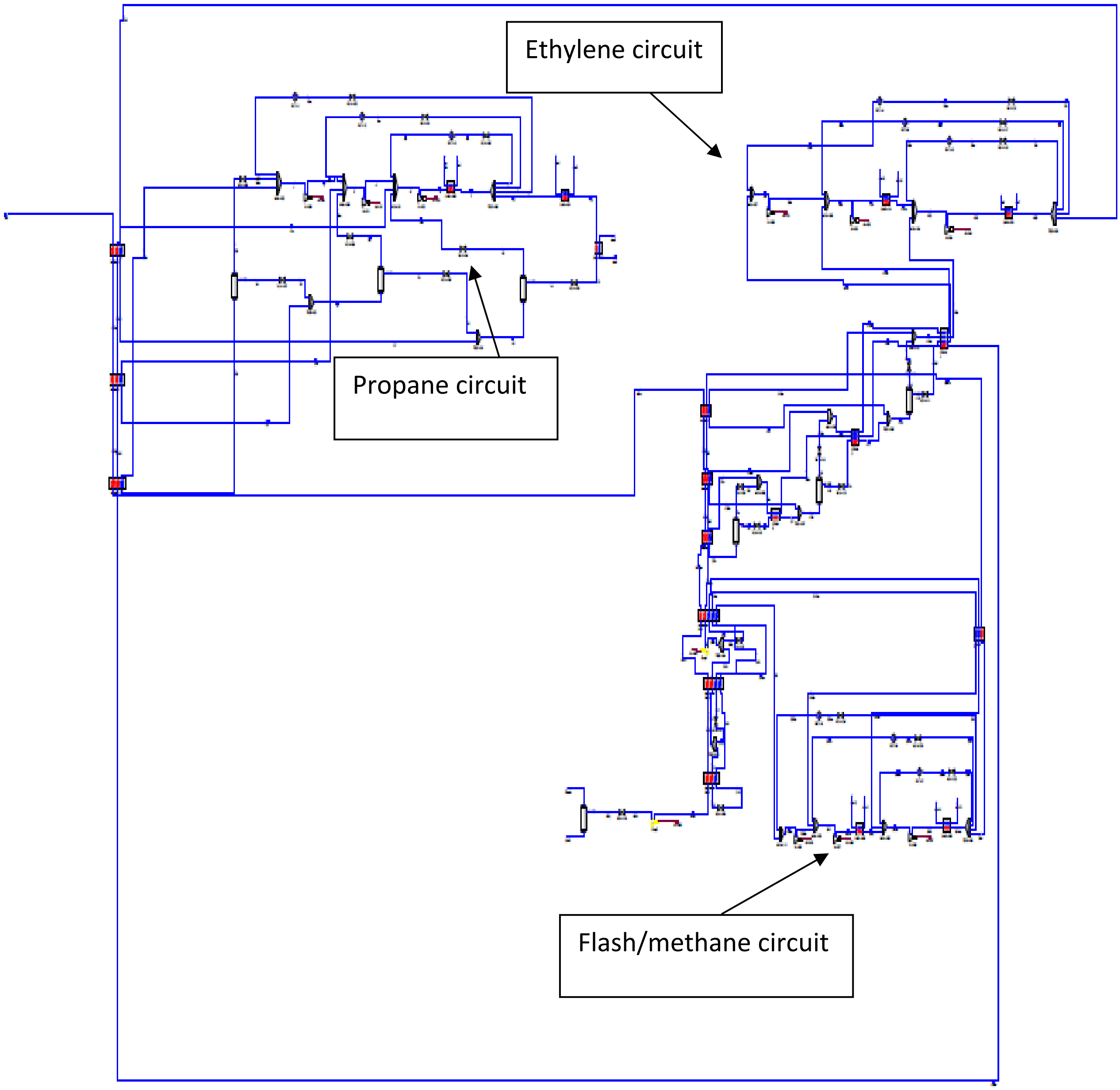

FIGURE 18 THE HYSYS® MODEL

To avoid the compressors from surging, an anti surge recycle system is included in the model. This is done by controlling the volumetric flow limit for the compressor 10% above the surge volumetric flow. If the compressor suction flow is less than the limit, an adjuster will increase the mass flow through the anti-surge recycle loop until the flowrate is sufficient. The linear equations for the surge and control line are found in Excel, the constants A and B are used in a spreadsheet in HYSYS® as shown in Figure 19.

	A	B	C	D	E
1			Ax+B		
2					
3	Compressor Head	4806 m	A	B	
4	MP Surge line	2.326e+005 m	26.76	1.040e+005	
5	MP control line	2.615e+005 m	30.35	1.156e+005	
6		compressor inlet	From Kettle I	From separator	From MP comp
7	MP comp. inlet	2.905e+005 m3/h	3.408e+004 m3/h	5.216e+004 m3/h	2.041e+005 m3/h
8	Exl. recycle	2.904e+005 m3/h			
9					
10	Target flow	2.904e+005 m3/h			
11	Surge flow	1.000e-003 kg/h			
12					
13					
14	Status	No Recycling			
15					

FIGURE 19 ANTI SURGE RECYCLE SPREADSHEET IN HYSYS®

The recycle loop, compressor, recycle heat exchanger and the recycling mass flow - adjuster are shown in Figure 20. Notice that the splitter (ReCycl splitter), which splits the compressor stream into four streams where the one in the bottom goes out to the LNG process. The three streams from the top are recycling streams for the three compressor stages. In this process it is chosen to take out all recycling streams from the high pressure side. This choice is based on space saving in a real life plant, where the three compressor stages actually are one compressor casing. It is probably more efficient to recycle over each pressure stage. The method used, is also used in (Wu, Feng et al. 2007).

Because of the harsh climate in arctic regions an anti icing system for the gas turbines is implemented in the model. This system adjusts the gas turbine inlet air temperature. If the ambient temperature drops below 4.4 °C the system will, by use of for example, a hot oil system, heat the inlet air temperature to 4.4 °C and keep it constant. If the ambient temperature drops below -1.1 °C the anti-icing system will keep the inlet air temperature 5.6 °C above the ambient air temperature (Pettersen 2010). This is a simple solution used in the industry.

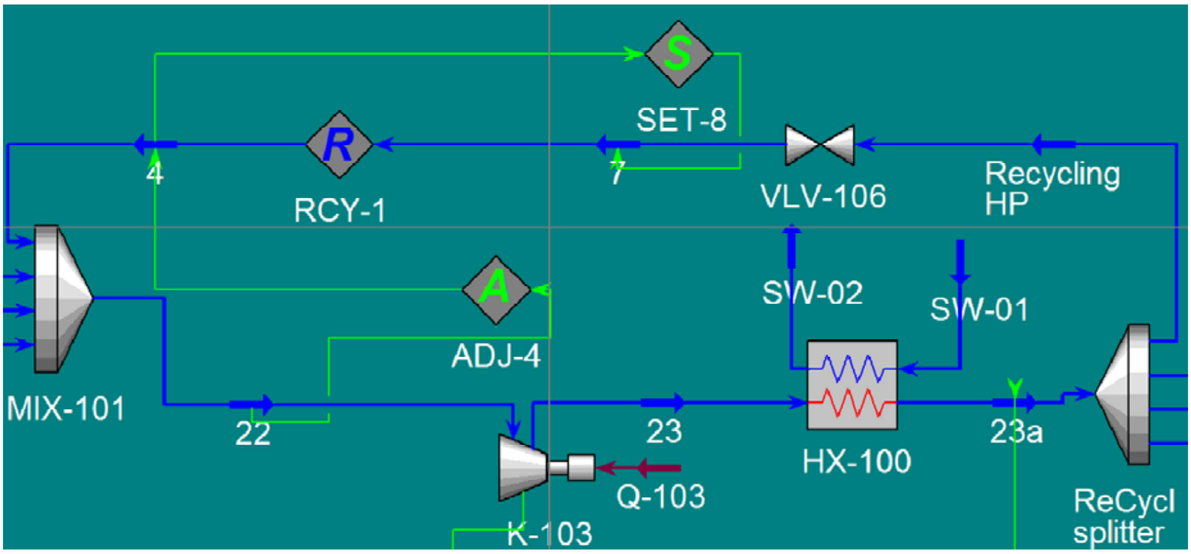

FIGURE 20 RECYCLE LOOP IN HYSYS®

All important heat exchangers are set with a fixed UA-value to simulate a fixed geometrical size of the heat exchangers. The value is taken from the design case. For example when the production rate of LNG increases, the UA – value of a heat exchanger in the process will change automatically. To adjust this value back to design, an adjuster controls the temperature difference in the heat exchanger. Adjusters are also used in compressor speed regulation and when matching the compressor work and the delivered power from the gas turbines, by adjusting the feed mass flow. A typical UA - adjuster is shown in Figure 21.

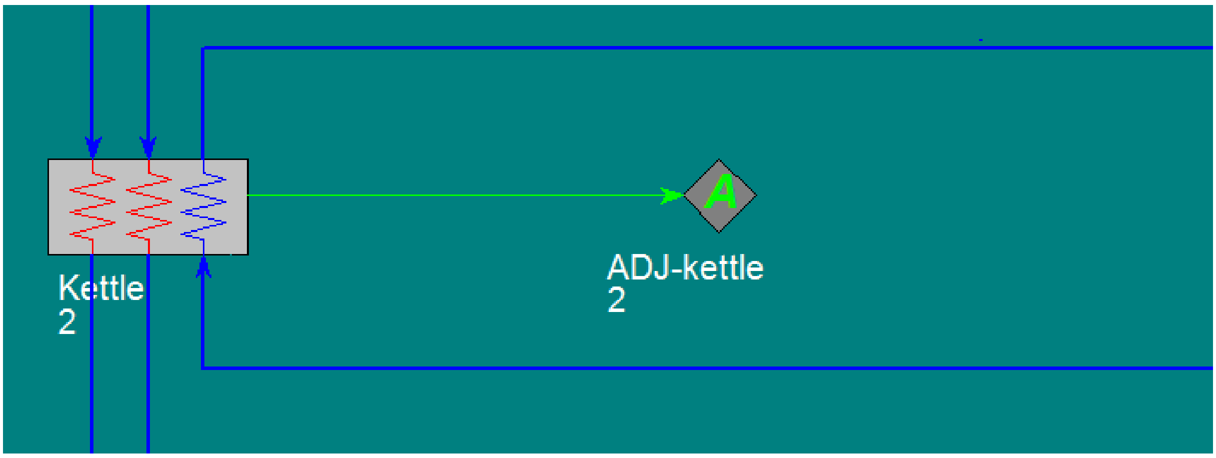

FIGURE 21 TYPICAL ADJUSTER FOR UA-VALUE ADJUSTMENT

Compressors have a limitation in the volumetric flow and the pressure ratio it can deliver at a certain compressor speed. A compressor map describes these limitations. A compressor map is implemented for all compressors in the model. HYSYS® uses the compressor map to determine the speed of the compressor, the polytrophic head, the volumetric flow and the polytrophic efficiency of the compressor. A typical compressor map is shown in Figure 22.

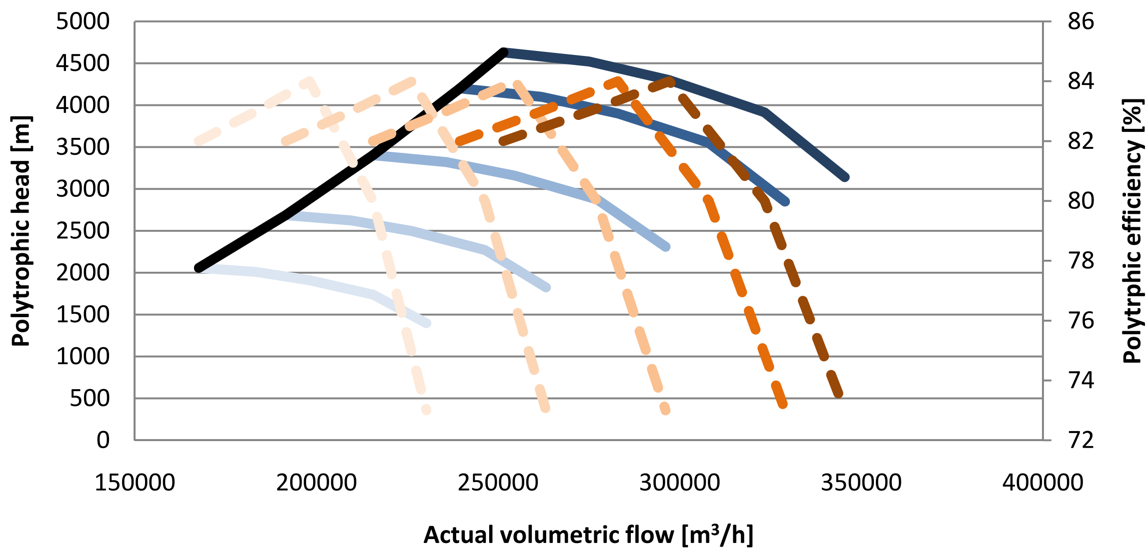

FIGURE 22 TYPICAL COMPRESSOR MAP

The blue lines represent different compressor speeds. The range in this compressor map is from 70% to 105% of the 3600rpm, from 2520 rpm to 3780 rpm. The darkest blue line represents 105% speed and the slightly lighter blue represents 100% speed and so on. The orange-colored dotted lines represent the efficiency at individual speeds, at various volumetric flows and polytrophic head. The darkest orange dotted line represents the efficiency at 105% speed, the slightly lighter orange dotted line represents the efficiency at 100% speed and so on. The black line represents the surge curve for this compressor, which means that it represents the minimum flow the compressor can deliver at different compressor speeds and polytrophic head. The end (right) of the compressor speed lines, represent the maximum flow of the compressor, also referred to as stone wall conditions. The area between the top and the bottom compressor speed lines and between the surge line and the stone wall points is defined as the valid operational area of the compressor. Notice that the volumetric flow limit of 10% above surge line is set in the simulations.

The compressor maps used in this project are compressor curves based on curves established by (Bakken and Sandvik 2010). The compressor curves are redesigned to match the flow rates and polytrophic head needed in the different cases. The redesigning is done by matching the actual volumetric flow needed with the volumetric flow in the best operating point of the compressor. The percentual distance between the speed lines is maintained constant both in polytrophic head and in actual volumetric flow. All compressor curves can be found in Appendix A.7 to A.12.

4.1 LIMITATIONS AND RESTRICTIONS IN THE MODEL

To make the results realistic, speed of the compressors, volumetric flow and head must be adjusted and the UA-values for heat exchangers must be held constant. This is done by varying several parameters. A list of variable parameters together with an explanation of what the parameter is used for is given in Table 5. The list also gives an indication on how rigid the model is.

TABLE 5 PARAMETERS THAT CAN VARY AND THEIR PURPOSE

Parameter	Purpose
Production of LNG (Feed mass flow)	***Can be used for regulation purposes***
LP - propane	Used to control UA value of E1C
MP - propane	Used to vary compressor speed of LP and MP compressor
HP– propane	Used to vary compressor speed of MP and HP compressor
HHP - propane	Restricted to follow the condensation pressure of propane
Natural gas temperature after Kettle 1	Used to control UA-value of E1A
Natural gas temperature after Kettle 2	Used to control UA-value of E1B
Natural gas temperature after Kettle 3	Held constant to obtain LPG extraction requirements
LP - ethylene	Used to control UA-value of E2C
MP - ethylene	Used to vary compressor speed of LP and MP compressor
HP– ethylene	Used to vary compressor speed of MP and HP compressor
HHP– ethylene	Used to achieve condensing pressure of ethylene after last propane stage
Natural gas temperature after Kettle 4	Used to control UA-value of E2A
Natural gas temperature after Kettle 5	Used to control UA-value of E2B
Natural gas temperature after Kettle 6	***Can be used for regulation purposes***
LP - pressure - methane/flash	Used to control UA value of E3C
MP - methane/flash	Used to vary compressor speed of LP and MP compressor
HP– methane/flash	Used to vary compressor speed of MP and HP compressor
HHP– methane/flash	***Can be used for regulation purposes***
Natural gas temperature after Kettle 4	Used to control UA-value of E3A
Natural gas temperature after Kettle 5	Used to control UA-value of E3B
Natural gas temperature after Kettle 6	Used to keep LNG and flash composition constant
Mass flow of air through all air cooled heat exchangers	***Can be used for regulation purposes***
Recirculation loop, mass flow, for anti surge recycling	***Used to handle anti surge in the compressor, but can also be used for regulation purposes***

5 SIMULATIONS

In this chapter the design specifications, driver configuration and cooling method for the simulated cases will be given.

Two types of cooling systems where selected; an air cooled plant and a water cooled plant. The different driver configurations chosen, with the design specifications are shown in Table 6. Indirect cooling was not simulated because it is assumed that this cooling method will behave similarly to direct seawater cooling, but with a larger temperature differences in the design, hence a lower efficiency. A maximum production limit is set at 120% of design production. Design production is based on available power from gas turbines at the design temperature. All gas turbines and electrical motors are assumed to operate at a 100% speed of 3600 rpm.

Case 2 is somehow different from the other cases when it comes to design production. The design production in this case is set at approximately the same design production as Case 1. If available power from six Frame 6B would be used, the production would be unrealistically high.

TABLE 6 CASES SIMULATED AND THEIR DESIGN PREMISES

Case	Cooling system	Driver selected	Design temperature	Design production
Case 1	Air cooling	6 x LM6000	20 °C	6.342 MTPA
Case 2	Air cooling	6 x Frame 6B	20 °C	6.336 MTPA
Case 3	Air cooling	6 x Electrical motor	20 °C	5.410 MTPA
Case 4	Water cooling	3 x LM6000	Water: 4 °C, air: 5°C	4.900 MTPA
Case 5	Water cooling	3 x Frame 6B	Water: 4 °C, air: 5°C	4.841 MTPA
Case 6	Water cooling	3 x or 6 x Electrical motor	Water: 4 °C, air: 5°C	4.193 MTPA

Driver selection is based on what is used in the industry today. Both Frame 6B and LM6000 are gas turbines in operation today, however LM6000 only as an electric power producer in an onsite power plant. Electrical motors for LNG plants are used at Hammerfest LNG.

Ambient air temperature design of 20 °C was chosen based on test simulations at constant production rate and experience from (Borlaug 2010). The test simulations pointed out that the process was able to cope with the extreme temperatures at this design. The 2in1 concept has been implemented in the air cooled cases using gas turbines.

The water cooled process is designed for a temperature slightly above the yearly mean for both water and air. The yearly average temperature for deep water is 3.3°C, and for air approximately 0.6°C. The 2in1 concept has been rejected for Case 4 and 5 because of extremely high production rates when using six LM6000, or six Frame6 in the water cooled plants. Three gas turbines, one for each circuit are chosen for Case 4 and 5. Case 6 has the possibility to work either with or without the 2in1 concept, but is based on production with three electrical motors of 40MW each.

To evaluate the process, simulations for the entire temperature range have been performed for the air cooled cases. Simulations with air cooling have been done from +30°C to -30°C with temperature steps of 10°C. In the water cooled cases, the monthly average temperatures have been used in the simulations directly.

In the simulations, the compressor's operating points are held inside the valid area of the compressor. This is done by utilizing the degrees of freedom in the model, adjusting production, mass flow of cooling air/water and/or compressor recycling. Compressor maps for all cases are found in tabular form in Appendices, Table 15 to Table 32.

The composition of the feed gas and methane/flash circuit are shown in Table 7. These compositions are used in all simulated cases.

TABLE 7 COMPOSITION OF FEED AND FLASH CIRCUIT

Component	Natural gas [mole%]	Flash circuit [mole%]
Nitrogen	0.0200	0.2131
Methane	0.9100	0.7868
Ethane	0.0560	0.0001
Propane	0.0110	0.0000
n-Butane	0.0025	0.0000
n-Pentane	0.0005	0.0000

The thermodynamic model used in Aspen HYSYS® is Peng-Robinson. The important heat exchanger designs are found in Table 8 to Table 13.

TABLE 8 HEAT EXCHANGERS DESIGN CASE 1

Case 1	Heat exchanger	UA [W/°C]	Q [kW]	Minimum approach [°C]	LMTD [°C]
Propane circuit	Condenser (CW1)	23127697	302450	10.94	13.08
	E1A	3811382	40295	2.00	10.57
	E1B	3604404	32551	2.00	9.03
	E1C	20260230	166583	2.00	8.22
Ethylene circuit	Intercooler (CW2)	320375	6137	15.00	19.16
	After-cooler (CW3)	1247201	39408	15.00	31.60
	CRHX 1	1026322	13684	8.09	13.33
	CRHX 2	695107	8546	7.93	12.29
	CRHX 3	173935	1791	7.99	10.30
	E2A	3789799	28386	2.00	7.49
	E2B	7903794	75523	2.00	9.56
	E2C	6501560	54238	2.00	8.34
Methane circuit	Intercooler (CW4)	326347	10669	15.00	32.69
	After-cooler (CW5)	843513	31905	15.00	37.82
	CRHX 4	1007619	41014	26.77	40.70
	E3A	8598332	38995	2.96	4.54
	E3B	5724866	23869	2.95	4.17
	E3C	3891774	18304	2.90	4.70

TABLE 9 HEAT EXCHANGERS DESIGN CASE 2

Case 2	Heat exchanger	UA [W/°C]	Q [kW]	Minimum approach [°C]	LMTD [°C]
Propane circuit	Condenser (CW1)	23101784	302193	10.95	13.08
	E1A	3808148	40261	2.00	10.57
	E1B	3601346	32523	2.00	9.03
	E1C	20243048	166442	2.00	8.22
Ethylene circuit	Intercooler (CW2)	320088	6132	15.00	19.16
	After-cooler (CW3)	1246063	39374	15.00	31.60
	CRHX 1	1025451	13672	8.09	13.33
	CRHX 2	694517	694517	7.93	12.29
	CRHX 3	173787	173787	7.99	10.30
	E2A	3786584	28362	2.00	7.49
	E2B	7897088	75458	2.00	9.56
	E2C	6496044	54192	2.00	8.34
Methane circuit	Intercooler (CW4)	326059	10660	15.00	32.69
	After-cooler (CW5)	842784	31878	15.00	37.82
	CRHX 4	1006764	40979	26.77	40.70
	E3A	8591036	38962	2.96	4.54
	E3B	5720008	23848	2.95	4.17
	E3C	3888472	3888472	2.90	4.70

TABLE 10 HEAT EXCHANGERS DESIGN CASE 3

Case 3	Heat exchanger	UA [W/°C]	Q [kW]	Minimum approach [°C]	LMTD [°C]
Propane circuit	**Condenser (CW1)**	18854437	258042	11.97	13.69
	E1A	3251766	34379	2.00	10.57
	E1B	3075178	3075178	2.00	9.03
	E1C	17285477	142124	2.00	8.22
Ethylene circuit	**Intercooler (CW2)**	271128	5236	15.00	19.31
	After-cooler (CW3)	1052382	33622	15.00	31.95
	CRHX 1	875630	11675	8.09	13.33
	CRHX 2	593046	7291	7.93	12.29
	CRHX 3	148396	1528	7.99	10.30
	E2A	3233352	24218	2.00	7.49
	E2B	6743299	64434	2.00	9.56
	E2C	5546952	46274	2.00	8.34
Methane circuit	**Intercooler (CW4)**	276841	9103	15.00	32.88
	After-cooler (CW5)	717659	27220	15.00	37.93
	CRHX 4	859673	34992	26.77	40.70
	E3A	7335860	33269	2.96	4.54
	E3B	4884298	20364	2.95	4.17
	E3C	3320354	15616	2.90	4.70

TABLE 11 HEAT EXCHANGERS DESIGN CASE 4

Case 4	Heat exchanger	UA [W/°C]	Q [kW]	Minimum approach [°C]	LMTD [°C]
Propane circuit	**Condenser (CW1)**	22766254	175794	6.00	7.72
	E1A	1926506	11716	2.00	6.08
	E1B	2492226	19908	2.00	7.99
	E1C	14480214	117598	2.00	8.12
Ethylene circuit	**Intercooler (CW2)**	808610	14649	6.00	18.12
	After-cooler (CW3)	1387733	32642	6.00	23.52
	CRHX 1	726691	9916	8.09	13.65
	CRHX 2	537066	6603	7.93	12.29
	CRHX 3	134389	1384	7.99	10.30
	E2A	1967631	15765	2.00	8.01
	E2B	6106768	58352	2.00	9.56
	E2C	5023350	41906	2.00	8.34
Methane circuit	**Intercooler (CW4)**	424724	11410	6.00	26.86
	After-cooler (CW5)	1008122	27163	6.00	26.95
	CRHX 4	1307567	29388	10.00	22.48
	E3A	6643395	30129	2.96	4.54
	E3B	4423246	18442	2.95	4.17
	E3C	3006931	14142	2.90	4.70

TABLE 12 HEAT EXCHANGERS DESIGN CASE 5

Case 5	Heat exchanger	UA [W/°C]	Q [kW]	Minimum approach [°C]	LMTD [°C]
Propane circuit	Condenser (CW1)	22463702	173695	6.00	7.73
	E1A	1903511	11576	2.00	6.08
	E1B	2462479	19670	2.00	7.99
	E1C	14307377	116194	2.00	8.12
Ethylene circuit	Intercooler (CW2)	798692	14474	6.00	18.12
	After-cooler (CW3)	1370752	32252	6.00	23.53
	CRHX 1	718017	9797	8.90	13.65
	CRHX 2	530655	6524	7.93	12.29
	CRHX 3	132784	1367	7.99	10.30
	E2A	1944146	15577	2.00	8.01
	E2B	6033877	57655	2.00	9.56
	E2C	4963391	41406	2.00	8.34
Methane circuit	Intercooler (CW4)	419564	11274	6.00	26.87
	After-cooler (CW5)	995860	26839	6.00	26.95
	CRHX 4	1291960	29038	10.00	22.48
	E3A	6564099	29769	2.96	4.55
	E3B	4370450	18222	2.95	4.17
	E3C	2971040	13973	2.90	4.70

TABLE 13 HEAT EXCHANGERS DESIGN CASE 6

Case 6	Heat exchanger	UA [W/°C]	Q [kW]	Minimum approach [°C]	LMTD [°C]
Propane circuit	Condenser (CW1)	19163940	150422	6.00	7.85
	E1A	1648457	10025	2.00	6.08
	E1B	2132529	17034	2.00	7.99
	E1C	12390316	100625	2.00	8.12
Ethylene circuit	Intercooler (CW2)	689128	12534	6.00	18.19
	After-cooler (CW3)	1183103	27931	6.00	23.61
	CRHX 1	621809	8485	8.09	13.65
	CRHX 2	459552	5650	7.93	12.29
	CRHX 3	114993	1184	7.99	10.30
	E2A	1683647	13490	2.00	8.01
	E2B	5225392	49930	2.00	9.56
	E2C	4298341	35858	2.00	8.34
Methane circuit	Intercooler (CW4)	362487	9763	6.00	26.93
	After-cooler (CW5)	860231	23243	6.00	27.01
	CRHX 4	1118849	25147	10.00	22.48
	E3A	5684568	25781	2.96	4.54
	E3B	3784849	15780	2.95	4.17
	E3C	2572947	12101	2.90	4.70

6 RESULTS

In this chapter the results from the simulations will be presented. The main focus is on:

- Operating points of the compressors
- Available power from driver and consumption by the compressors
- Power load distribution and power split

Operating points for the compressors gives information about where in the compressor map are the compressors operating. This also means what speed the compressor is operating at. This gives information about how close or far from the best operating point the compressors are. It is chosen to show the compressor map and operating points for the LP compressors in each circuit in this chapter. All compressor maps are found in the appendices.

The lines in the compressor map represent the compressor speed at different operating conditions. The line in the top represents 105% of the compressor design speed, the lines under represents 100% speed, 90% speed, 80% speed and the bottom one 70% of design speed. The operating point will approach surge at 30 °C, 20°C is the design point. The orange line intersecting all speed lines are the surge control line and it represents the minimum flow allowed through the compressor at the different compressor speeds. An explanation of the colored speed lines are given in Figure 23. The same color codes apply for all compressor curves in this thesis.

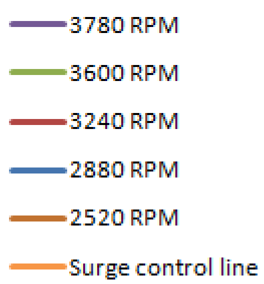

FIGURE 23 COLOR CODES FOR COMPRESSOR SPEED

The difference in available power from gas turbines and consumption by the compressors implies how well suited the driver are for that specific plant, and if it is possible to operate the plant at all temperatures. It also indicates how flexible the plant is when it comes to increasing the capacity when available power increases.

Power load distribution is important to evaluate how well suited the drivers are for the plant, and to see how much power that have to be transferred between the three circuits. Power split means how much power each circuit uses. This can be compared to the available power each individual driver can deliver. Since electrical drives can be customized to a specific compressor, the power split for Case 3 and 6 are excluded.

Process efficiency and capacity will be highlighted in Chapter 7 Discussion.

6.1 Air cooled process

The process solution utilizing air cooling will be presented in this subchapter. The operating points, available power compared to power consumed and power load distribution of Case 1 will be presented first, then for Case 2 and Case 3. The operating points from all air cooled cases can be found in Appendix A.1 to A.3.

6.1.1 Case 1

Case 1 is an air cooled case, using six LM6000 gas turbines as direct compressor drive. The design temperature is 20°C and the design production is 6.342 MTPA.

The operating points for the LP propane compressor for Case 1 are shown in Figure 24. When air temperature drops, the production increases. The production rate has to be held constant from below 10°C. At below 10°C the compressor speed has to be reduced, and the operating point (compressor speed) goes down parallel to the surge control line. The MP and HP propane compressor behaves similarly but reaches stone wall conditions at -10 °C, see Appendix A.1, Figure 64. This is avoided by lowering the air mass flow through the propane condenser, hence reducing the cooling duty, and by that increasing the polytrophic head.

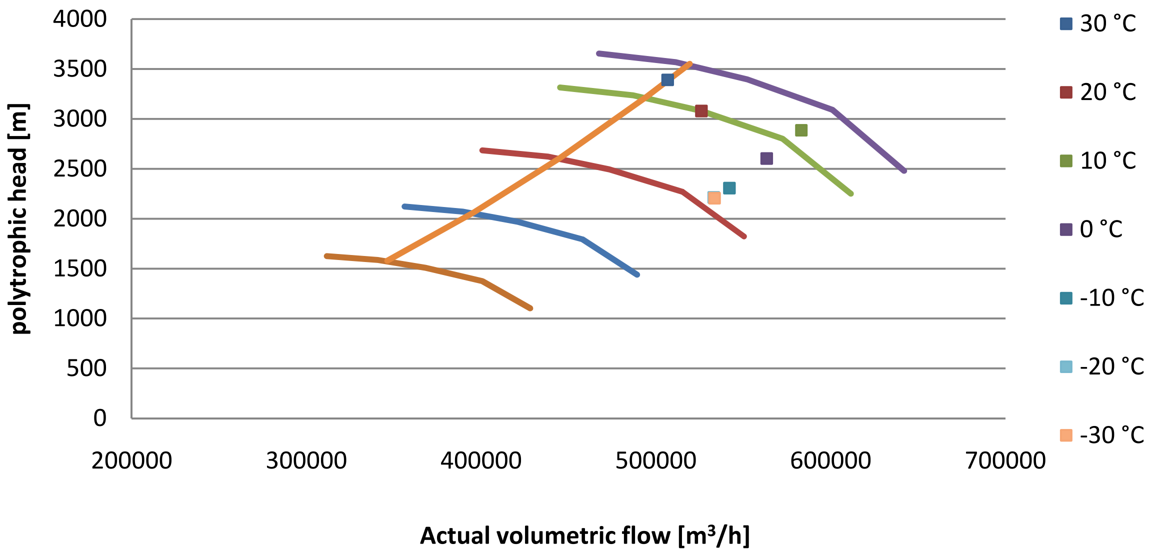

FIGURE 24 LP PROPANE COMPRESSOR CASE 1

The operating points for the LP ethylene compressor are shown in Figure 25. At 30°C the compressor approaches surge. When temperature decreases, the compressor reaches maximum polytrophic head and speed. Hence the plant production approaches maximum. The ethylene compressors are the limiting factors for production increase. The MP and HP ethylene compressor behaves similarly; see Appendix A.2, Figure 65.

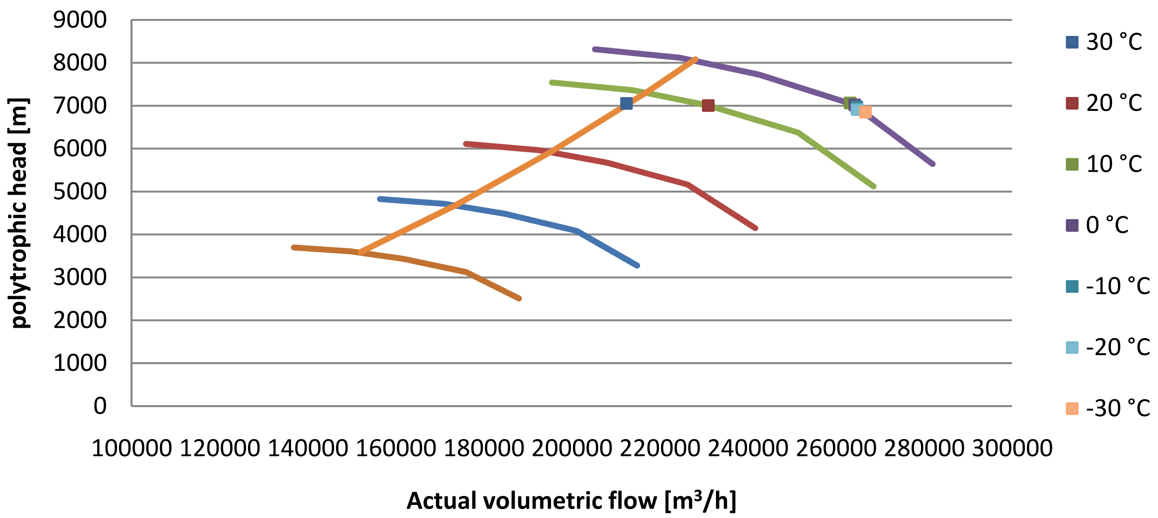

FIGURE 25 LP ETHYLENE COMPRESSOR CASE 1

The operating points for the LP methane/flash compressor are shown in Figure 26. The compressor is approaching surge at 30°C. At 10°C the compressor is close to maximum polytrophic head at maximum speed. When temperature drops further the compressor has to reduce its speed. The MP and HP compressor behaves similarly; see Appendix A.1, Figure 66.

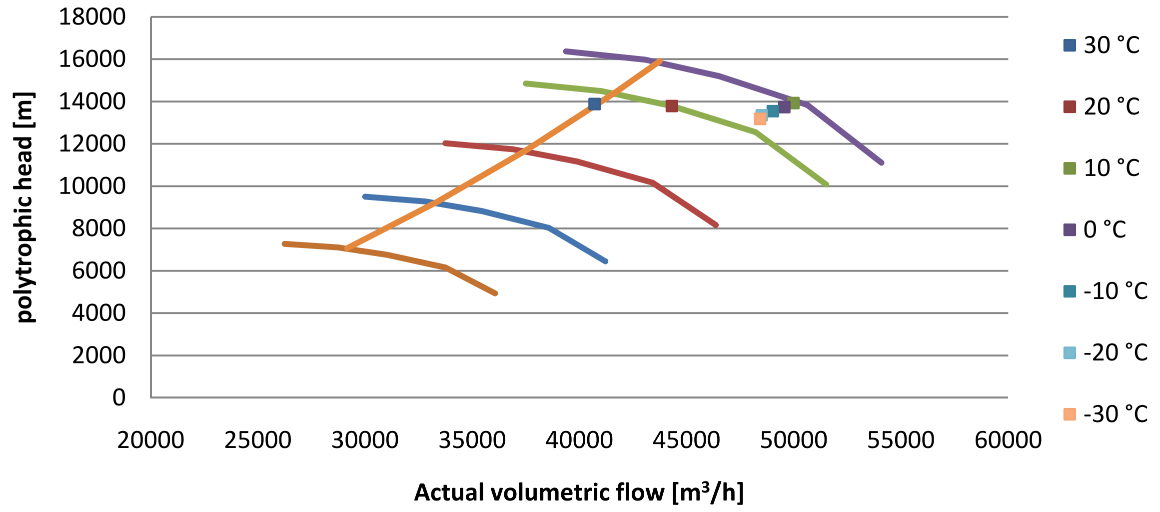

FIGURE 26 LP FLASH/METHANE COMPRESSOR CASE 1

The difference between the amount of power needed by the refrigerant compressors and the power available from the gas turbines is shown in Figure 27. The compressor need more power than the gas turbines can deliver at 30 °C. At 20°C the difference is 0MW because this is the design temperature. The difference increases positively when temperature drops.

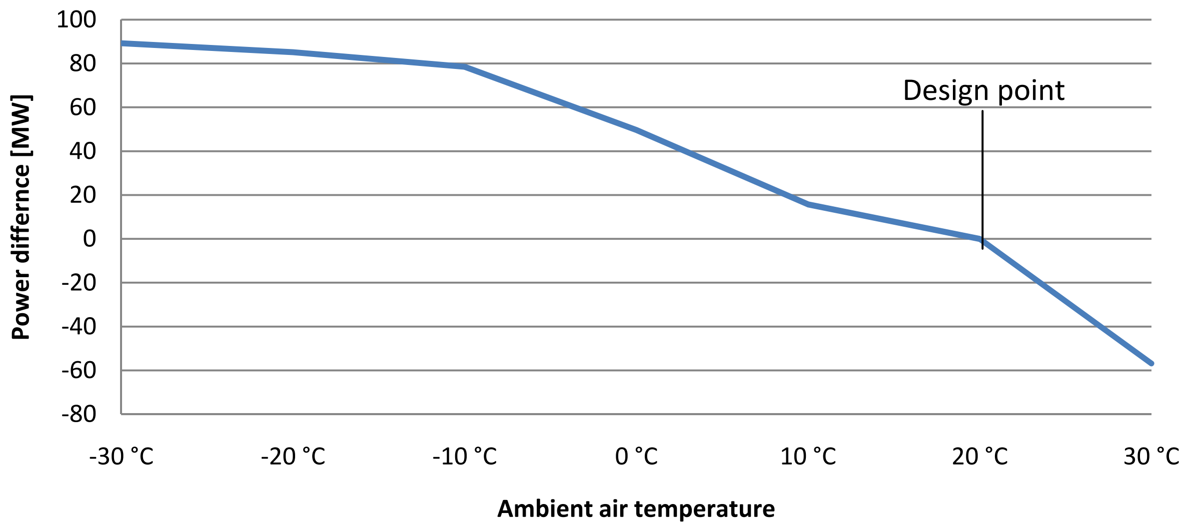

FIGURE 27 DIFFERENCE BETWEEN AVAILABLE AND CONSUMED POWER CASE 1

The power load distribution for the three circuits, for the entire temperature range in Case 1 is shown in Figure 28. The pre-cooling load decreases with decreasing temperature. The sub-cooling circuit is the circuit least sensitive for the change in air temperature. At high temperatures the pre-cooling circuit uses most power. Between 20°C and 10°C the liquefaction circuit becomes the most power demanding circuit.

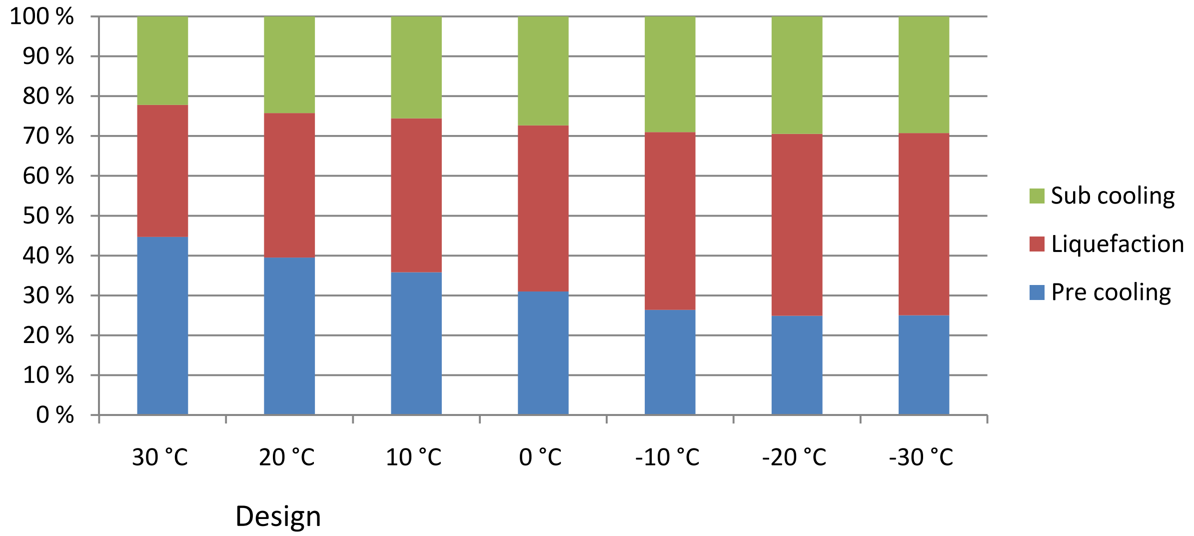

FIGURE 28 POWER LOAD DISTRIBUTION FOR CASE 1

The power split describes the power each circuit uses compared to what the driver delivers to each circuit. The power split for the three circuits in the design case is shown in Figure 29. Approximately 20 MW needs to be transferred from the sub-cooling shaft to the pre-cooling and liquefaction shaft.

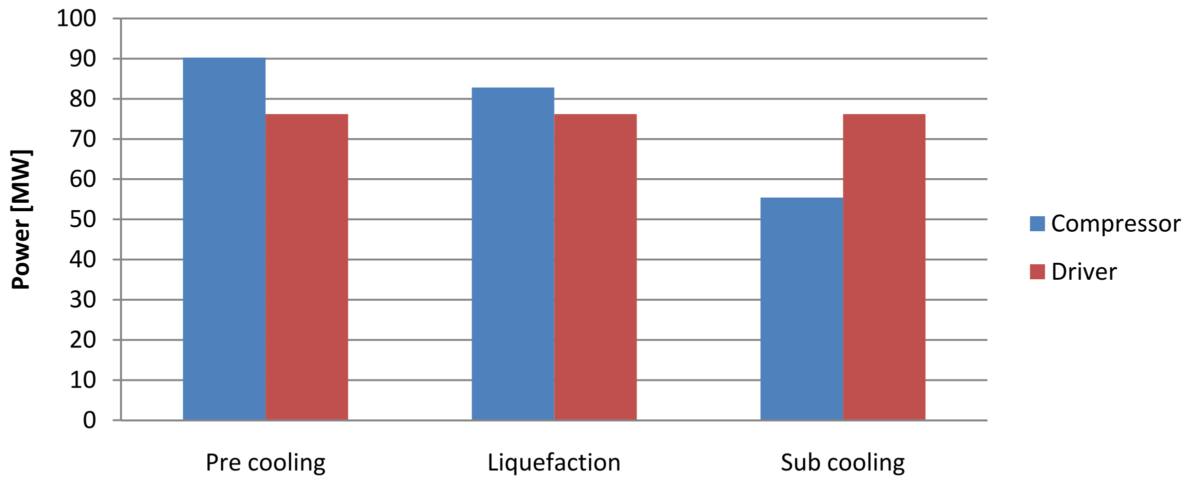

FIGURE 29 POWER SPLIT IN DESIGN CASE 1

6.1.2 Case 2

Case 2 is an air cooled case, using six Frame 6B gas turbines as direct compressor drive. The design temperature is 20°C and the design production is 6.336 MTPA.

The operating points for the LP propane compressor in Case 2 are shown in Figure 30. The operating point approaches surge at 30°C and are higher than the speed limit of 102% for Frame 6B. When the temperature decreases, the operating points tend to reduce in polytrophic head and compressor speed. At temperatures at -20°C and below, the operating points has to be controlled to match the required compressor speed at minimum 95% design speed. The MP and HP propane compressor behaves similar, see Appendix A.2, Figure 67.

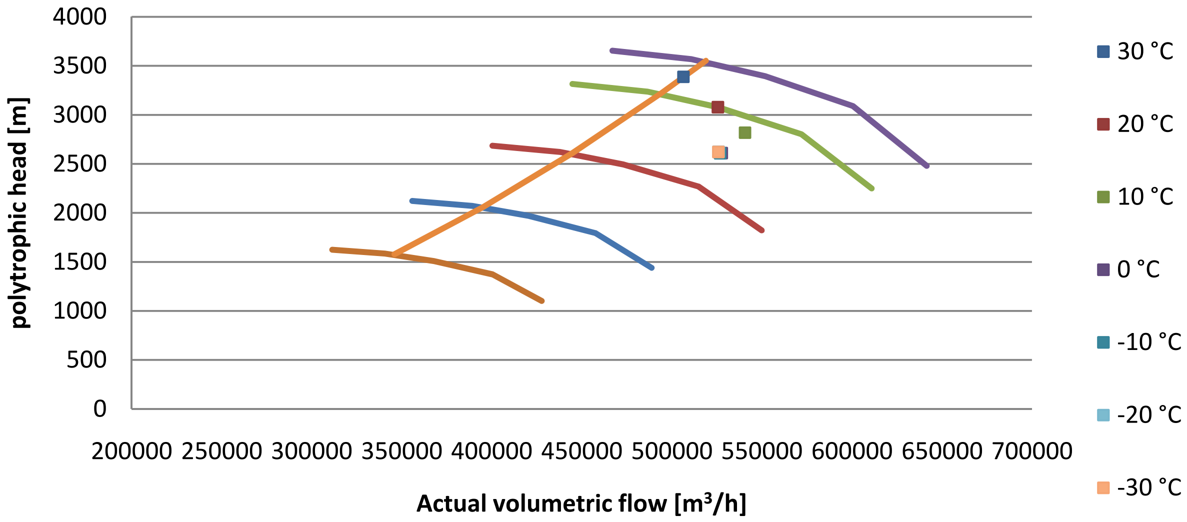

FIGURE 30 LP PROPANE COMPRESSOR CASE 2

The operating points for the LP ethylene compressor are shown in Figure 31. The compressor approaches surge at 30 °C. At approximately 10 °C maximum speed of the compressor driver is reach, 3672 rpm. From this temperature and below, the ethylene compressors are the bottleneck for increasing production. The MP and HP ethylene compressor behaves similar, see Appendix A.2, Figure 68.

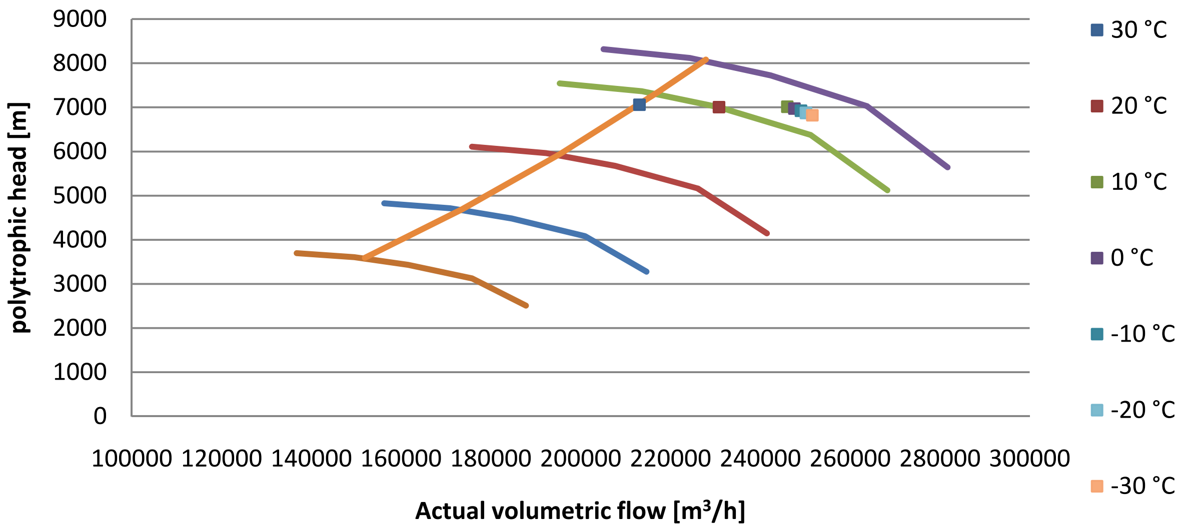

FIGURE 31 LP ETHYLENE COMPRESSOR CASE 2

The operating points of the LP flash compressor are shown in Figure 32. The compressor approaches surge at 30 °C. At -10°C the compressor speed is close to the maximum speed of the driver, but the polytrophic head is going down when the temperature decreases further. The MP and HP methane/flash compressor behaves similar, see Appendix A.2, Figure 69.

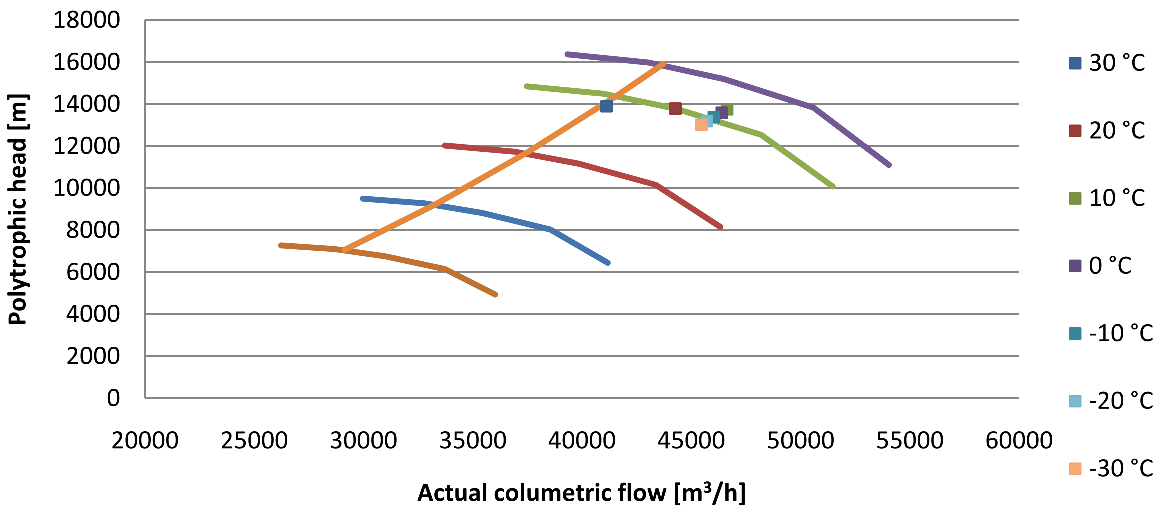

FIGURE 32 LP FLASH/METHANE COMPRESSOR CASE 2

The difference between the amount of power needed by the refrigerant compressors and the power available from the gas turbines in Case 2 is shown in Figure 33. The difference increases positively when temperature decreases.

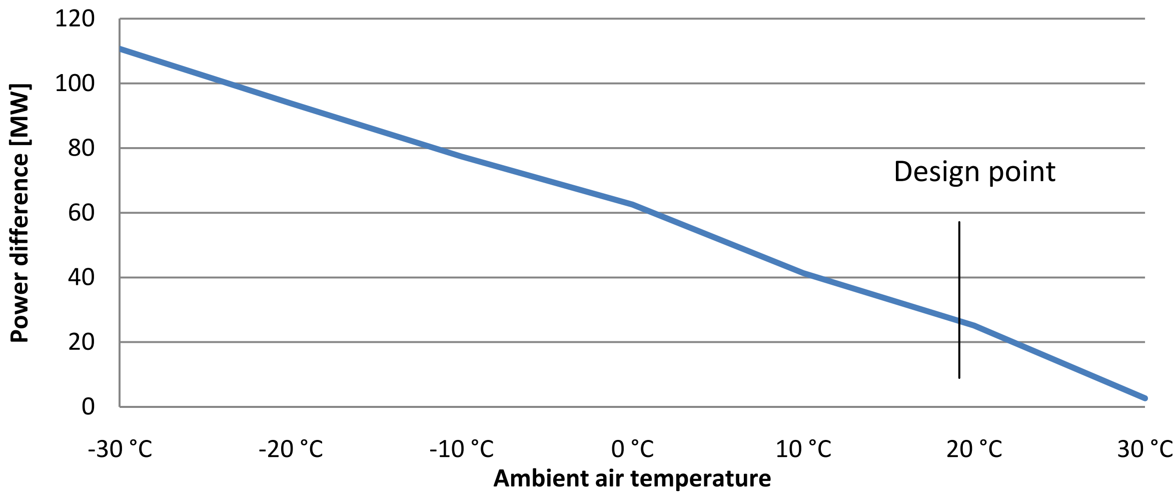

FIGURE 33 DIFFERENCE BETWEEN AVAILABLE AND CONSUMED POWER CASE 2

The power load distribution for the three circuits, for the entire temperature range in Case 2 is shown in Figure 34. The pre-cooling load decreases with decreasing temperature. The sub-cooling circuit is the circuit least sensitive for the change in air temperature. At high temperatures the pre-cooling circuit uses most power. Between 20°C and 10°C the liquefaction circuit becomes the most power demanding circuit.

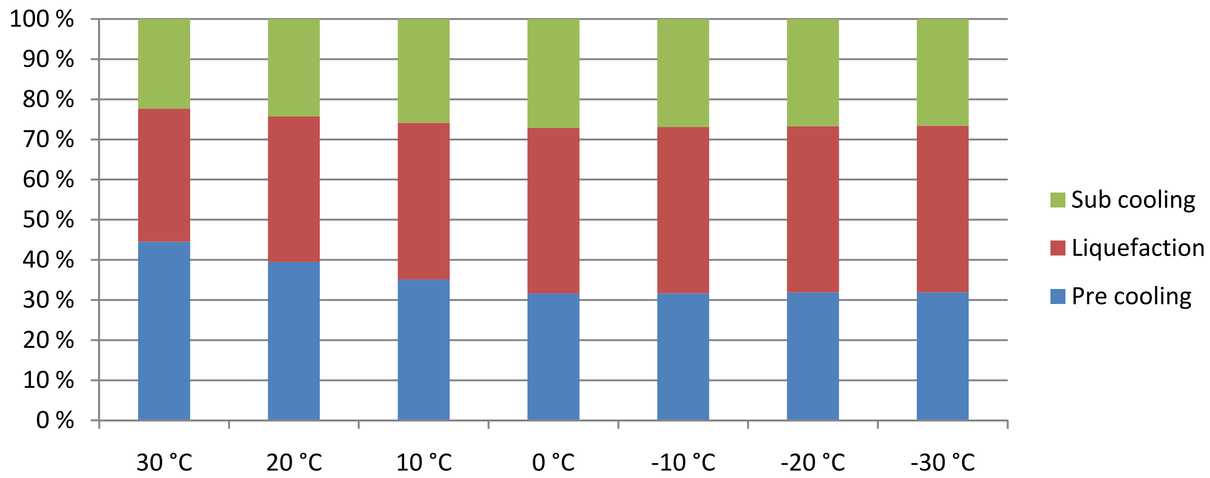

FIGURE 34 POWER LOAD DISTRIBUTION FOR CASE 2

The power split between the three circuits in the design case is shown in Figure 35. Since the gas turbine delivers more than the compressors need, there is less need for transferring power between the circuits. The pre-cooling circuit needs approximately 5 MW.

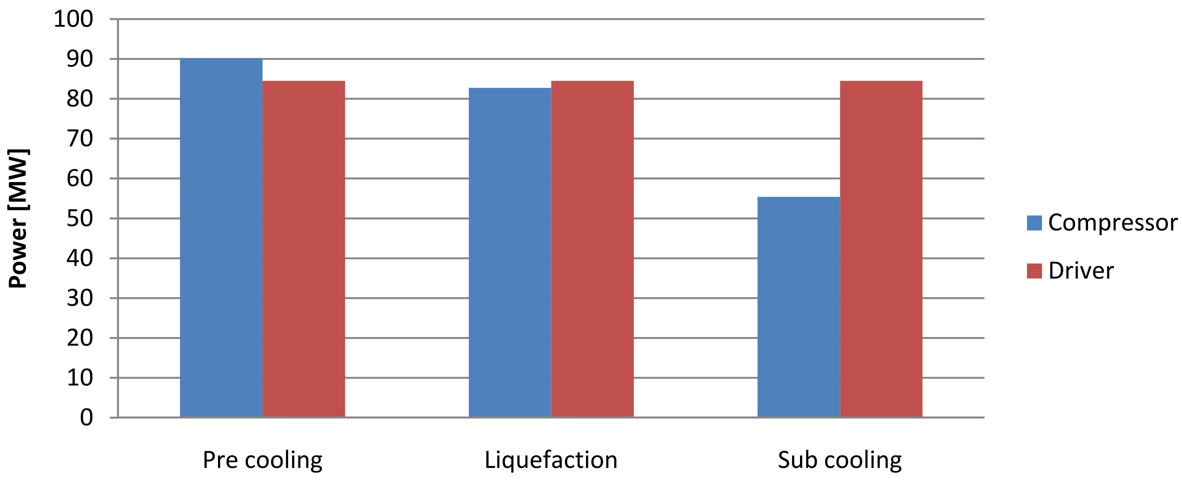

FIGURE 35 POWER SPLIT IN DESIGN CASE 2

6.1.3 Case 3

Case 3 is an air cooled case, using six 32.5MW electrical motors as compressor drive. The design temperature is 20°C and the design production is 5.410 MTPA.

The operating points for the LP propane compressor in Case 3 are shown in Figure 36. At 30°C the compressor approaches surge. When temperature decreases the polytrophic head and compressor speed decreases. The MP and HP propane compressor approaches stone wall conditions at -10 °C and are controlled by reducing the mass flow of air through the propane condenser, hence reducing the cooling load, and increasing the polytrophic head and compressor speed, see Appendix A.3, Figure 70.

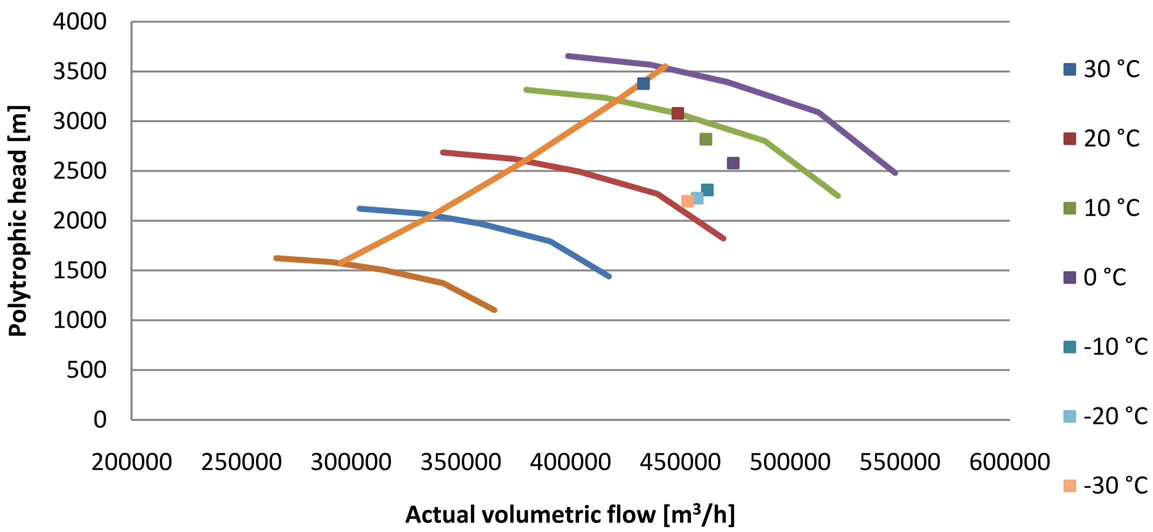

FIGURE 36 LP PROPANE COMPRESSOR CASE 3

The operating points for the LP ethylene compressor are shown in Figure 37. The compressor approaches surge at 30°C. At 0°C the compressor delivers maximum polytrophic head and maximum compressor speed which makes the ethylene compressors the limiting unit for increased production. Below 0°C the operating points follows the maximum speed line. The MP and HP ethylene compressors behave similarly, see Appendix A.3, Figure 71.

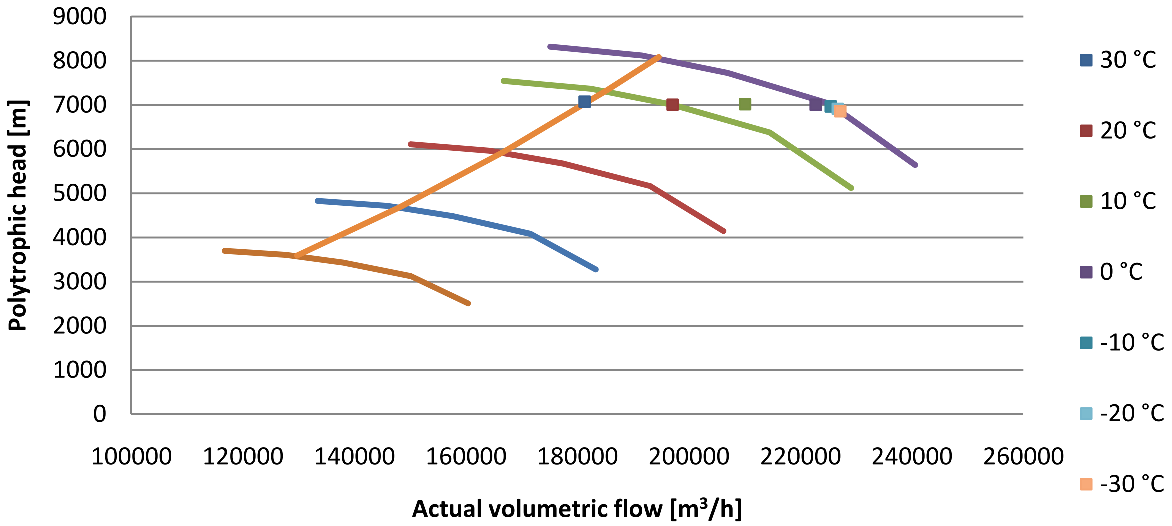

FIGURE 37 LP ETHYLENE COMPRESSOR CASE 3

The operating points of the LP flash compressor in Case 3 are shown in Figure 38. The compressor approaches surge at 30°C. When temperature falls and production increases the operating points are moving left in the compressor map. When production levels out at lower temperatures, the polytrophic head falls. The MP and HP compressor behave similarly; see Appendix A.3, Figure 72.

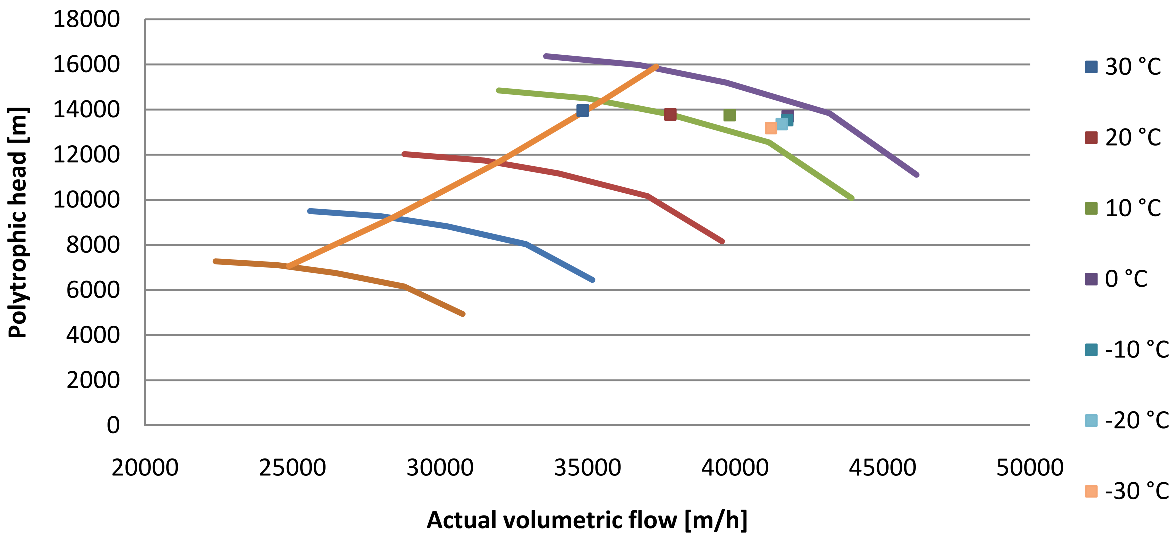

FIGURE 38 LP FLASH/METHANE COMPRESSOR CASE 3

The difference between the amount of power needed by the refrigerant compressors and available electrical power for the driver in Case 3 is shown in Figure 39. At 30°C the compressors needs slightly more than what is available. From 20°C to 0°C the compressor work and available power matches. From 0°C and further down in temperature, there is an excess of power. The reason seems to be that below 0°C the production is not increased anymore (it is close to constant), and the process cannot utilize the enhanced process efficiency that occur when temperature decreases further. This leads to an excess of power below 0°C.

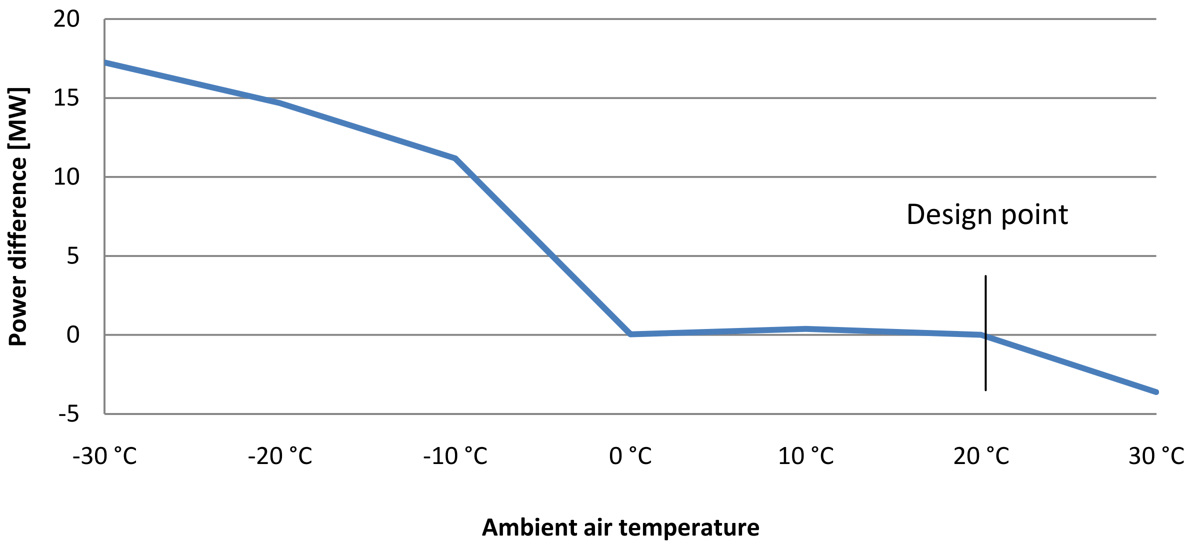

FIGURE 39 DIFFERENCE BETWEEN AVAILABLE AND CONSUMED POWER CASE 3

The power load distribution for the three circuits, for the entire temperature range in Case 2 is shown in Figure 40. The pre-cooling load decreases with decreasing temperature. The sub-cooling circuit is least sensitive for the change in air temperature. At high temperatures the pre-cooling circuit uses most power. Between 20°C and 10°C the liquefaction circuit becomes the most power demanding circuit.

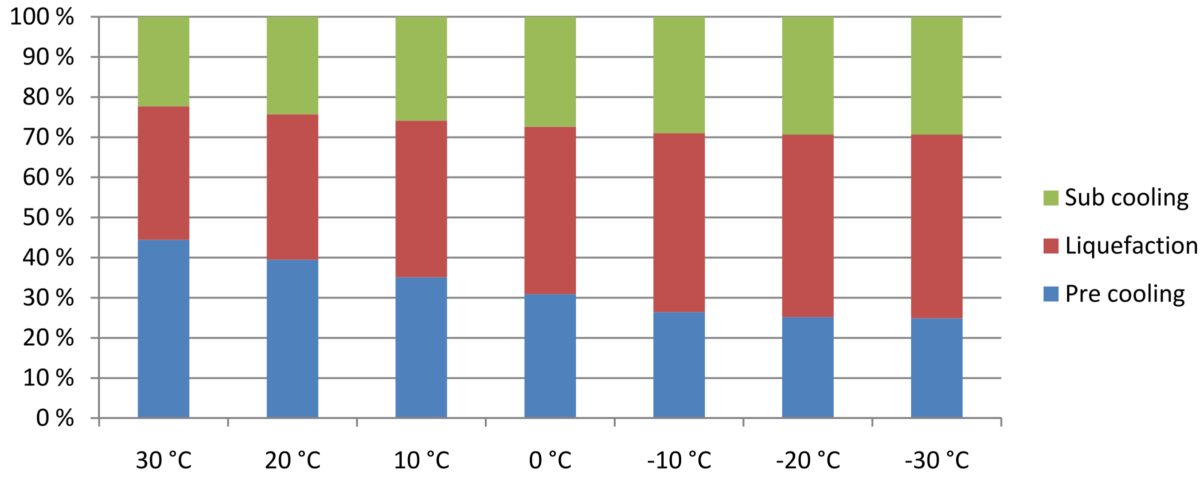

FIGURE 40 POWER LOAD DISTRIBUTION FOR CASE 3

6.2 WATER COOLED PROCESS

The process solution utilizing water cooling will be presented in this subchapter. The operating points and power load distribution of Case 4 will be presented first, followed by Case 5 and Case 6. For the water cooled cases the results are based on yearly temperature data. The operating points for the water cooled cases can be found in Appendix A.4 to A.6.

Notice that the comparison of power available and power needed by the compressors is excluded in the water cooled cases. The reason is that they are matching. There are no excess of power or need for import of power, because of operation close to design throughout the year.

6.2.1 CASE 4

Case 4 is a water cooled case, using three LM6000 gas turbines as direct compressor drive. The design temperature is 4°C water and 5°C air temperature and the design production is 4.9 MTPA.

The operating points for the LP propane compressor for Case 4 are shown in Figure 41. The polytrophic head is high when the water temperature is high. When air temperature is high the operating points tend to move left in the compressor map. The MP and HP propane compressor behaves similarly; see Appendix A.4, Figure 73. Temperatures are shown in brackets (seawater temperature, air temperature)

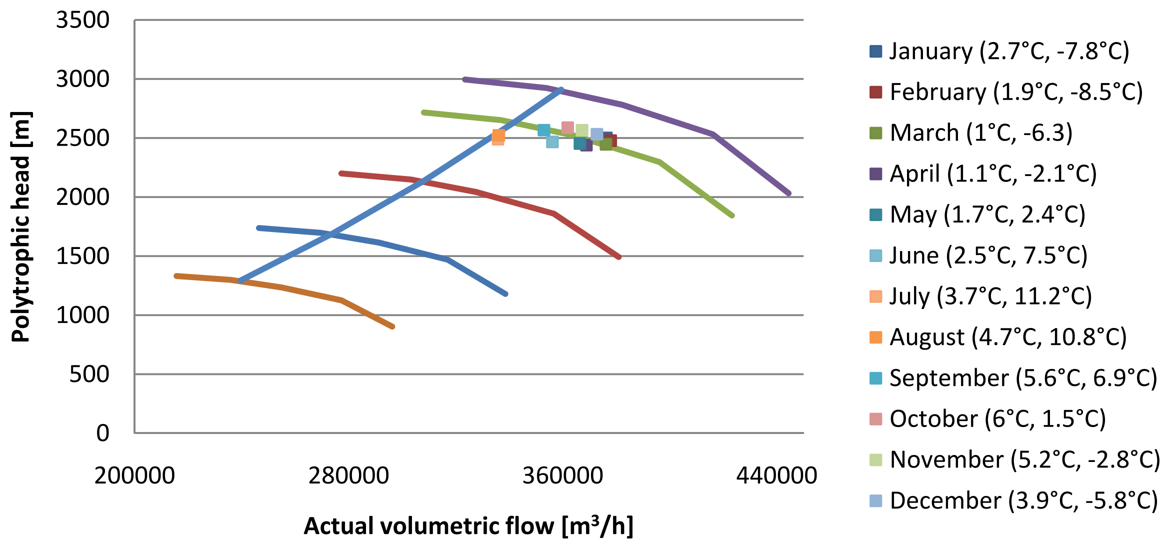

FIGURE 41 LP PROPANE COMPRESSOR CASE 4

The operating points for the LP ethylene compressor are shown in Figure 42. The operating points follow the production by moving left at high temperatures (low production) and right at low temperatures (high production). The MP and HP ethylene compressors behave similarly; see Appendix A.4, Figure 74.

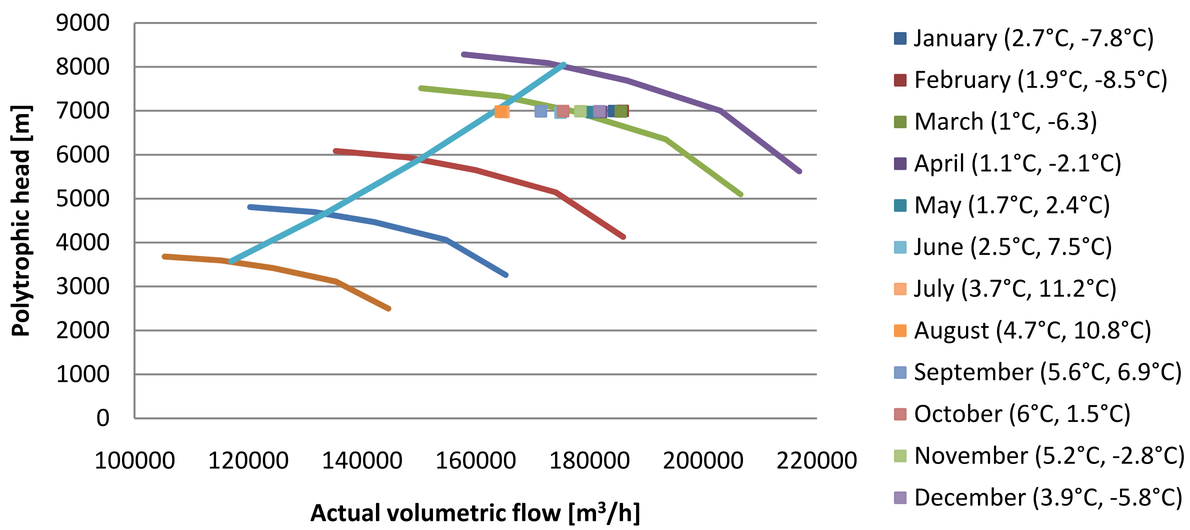

FIGURE 42 LP ETHYLENE COMPRESSOR CASE 4

The operating points of the LP flash/methane compressor are shown in Figure 43. The compressor is behaving similar to the ethylene compressor, the operating points move left at low production and right at high production. The operating points are close to the surge control line in the summer months. The MP and HP compressor behaves similarly; see Appendix A.4, Figure 75.

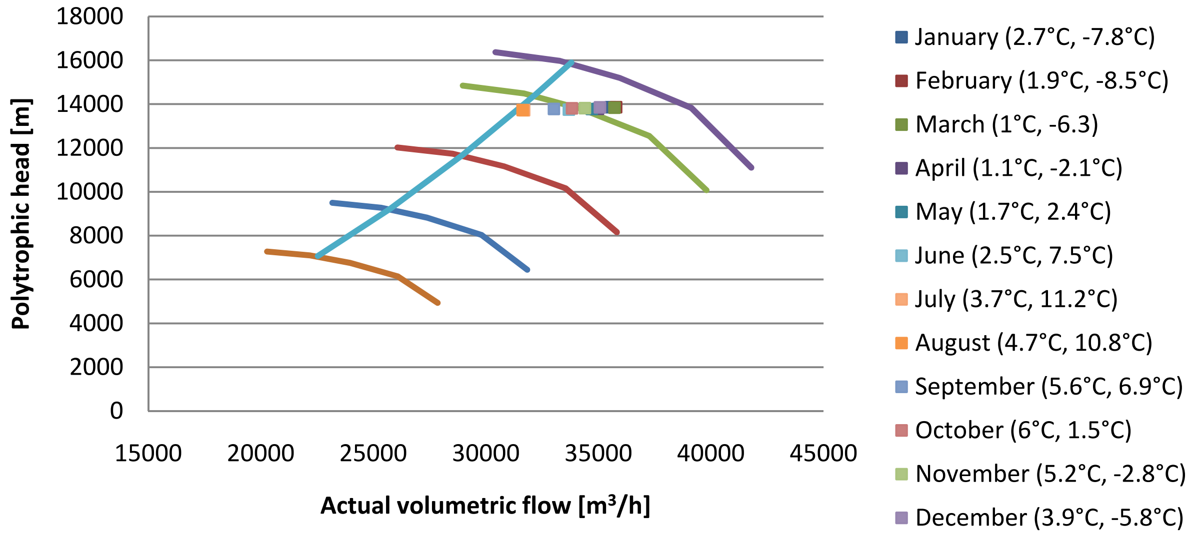

FIGURE 43 LP FLASH/METHANE COMPRESSOR

The load distribution for Case 4 is shown in Figure 44. The average load distribution per month is quite stable, varying not more than 2.2 % for the pre-cooling circuit, 1.3% for the liquefaction circuit and 0.9% for the sub-cooling circuit. The liquefaction circuit has the highest power consumption.

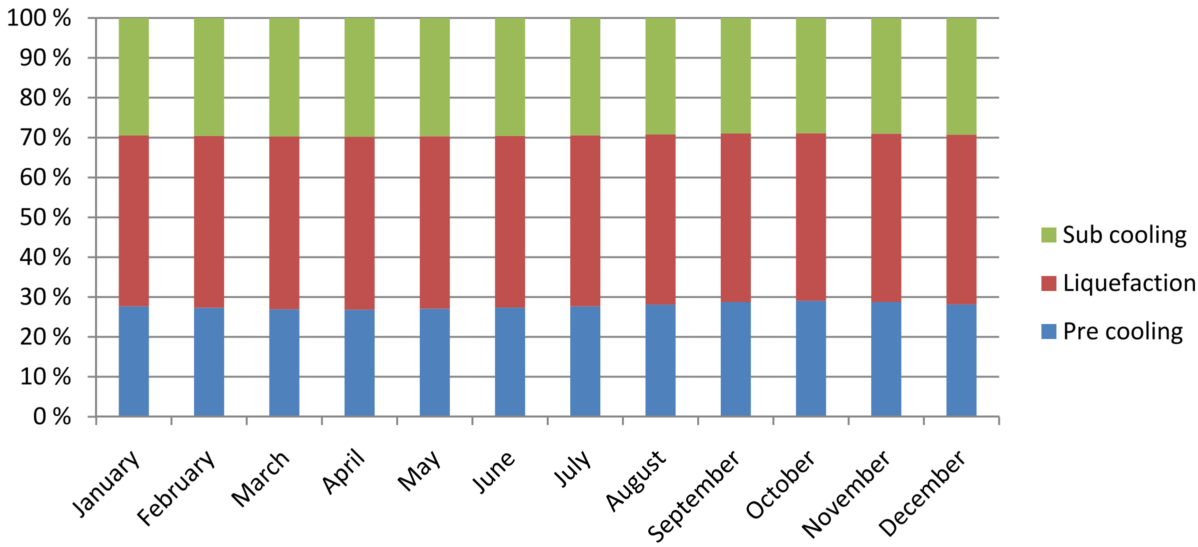

FIGURE 44 POWER LOAD DISTRIBUTION CASE 4

The power split between the three circuits in design is given in Figure 45. There is a need for transfer of approximately 13 MW from the pre-cooling circuit and sub-cooling circuit to the liquefaction circuit.

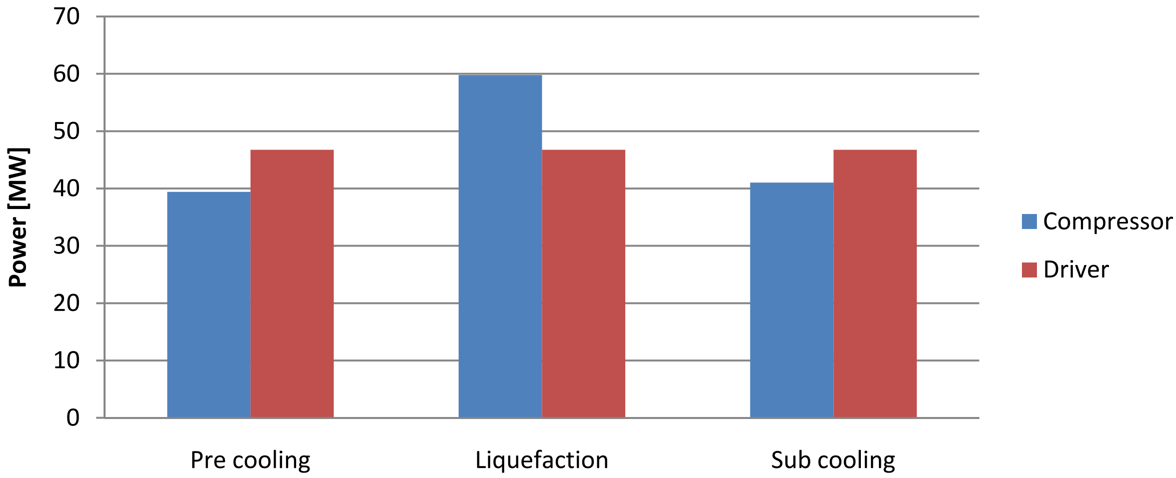

FIGURE 45 POWER SPLIT IN DESIGN CASE 4

6.2.2 CASE 5

Case 5 is a water cooled case, using three Frame 6B gas turbines as direct compressor drive. The design temperature is 4°C water and 5°C air temperature and the design production is 4.841 MTPA.

The operating points for the LP propane compressor for Case 5 are shown in Figure 46. The polytrophic head is high when water temperature is high. When air temperature is high the operating points tend to move left in the compressor map. The MP and HP propane compressor behave similarly; see Appendix A.5, Figure 76. The temperatures for each month are shown in brackets; (seawater temperature, air temperature).

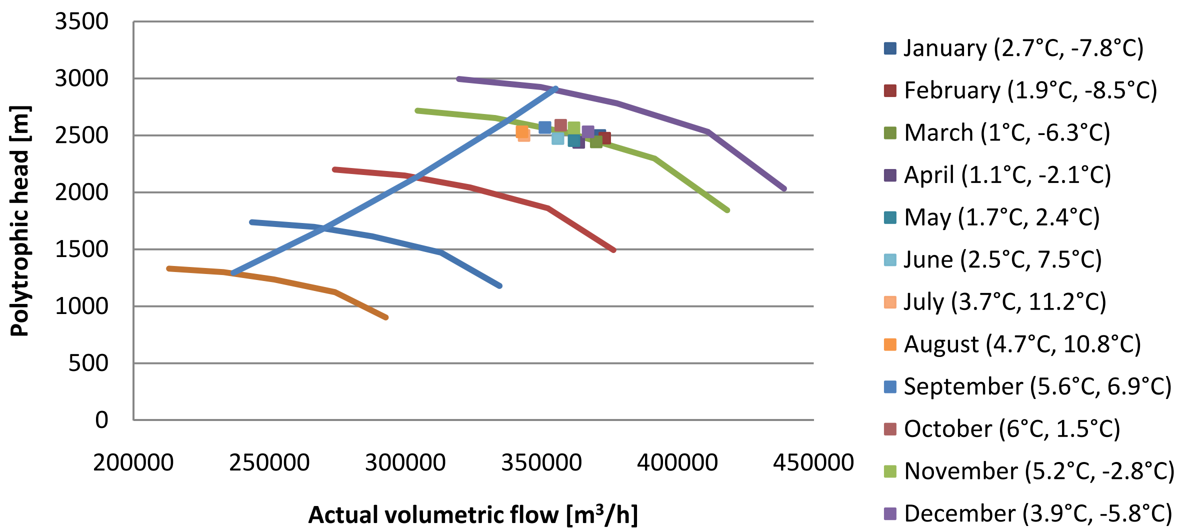

FIGURE 46 LP PROPANE COMPRESSOR CASE 5

The operating points for the LP ethylene compressor are shown in Figure 47. The operating points move right when production is increased, and left when production is decreased. The MP and HP ethylene compressor behave similarly; see Appendix A.5, Figure 77.

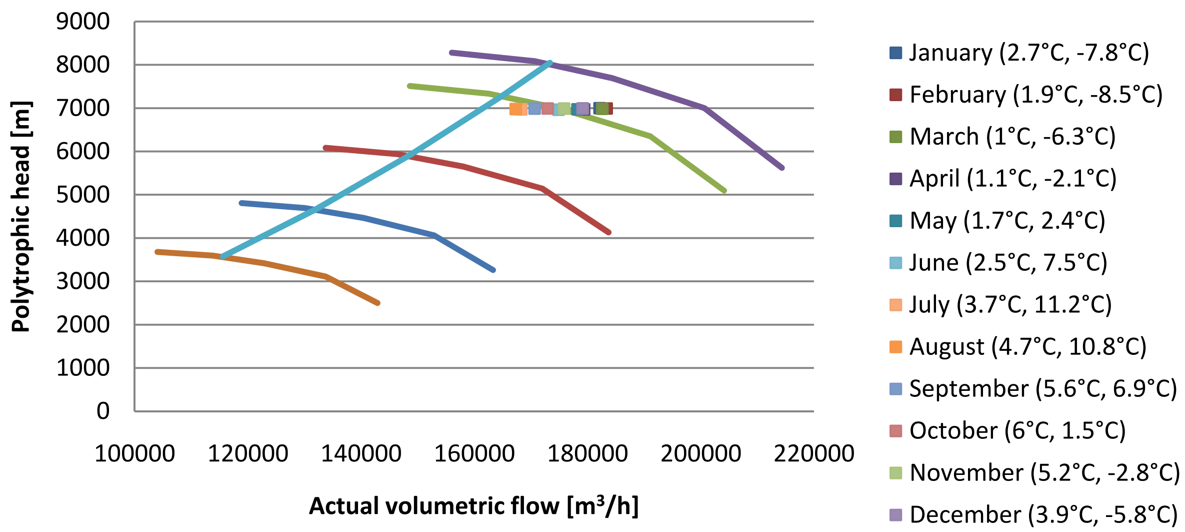

FIGURE 47 LP ETHYLENE COMPRESSOR CASE 5

The operating points of the LP flash/methane compressor are shown in Figure 48. The operating points tend to move left as temperature goes up (production falls) and right as temperature decreases (production rises). The MP and HP methane/flash compressor behave similarly, se Appendix A.5, Figure 78.

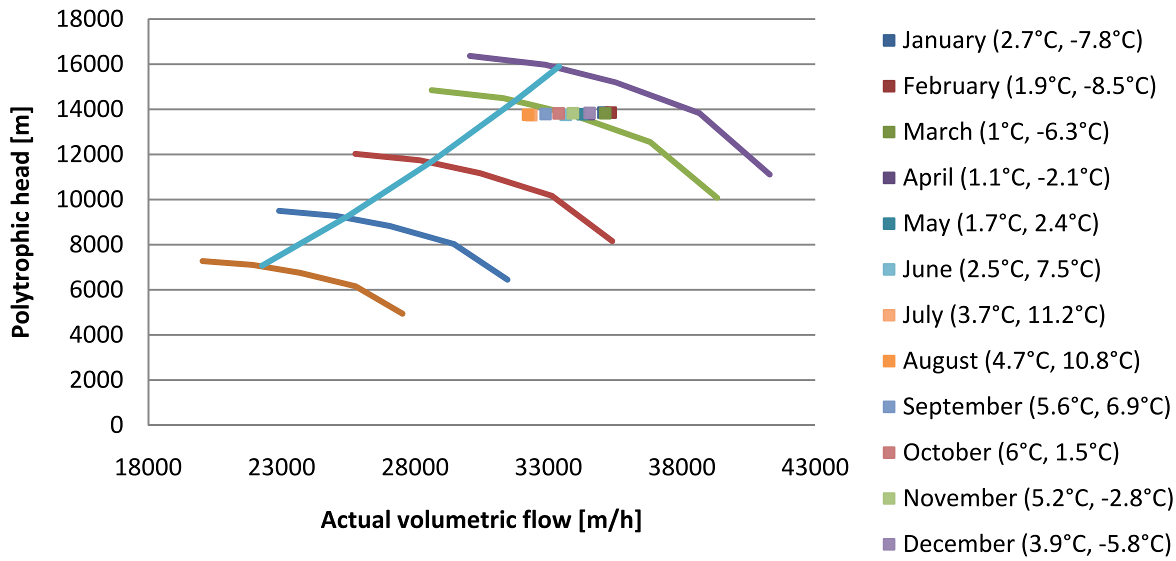

FIGURE 48 LP FLASH/METHANE COMPRESSOR CASE 5

The power load distribution for Case 5 is shown in Figure 49. The load distribution is quite stable throughout the year. The variation is identical to the variation in Case 4.

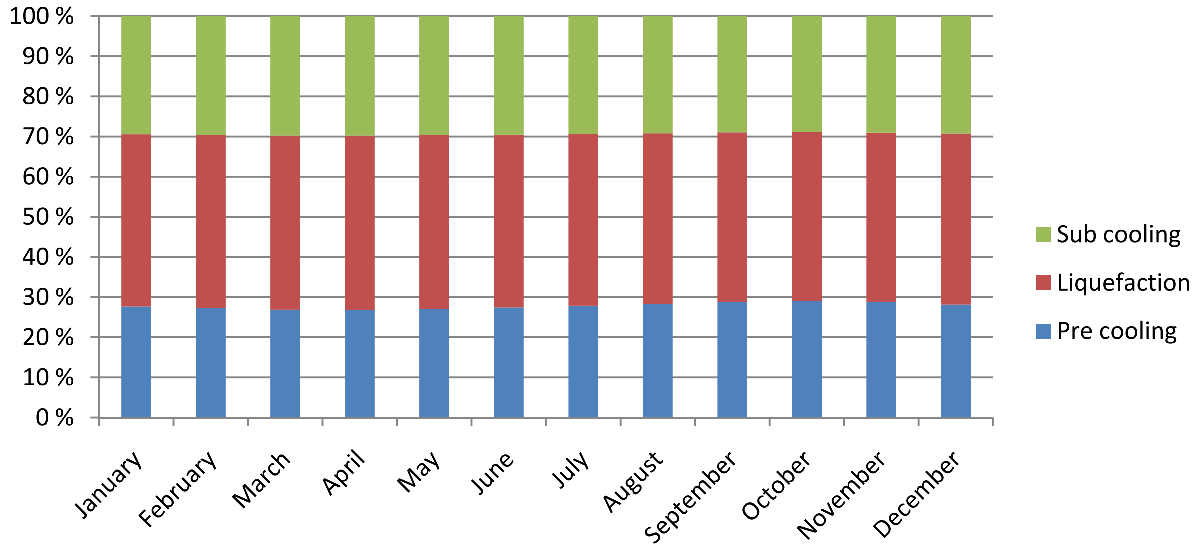

FIGURE 49 POWER LOAD DISTRIBUTION CASE 5

The power split between the three circuits in design for Case 5 is shown in Figure 50. Approximately 13 MW has to be transferred from pre-cooling and sub-cooling circuit to the liquefaction circuit through a helper motor.

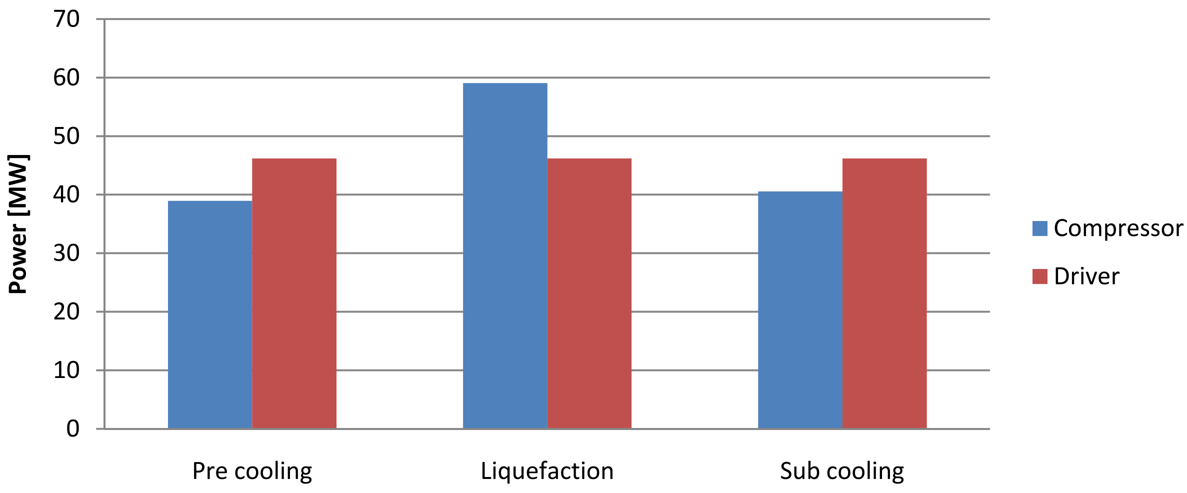

FIGURE 50 POWER SPLIT IN DESIGN CASE 5

6.2.3 Case 6

Case 6 is a water cooled case, using three or six electrical motors as compressor drive. The design temperature is 4°C water and 5°C air temperature and the design production is 4.193 MTPA.

The operating points of the LP propane compressor for Case 6 are shown in Figure 51. Since the power available is constant the air temperature does not affect the process. This makes the operating points more stable, and will vary only as a function of the water temperature. The MP and HP propane compressors behave similarly; see Appendix A.6, Figure 79.

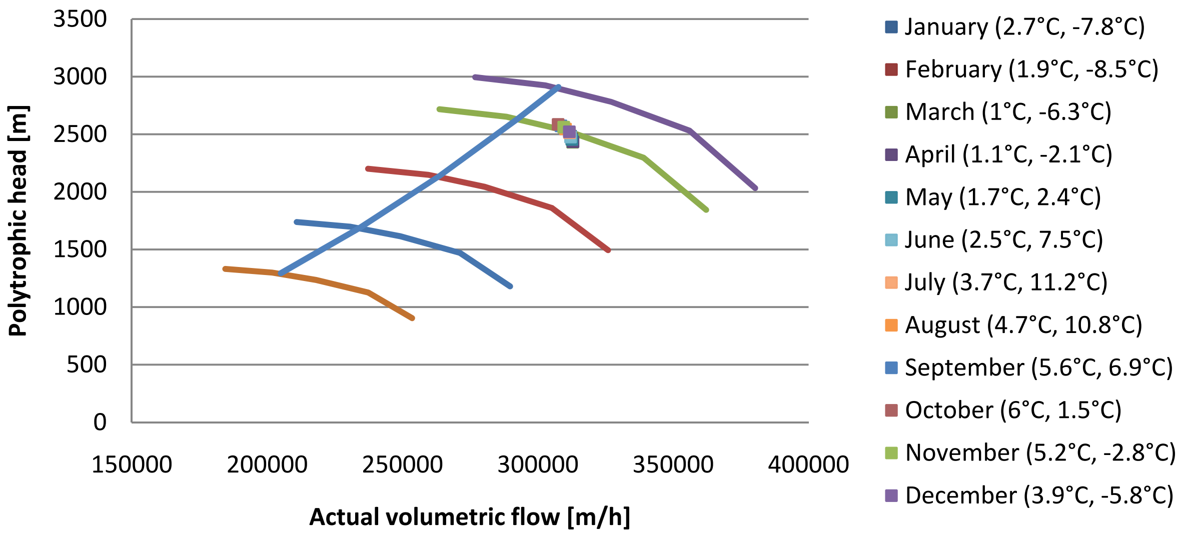

FIGURE 51 LP PROPANE COMPRESSOR CASE 6

The operating points of the LP ethylene compressor for Case 6 are shown in Figure 52. Because of the constant power available the operating points are not varying that much. The operating points tend to follow the production, moving left at high temperature (low production) and right at decreasing temperature (higher production). The MP and HP ethylene compressors are behaving similarly; see Appendix A.6, Figure 80.

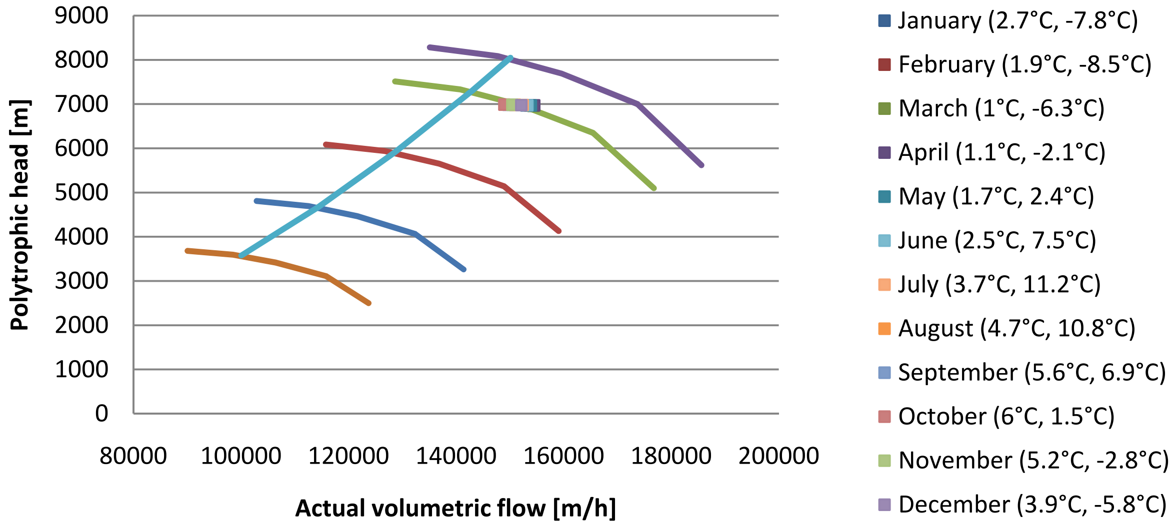

FIGURE 52 LP ETHYLENE COMPRESSOR CASE 6

The operating points for the LP flash/methane compressor are shown in Figure 53. The operating points vary in a small degree, only affected by production variation, because of the constant available power. The MP and HP compressors behave similar, see Appendix A.6, Figure 81.

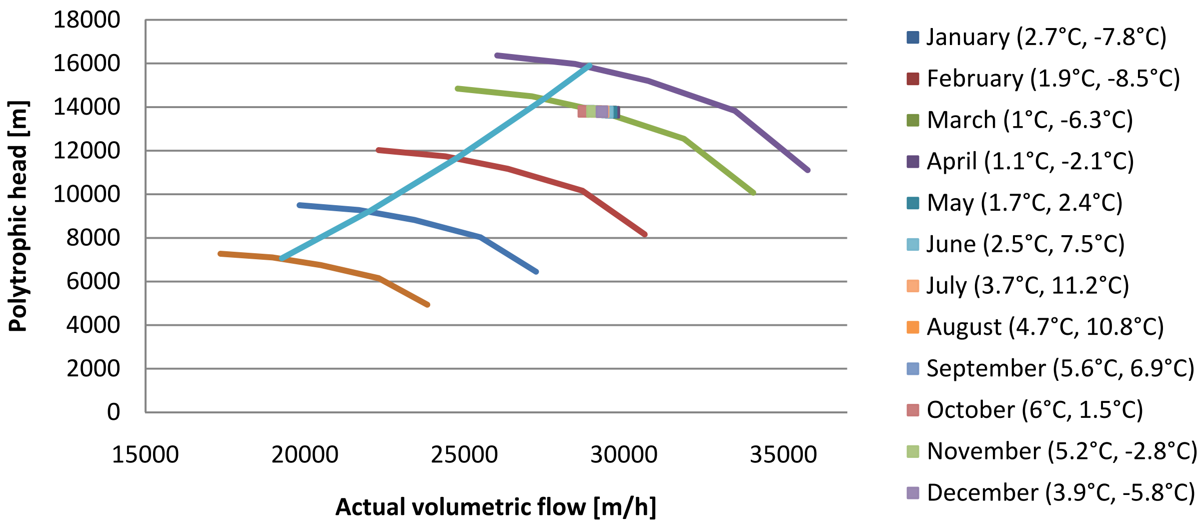

FIGURE 53 LP FLASH/METHANE COMPRESSOR CASE 6

The load distribution for Case 6 is shown in Figure 54. The average load distribution per month is stable, varying not more than 2.3 % for the pre-cooling circuit, 1.4% for the liquefaction circuit and 0.9% for the sub-cooling circuit. The liquefaction circuit stands for the highest power consumption.

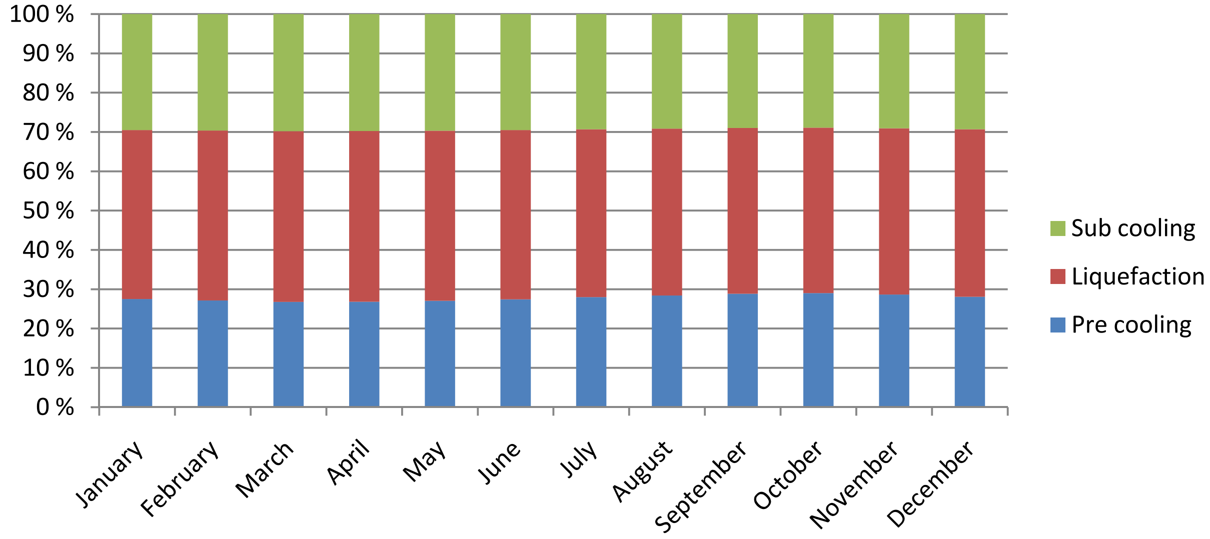

FIGURE 54 POWER LOAD DISTRIBUTION CASE 6

7 DISCUSSION

This chapter contains the review of the results, discussion of compressor behavior, compressor and driver matching, LNG production as function of temperature, process efficiency, effect of change in flash composition and the 2in1 concept.

7.1 REVIEW OF THE RESULTS

As expected for the air cooled cases the operating points of the propane compressors are most affected by the variation in air temperature. All air cooled cases approach the surge control line at 30°C. At extreme low temperatures the compressors has to be controlled to avoid stone wall conditions.

The ethylene compressors are affected by temperature variation directly to a certain degree but are in a more distinct degree affected indirectly by increased production which is a result of lower temperature. The polytrophic head is slightly reduced as the temperature decreases, but moves strongly to the right when production increases because of this temperature reduction. At 30°C when the production has to be decreased, the polytrophic head is reduced. The ethylene compressors are sensitive to increased production and will reach maximum polytrophic head and maximum speed at 10°C for Case 1 and 2 and at 0°C for Case 3. At this temperature the production can only be increased in a small degree.

The operating points of the methane/flash gas compressors are somehow connected directly to the air temperature, but as for the ethylene compressors, the methane/flash compressors are most sensitive indirectly through increased production. For Case 1 and 2 the polytrophic head goes down at temperatures below 10°C. The production increment below 10°C is small. At 30°C when the production decreases, the polytrophic head is reduced.

For the water cooled cases, the operating points of the propane compressors don't vary much because of the low variation in seawater temperature. For Case 4 the operating points are close to the surge control line in July and August. Case 5 is not that close to surge control line because Frame 6B has a less steep power curve than LM6000. The propane compressors in Case 6 have a smaller variation inside the compressor map due to the available power is assumed independent of the air temperature and regarded as constant. The condensing pressure is only dependent on water temperature which does not vary that much.

The ethylene compressors are in a low degree affected by the water temperature, because of the small difference between the high and low water temperature. The polytrophic head are close to constant for all water cooled cases. Variation in production affects the compressors.

The flash/methane compressors are behaving similarly to the ethylene compressors, being in a small degree affected by temperature change directly, but are affected indirectly by the variation in production .

The difference between available power and power needed by the compressor gives an indication of how well the driver can match the compressor at any temperature. For Case 1 the driver cannot deliver enough power at 30 °C. From 20°C and below there is an excess of power. For Case 2, the driver configuration at design can deliver more power than necessary. At 30°C the difference is positive and there is no need for external import of power. Case 3 has a difference of -4 MW at 30°C. The difference becomes 0 MW at 20°C and becomes positive at 0°C. The water cooled cases does not have problems with insufficiency of power because the average temperatures have been used in the simulations and not extreme temperatures.

The power load distribution for the air cooled cases shift from the pre-cooling being the most power consuming circuit at high temperatures, to liquefaction circuit being the largest power consumer at low temperatures. The water cooled cases have a stable load distribution throughout the year.

The power split in Case 1 shows a need for transferring approximately 20 MW from the sub-cooling shafts to the liquefaction and pre-cooling shafts. Case 2 shows little need for transfer of power, the pre-cooling shaft has a need for 5 MW. In Case 4 there is a need for 13 MW transfer from the pre-cooling and sub-cooling circuit to the liquefaction circuit. Case 5 is similar to Case 4.

7.2 COMPRESSOR BEHAVIOR

Case 1 is an air cooled process designed for a high air temperature of 20 °C, 10°C colder than the highest extreme temperatures that can occur in an arctic climate. Since the process is not designed for the highest possible temperature, it is expected that the operating points will move above the 100% speed line in the compressor map at the highest extreme temperature.

The operating points of the compressors remain inside the valid operational area of the compressor at all temperatures as Figure 24, Figure 25 and Figure 26 show. Reducing air mass flow through the propane condenser to avoid stone wall conditions has to be done.

Case 2 is designed for a high summer temperature of 20°C. Since the driver is an industrial gas turbine, the maximum speed of the compressors/drivers is 3672rpm. This speed is exceeded with approximately 30rpm in the propane compressors, at 30°C, which means that operating the plant at this temperature can be difficult or impossible.

A method of reducing the polytrophic head, hence reducing the compressor speed, is by reducing production, in such amount that the temperature difference in the propane condenser decreases. This is done to lower the condensing pressure of propane sufficiently. The condensing temperature can though not be lower than 0°C difference from the cooling temperature because this is the theoretical minimum temperature difference in a heat exchanger. Another way of reducing the polytrophic head and speed of the compressor is by increasing the low suction pressure in the propane circuit, this will lead to a lower polytrophic head, and a lower compressor speed. A consequence of doing this is that the temperature of the natural gas out of the propane circuit is increased, and may cause trouble for LPG extraction. None of these two control methods were tried in this project.

Case 3 is also designed for a high summer temperature of 20°C. The compressors have no problems operating at temperatures lower or higher than design.

When production increases at lower temperature because of more available power and a more efficient process, the ethylene compressors are the compressors that first reach maximum polytrophic head and maximum speed. Reaching these limits makes ethylene compressors the limiting component in the process, because they prevent the process from having a larger production increase at lower temperatures. All air cooled cases had this kind of behavior.

The water cooled cases has no considerable challenges related to compressor operation, because of the low variation in water temperatures and condensing pressures.

7.3 Compressor and driver matching

When designing an LNG process a match between the driver sizes available in the market and the plant size is important.

Case 1 utilizes six LM6000 aero derivative gas turbines with two turbines per circuit in a 2in1 concept. At 30°C the process will have problems operating because of a lack of power. This implies that design temperature may be too low. A higher design temperature will lead to even lower process efficiency when operating at normal lower temperatures. At lower temperatures the process is not able to utilize the available power from the gas turbines, leaving them to operate off design and with a lower efficiency.

Two gas turbines per circuit mean that there are two compressors per circuit. This means that the propane compressors have a maximum volumetric flow of slightly above 300 000 m^3/h per compressor. As a technical limit, (Bakken 2011) sets a maximum actual volumetric flow, currently at 200 000 m^3 to 250 000m^3/h. This maximum limit indicates that this design is too optimistic when it comes to production capacity or that there is a need for more than one compressor casing per driver shaft that operates in parallel.

Case 2 utilizes six Frame 6 industrial gas turbines with two turbines per circuit. To prevent the design from being too unrealistic the design was made at approximately the same production rate as Case 1. At 20°C design temperature the power available from the gas turbines is very high compared to what the compressors needs. At 30 °C the difference between power available and power needed are close to 0 MW. This means that the plant is able to operate at the entire temperature range, but the gas turbines have to operate off-design most of the year at a lower efficiency and the driver configuration is oversized. Instead of Frame 6, Frame 5 could be used for this kind of evaluation, since it is assumed to behave similar to Frame 6 but with a lower power output.

Case 3 utilizes a 2in1 concept with six electrical motors with two motors per circuit. In design the motors deliver approximately 77MW to the pre-cooling circuit, approximately 71MW to the liquefaction circuit and 47MW to the sub-cooling circuit. At 30°C the compressors need approximately 4MW more than the design, which should be possible to import. The two liquid expanders in the process deliver together approximately 2 MW that should be used. At lower temperatures than 0°C the power demand of the plant is less than design.

Case 4 utilizes three LM6000 aero derivative gas turbines, one on each cooling circuit. In July and August the compressors are close to the surge control line. This means that there is not much room for decreased production if air temperature increases, because the minimum power required by the compressors is reached. These months are the months with expectations for extreme high temperatures. This implies that the air temperature design could be set higher to compensate for the low power delivered at high temperatures.

Case 5 utilized three Frame 6 industrial gas turbines, one for each cooling circuit. This case has no problems operating at normal temperatures, but challenges might occur at extreme temperatures. The power output as a function of temperature for Frame 6 is not as steep as for LM6000.

Case 6 utilizes either six electrical motors, two on each circuit or three motors, one on each circuit. The pre-cooling compressors demand approximately 34 MW, the liquefaction compressors demand approximately 51 MW and the sub-cooling compressors demands 35 MW in design. Both three and six electrical motors are possible because their size do not exceed 65 MW.

7.4 Effect of ambient temperature on LNG production

The power output of a gas turbine is dependent on ambient air temperature. The power needed by the LNG process also varies with varying ambient cooling temperature. When cooling temperature is reduced an LNG process with gas turbine drive will get a double effect. The gas turbine produces more power, and at the same time the process can produce more because of higher process efficiency. The opposite effect happens when temperature increases. The possibility to utilize and/or withstand these effects is important in the choice of refrigerant, design and driver selection.

A yearly production profile for Case 1, 2 and 3 is shown in Figure 55. Both Case 1 and Case 2 are too optimistic when it comes to production, which is high. Case 2 are close to maximum production throughout the year and do not vary much. The reason is the driver speed limitation from 95% to 102%. The gas turbines operate at maximum speed large parts of the year.

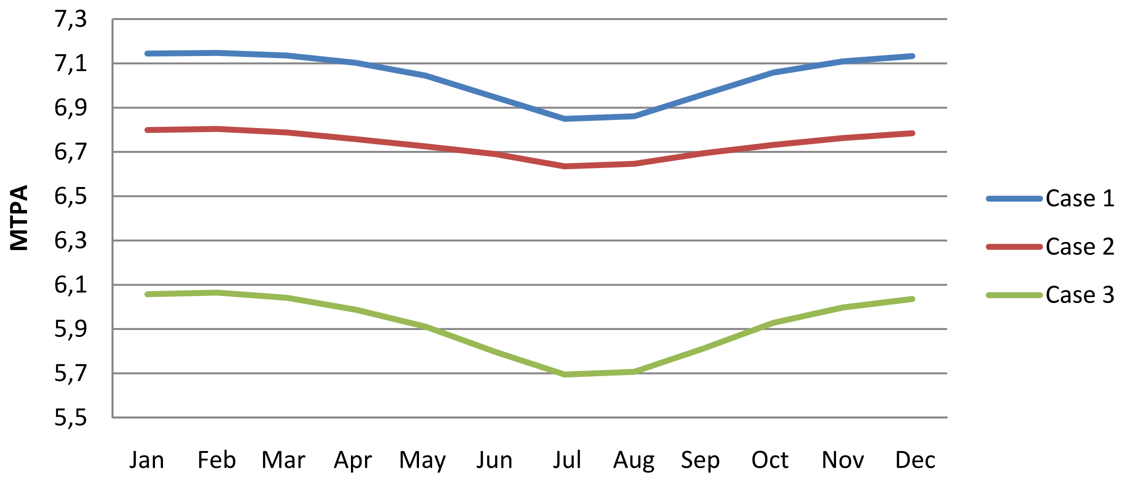

FIGURE 55 YEARLY PRODUCTION PROFILE CASE 1, CASE 2 AND CASE 3

To get a better impression on the scale of variation, a relative production profile has been made. The production is relative to the design production and is shown in Figure 56. Case 3 has the largest variation and is most flexible. Case 1 has the highest production compared to design and as mentioned earlier, Case 2 has the lowest production variation. Because of the constant available power in Case 3 the production will be able to vary more than Case 1. The increase in power available for Case 1 at lower temperatures makes the production reaching maximum production faster for Case 1 than for Case 3, and this is the reason for the larger variation in Case 3. The production lies considerably above design production the entire year. The curves are similar to what (Josten and Kennedy 2008) has found.

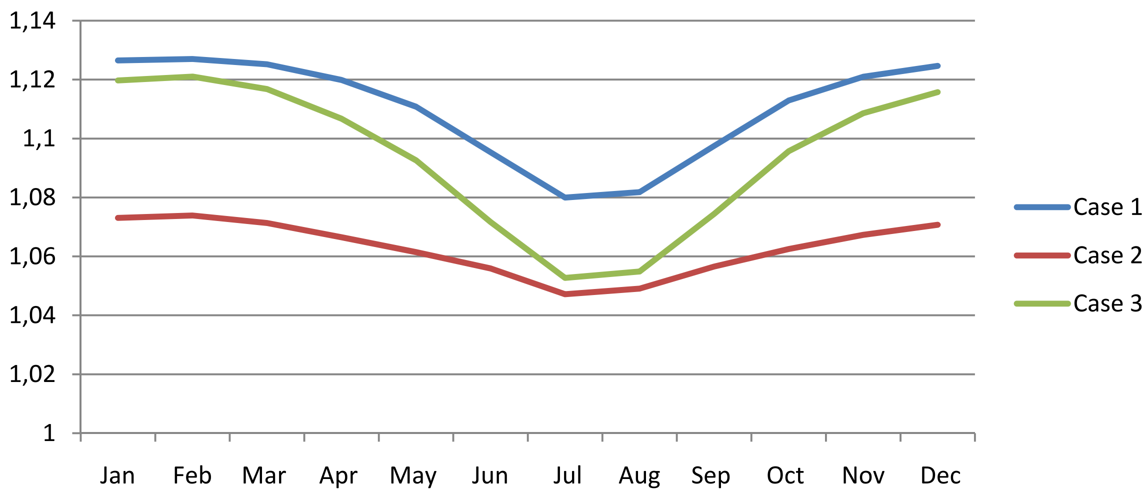

FIGURE 56 RELATIVE PRODUCTION FOR CASE 1, CASE 2 AND CASE 3

A yearly production profile for Cases 4, 5 and 6 is shown in Figure 57. Case 4 and 5 has the largest variation in production because of the gas turbines dependence of the air temperature. Case 5 and 6 are close in production size because the LM6000 and Frame 6B are similar in power output. Case 6 varies with water temperature, and is completely independent of the air temperature. Even though Case 6 is producing less than Case 4 and 5, it should be noticed that Case 6 can be scaled up to approximately the same production size as Case 4 and 5 without behaving differently.

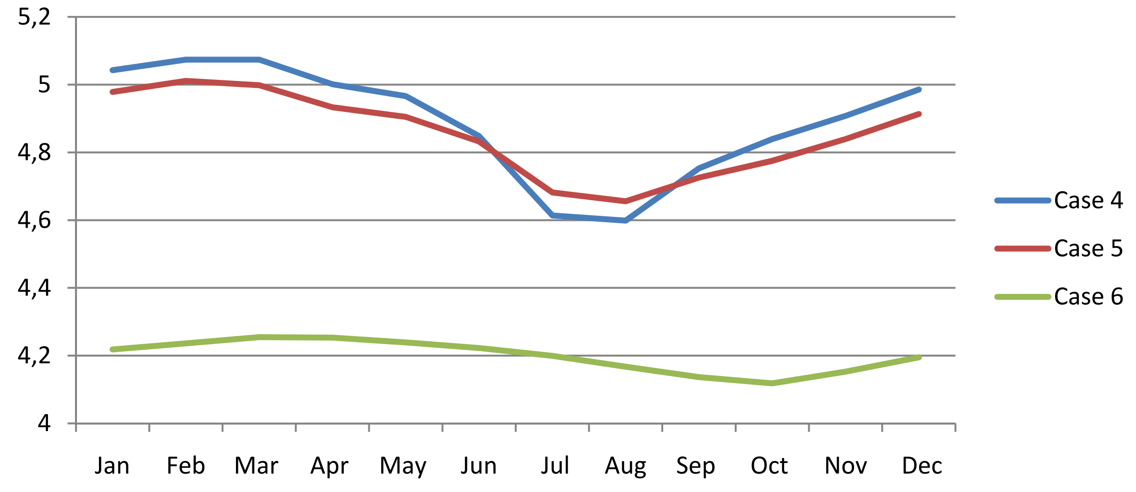

FIGURE 57 YEARLY PRODUCTION PROFILE CASE 4, CASE 5 AND CASE 6

Equally to Figure 56 a relative production profile for Case 4, 5 and 6 has been made, see Figure 58. The cases are operating close to design throughout the year. Case 6 has the most stable production, around its design condition.

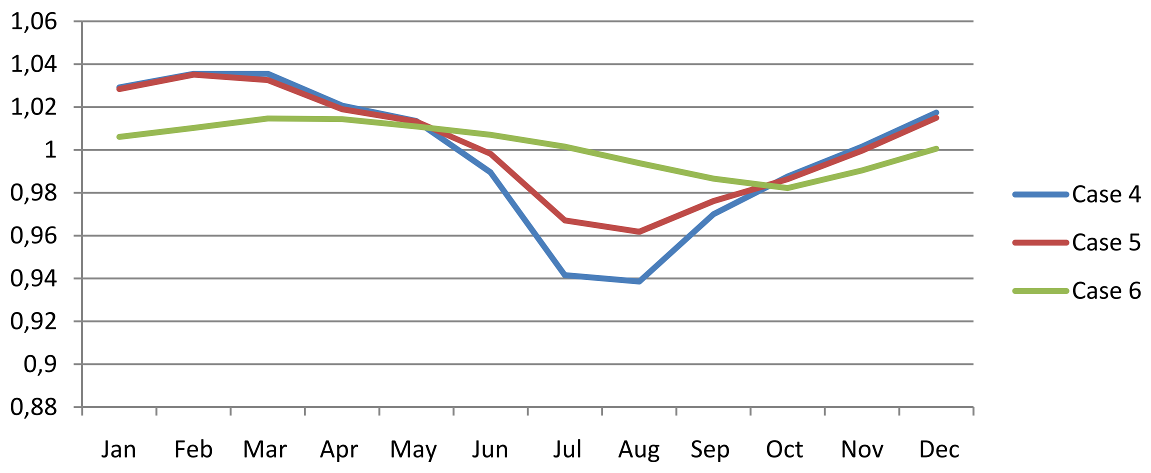

FIGURE 58 RELATIVE PRODUCTION FOR CASE 4, CASE 5 AND CASE 6

The air cooled cases are all operating off-design the entire year as opposed to the water cooled cases which are operating close to design. The production profile varies with seasonal temperature variations.

For an LNG plant, it is important to be reliable when it comes to delivering the right amount of LNG at the right time. A most likely desirable solution is to have an as low as possible variation in production throughout the year. The water cooled process using electrical compressor drives seems to be the desirable solution because of its stable production.

7.5 PROCESS EFFICIENCY AND DESIGN CONSIDERATIONS

Specific power consumption is a measure for the process efficiency. It tells how many kWh used to produce one kg of LNG. The specific power as a function of air temperature for Cases 1, 2 and 3 are given in Figure 59. The three cases are similar, but Case 1 has a higher specific work at temperatures around 10°C. The reason is the distinct increase in power when temperature decreases for the LM6000 which leads to increase in production. This again leads to the compressors operating with a high volumetric flow and at a lower efficiency. Case 2 has a restriction in driver speed and will not have the possibility to increase production like Case 1. Case 3 has constant power available and will not be able to increase production that much when temperature decreases and will operate at a higher compressor efficiency than Case 1. At lower temperatures, Case 2 is regulated to avoid a too low compressor/driver speed which leads to higher specific power. Case 1 and Case 3 have a larger span in operating speed and utilization of this is shown at lower temperatures.

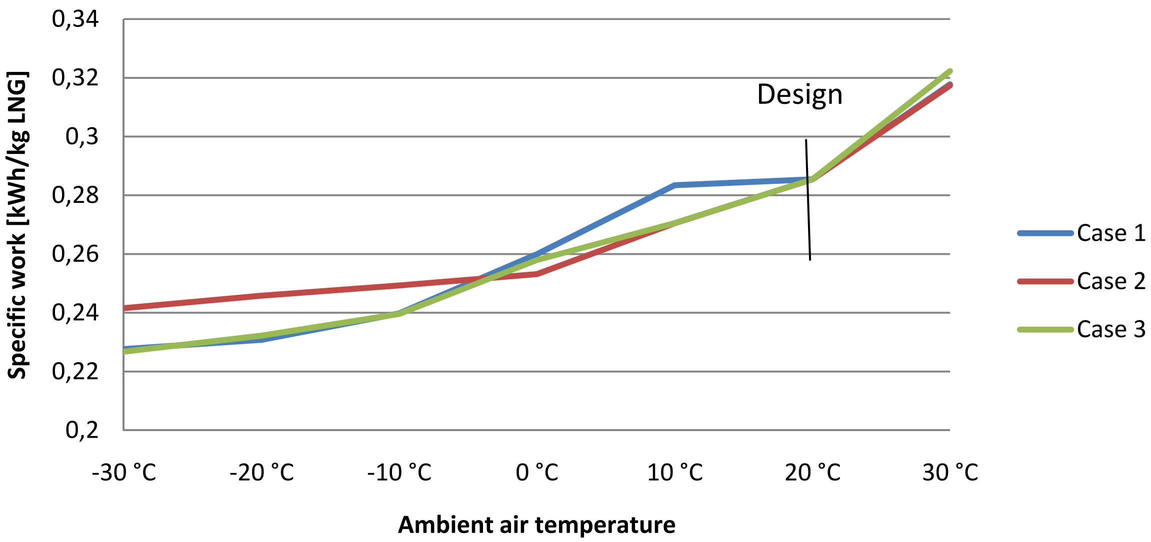

FIGURE 59 SPECIFIC WORK AS FUNCTION OF TEMPERATURE

To see the efficiency of the processes on a yearly basis, the specific work has been connected to statistical average temperatures for the entire year (Table 1). This is shown in Figure 60. Case 1 has the highest specific work in the warmest month but is together with Case 3 most efficient in the coldest months.

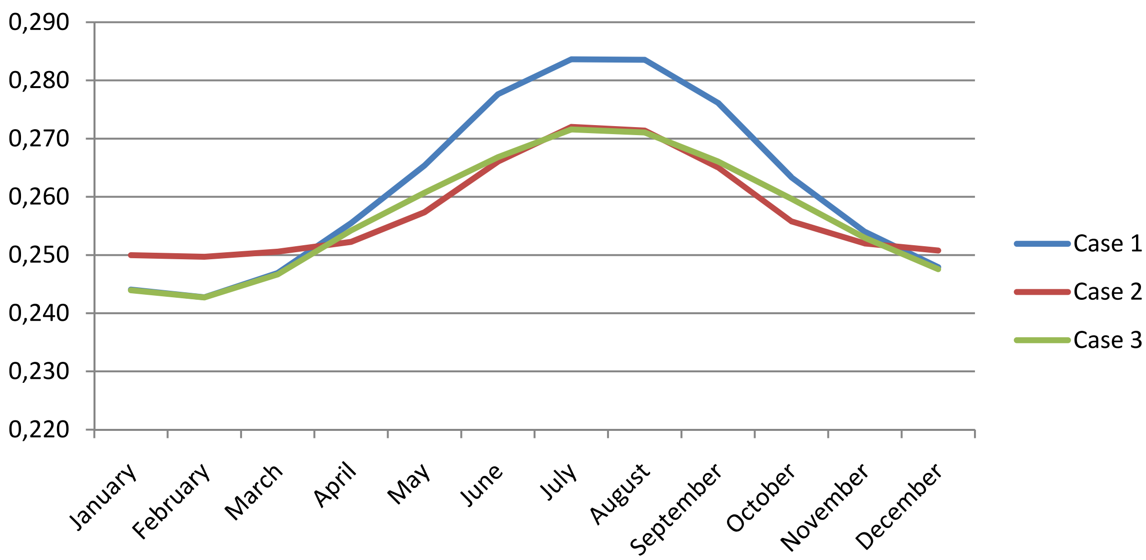

FIGURE 60 SPECIFIC WORK ON A YEARLY BASIS CASE 1, CASE 2, CASE 3

Case 4, 5 and 6 was not simulated with extreme temperatures, but with the monthly average temperatures. Specific work on a yearly basis for Case 4, 5 and 6 is shown in Figure 61. The low water temperature from January to June makes Case 6 the most efficient process. Case 4 and Case 5 has a higher specific work in the same period (January to June) because of the dependency of the process on the air temperature, and since air temperature is low the gas turbines can produce more power. More power means that the process can increase production; hence compressors are operating further away from best efficiency point.

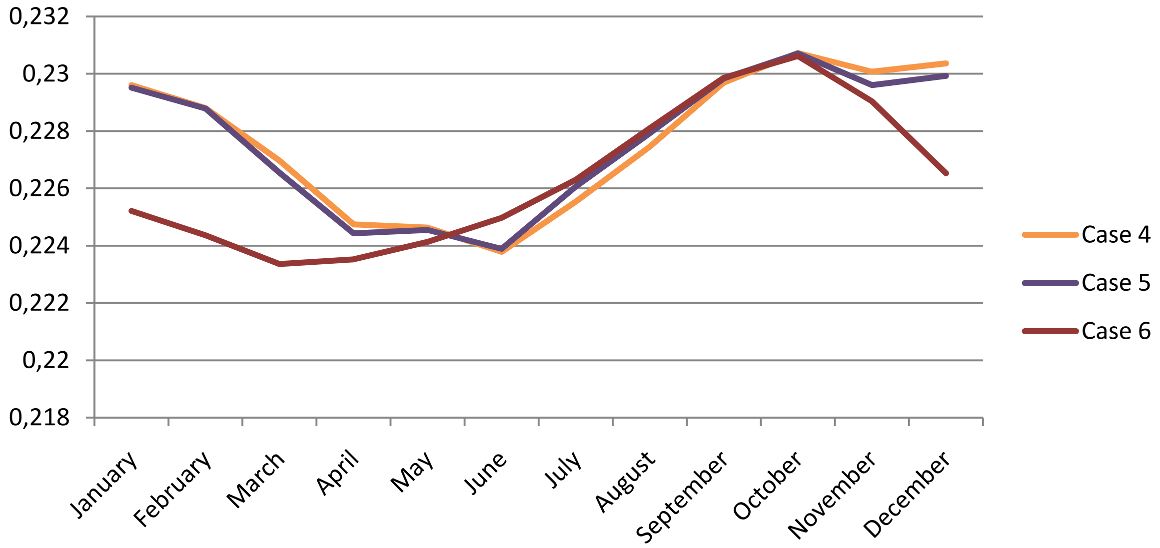

FIGURE 61 SPECIFIC WORK ON A YEARLY BASIS CASE 4, CASE 5, CASE 6

The air cooled processes are less efficient than the water cooled processes. The air cooled processes operate off-design throughout the year while the water cooled processes operates close to design. Case 6 operates the first half of the year slightly below the design and the other half slightly above. This makes Case 6 the most efficient process of all cases. Specific work for an ideal, reversible LNG process is 0.11 kWh/kg of LNG for cooling of gas at 10°C and 60 bar (Pettersen 2009). A large world scale LNG plant consumes typically 5.5 – 6 kWh per kmole LNG produced (Hasan, Karimi et al. 2009) which corresponds to 0.315 kWh /kg LNG using the molar weight of Table 7s feed composition.

Making the process more flexible with regard to production increase, a design closer to the surge control line could be possible. A design close to surge will though most likely lead to even less flexibility at higher temperatures when production has to be decreased.

7.6 Effect of change in flash composition

The feed gas composition may change due to tie in of new gas fields or because of maturation of the producing gas field. This can lead to change in the flash gas composition, which is used as the sub-cooling refrigerant. Most of the heavy hydrocarbons are separated out before the gas enters the LNG process, which means that the main component to change is the nitrogen composition. Change in the nitrogen composition means a change in the molar weight of the refrigerant and will affect the compressor curves in the sub-cooling circuit. The equation for polytrophic head of a compressor is shown in (9). Where H_p is polytrophic head, n is the polytrophic exponent, Z is the compressibility factor, R is the ideal gas constant, T is temperature, g is gravity, M is molar weight, P_1 is the compressor suction pressure and P_2 is the compressor discharge pressure.

$$H_p = \frac{n}{n-1}\frac{ZRT}{gM}\left(\frac{P_2}{P_1}^{\frac{n-1}{n}} - 1\right) \tag{9}$$

If the molar weight changes the polytrophic head will change, and the compressor curves will also change. (Bakken 2011) defines a change in molar weight of more than 10 % from design, before a need for a new design of compressor curves are necessary. In a methane/nitrogen mixture the molar weight changes with the nitrogen content, see Table 14. A change in molar weight of more than approximately ±10% will in this case mean a nitrogen content of more than approximately 35% or less than approximately 5%.

TABLE 14 NITROGEN CONTENT, MOLAR WEIGHT AND PERCENTAGE CHANGE IN MOLAR WEIGHT

N_2 content [%]	Molar weight [kg/kmole]	Change from design [%]
35 %	20,23	9,7 %
30 %	19,63	6,5 %
25 %	19,04	3,2 %
21 %	18,44	-
15 %	17,84	-3,2 %
10 %	17,24	-6,5 %
5 %	16,64	-9,7 %

To examine the effect of change in flash/methane circuit composition on the HYSYS® model, simulations were done varying the N_2 composition with approximately ±5% of the design composition used in Table 7. The production and cooling temperature was held constant, while consumed power was not controlled. Case 1 has been used as a basis with six LM6000 drivers. The operating points of flash/methane compressor and ethylene compressor are shown in Figure 62 and Figure 63. The flash compressors approach surge at 15% N_2 and the recycle loop has to be activated at lower than 15% N_2 content. At higher N_2 content (between 20% -25%) the flash compressors will have problems delivering the required pressure and adjusting of for example discharge pressure has to be done to operate the plant. The ethylene compressors will in a smaller degree be affected by the compositional change. The ethylene compressors are however affected opposite of the flash compressors. This is believed to be caused by a load shift between the methane/flash circuit and the ethylene circuit, when the N_2 content changes. The propane compressors are affected the same way as the ethylene compressors, but with less impact. The propane compressor curves are not shown. The possibility of change in molar weight in the flash/methane composition should be accounted for when designing the LNG production process.

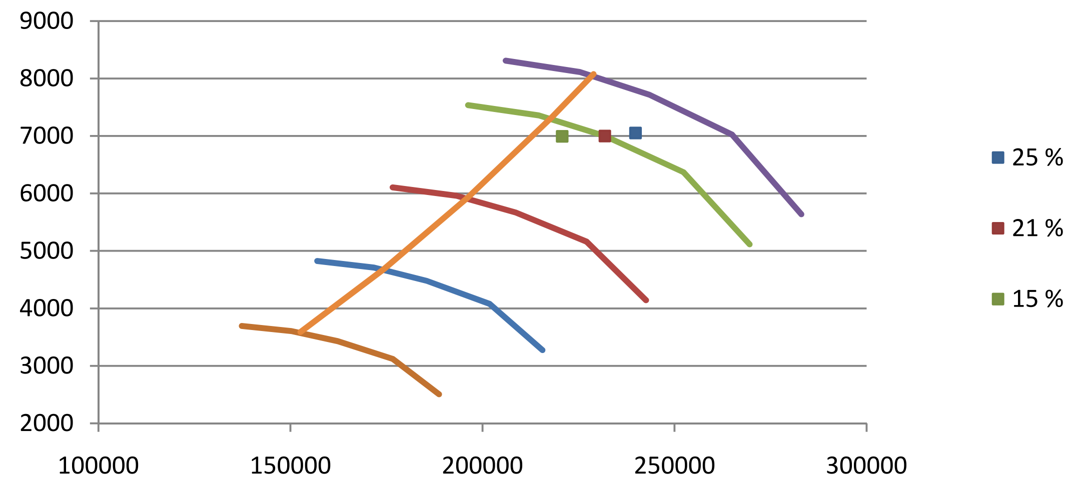

FIGURE 62 OPERATING POINTS, LP ETHYLENE COMPRESSOR, VARYING FLASH COMPOSITION

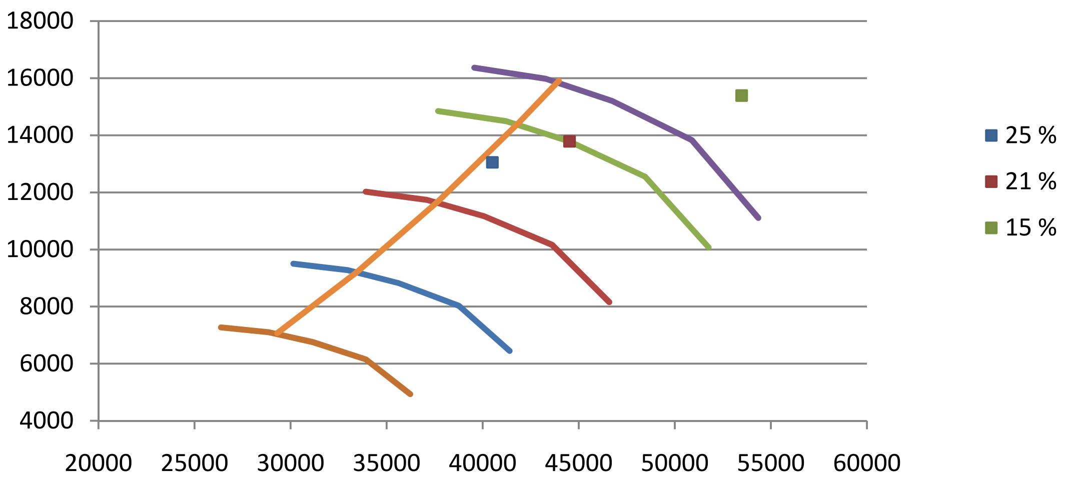

FIGURE 63 OPERATING POINTS, LP METHANE/FLASH COMPRESSOR, VARYING FLASH COMPOSITION

7.7 2IN1 CONCEPT

The 2in1 concept makes the ConocoPhillips more flexible. The plant can operate with one, two or even three compressors offline. According to (ConocoPhillips 2010) the 2in1 concept has the following advantages:

- High production efficiency
- Wide range of capacity flexibility
- Maintenance flexibility
- Optimized plant efficiency

According to (ConocoPhillips 2010) the plant can produce up to 60% of design when one half of compressor power is off line. They claim that a large flexibility in operation of plant, with possibility of sustainable production as low as 10% for extended periods of time. Maintenance can be done while plant is operating at period with low production. Mix and number of gas turbines/ compressors can be used to optimize the efficiency of the plant and equipment at off design production rates.

The 2in1 concept will lead to a larger number of rotary units in a LNG plant. More rotary equipment means higher probability of failure. A distinct need for maintenance is one of the disadvantages for the ConocoPhillips Optimized Cascade LNG process (Mokhatab and Economides 2006). Most papers about the 2in1 concept are published by ConocoPhillips or their partners and may be influenced by that.

7.8 SUMMARY OF DISCUSSION

The results show off-design operation for all air cooled processes, high specific power consumption and a lower flexibility in production (lower than water cooled process) throughout the year. This leads to a conclusion that air cooling in ConocoPhillips Optimized Cascade LNG process operating in arctic climate, may not be the optimal cooling method.

Using propane as a pre-cooling refrigerant in an air cooled plant is challenging because of large variation in condensing pressure. Work done by (Borlaug 2010) and (Vebenstad 2010) describes similar challenges in a C3MR process. A mixed refrigerant in the pre-cooling circuit could damp the variations by changing composition as cooling temperature changes. Use of propylene instead of propane can be advantageous for operation in cold climate.

The water cooled cases operate close to design conditions throughout the year. High efficiency and flexibility in production capacity means that water cooling probably is the best cooling method for operation in arctic climate for the ConocoPhillips Optimized Cascade LNG process when optimizing process efficiency and capacity.

There are pros and cons regarding the selected driver configurations for seawater cooling in this project.

- LM6000 as driver will lead to the possibility of large production increment in the winter time, but the large production increment also leads to low efficient operation for the compressors. This driver configuration will also lead to low production capacity in the summer. LM6000 has a high thermal efficiency.
- Frame 6B as driver will lead to more stable production throughout the year but will also lead to low flexibility operation at because of narrow compressor speed range (95%-102%). Frame 6B has the lowest thermal efficiency of the selected driver configurations.
- Electrical motors driven by electricity from the electrical grid show high process efficiency, possibility to keep production stable during summer months and the opportunity to increase production when seawater temperature decreases. Question should be raised to where the electrical power comes from.

Electrical motors utilizing electricity from the grid seem to be the optimal driver solution for water cooled ConocoPhillips Optimized Cascade LNG process operating in arctic climate.

7.9 SOURCES OF UNCERTAINTY

The production capacity in the air cooled cases is too high. The propane compressor size in Case 1 and Case 2 is at least 50 000 m^3/h too large compared to what is technically possible per now (Bakken 2011). A design with a lower production will though behave similarly, and the main results are usable like specific power and the compressors' operating points.

The polytrophic efficiency for compressors with a lower actual volumetric flow than 10 m^3/s which corresponds to 36 000 m^3/h tends to be lower (Bakken 2010). This is not taken into account. The same compressor efficiencies are used in all circuits, see Appendix A.7 to A.12.

The natural gas feed temperature is assumed to follow the air or water temperature with 15°C (air cooling) and 6°C (water cooling) difference. Using a heat exchanger on the natural gas feed instead would make the simulations more realistic.

The gas turbines have an assumed power curve as function of temperature. The power output is assumed to be a linear or a polynomial relationship with decreasing temperature. The gas turbines may have a maximum delivered power output at a given temperature. The maximum power output limit has not been taken into consideration. The gas turbine operating map has not been taken into consideration. All gas turbines and electrical motors are assumed to operate at a design speed of 3600 rpm.

Two liquid expanders are included in the process model. The work recovered by those is not taken into consideration in the results.

The ConocoPhillips Optimized Cascade LNG process will in real life have a different process solution than the one used in this project. Therefore the model used, is not a real life reflection of the ConocoPhillips Optimized Cascade LNG process, but is close enough for the purpose of this project.

8 CONCLUSION

The results show that an air cooled system will operate off-design most of year. The large difference between the design temperature and the average air temperature lead to the compressors operating off-design, with a lower polytrophic efficiency. The aero derivative driver configuration (Case 1) will have problems operating at extreme temperatures because of lack of power, and a higher design temperature is needed. A higher design temperature will lead to lower process efficiency when air temperature is normal. The heavy duty gas turbine configuration (Case 2) has also problems operating at extreme temperatures because of the speed limitation for the driver and a higher design temperature could be needed. The electrical driver configuration (Case 3) has no problems operating, but will as all air cooled cases operate with low process efficiency and a lower possibility for increased production at lower temperatures. Air cooling for the ConocoPhillips Optimized Cascade LNG process operating in arctic climate is most likely not the preferred cooling method.

The water cooled process will have its design closer to normal temperatures and will operate at –or close to design most parts of the year. The aero derivative gas turbine driver configuration (Case 4) will have the largest variation in production and the lowest production when the temperature is high. Case 4 is close to surge in the summer. Problems can arise if extreme temperatures occur. The heavy duty gas turbine driver configuration (Case 5) has lower variation in production than Case 4, and slightly higher process efficiency. The electrical drive case (Case 6) will have the most stable production throughout the year. Small difference between the normal temperature and the design temperature makes the process efficiency highest of all cases on a yearly basis.

A water cooled system utilizing electric drives with a constant power supply seems to be the best solution when it comes to maximizing production and process efficiency for the ConocoPhillips Optimized Cascade LNG process operating in arctic climate on a yearly basis.

9 Recommendations for further work

Case 4, 5 and 6 have not been simulated for the extreme air temperatures. Case 6 is not dependent of air temperature, but Case 4 and Case 5 are dependent of the air temperature through the gas turbine driver. During extremely hot days, the power output will be significantly lower than normal, and this will affect the operation of the process. Simulating the water cooled cases with the gas turbine drives for the extreme temperatures could be useful to establish the operational area of the process.

In 2009, ConocoPhillips Company sent a patent application for utilizing a new refrigerant in the Optimized Cascade LNG process (Ransbarger 2009) for operation in colder climate. This particular refrigerant is thought to be propylene. An evaluation with propylene as pre-cooling refrigerant could be useful.

Investigation of Frame 5 and/or LM2500 as a compressor driver could be of interest, when considering the 2in1 concept with water cooling.

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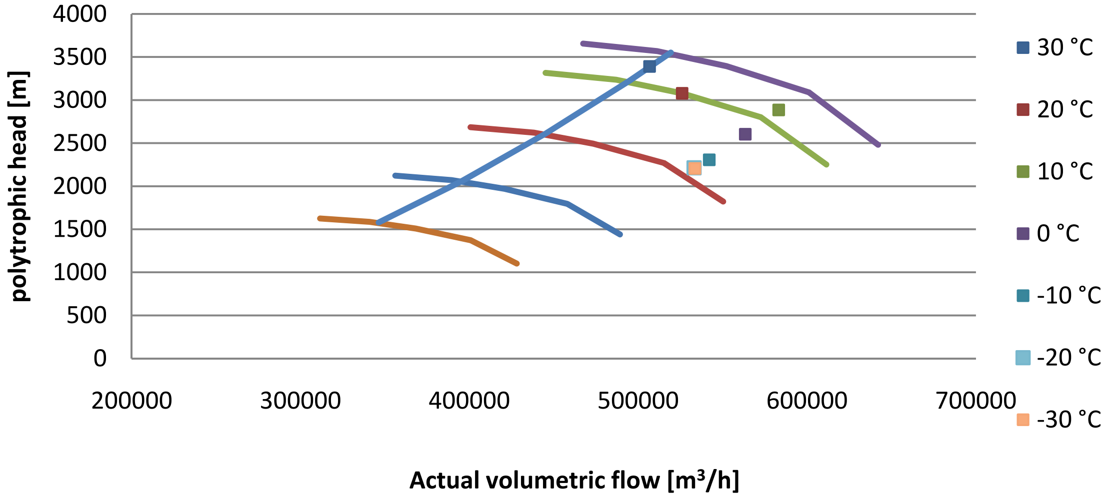
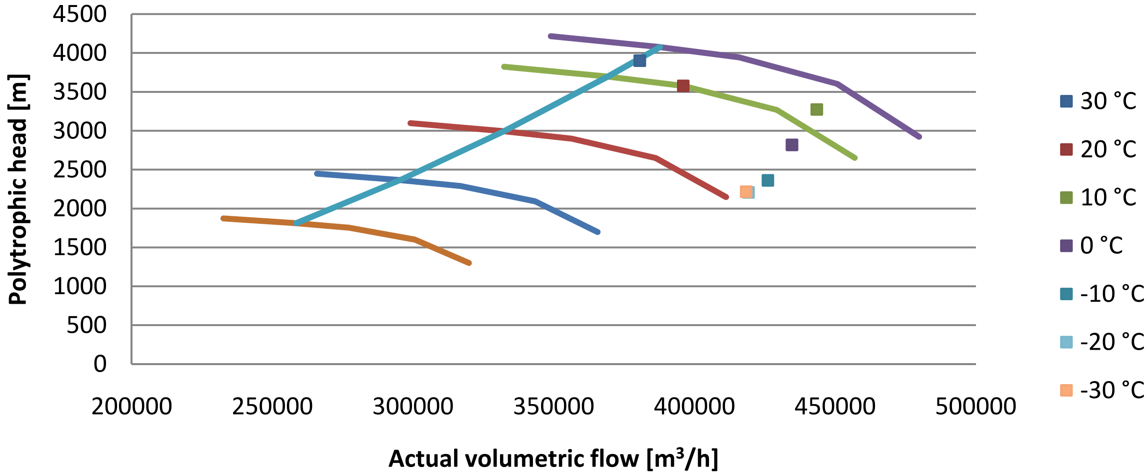
11 Appendices

A.1 Operating points Case 1





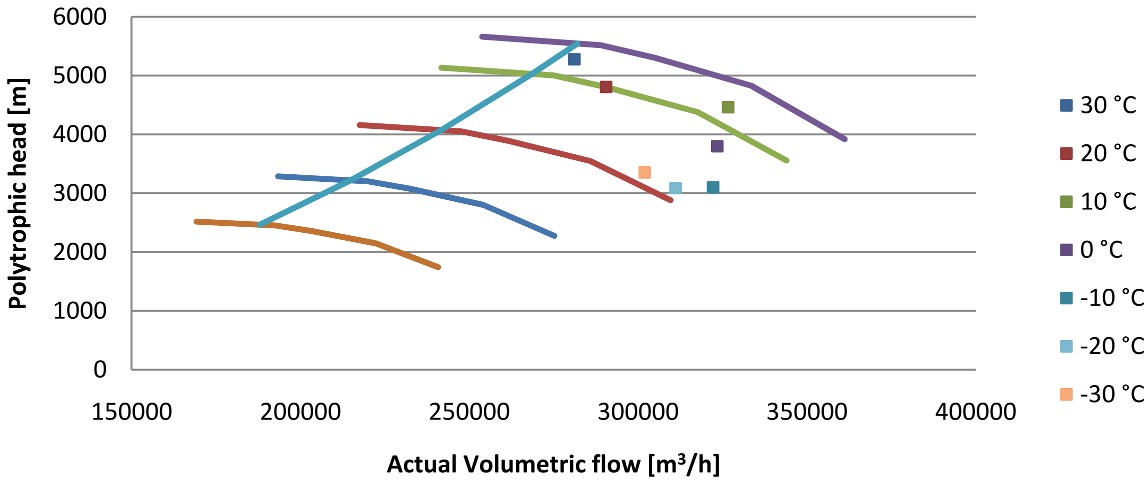


FIGURE 64 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) PROPANE COMPRESSORS CASE 1

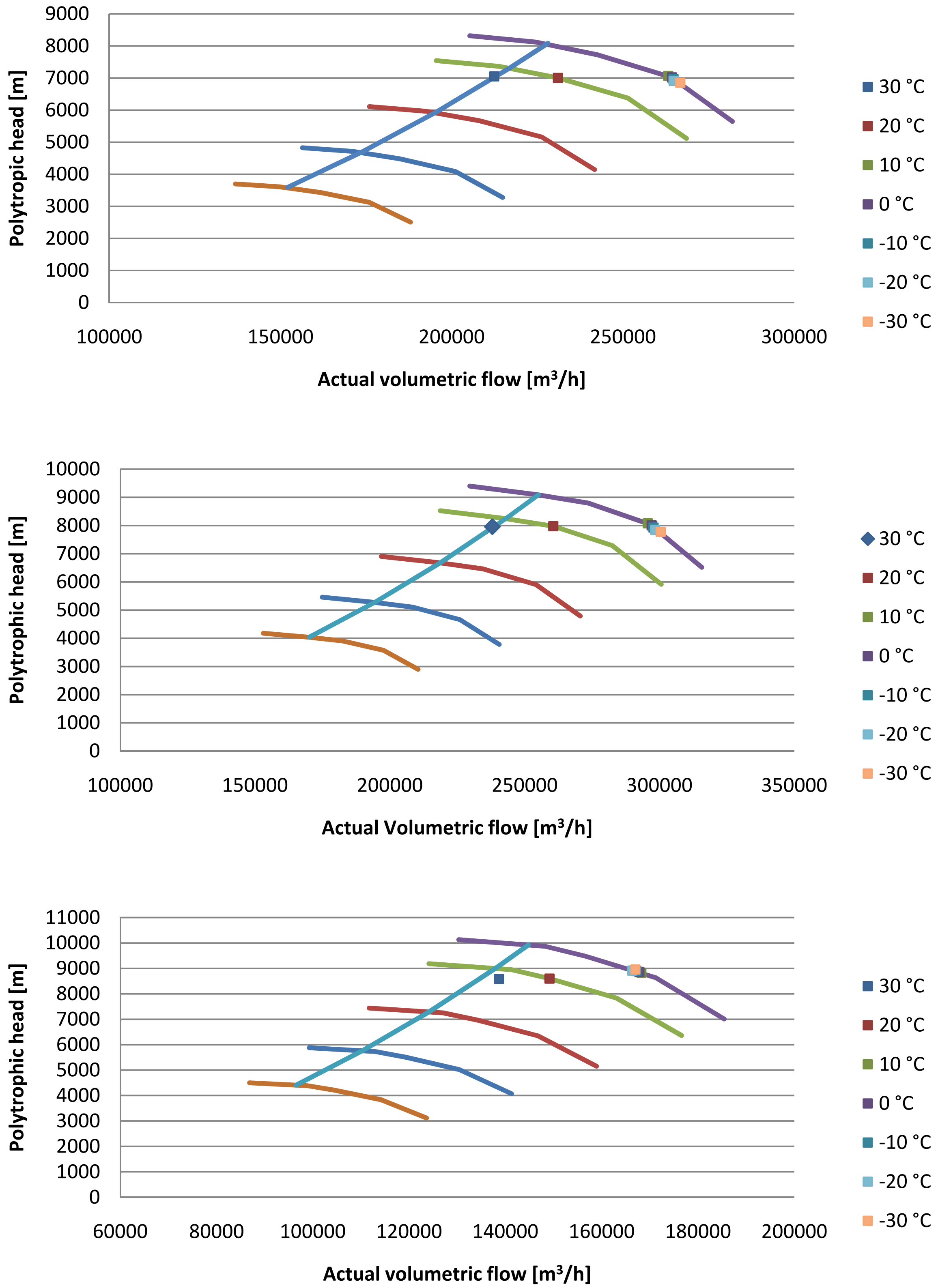


FIGURE 65 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) ETHYLENE COMPRESSORS CASE 1

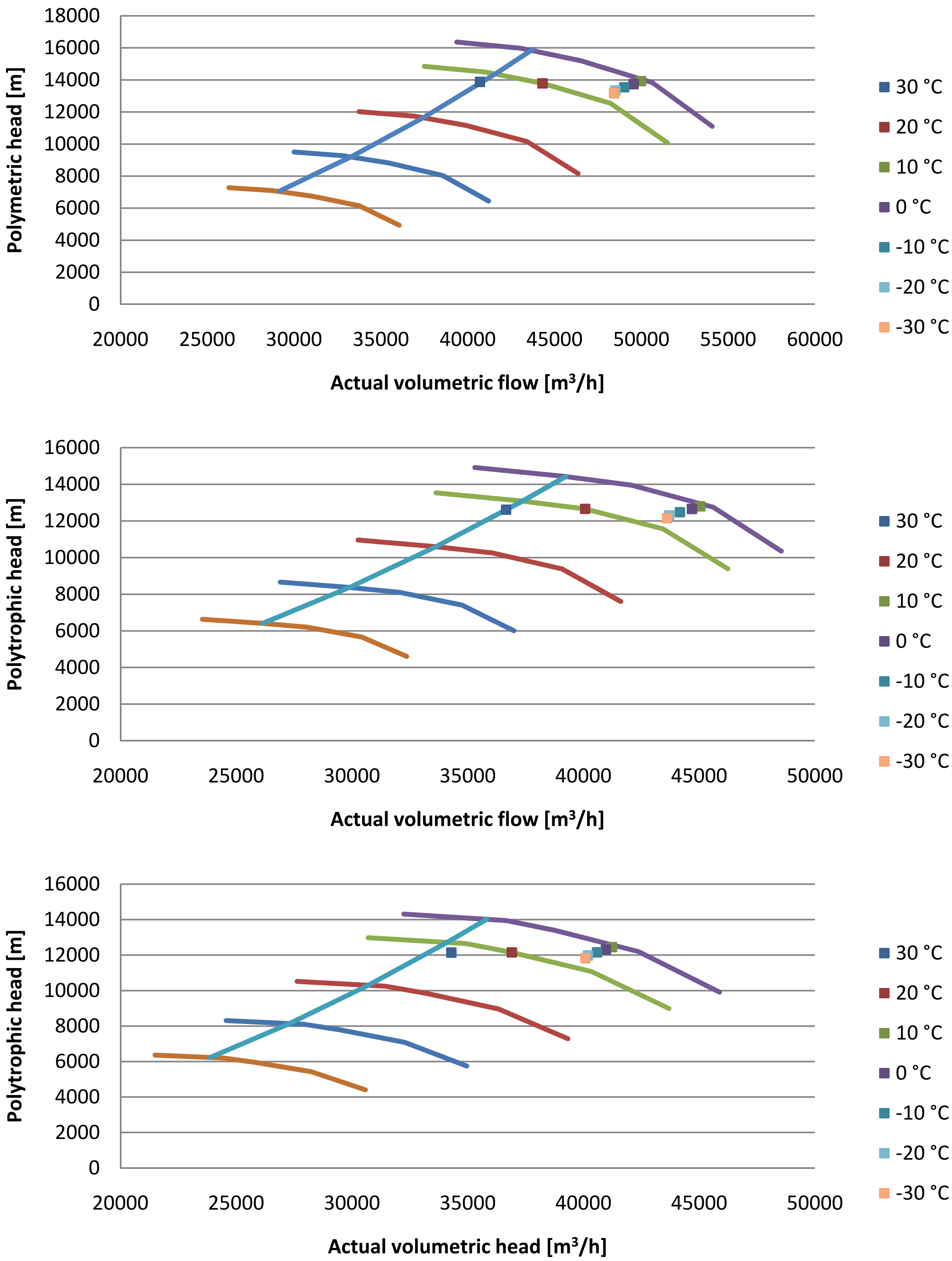
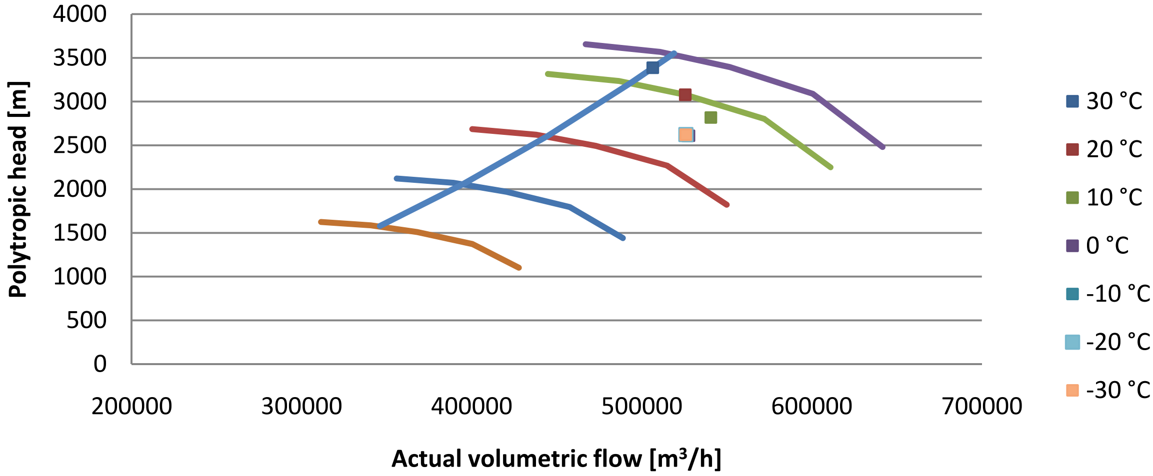
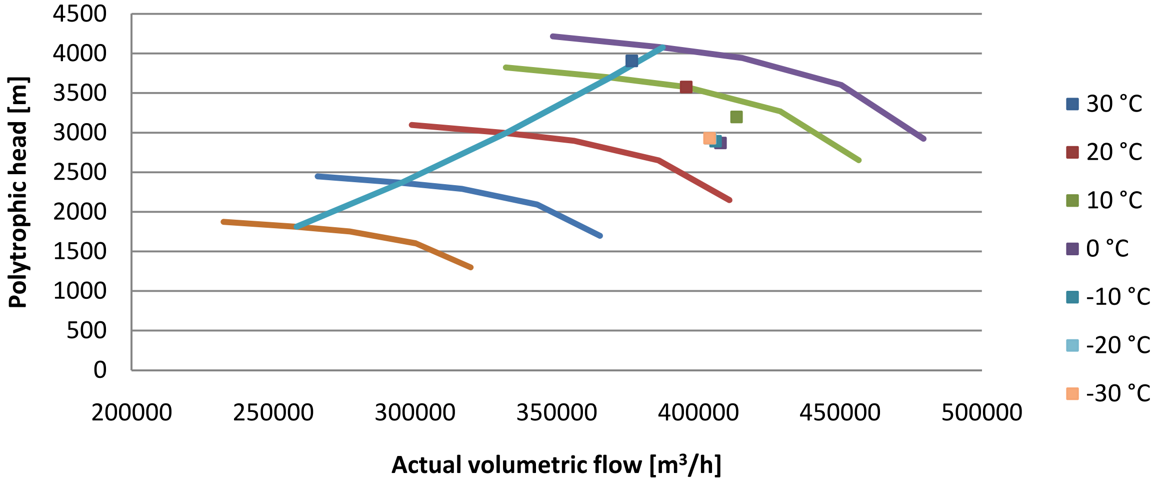


FIGURE 66 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) METHANE/FLASH COMPRESSORS CASE 1

A.2 Operating points Case 2





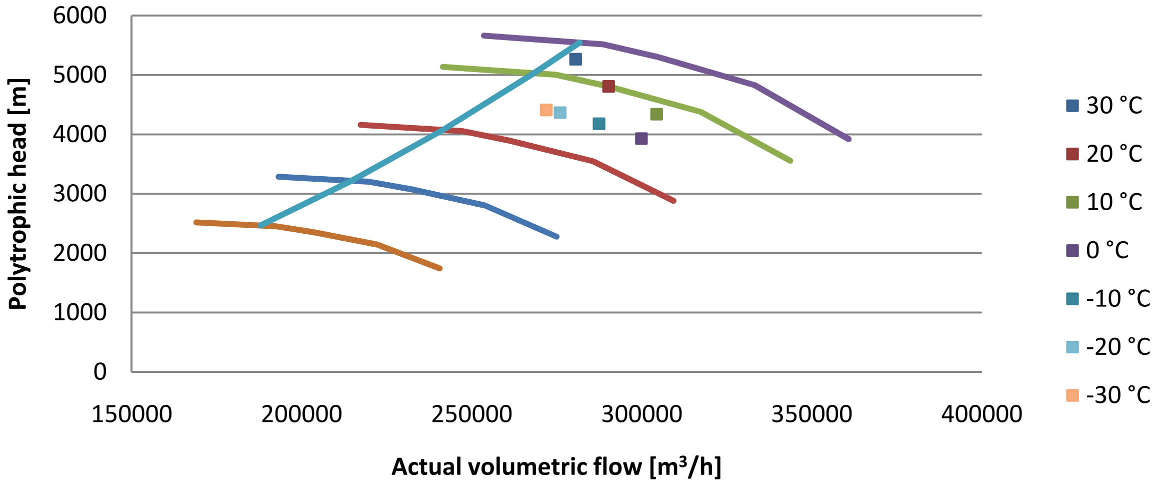


FIGURE 67 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) PROPANE COMPRESSORS CASE 2

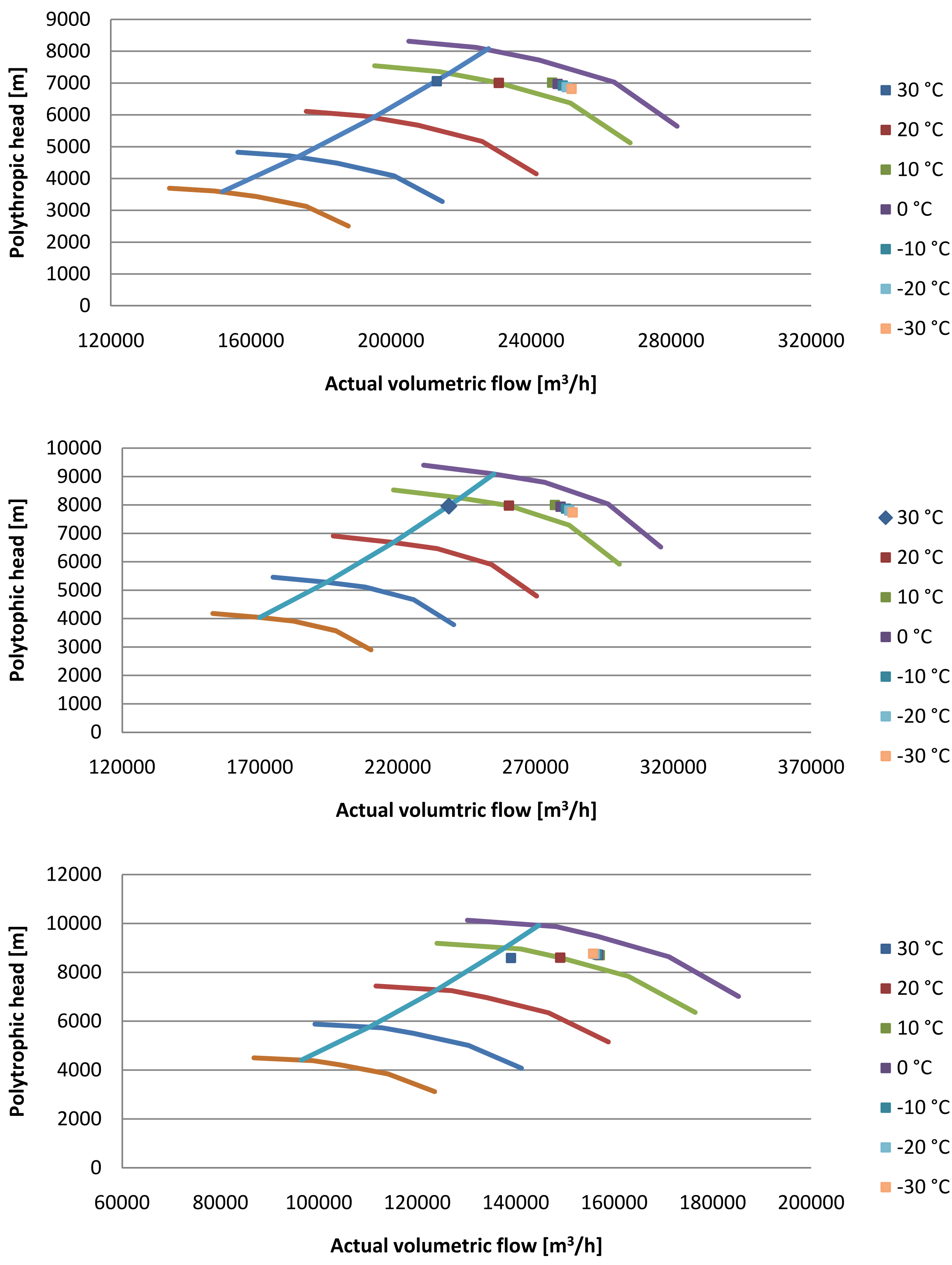


FIGURE 68 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) ETHYLENE COMPRESSORS CASE 2

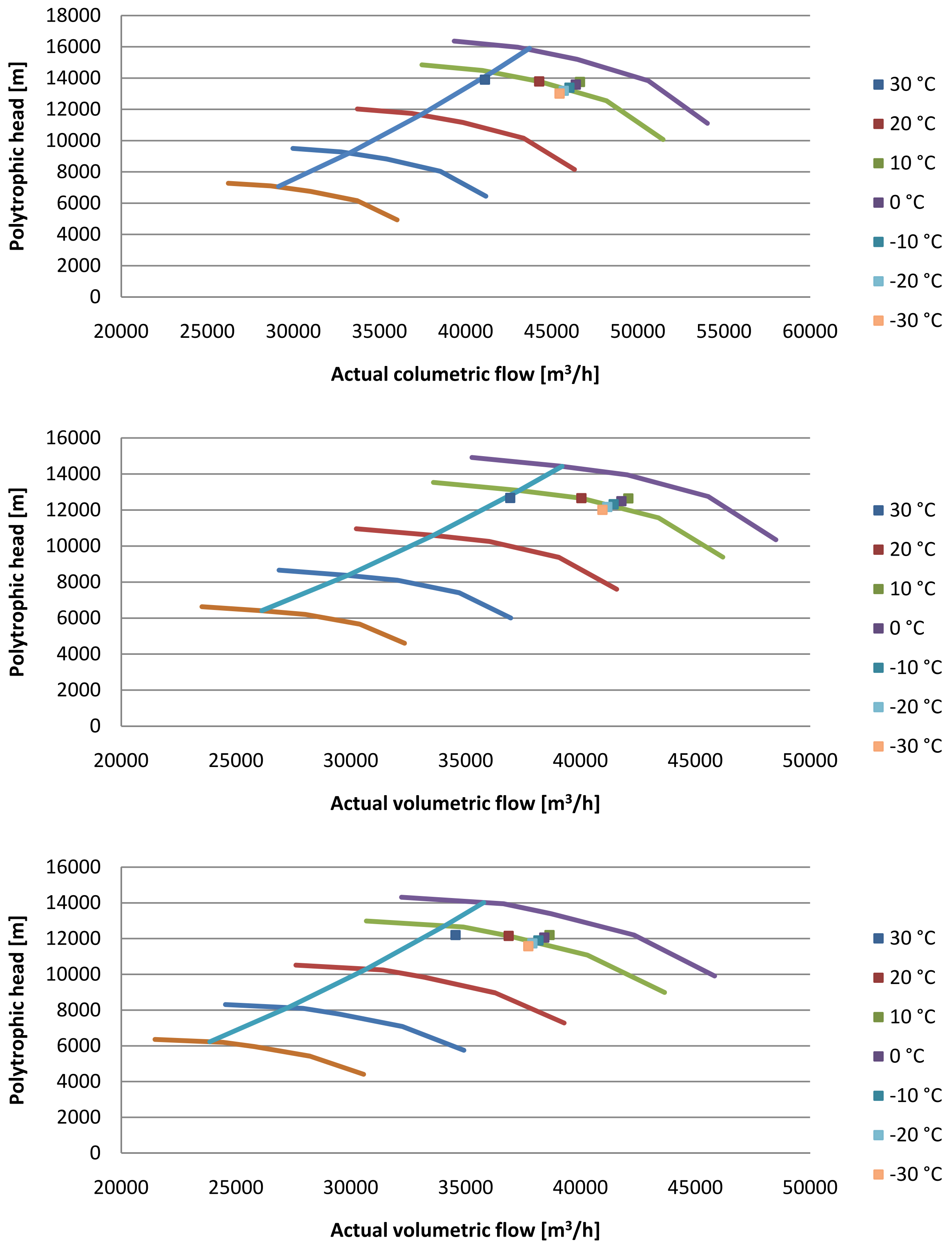


FIGURE 69 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) METHANE/FLASH COMPRESSORS CASE 2

A.3 Operating points Case 3

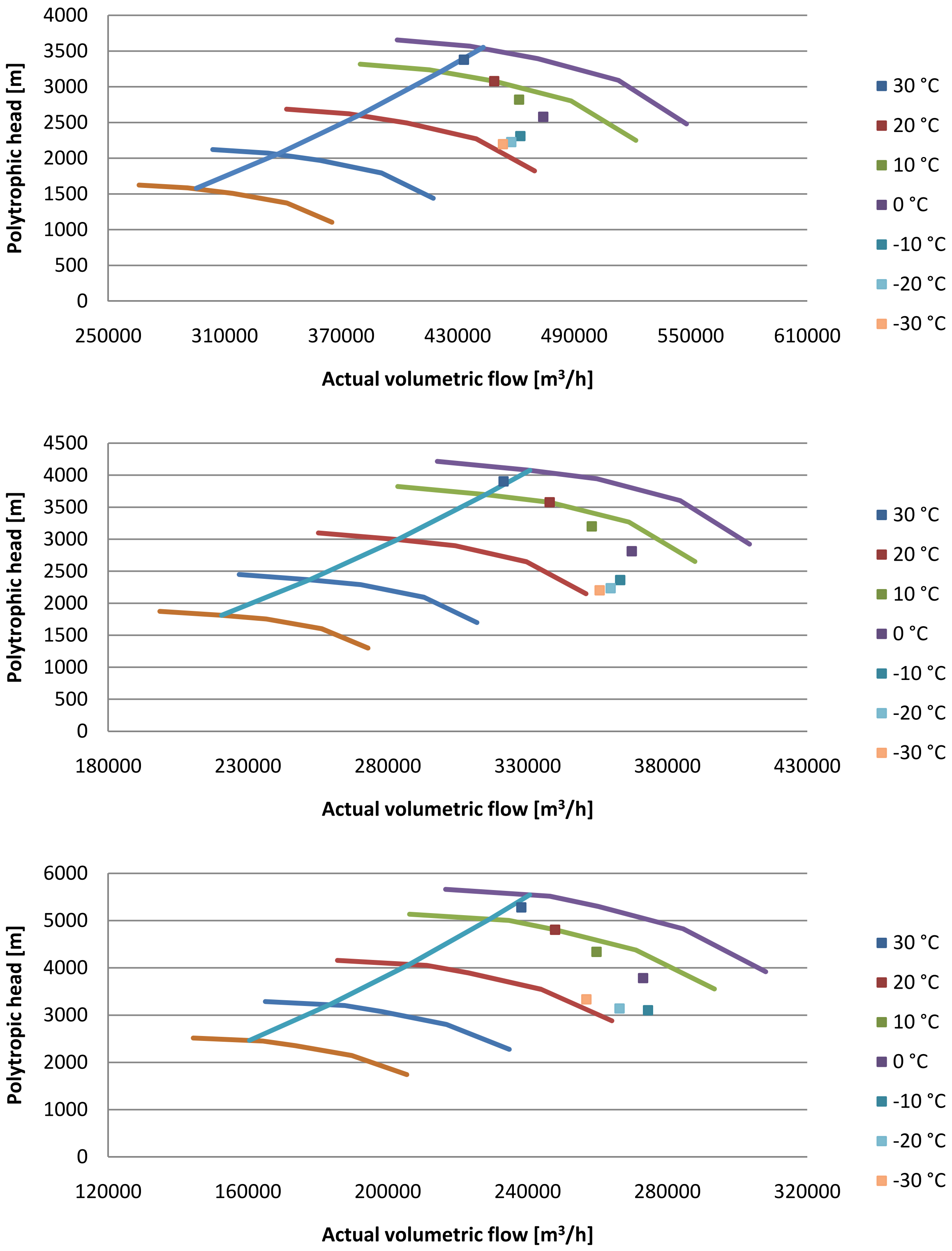


FIGURE 70 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) PROPANE COMPRESSORS CASE 3

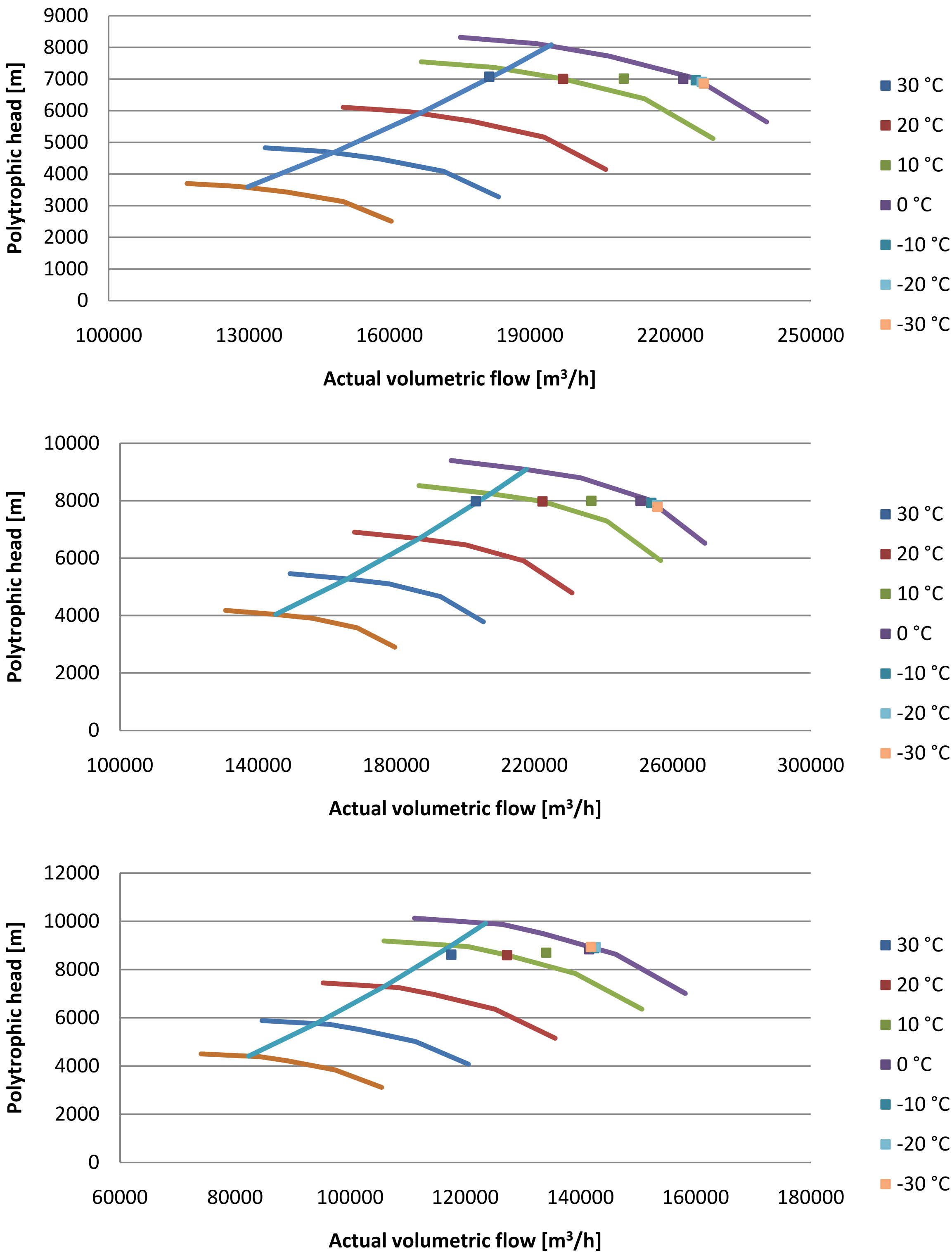


FIGURE 71 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) ETHYLENE COMPRESSORS CASE 3

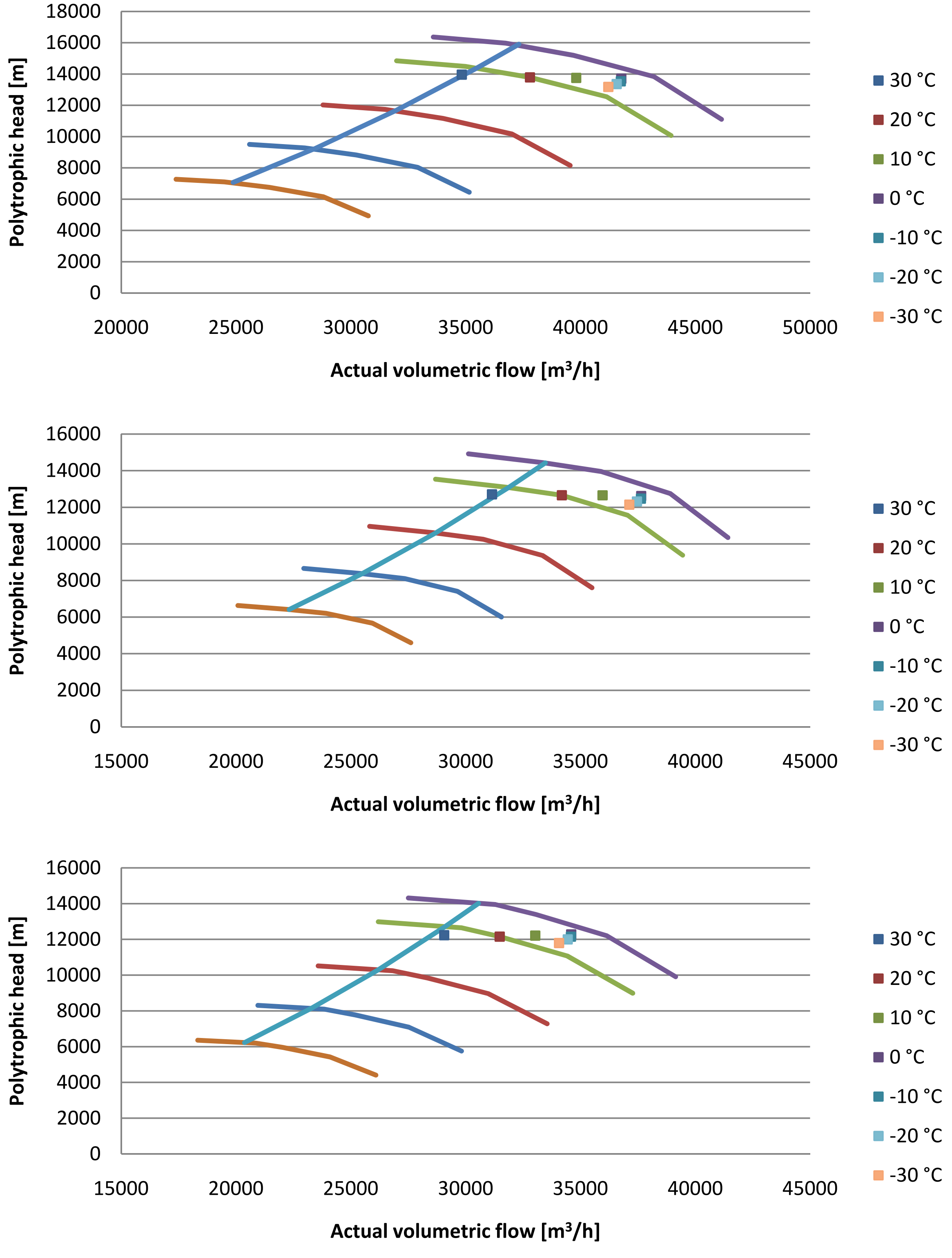


FIGURE 72 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) METHANE/FLASH COMPRESSORS CASE 3

A.4 Operating points Case 4

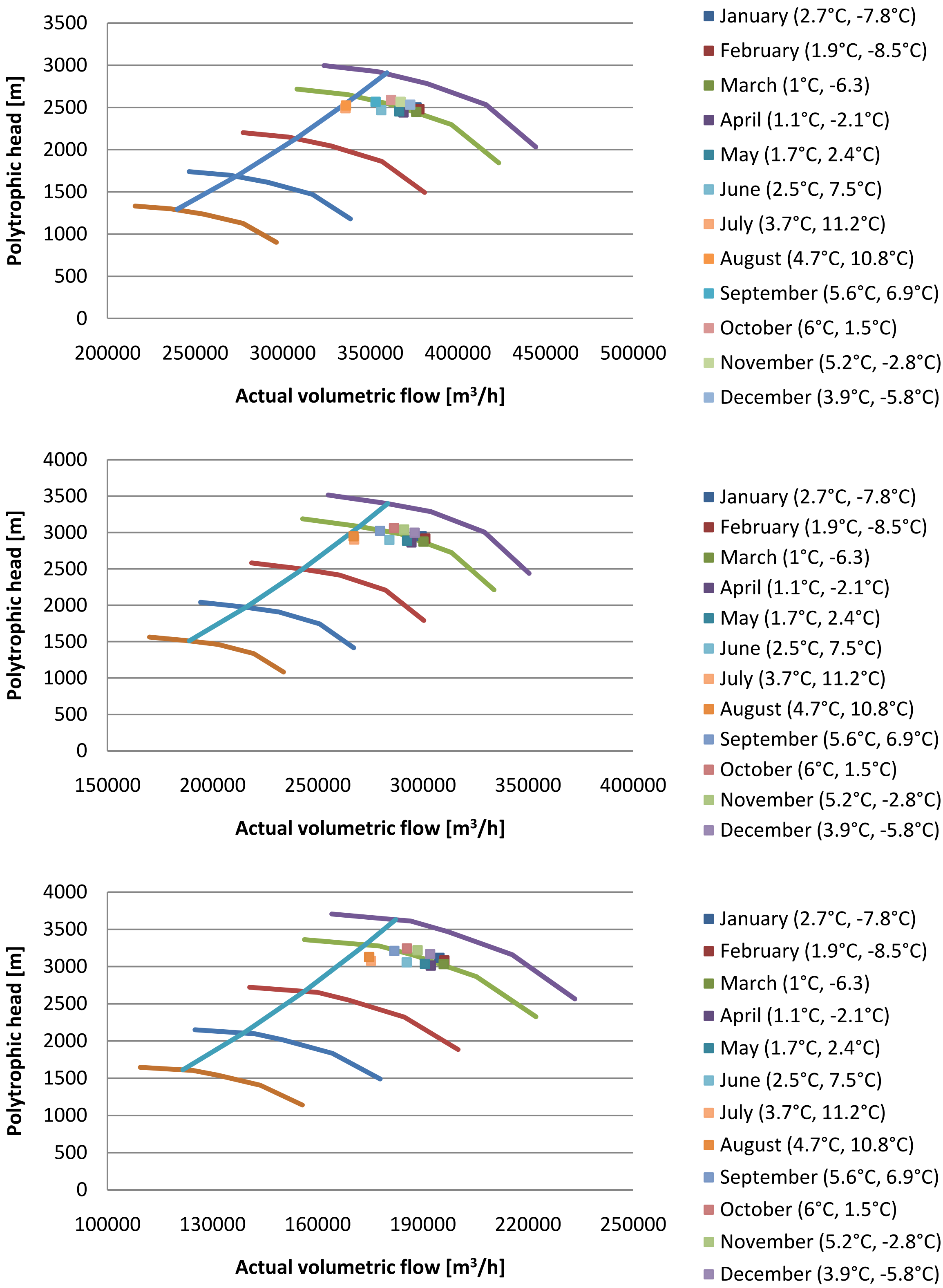


FIGURE 73 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) PROPANE COMPRESSORS CASE 4

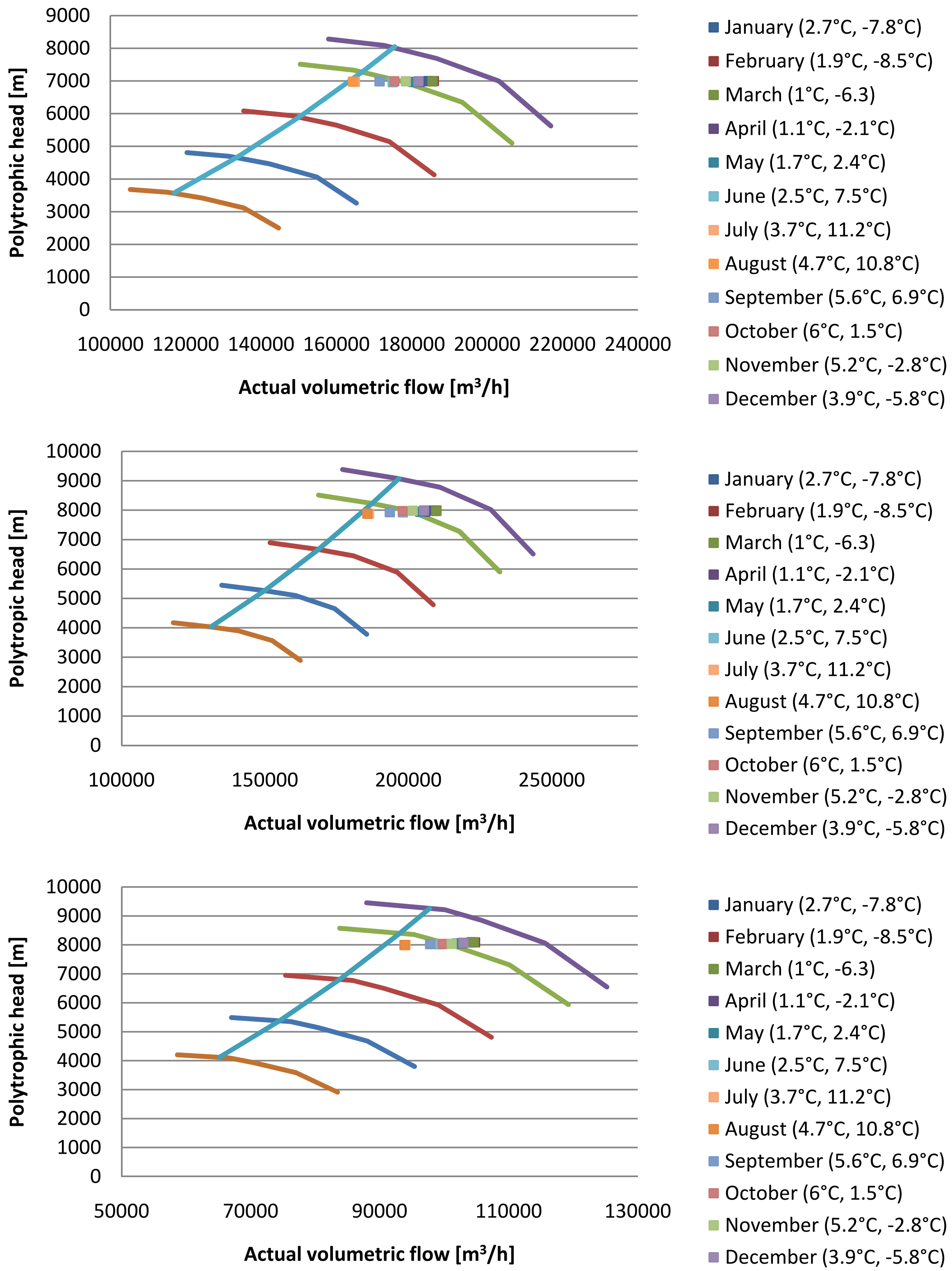
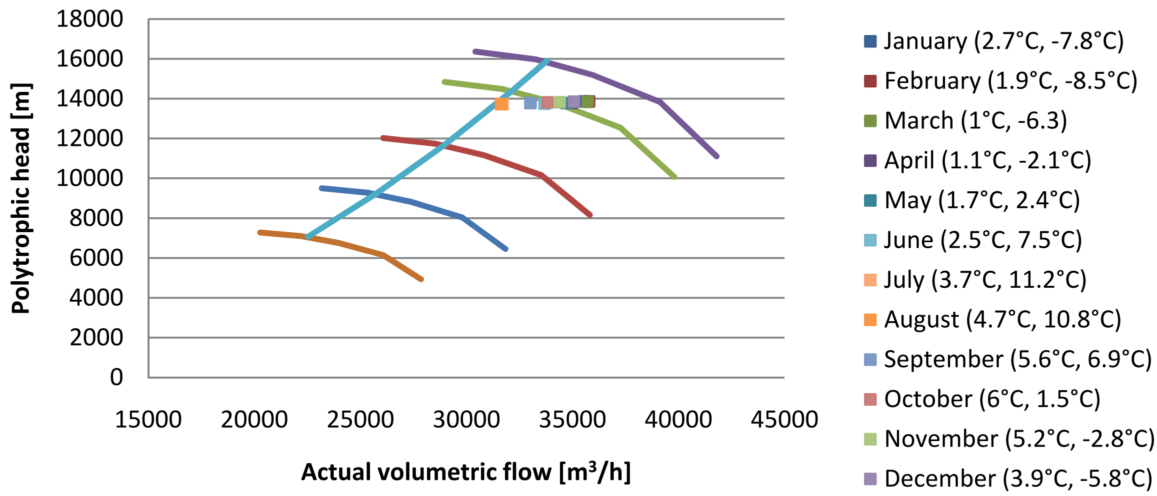
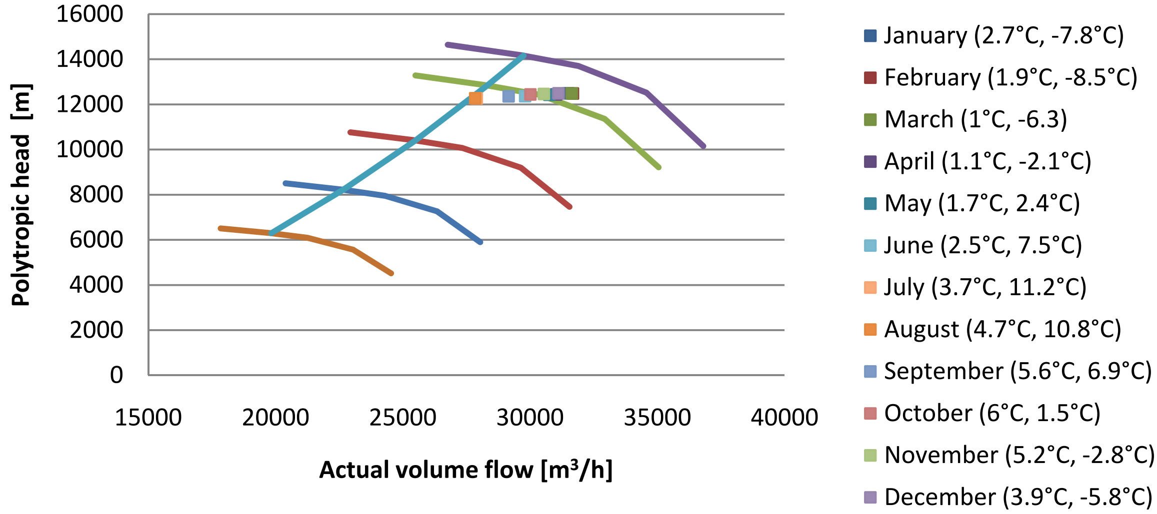


FIGURE 74 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) ETHYLENE COMPRESSORS CASE 4





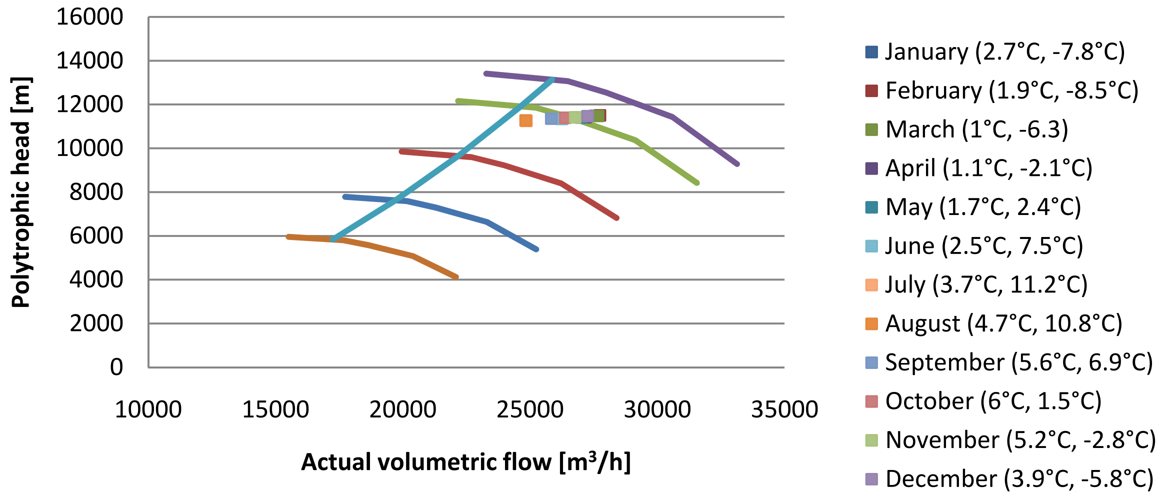
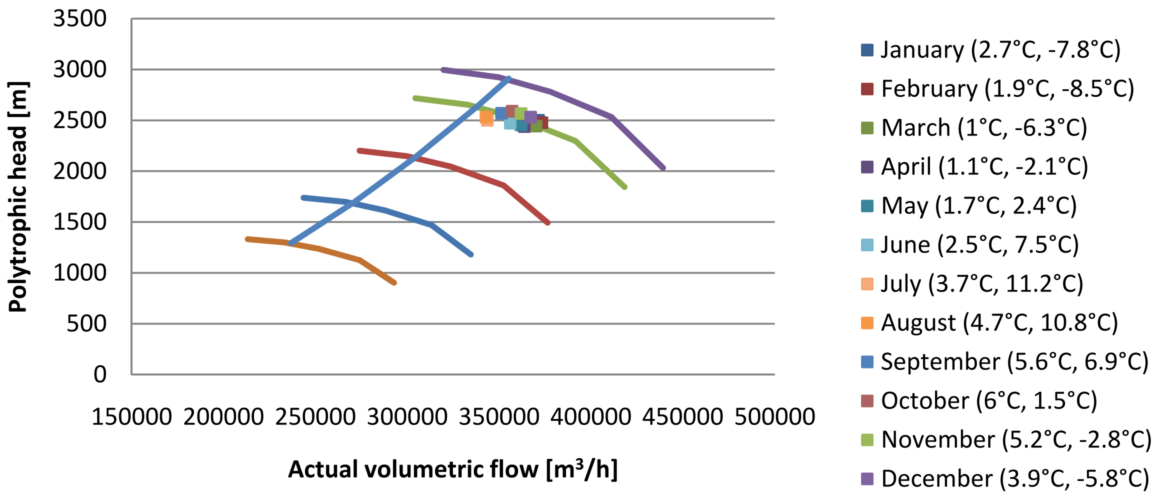
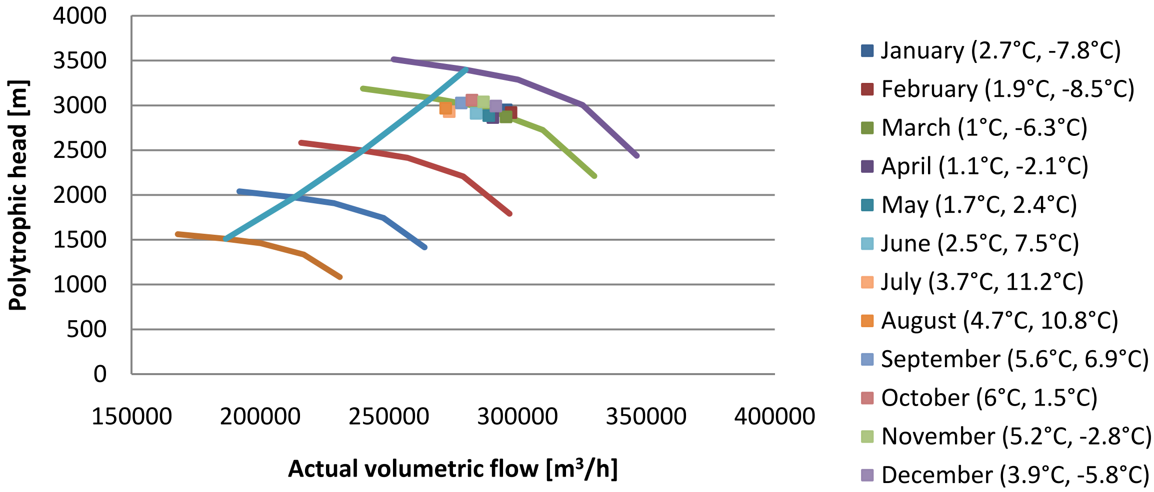


FIGURE 75 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) METHANE/FLASH COMPRESSORS CASE 4

A.5 Operating points Case 5





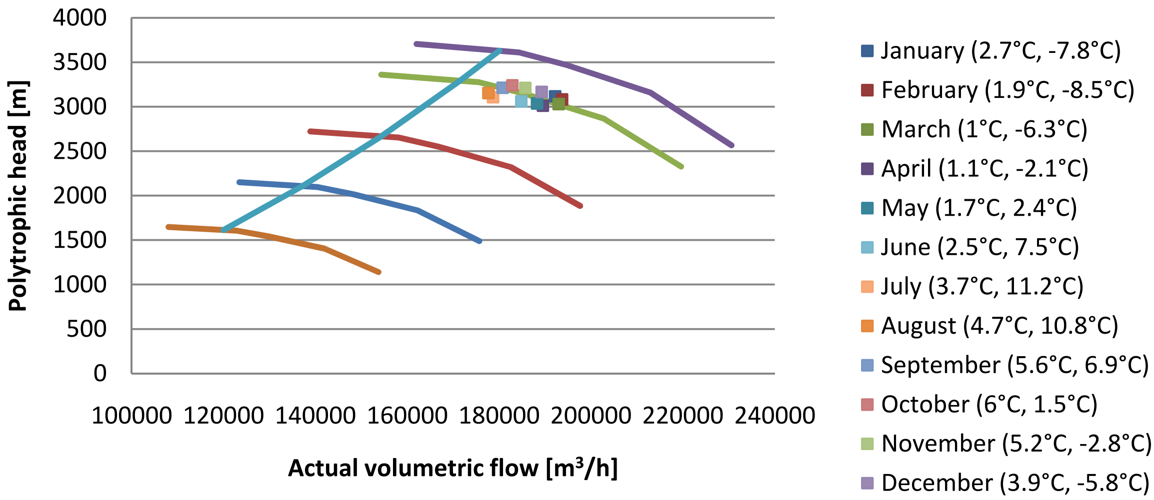


Figure 76 LP (at the top), MP and HP (at the bottom) propane compressors case 5

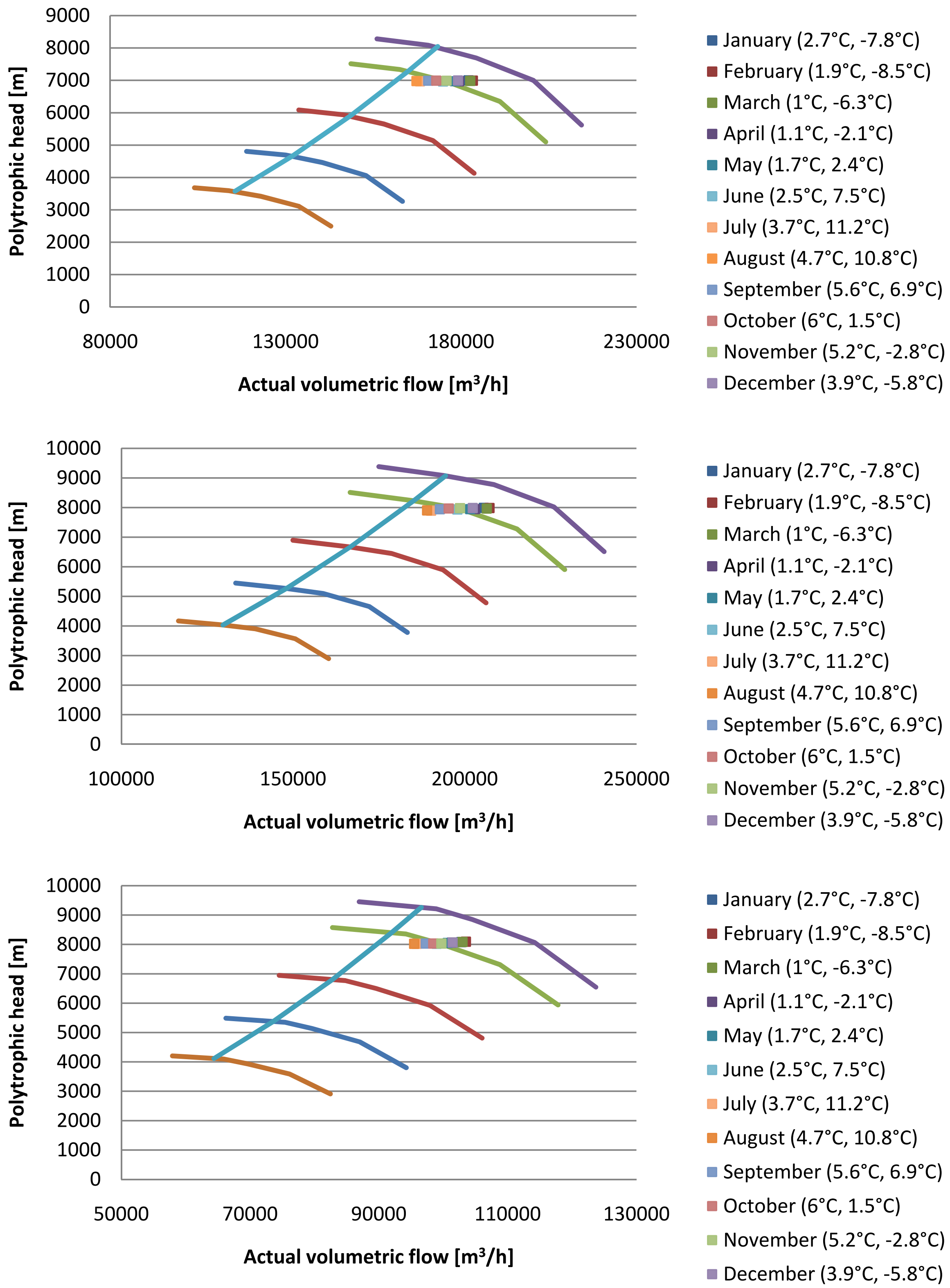


FIGURE 77 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) ETHYLENE COMPRESSORS CASE 5

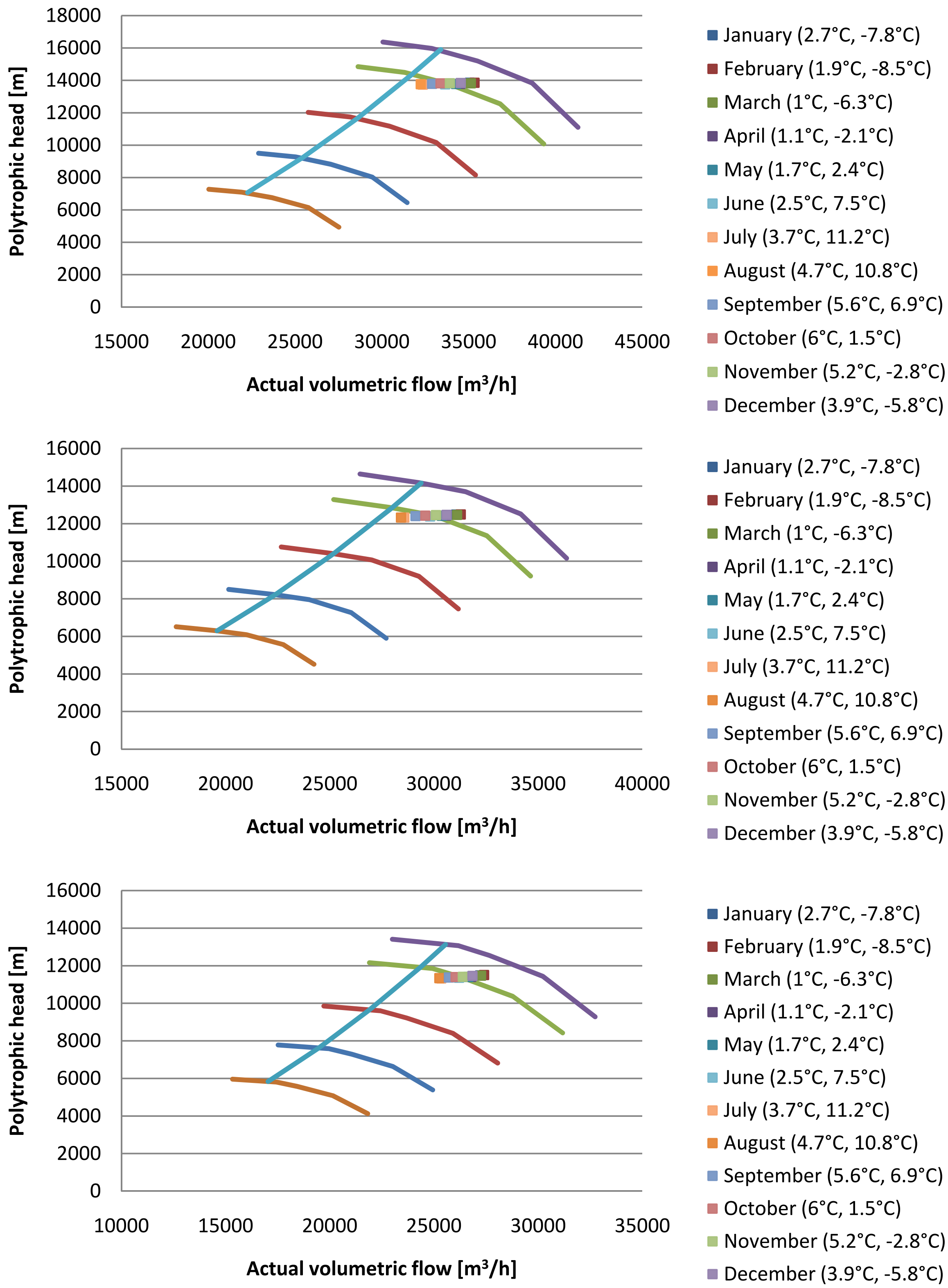
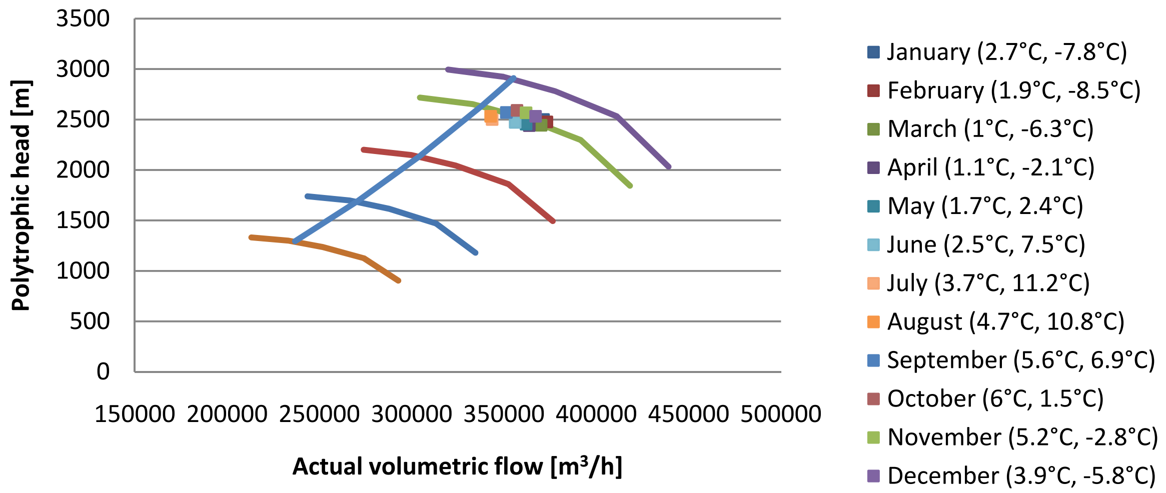
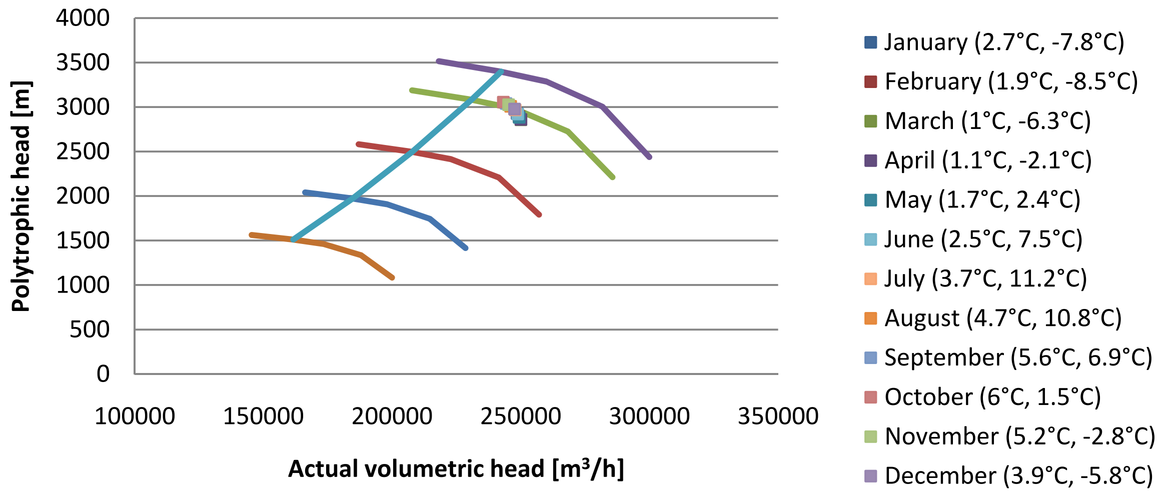


FIGURE 78 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) METHANE/FLASH COMPRESSORS CASE 5

A.6 Operating points Case 6





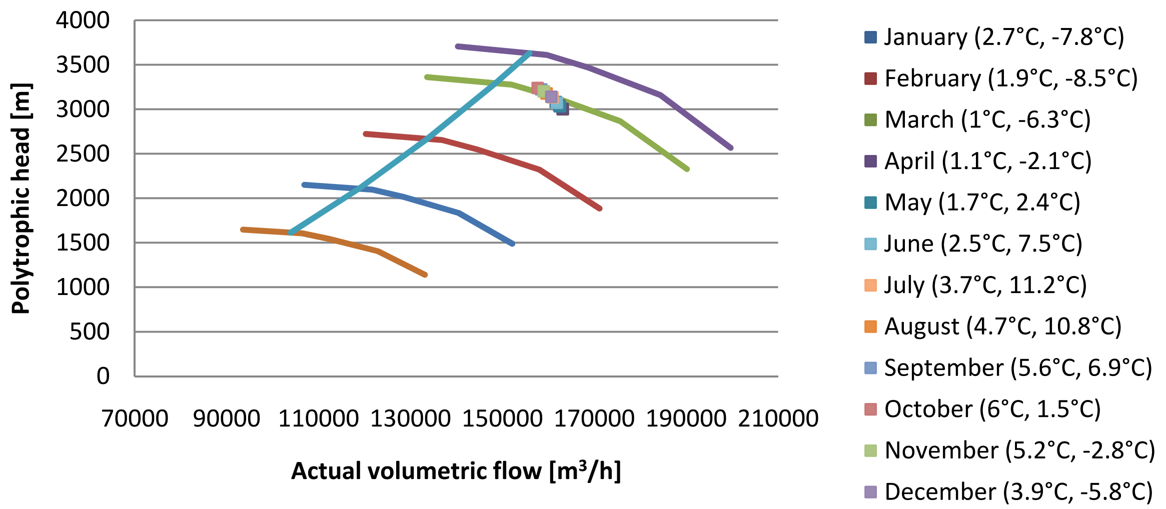
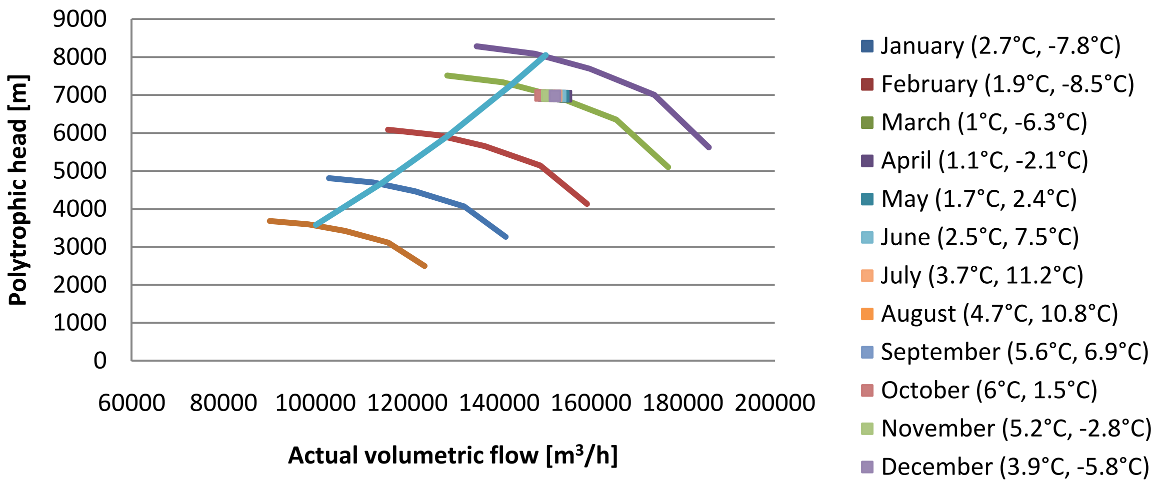
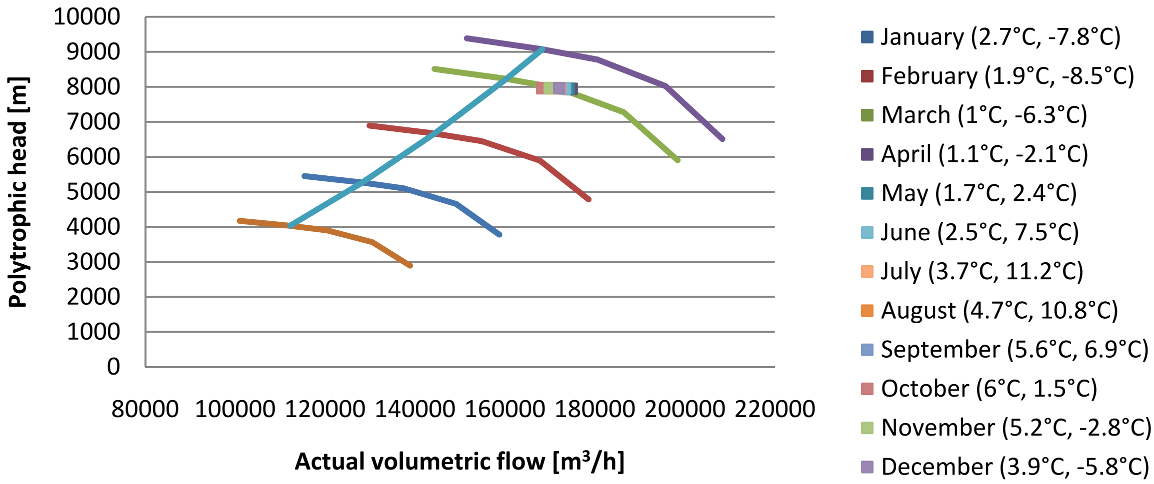


Figure 79 LP (at the top), MP and HP (at the bottom) propane compressors case 6





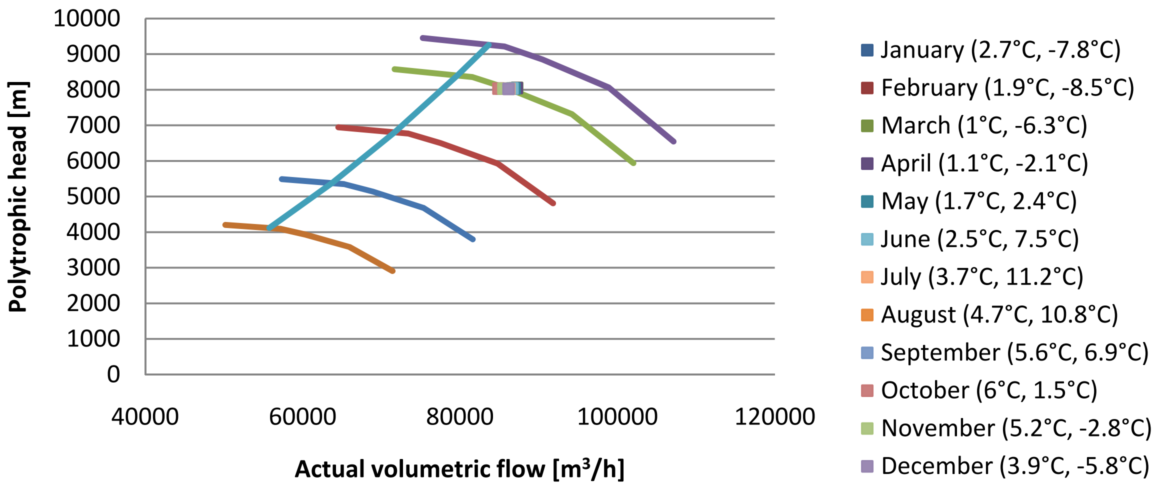


FIGURE 80 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) ETHYLENE COMPRESSORS CASE 6

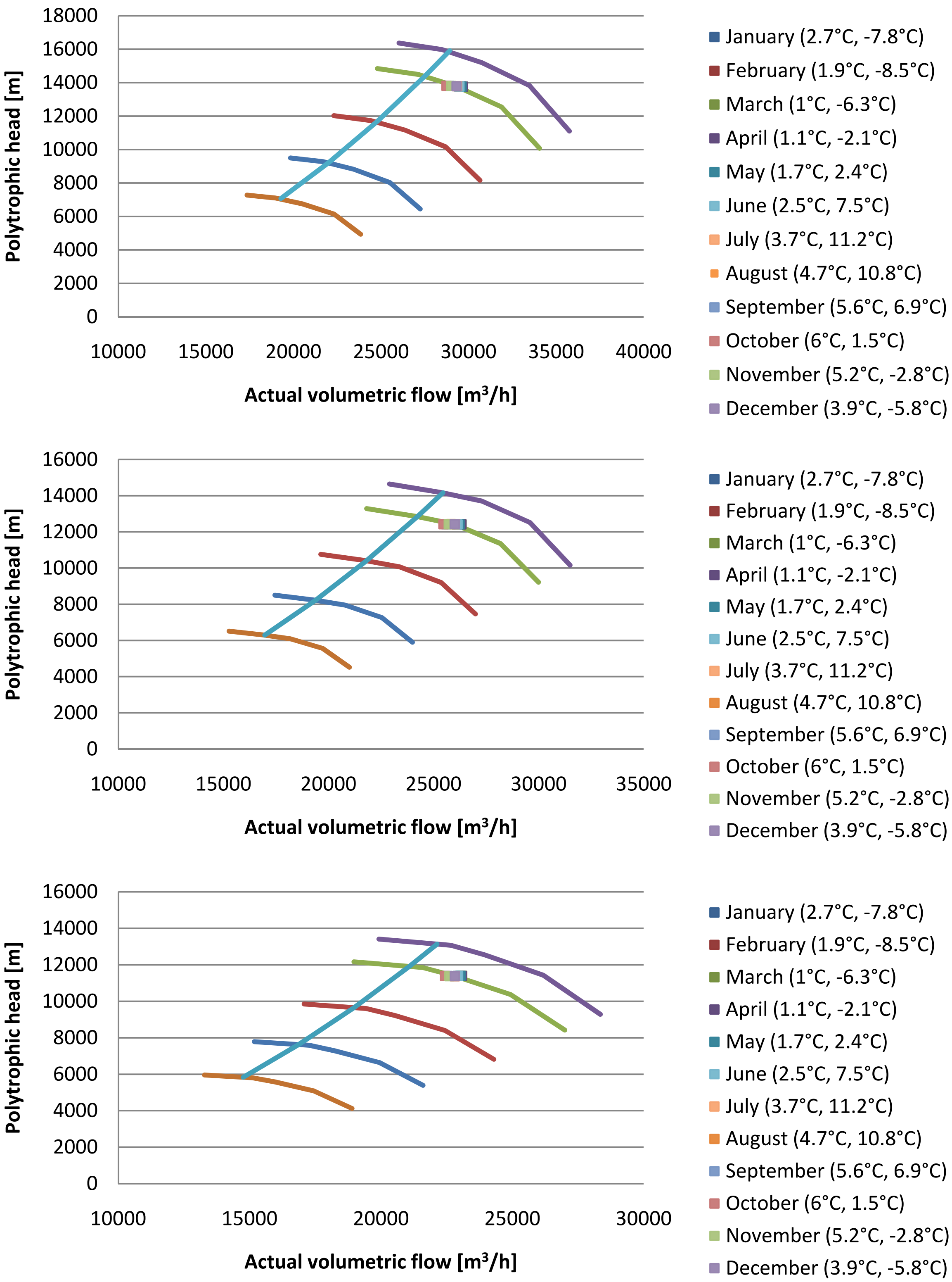


FIGURE 81 LP (AT THE TOP), MP AND HP (AT THE BOTTOM) METHANE/FLASH COMPRESSORS CASE 6

A.7 Compressor curves case 1

TABLE 15 PROPANE COMPRESSOR CURVES CASE 1

LP propane			MP propane			HP propane		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
311605	1625	82.0	232621	1874	82.0	169181	2516	83.0
340879	1586	83.0	257822	1813	83.0	192498	2452	84.5
368202	1509	84.0	277207	1753	84.0	203343	2355	85.0
400728	1373	80.0	300469	1602	80.0	222322	2146	81.5
428051	1102	73.0	319854	1299	73.0	240758	1742	74.0
2880			2880			2880		
356120	2122	82.0	265853	2447	82.0	193350	3287	83.0
389576	2071	83.0	294654	2368	83.0	219998	3203	84.5
420802	1970	84.0	316808	2289	84.0	232392	3076	85.0
457975	1793	80.0	343393	2092	80.0	254082	2802	81.5
489201	1440	73.0	365548	1697	73.0	275152	2275	74.0
3240			3240			3240		
400635	2685	82.0	299085	3097	82.0	217519	4160	83.0
438273	2622	83.0	331485	2997	83.0	247497	4053	84.5
473402	2494	84.0	356409	2897	84.0	261441	3893	85.0
515222	2270	80.0	386318	2648	80.0	285842	3547	81.5
550351	1822	73.0	411241	2148	73.0	309546	2880	74.0
3600			3600			3600		
445150	3315	82.0	332316	3824	82.0	241688	5135	83.0
486970	3236	83.0	368317	3700	83.0	274997	5004	84.5
526002	3079	84.0	396010	3577	84.0	290490	4806	85.0
572469	2802	80.0	429242	3269	80.0	317602	4379	81.5
611501	2250	73.0	456935	2652	73.0	343940	3555	74.0
3780			3780			3780		
467408	3655	82.0	348932	4216	82.0	253772	5662	83.0
511319	3568	83.0	386733	4080	83.0	288747	5517	84.5
552303	3394	84.0	415811	3944	84.0	305014	5299	85.0
601093	3090	80.0	450704	3604	80.0	333482	4827	81.5
642076	2480	73.0	479781	2924	73.0	361137	3920	74.0

TABLE 16 ETHYLENE COMPRESSOR CURVES CASE 1

LP ethylene			MP ethylene			HP ethylene		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
136837	3696	82.0	153076	4178	82.0	86863	4502	83.0
149693	3608	83.0	169659	4043	83.0	98834	4387	84.5
161691	3432	84.0	182416	3909	84.0	104402	4214	85.0
175974	3124	80.0	197723	3572	80.0	114146	3839	81.5
187973	2508	73.0	210479	2898	73.0	123612	3117	74.0
2880			2880			2880		
156385	4828	82.0	174944	5457	82.0	99272	5880	83.0
171077	4713	83.0	193896	5281	83.0	112953	5730	84.5
184789	4483	84.0	208475	5105	84.0	119317	5503	85.0
201114	4081	80.0	225969	4665	80.0	130453	5014	81.5
214826	3276	73.0	240548	3785	73.0	141271	4071	74.0
3240			3240			3240		
175934	6110	82.0	196812	6907	82.0	111680	7442	83.0
192462	5965	83.0	218133	6684	83.0	127072	7252	84.5
207888	5674	84.0	234534	6461	84.0	134231	6965	85.0
226253	5164	80.0	254215	5904	80.0	146760	6345	81.5
241679	4146	73.0	270616	4790	73.0	158930	5152	74.0
3600			3600			3600		
195482	7543	82.0	218680	8527	82.0	124089	9187	83.0
213846	7364	83.0	242370	8252	83.0	141191	8953	84.5
230987	7004	84.0	260594	7977	84.0	149146	8599	85.0
251392	6376	80.0	282462	7289	80.0	163066	7834	81.5
268532	5119	73.0	300685	5914	73.0	176589	6361	74.0
3780			3780			3780		
205256	8316	82.0	229614	9401	82.0	130294	10129	83.0
224539	8118	83.0	254489	9097	83.0	148251	9871	84.5
242536	7722	84.0	273623	8794	84.0	156603	9480	85.0
263962	7029	80.0	296585	8036	80.0	171220	8637	81.5
281959	5643	73.0	315719	6520	73.0	185418	7013	74.0

TABLE 17 METHANE/FLASH COMPRESSOR CURVES CASE 1

LP methane/flash			MP methane/flash			HP methane/flash		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
26250	7274	82.0	23542	6630	82.0	21495	6362	83.0
28716	7101	83.0	26092	6416	83.0	24458	6199	84.5
31018	6754	84.0	28054	6202	84.0	25835	5954	85.0
33758	6148	80.0	30408	5668	80.0	28247	5424	81.5
36059	4936	73.0	32370	4598	73.0	30589	4405	74.0
2880			2880			2880		
30000	9501	82.0	26905	8660	82.0	24566	8309	83.0
32818	9275	83.0	29819	8381	83.0	27951	8097	84.5
35449	8822	84.0	32061	8101	84.0	29526	7777	85.0
38580	8030	80.0	34752	7403	80.0	32282	7085	81.5
41211	6447	73.0	36994	6006	73.0	34959	5753	74.0
3240			3240			3240		
33750	12024	82.0	30268	10960	82.0	27636	10516	83.0
36921	11738	83.0	33547	10607	83.0	31445	10248	84.5
39880	11166	84.0	36069	10253	84.0	33217	9843	85.0
43403	10164	80.0	39096	9369	80.0	36317	8967	81.5
46362	8159	73.0	41618	7601	73.0	39329	7281	74.0
3600			3600			3600		
37500	14845	82.0	33631	13531	82.0	30707	12983	83.0
41023	14492	83.0	37274	13095	83.0	34939	12652	84.5
44311	13785	84.0	40077	12658	84.0	36908	12152	85.0
48225	12548	80.0	43440	11567	80.0	40352	11070	81.5
51513	10073	73.0	46242	9384	73.0	43699	8989	74.0
3780			3780			3780		
39375	16367	82.0	35312	14918	82.0	32243	14314	83.0
43074	15977	83.0	39138	14437	83.0	36686	13949	84.5
46526	15198	84.0	42081	13956	84.0	38753	13397	85.0
50637	13834	80.0	45612	12752	80.0	42370	12205	81.5
54089	11106	73.0	48555	10346	73.0	45884	9910	74.0

A.8 COMPRESSOR CURVES CASE 2

TABLE 18 PROPANE COMPRESSOR CURVES CASE 2

LP propane			MP propane			HP propane		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
311341	1625	82.0	232424	1874	82.0	169038	2516	83.0
340590	1586	83.0	257603	1813	83.0	192335	2452	84.5
367890	1509	84.0	276972	1753	84.0	203171	2355	85.0
400389	1373	80.0	300214	1602	80.0	222133	2146	81.5
427688	1102	73.0	319583	1299	73.0	240554	1742	74.0
2880			2880			2880		
355819	2122	82.0	265628	2447	82.0	193186	3287	83.0
389246	2071	83.0	294404	2368	83.0	219811	3203	84.5
420445	1970	84.0	316540	2289	84.0	232195	3076	85.0
457587	1793	80.0	343102	2092	80.0	253866	2802	81.5
488786	1440	73.0	365238	1697	73.0	274919	2275	74.0
3240			3240			3240		
400296	2685	82.0	298831	3097	82.0	217334	4160	83.0
437902	2622	83.0	331204	2997	83.0	247288	4053	84.5
473001	2494	84.0	356107	2897	84.0	261219	3893	85.0
514786	2270	80.0	385990	2648	80.0	285600	3547	81.5
549885	1822	73.0	410893	2148	73.0	309284	2880	74.0
3600			3600			3600		
444773	3315	82.0	332034	3824	82.0	241483	5135	83.0
486558	3236	83.0	368005	3700	83.0	274764	5004	84.5
525557	3079	84.0	395674	3577	84.0	290244	4806	85.0
571984	2802	80.0	428878	3269	80.0	317333	4379	81.5
610983	2250	73.0	456547	2652	73.0	343648	3555	74.0
3780			3780			3780		
467012	3655	82.0	348636	4216	82.0	253557	5662	83.0
510886	3568	83.0	386405	4080	83.0	288502	5517	84.5
551834	3394	84.0	415458	3944	84.0	304756	5299	85.0
600583	3090	80.0	450322	3604	80.0	333200	4827	81.5
641532	2480	73.0	479375	2924	73.0	360831	3920	74.0

TABLE 19 ETHYLENE COMPRESSOR CURVES CASE 2

LP ethylene			MP ethylene			HP ethylene		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
136721	3696	82.0	152946	4178	82.0	86789	4502	83.0
149566	3608	83.0	169515	4043	83.0	98750	4387	84.5
161554	3432	84.0	182261	3909	84.0	104314	4214	85.0
175825	3124	80.0	197555	3572	80.0	114050	3839	81.5
187813	2508	73.0	210301	2898	73.0	123507	3117	74.0
2880			2880			2880		
156253	4828	82.0	174795	5457	82.0	99187	5880	83.0
170932	4713	83.0	193732	5281	83.0	112857	5730	84.5
184633	4483	84.0	208298	5105	84.0	119216	5503	85.0
200943	4081	80.0	225778	4665	80.0	130342	5014	81.5
214644	3276	73.0	240344	3785	73.0	141151	4071	74.0
3240			3240			3240		
175784	6110	82.0	196645	6907	82.0	111586	7442	83.0
192299	5965	83.0	217948	6684	83.0	126965	7252	84.5
207712	5674	84.0	234335	6461	84.0	134117	6965	85.0
226061	5164	80.0	254000	5904	80.0	146635	6345	81.5
241474	4146	73.0	270387	4790	73.0	158795	5152	74.0
3600			3600			3600		
195316	7543	82.0	218494	8527	82.0	123984	9187	83.0
213665	7364	83.0	242165	8252	83.0	141072	8953	84.5
230791	7004	84.0	260372	7977	84.0	149019	8599	85.0
251179	6376	80.0	282222	7289	80.0	162928	7834	81.5
268305	5119	73.0	300430	5914	73.0	176439	6361	74.0
3780			3780			3780		
205082	8316	82.0	229419	9401	82.0	130183	10129	83.0
224348	8118	83.0	254273	9097	83.0	148125	9871	84.5
242330	7722	84.0	273391	8794	84.0	156470	9480	85.0
263738	7029	80.0	296333	8036	80.0	171074	8637	81.5
281720	5643	73.0	315451	6520	73.0	185261	7013	74.0

TABLE 20 METHANE/FLASH COMPRESSOR CURVES CASE 2

LP methane/flash			MP methane/flash			HP methane/flash		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
26228	7274	82.0	23522	6630	82.0	21477	6362	83.0
28692	7101	83.0	26070	6416	83.0	24437	6199	84.5
30991	6754	84.0	28030	6202	84.0	25813	5954	85.0
33729	6148	80.0	30382	5668	80.0	28223	5424	81.5
36029	4936	73.0	32342	4598	73.0	30563	4405	74.0
2880			2880			2880		
29974	9501	82.0	26882	8660	82.0	24545	8309	83.0
32790	9275	83.0	29794	8381	83.0	27928	8097	84.5
35419	8822	84.0	32034	8101	84.0	29501	7777	85.0
38547	8030	80.0	34722	7403	80.0	32255	7085	81.5
41176	6447	73.0	36963	6006	73.0	34929	5753	74.0
3240			3240			3240		
33721	12024	82.0	30242	10960	82.0	27613	10516	83.0
36889	11738	83.0	33518	10607	83.0	31419	10248	84.5
39846	11166	84.0	36038	10253	84.0	33189	9843	85.0
43366	10164	80.0	39063	9369	80.0	36286	8967	81.5
46323	8159	73.0	41583	7601	73.0	39295	7281	74.0
3600			3600			3600		
37468	14845	82.0	33602	13531	82.0	30681	12983	83.0
40988	14492	83.0	37243	13095	83.0	34910	12652	84.5
44273	13785	84.0	40043	12658	84.0	36876	12152	85.0
48184	12548	80.0	43403	11567	80.0	40318	11070	81.5
51470	10073	73.0	46203	9384	73.0	43662	8989	74.0
3780			3780			3780		
39341	16367	82.0	35282	14918	82.0	32215	14314	83.0
43037	15977	83.0	39105	14437	83.0	36655	13949	84.5
46487	15198	84.0	42045	13956	84.0	38720	13397	85.0
50594	13834	80.0	45573	12752	80.0	42334	12205	81.5
54043	11106	73.0	48513	10346	73.0	45845	9910	74.0

A.9 Compressor curves case 3

TABLE 21 PROPANE COMPRESSOR CURVES CASE 3

LP propane			MP propane			HP propane		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
265853	1625	82.0	198466	1874	82.0	144341	2516	83.0
290829	1586	83.0	219967	1813	83.0	164234	2452	84.5
314140	1509	84.0	236506	1753	84.0	173487	2355	85.0
341891	1373	80.0	256352	1602	80.0	189679	2146	81.5
365201	1102	73.0	272891	1299	73.0	205408	1742	74.0
2880			2880			2880		
303832	2122	82.0	226819	2447	82.0	164961	3287	83.0
332376	2071	83.0	251391	2368	83.0	187696	3203	84.5
359017	1970	84.0	270292	2289	84.0	198271	3076	85.0
390732	1793	80.0	292974	2092	80.0	216776	2802	81.5
417373	1440	73.0	311876	1697	73.0	234752	2275	74.0
3240			3240			3240		
341811	2685	82.0	255171	3097	82.0	185581	4160	83.0
373923	2622	83.0	282814	2997	83.0	211158	4053	84.5
403894	2494	84.0	304079	2897	84.0	223054	3893	85.0
439574	2270	80.0	329596	2648	80.0	243873	3547	81.5
469545	1822	73.0	350860	2148	73.0	264096	2880	74.0
3600			3600			3600		
379790	3315	82.0	283523	3824	82.0	206201	5135	83.0
415470	3236	83.0	314238	3700	83.0	234620	5004	84.5
448771	3079	84.0	337865	3577	84.0	247838	4806	85.0
488415	2802	80.0	366217	3269	80.0	270970	4379	81.5
521716	2250	73.0	389844	2652	73.0	293440	3555	74.0
3780			3780			3780		
398780	3655	82.0	297699	4216	82.0	216511	5662	83.0
436244	3568	83.0	329950	4080	83.0	246351	5517	84.5
471210	3394	84.0	354758	3944	84.0	260230	5299	85.0
512836	3090	80.0	384528	3604	80.0	284518	4827	81.5
547802	2480	73.0	409337	2924	73.0	308112	3920	74.0

TABLE 22 ETHYLENE COMPRESSOR CURVES CASE 3

LP ethylene			MP ethylene			HP ethylene		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
116746	3696	82.0	130600	4178	82.0	74109	4502	83.0
127714	3608	83.0	144749	4043	83.0	84322	4387	84.5
137950	3432	84.0	155632	3909	84.0	89073	4214	85.0
150137	3124	80.0	168692	3572	80.0	97387	3839	81.5
160373	2508	73.0	179575	2898	73.0	105462	3117	74.0
2880			2880			2880		
133424	4828	82.0	149257	5457	82.0	84696	5880	83.0
145958	4713	83.0	165427	5281	83.0	96369	5730	84.5
157657	4483	84.0	177865	5105	84.0	101798	5503	85.0
171585	4081	80.0	192791	4665	80.0	111299	5014	81.5
183284	3276	73.0	205229	3785	73.0	120529	4071	74.0
3240			3240			3240		
150102	6110	82.0	167915	6907	82.0	95283	7442	83.0
164203	5965	83.0	186105	6684	83.0	108415	7252	84.5
177364	5674	84.0	200098	6461	84.0	114522	6965	85.0
193033	5164	80.0	216890	5904	80.0	125211	6345	81.5
206194	4146	73.0	230882	4790	73.0	135595	5152	74.0
3600			3600			3600		
166780	7543	82.0	186572	8527	82.0	105870	9187	83.0
182448	7364	83.0	206784	8252	83.0	120461	8953	84.5
197072	7004	84.0	222331	7977	84.0	127247	8599	85.0
214481	6376	80.0	240988	7289	80.0	139124	7834	81.5
229104	5119	73.0	256536	5914	73.0	150661	6361	74.0
3780			3780			3780		
175119	8316	82.0	195900	9401	82.0	111163	10129	83.0
191570	8118	83.0	217123	9097	83.0	126484	9871	84.5
206925	7722	84.0	233448	8794	84.0	133610	9480	85.0
225205	7029	80.0	253038	8036	80.0	146080	8637	81.5
240560	5643	73.0	269363	6520	73.0	158194	7013	74.0

TABLE 23 METHANE/FLASH COMPRESSOR CURVES CASE 3

LP methane/flash			MP methane/flash			HP methane/flash		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
22395	7274	82.0	20085	6630	82.0	18338	6361	83.0
24499	7100	83.0	22260	6416	83.0	20866	6199	84.5
26463	6754	84.0	23934	6202	84.0	22042	5954	85.0
28801	6148	80.0	25943	5667	80.0	24099	5424	81.5
30764	4935	73.0	27616	4598	73.0	26097	4404	74.0
2880			2880			2880		
25595	9500	82.0	22954	8659	82.0	20958	8309	83.0
27999	9274	83.0	25441	8380	83.0	23847	8097	84.5
30243	8822	84.0	27353	8101	84.0	25190	7777	85.0
32915	8030	80.0	29649	7402	80.0	27542	7085	81.5
35159	6446	73.0	31562	6006	73.0	29826	5752	74.0
3240			3240			3240		
28794	12024	82.0	25823	10960	82.0	23578	10516	83.0
31499	11738	83.0	28621	10606	83.0	26828	10247	84.5
34024	11165	84.0	30773	10253	84.0	28339	9842	85.0
37030	10163	80.0	33355	9369	80.0	30984	8966	81.5
39554	8159	73.0	35507	7601	73.0	33554	7280	74.0
3600			3600			3600		
31993	14845	82.0	28692	13531	82.0	26198	12983	83.0
34999	14491	83.0	31801	13094	83.0	29809	12651	84.5
37804	13784	84.0	34192	12658	84.0	31488	12151	85.0
41144	12547	80.0	37061	11566	80.0	34427	11070	81.5
43949	10073	73.0	39452	9384	73.0	37282	8988	74.0
3780			3780			3780		
33593	16366	82.0	30127	14918	82.0	27508	14313	83.0
36749	15976	83.0	33391	14436	83.0	31299	13948	84.5
39695	15197	84.0	35901	13955	84.0	33063	13397	85.0
43201	13833	80.0	38914	12752	80.0	36148	12205	81.5
46147	11105	73.0	41425	10346	73.0	39146	9910	74.0

A.10 Compressor curves case 4

TABLE 24 PROPANE COMPRESSOR CURVES CASE 4

LP propane			MP propane			HP propane		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
215688	1331	82.0	169943	1562	82.0	109319	1647	83.0
235950	1300	83.0	188354	1512	83.0	124385	1605	84.5
254863	1236	84.0	202515	1461	84.0	131393	1542	85.0
277377	1125	80.0	219510	1335	80.0	143656	1404	81.5
296289	903	73.0	233672	1083	73.0	155569	1140	74.0
2880			2880			2880		
246500	1739	82.0	194221	2040	82.0	124936	2151	83.0
269658	1697	83.0	215261	1974	83.0	142155	2096	84.5
291271	1615	84.0	231446	1909	84.0	150163	2014	85.0
317002	1470	80.0	250868	1744	80.0	164179	1834	81.5
338616	1180	73.0	267053	1415	73.0	177794	1489	74.0
3240			3240			3240		
277313	2201	82.0	218498	2582	82.0	140553	2723	83.0
303365	2148	83.0	242169	2499	83.0	159924	2653	84.5
327680	2044	84.0	260377	2416	84.0	168934	2548	85.0
356627	1860	80.0	282227	2207	80.0	184701	2322	81.5
380943	1493	73.0	300435	1791	73.0	200018	1885	74.0
3600			3600			3600		
308125	2717	82.0	242776	3188	82.0	156170	3361	83.0
337072	2652	83.0	269076	3085	83.0	177693	3276	84.5
364089	2523	84.0	289308	2982	84.0	187704	3146	85.0
396253	2296	80.0	313585	2725	80.0	205223	2866	81.5
423270	1844	73.0	333817	2211	73.0	222242	2327	74.0
3780			3780			3780		
323531	2995	82.0	254915	3515	82.0	163979	3706	83.0
353926	2924	83.0	282530	3401	83.0	186578	3611	84.5
382294	2782	84.0	303773	3288	84.0	197090	3469	85.0
416065	2532	80.0	329265	3004	80.0	215485	3160	81.5
444433	2033	73.0	350507	2438	73.0	233354	2566	74.0

TABLE 25 ETHYLENE COMPRESSOR CURVES CASE 4

LP ethylene			MP ethylene			HP ethylene		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
105275	3681	82.0	118052	4171	82.0	58653	4203	83.0
115165	3593	83.0	130841	4036	83.0	66736	4095	84.5
124396	3418	84.0	140679	3902	84.0	70496	3933	85.0
135385	3111	80.0	152484	3565	80.0	77076	3583	81.5
144616	2498	73.0	162322	2893	73.0	83467	2910	74.0
2880			2880			2880		
120314	4808	82.0	134917	5447	82.0	67032	5489	83.0
131617	4693	83.0	149533	5272	83.0	76270	5349	84.5
142167	4465	84.0	160776	5096	84.0	80567	5138	85.0
154726	4064	80.0	174268	4657	80.0	88087	4680	81.5
165275	3263	73.0	185511	3778	73.0	95391	3800	74.0
3240			3240			3240		
135353	6085	82.0	151782	6894	82.0	75411	6947	83.0
148069	5940	83.0	168225	6672	83.0	85804	6770	84.5
159938	5650	84.0	180873	6449	84.0	90638	6502	85.0
174066	5143	80.0	196051	5893	80.0	99097	5924	81.5
185934	4129	73.0	208700	4781	73.0	107315	4810	74.0
3600			3600			3600		
150393	7512	82.0	168646	8511	82.0	83790	8577	83.0
164522	7334	83.0	186916	8237	83.0	95338	8358	84.5
177708	6976	84.0	200970	7962	84.0	100709	8027	85.0
193407	6350	80.0	217835	7276	80.0	110108	7313	81.5
206594	5098	73.0	231889	5903	73.0	119239	5938	74.0
3780			3780			3780		
157912	8282	82.0	177079	9384	82.0	87979	9456	83.0
172748	8085	83.0	196262	9081	83.0	100104	9214	84.5
186594	7691	84.0	211019	8778	84.0	105744	8850	85.0
203077	7001	80.0	228726	8022	80.0	115614	8063	81.5
216924	5620	73.0	243483	6508	73.0	125201	6547	74.0

TABLE 26 METHANE/FLASH COMPRESSOR CURVES CASE 4

LP methane/flash			MP methane/flash			HP methane/flash		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
20282	7274	82.0	17846	6509	82.0	15521	5959	83.0
22187	7101	83.0	19780	6299	83.0	17660	5807	84.5
23965	6754	84.0	21267	6089	84.0	18655	5578	85.0
26082	6148	80.0	23052	5564	80.0	20396	5081	81.5
27861	4936	73.0	24539	4514	73.0	22087	4126	74.0
2880			2880			2880		
23179	9501	82.0	20396	8502	82.0	17738	7783	83.0
25357	9275	83.0	22605	8228	83.0	20182	7585	84.5
27389	8822	84.0	24305	7953	84.0	21320	7285	85.0
29809	8030	80.0	26345	7268	80.0	23309	6637	81.5
31841	6447	73.0	28044	5896	73.0	25242	5389	74.0
3240			3240			3240		
26076	12024	82.0	22945	10760	82.0	19955	9851	83.0
28526	11738	83.0	25431	10413	83.0	22705	9599	84.5
30813	11166	84.0	27343	10066	84.0	23984	9220	85.0
33535	10164	80.0	29638	9198	80.0	26223	8399	81.5
35821	8159	73.0	31550	7463	73.0	28398	6820	74.0
3600			3600			3600		
28974	14845	82.0	25495	13284	82.0	22172	12161	83.0
31696	14492	83.0	28257	12856	83.0	25228	11851	84.5
34236	13785	84.0	30381	12427	84.0	26649	11383	85.0
37261	12548	80.0	32931	11356	80.0	29137	10370	81.5
39801	10073	73.0	35055	9213	73.0	31553	8420	74.0
3780			3780			3780		
30422	16367	82.0	26770	14646	82.0	23281	13408	83.0
33281	15977	83.0	29670	14173	83.0	26490	13066	84.5
35948	15198	84.0	31900	13701	84.0	27982	12549	85.0
39124	13834	80.0	34577	12520	80.0	30594	11433	81.5
41791	11106	73.0	36808	10158	73.0	33131	9283	74.0

A.11 Compressor curves case 5

TABLE 27 PROPANE COMPRESSOR CURVES CASE 5

LP propane			MP propane			HP propane		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
213113	1331	82.0	167915	1562	82.0	108014	1647	83.0
233134	1300	83.0	186105	1512	83.0	122901	1605	84.5
251820	1236	84.0	200098	1461	84.0	129825	1542	85.0
274066	1125	80.0	216890	1335	80.0	141942	1404	81.5
292752	903	73.0	230883	1083	73.0	153712	1140	74.0
2880			2880			2880		
243558	1739	82.0	191902	2040	82.0	123445	2151	83.0
266439	1697	83.0	212692	1974	83.0	140458	2096	84.5
287795	1615	84.0	228684	1909	84.0	148371	2014	85.0
313218	1470	80.0	247874	1744	80.0	162219	1834	81.5
334574	1180	73.0	263866	1415	73.0	175671	1489	74.0
3240			3240			3240		
274003	2201	82.0	215890	2582	82.0	138875	2723	83.0
299744	2148	83.0	239278	2499	83.0	158015	2653	84.5
323769	2044	84.0	257269	2416	84.0	166917	2548	85.0
352371	1860	80.0	278858	2207	80.0	182496	2322	81.5
376396	1493	73.0	296849	1791	73.0	197630	1885	74.0
3600			3600			3600		
304447	2717	82.0	239878	3188	82.0	154306	3361	83.0
333049	2652	83.0	265865	3085	83.0	175572	3276	84.5
359744	2523	84.0	285855	2982	84.0	185464	3146	85.0
391523	2296	80.0	309842	2725	80.0	202774	2866	81.5
418218	1844	73.0	329832	2211	73.0	219589	2327	74.0
3780			3780			3780		
319670	2995	82.0	251872	3515	82.0	162021	3706	83.0
349701	2924	83.0	279158	3401	83.0	184351	3611	84.5
377731	2782	84.0	300147	3288	84.0	194737	3469	85.0
411099	2532	80.0	325334	3004	80.0	212913	3160	81.5
439129	2033	73.0	346324	2438	73.0	230569	2566	74.0

TABLE 28 ETHYLENE COMPRESSOR CURVES CASE 5

LP ethylene			MP ethylene			HP ethylene		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
104018	3681	82.0	116643	4171	82.0	57953	4203	83.0
113790	3593	83.0	129280	4036	83.0	65940	4095	84.5
122911	3418	84.0	139000	3902	84.0	69655	3933	85.0
133769	3111	80.0	150664	3565	80.0	76156	3583	81.5
142890	2498	73.0	160385	2893	73.0	82471	2910	74.0
2880			2880			2880		
118878	4808	82.0	133307	5447	82.0	66232	5489	83.0
130046	4693	83.0	147748	5272	83.0	75360	5349	84.5
140470	4465	84.0	158857	5096	84.0	79605	5138	85.0
152879	4064	80.0	172188	4657	80.0	87035	4680	81.5
163302	3263	73.0	183297	3778	73.0	94253	3800	74.0
3240			3240			3240		
133738	6085	82.0	149970	6894	82.0	74511	6947	83.0
146302	5940	83.0	166217	6672	83.0	84780	6770	84.5
158028	5650	84.0	178714	6449	84.0	89556	6502	85.0
171989	5143	80.0	193711	5893	80.0	97915	5924	81.5
183715	4129	73.0	206209	4781	73.0	106034	4810	74.0
3600			3600			3600		
148598	7512	82.0	166633	8511	82.0	82790	8577	83.0
162558	7334	83.0	184685	8237	83.0	94200	8358	84.5
175587	6976	84.0	198571	7962	84.0	99507	8027	85.0
191098	6350	80.0	215235	7276	80.0	108794	7313	81.5
204128	5098	73.0	229121	5903	73.0	117816	5938	74.0
3780			3780			3780		
156028	8282	82.0	174965	9384	82.0	86929	9456	83.0
170686	8085	83.0	193919	9081	83.0	98910	9214	84.5
184367	7691	84.0	208500	8778	84.0	104482	8850	85.0
200653	7001	80.0	225996	8022	80.0	114234	8063	81.5
214334	5620	73.0	240577	6508	73.0	123707	6547	74.0

TABLE 29 METHANE/FLASH COMPRESSOR CURVES CASE 5

LP methane/flash			MP methane/flash			HP methane/flash		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
20040	7274	82.0	17633	6509	82.0	15335	5959	83.0
21922	7101	83.0	19544	6299	83.0	17449	5807	84.5
23679	6754	84.0	21013	6089	84.0	18432	5578	85.0
25771	6148	80.0	22776	5564	80.0	20152	5081	81.5
27528	4936	73.0	24246	4514	73.0	21823	4126	74.0
2880			2880			2880		
22902	9501	82.0	20152	8502	82.0	17526	7783	83.0
25054	9275	83.0	22336	8228	83.0	19942	7585	84.5
27062	8822	84.0	24015	7953	84.0	21065	7285	85.0
29453	8030	80.0	26030	7268	80.0	23031	6637	81.5
31461	6447	73.0	27710	5896	73.0	24941	5389	74.0
3240			3240			3240		
25765	12024	82.0	22671	10760	82.0	19717	9851	83.0
28186	11738	83.0	25128	10413	83.0	22434	9599	84.5
30445	11166	84.0	27017	10066	84.0	23698	9220	85.0
33134	10164	80.0	29284	9198	80.0	25910	8399	81.5
35393	8159	73.0	31173	7463	73.0	28059	6820	74.0
3600			3600			3600		
28628	14845	82.0	25191	13284	82.0	21908	12161	83.0
31317	14492	83.0	27920	12856	83.0	24927	11851	84.5
33828	13785	84.0	30019	12427	84.0	26331	11383	85.0
36816	12548	80.0	32538	11356	80.0	28789	10370	81.5
39326	10073	73.0	34637	9213	73.0	31176	8420	74.0
3780			3780			3780		
30059	16367	82.0	26450	14646	82.0	23003	13408	83.0
32883	15977	83.0	29315	14173	83.0	26173	13066	84.5
35519	15198	84.0	31520	13701	84.0	27648	12549	85.0
38657	13834	80.0	34165	12520	80.0	30228	11433	81.5
41292	11106	73.0	36369	10158	73.0	32735	9283	74.0

A.12 COMPRESSOR CURVES CASE 6

TABLE 30 PROPANE COMPRESSOR CURVES CASE 6

LP propane			MP propane			HP propane		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
184558	1331	82.0	145416	1562	82.0	93541	1647	83.0
201896	1300	83.0	161169	1512	83.0	106433	1605	84.5
218079	1236	84.0	173287	1461	84.0	112429	1542	85.0
237344	1125	80.0	187828	1335	80.0	122923	1404	81.5
253526	903	73.0	199946	1083	73.0	133116	1140	74.0
2880			2880			2880		
210923	1739	82.0	166189	2040	82.0	106904	2151	83.0
230739	1697	83.0	184193	1974	83.0	121638	2096	84.5
249233	1615	84.0	198042	1909	84.0	128491	2014	85.0
271250	1470	80.0	214661	1744	80.0	140483	1834	81.5
289744	1180	73.0	228510	1415	73.0	152133	1489	74.0
3240			3240			3240		
237289	2201	82.0	186963	2582	82.0	120267	2723	83.0
259581	2148	83.0	207217	2499	83.0	136843	2653	84.5
280387	2044	84.0	222797	2416	84.0	144552	2548	85.0
305156	1860	80.0	241494	2207	80.0	158044	2322	81.5
325962	1493	73.0	257074	1791	73.0	171150	1885	74.0
3600			3600			3600		
263654	2717	82.0	207736	3188	82.0	133630	3361	83.0
288423	2652	83.0	230241	3085	83.0	152047	3276	84.5
311541	2523	84.0	247553	2982	84.0	160613	3146	85.0
339062	2296	80.0	268326	2725	80.0	175604	2866	81.5
362180	1844	73.0	285638	2211	73.0	190166	2327	74.0
3780			3780			3780		
276837	2995	82.0	218123	3515	82.0	140312	3706	83.0
302844	2924	83.0	241753	3401	83.0	159650	3611	84.5
327118	2782	84.0	259930	3288	84.0	168644	3469	85.0
356016	2532	80.0	281743	3004	80.0	184384	3160	81.5
380289	2033	73.0	299919	2438	73.0	199675	2566	74.0

TABLE 31 ETHYLENE COMPRESSOR CURVES CASE 6

LP ethylene			MP ethylene			HP ethylene		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
90081	3681	82.0	101014	4171	82.0	50188	4203	83.0
98544	3593	83.0	111957	4036	83.0	57104	4095	84.5
106442	3418	84.0	120375	3902	84.0	60322	3933	85.0
115845	3111	80.0	130477	3565	80.0	65952	3583	81.5
123744	2498	73.0	138894	2893	73.0	71421	2910	74.0
2880			2880			2880		
102950	4808	82.0	115445	5447	82.0	57357	5489	83.0
112621	4693	83.0	127951	5272	83.0	65262	5349	84.5
121648	4465	84.0	137572	5096	84.0	68939	5138	85.0
132394	4064	80.0	149116	4657	80.0	75373	4680	81.5
141421	3263	73.0	158736	3778	73.0	81624	3800	74.0
3240			3240			3240		
115818	6085	82.0	129875	6894	82.0	64527	6947	83.0
126699	5940	83.0	143945	6672	83.0	73420	6770	84.5
136854	5650	84.0	154768	6449	84.0	77556	6502	85.0
148944	5143	80.0	167756	5893	80.0	84795	5924	81.5
159099	4129	73.0	178579	4781	73.0	91827	4810	74.0
3600			3600			3600		
128687	7512	82.0	144306	8511	82.0	71696	8577	83.0
140776	7334	83.0	159939	8237	83.0	81578	8358	84.5
152060	6976	84.0	171965	7962	84.0	86174	8027	85.0
165493	6350	80.0	186395	7276	80.0	94216	7313	81.5
176777	5098	73.0	198421	5903	73.0	102030	5938	74.0
3780			3780			3780		
135121	8282	82.0	151521	9384	82.0	75281	9456	83.0
147815	8085	83.0	167936	9081	83.0	85657	9214	84.5
159663	7691	84.0	180563	8778	84.0	90482	8850	85.0
173768	7001	80.0	195715	8022	80.0	98927	8063	81.5
185615	5620	73.0	208342	6508	73.0	107131	6547	74.0

TABLE 32 METHANE/FLASH COMPRESSOR CURVES CASE 6

LP methane/flash			MP methane/flash			HP methane/flash		
2520			2520			2520		
Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %	Vol. flow	Head	Efficiency %
17354	7274	82.0	15271	6509	82.0	13281	5959	83.0
18985	7101	83.0	16925	6299	83.0	15111	5807	84.5
20506	6754	84.0	18198	6089	84.0	15962	5578	85.0
22318	6148	80.0	19725	5564	80.0	17452	5081	81.5
23840	4936	73.0	20997	4514	73.0	18899	4126	74.0
2880			2880			2880		
19834	9501	82.0	17452	8502	82.0	15178	7783	83.0
21697	9275	83.0	19343	8228	83.0	17270	7585	84.5
23436	8822	84.0	20797	7953	84.0	18243	7285	85.0
25506	8030	80.0	22542	7268	80.0	19945	6637	81.5
27245	6447	73.0	23997	5896	73.0	21599	5389	74.0
3240			3240			3240		
22313	12024	82.0	19634	10760	82.0	17075	9851	83.0
24409	11738	83.0	21761	10413	83.0	19428	9599	84.5
26365	11166	84.0	23397	10066	84.0	20523	9220	85.0
28695	10164	80.0	25360	9198	80.0	22438	8399	81.5
30651	8159	73.0	26996	7463	73.0	24299	6820	74.0
3600			3600			3600		
24792	14845	82.0	21815	13284	82.0	18972	12161	83.0
27121	14492	83.0	24179	12856	83.0	21587	11851	84.5
29295	13785	84.0	25996	12427	84.0	22803	11383	85.0
31883	12548	80.0	28178	11356	80.0	24931	10370	81.5
34057	10073	73.0	29996	9213	73.0	26999	8420	74.0
3780			3780			3780		
26032	16367	82.0	22906	14646	82.0	19921	13408	83.0
28477	15977	83.0	25387	14173	83.0	22666	13066	84.5
30760	15198	84.0	27296	13701	84.0	23943	12549	85.0
33477	13834	80.0	29587	12520	80.0	26178	11433	81.5
35760	11106	73.0	31496	10158	73.0	28349	9283	74.0