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Comparative study of CO_2-N_2 and N_2-N_2 dual expansion in natural gas liquefaction process

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Abstract

The processes were modelled using the Aspen Hysys version 11. The paper compared two refrigeration systems with different refrigerants, CO_2-N_2 and N_2-N_2, and their expenders. The parameters compared are the liquefaction power, specific power, production capacity, and heat duty of the expander cycle. The liquefaction power of CO_2-N_2 (547.669kW) is lower than that of N_2-N_2 (815.85kW). The specific power consumption for CO_2-N_2 was 0.44096kW/kg, and for N_2-N_2 was 0.6569kW/kg. The production capacity N_2-N_2 gave a higher value of 6945.6MTPA than CO_2-N_2 4904.38MTPA.

Keywords: Optimization; Liquified Nigeria Gas (LNG); Natural Gas; Expander; Liquefaction Power; Specific Power consumption; Production Capacity

1. Introduction

In recent years, the environmental effect of flared associated gas from offshore fields has escalated to the point that its correct management has become a need to produce oil. This has caused the management of the associated gas to become a prerequisite for oil production. Most of the world's natural gas reserves are offshore, and some offshore deposits are now inaccessible. Natural gas trapped offshore must first be brought onshore before being processed further down the value chain. This is a procedure that always requires the employment of expensive equipment. To turn the natural gas that is now trapped beneath the ocean floor into a commodity that can be sold, it will be necessary to implement offshore solutions such as floating production storage and offloading facilities (FPSO). Because of its comparatively low initial investment cost, quick building duration, and high degree of mobility between fields, the industry has taken a strong interest in the design of the liquefied natural gas floating production storage and offloading (LNG-FPSO) vessel (Barclay *et al.*, 2005).

Natural gas has quickly become one of the most essential players in the energy market because it can be used to power homes and businesses and as a chemical feedstock for the petrochemical industry (Lee et al., 2012).

To achieve liquefaction, natural gas must be brought to very low temperatures via heating (Muwarure et al., 2023). Because of this, it is of the utmost importance to stress that the efficacy with which the refrigeration process uses electrical power is directly linked to how cost-effective it is to manufacture LNG (Khan et al., 2014). The most significant disadvantage is the high amount of energy necessary for operation (Smith, 2005).

As a result of improvements made to the liquefaction stage and the driving cycle, LNG plants could cut their overall energy use. When a refrigeration system is optimized, the result is typically the best cooling performance for the lowest possible cost (usually life-cycle cost). Since energy and equipment costs are anticipated to continue to climb, it is of the utmost significance to optimize both newly installed systems and those already in place. Compressors, condensers,

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evaporators, heat exchangers, vessels, pipework, expansion valves, and fillers comprise the bulk of the components involved in the refrigeration cycle (Martin et al., 2003).

This work aims to achieve the following objectives: Calculating the Liquefaction power, Specific power consumption, Production capacity, and heat duty of the expander cycles for N_2-N_2 and CO_2-N_2, measuring the Performance Coefficient (COP) using simulation.

2. Material and methods

Figure 1 below describes the breakdown of the activities carried out to achieve the purpose of this research.

The materials used in this research are two software, which are Aspen Hysys and Microsoft Office (Excel 365). The Aspen Hysys was used for the simulation process, while the Microsoft Excel was used for data plotting and calculations.

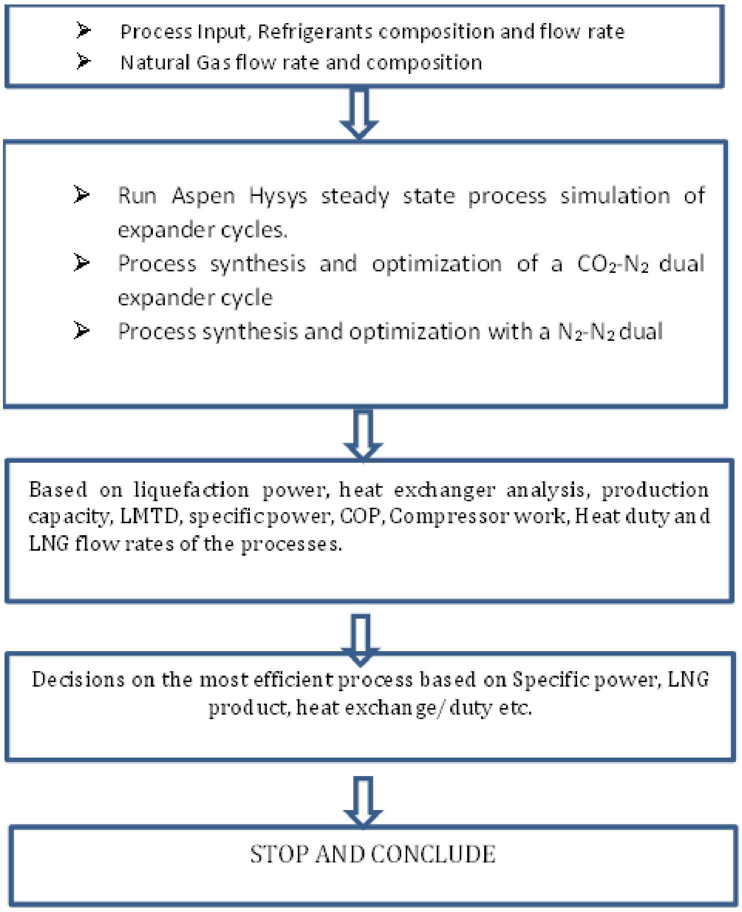

Figure 1 Breakdown of the entire Process

Table 1 Input data (Source: Khan et al., 2014)

Property	**Condition**
Property calculation	Peng Robinson
NG Temp	30 °C
NG pressure	50bar
NG mass flow rate	1242kg/hr
CO_2 mass flow rate	5521kg/hr

N_2 mass flow rate	5518kg/hr
NG composition	(mole fraction)
Nitrogen	0.0022
Methane	0.0022
Ethane	0.0536
Propane	0.0214
I-Butane	0.0046
n-Butane	0.0047
I-Pentane	0.0001
Refrigerant Composition	Mole fraction
CO_2 (precooling)	1
N_2 (sub-cooling)	1

2.1. Description of Process Flow Sheet

The feed, denoted NG l, passes through the LNG-100 heat exchanger, where it is precooled by CO_2. The gas then passes through the LNG-101 exchanger, which is subcooled and exchanges heat with the expanded Nitrogen stream N4. The gas finally passes through the JT valve as LNG after undergoing an expansion process for further pressure reduction. The flash vapour exiting the separator is recompressed and cooled to room temperature as Recycle NG.

2.1.1. Description of the Process CO_2-N_2 Dual Expander

The process consists of two refrigerants, Carbon dioxide, and Nitrogen, respectively; the two refrigerant loops are sufficient for cooling Natural gas by taking heat from the Natural gas and rejecting it to ambient. As the single expander cycle states, CO2 is used to precool both Natural Gas and Nitrogen refrigerants.

The treated Natural Gas is denoted by stream NG (l), which is precooled by CO_2 as it enters the LNG exchanger 100, leaving at pressure and temperature values of 30 ^{o}C and 500kpa. The stream leaves as NG2 at a temp and pressure values of -46.5 °C and 4970kpa. Stream NG2 thus enters the LNG 101, where it is being sub-cooled by Nitrogen and exchanges heat with the expanded Nitrogen stream N4; it leaves the exchanger as NG3, where it undergoes further pressure reduction as it 1s being expanded in a Joule Thomson Valve. The temperature and pressure values of stream NG3 are -154 °C and 4960kpa; the steam exits the JT Valve as LNG at -158.7°C and atmospheric pressure of 120kpa before it enters a Separator where the vapor and the liquid portions of the LNG are separated. The flash vapour from the Separator is again recompressed and cooled to ambient condition, after which it is thus recycled back as Recycle NG to a mixer with the inlet Natural Gas stream NG.

The expanded CO_2 stream from the expander leaves at pressure and temperature values of -49.6 °C and 686kpa as Stream CO_2 1; it enters LNG 100 and precools both the Nitrogen and the Natural Gas stream; it exits the exchanger as stream CO_2 2 at pressure and temperature values of -1.68 °C and 685kpa, it then undergoes three compression stages. In the first compression, the temperature and pressure values of CO_2 3 after the compression of stream CO_2 2 are 66.43 °C and 1503kpa. The heat was rejected in the cooler, leaving the cooler as CO_2 4 at temperature and pressure values of 35 °C and 1478kpa. The Second Stage compression was done; Stream CO_2 6 leaves the cooler at pressure and temperature values 300C and 3293kpa. The third compression stage was also completed, leaving at a discharge pressure of 7240kpa and temperature of 105.8 °C as stream CO_2 7; it thus enters a cooler, and heat exchange occurs. It leaves the cooler as CO2 8 at a temperature of 500 ^{o}C and pressure value of 7215kpa. Stream CO_2 8 now enters the expander for isentropic pressure and temperature reduction. The discharge from the expander is now the stream CO_2 1 at temperature and pressure values of -49°C and 686kpa.

Stream N3 undergoes an isentropic expansion in an expander K103 at temperature and pressure values of -46.17 °C and 9960kpa, and the stream leaves the expander as N4 at temperature and pressure values of -154.7 °C and 640kpa respectively, the expanded stream N4 enters the heat exchanger LNG 101 and exits as N5 at temperature and pressure values of -49.2 °C and 630kpa, providing subcooling effect on the already precooled Natural Gas stream NG 2, it exits the exchanger LNG 101 at these pressure and temperature values and undergoes three-stage compression. The first stage compression was done at pressure and temperature values of stream N5. The discharge from the compression is stream N6 at temperature and pressure values of 41.03 °C and 1580 kpa, the stream enters a cooler, and the stage is completed as stream N7 at (30 °C and 1566 kpa). The second stage compression starts from N7 and ends at N8 (153 °C and 4010kpa). Stream N8 enters a cooler and is cooled. It exits as N9 (30 °C, 3957kpa). The third compression stage starts from N9 and ends with N10 (151.4°C. 10003kpa). N10 enters a cooler and exits as N2 1(30°C. 1000Okpa); the cooled N2 I stream thus enters the exchanger LNG 100 where it is being precooled by CO2 1, it exits as N_2 2 (-17°C, 9970kpa) before it enters the exchanger LNG 101, and the cycle continues.

2.1.2. Simulation of a N2-N2 Dual Expander Cycle

This liquefaction process is a dual nitrogen expander cycle, and it consists of two refrigerant cycles that use Nitrogen as a precooling and sub-cooling/ condensation refrigerant. The process flow sheet was developed using Peng Robinson's Equation of State in ASPEN HYSYS.

Description of the Process Flowsheet

The treated Natural Gas is denoted by stream NGI where it is being precooled by Nitrogen as it enters the LNG exchanger 100 at pressure and temperature values of 30°C and 5000kpa, the stream leaves as NG 2 at a temp and pressure values of -40°C and 4970kpa, stream NG2 thus enters the LNG 101 where it is being sub-cooled by Nitrogen and exchanges heat with the expanded Nitrogen stream N4, it leaves the exchanger as NG3 where it undergoes further pressure reduction as it is being expanded in a Joule Thomson Valve. The temperature and pressure values of stream NG3 are -115°C and 4960kpa. The steam exits the JT Valve as LNG at -I58.0°C and an atmospheric pressure of 120kpa before it enters a Separator where the vapour and the liquid portions of the LNG are separated. The flash vapour consists of about 32.5% LNG vapour which is compressed and recycled back to Natural Gas Inlet stream.

The expanded Nitrogen stream from the expander leaves at pressure and temperature values of 88.600C and 686kpa as Stream N-1, it enters LNG 100 and precools both the other Nitrogen and the Natural Gas streams; it exits the exchanger as Stream N-2 at pressure and temperature values of 25°C and 685kpa. The stream then undergoes three compression stages. In the first compression stage, the temperature and pressure values of N-3 after the compression of stream N-2 are 105 °C and 1503kpa. The heat of compression was rejected in the cooler, and the stream left the cooler as N-4 at temperature and pressure values of 30°C and 1478kpa. The Second Stage compression was done; Stream N-6 leaves the cooler at pressure and temperature values of 30 °C and 3293kpa. The third compression stage was also completed, leaving at a discharge pressure of 7240kpa and temperature of 130.9°C as stream N-7. It thus enters a cooler, and heat exchange takes place. It leaves the cooler as N-8 at a temperature of 30 °C and pressure value of 7215kpa. Stream N-8 now enters the expander for isentropic pressure and temperature reduction, and the discharge from the expander is now the stream N-I at temperature and pressure values of 88.66 °C and 686kpa.

Stream N3 undergoes an isentropic expansion in an expander KI03 at temperature and pressure values of -38°C and 9960kpa, the stream leaves the expander as N4 at temperature and pressure values of -144°C and 630kpa, respectively, and the expanded stream N4 enters the heat exchanger LNG 101 and exits as N5 at temperature and pressure values of -340 °C and 620kpa, providing subcooling effect on the already precooled Natural Gas stream NG 2, it exits the exchanger LNG 101 at these pressure and temperature values and undergoes three-stage compression. The first stage compression was done at pressure and temperature values of stream N5. The discharge from the compression is stream N6 at temperature and pressure values of 63.89 °C and 1580kpa. The stream enters a cooler, completing the stage as stream N7 at (30 °C and 1566kpa). The second stage compression starts from N7 and ends at N8 (153 °C and 4010kpa). Stream N8 enters a cooler and is being cooled. It exits as N9 (30 °C, 3957kpa). The third compression stage starts from N9 and ends with N10 (151.4 °C. 10003kpa). N10 enters a cooler and exits as N2 (30 °C, 10000kpa). The cooled NI stream thus enters the exchanger LNG and repeats the process.

The following equations were also used for analysis.

Liquefaction power required:

Power req=Heat Flow outlet - Heat Flow inlet ……….. (1)

The governing equation for the Coefficient of Performance is provided below (COP)

$$\text{COP} = \frac{Q_0}{w} \quad \text{………… (2)}$$

Q is the energy added by cooling natural gas, and W is the network.

$$\text{Specific power} = \text{Liquefaction Power}/ \text{Mass flow rate LNG}$$

3. Results and discussion

Analysis of the heat exchangers, heat duty, temperature approach, heat transfer coefficient, and liquefaction power are required. Specific power consumption, production capacity, Natural Gas mass flow rates, Coefficient of Performance, LMTD, and Compressor work are discussed in this section.

Table 2 summarizes some differences between the first heat exchanger (LNG, year, 100) of the CO_2- N_2 and the N_2 – N_2 dual expansion cycles. Both processes have the same side pressures, but the nitrogen-nitrogen cycle's minimum approach is greater than the CO_2 – N_2 cycle. The hot side and cold side (these can also be referred to as the streams) are the same. However, the LNG outlet temperatures differ as CO_2 – N_2 yield -48 ^oC and N_2 – N_2 yield -40 ^OC.

Table 3 displays the differences between the second heat exchanger (LNG, year, 101) of the CO_2- N_2 and the N_2 – N_2 dual expansion cycles. Both processes have the same side pressure drop (10kPa), but the minimum approach of the nitrogen - nitrogen cycle is now lesser than the CO_2 – N_2 cycle. The hot side and cold side (these can also be referred to as the streams) are the same. However, the LNG outlet temperatures differ as CO_2 – N_2 yield -104.5^oC and N_2 – N_2 yield -115^OC.

Table 4 shows that from the processes simulated, the dual expander process of N_2-N_2 has a higher heat transfer coefficient (UA) than CO_2-N_2. Table 5 shows that the heat duty of the N_2-N_2 is also more significant than the heat duty of CO_2-N_2. Table 6 shows the specific power requirement, a function of power consumed, and the LNG produced. The specific power consumed in the N_2-N_2 process, which is 0.656884058 kWh/kg LNG, is higher than the specific power consumed for the CO_2-N_2 process, which is 0.440957327kWh/kg LNG.

From Table 7, it can be deduced that more power is required to drive the N_2-N_2 cycle (815.85kW) compared to the CO_2-N_2 cycle (547.669kW). However, the production capacity of the N_2-N_2 (6945.6MTPA) is greater than the CO_2-N_2 (4904.38MTPA).

Table 2 Comparison of LNG 100 of both cycles

Name	**LNG 100 (CO_2 – N_2)**	**LNG 100 (N_2 – N_2)**
Number of sides	3	3
LMTD (C)	14.89	20.21
UA (KJ/C-h)	4.118×10^4	3.120×10^4
Minimum Approach (C)	0.998	5.000
LNG Outlet Temperature(C)	-48	-40
Side Pressure drop (kPa)	30	30
Number of Hot sides	2	2
Number of Cold sides	1	1

Table 3 Comparison of LNG 101 of both cycles

Name	**LNG 100 (CO_2 – N_2)**	**LNG 100 (N_2 – N_2)**
Number of sides	3	3
LMTD (^oC)	37.34	16.34
UA (KJ/C-h)	1.635×10^4	3.120×10^4
Minimum Approach (^oC)	32.2	8.087
LNG Outlet Temperature(^oC)	-104.5	-115
Side Pressure drop (kPa)	10	10
Number of Hot sides	2	2
Number of Cold sides	1	1

Table 4 Comparison of heat transfer coefficient (UA) of both cycles

Process	**LNG 100 UA (KJ/C-h)**	**LNG 101 UA (KJ/C-h)**	**Total UA (KJ/C-h)**
CO_2 – N_2	41187.06	16353.63	57540.7
N_2 – N_2	32795.07	39932.15	72727.22

Table 5 Comparison of heat duty of both cycles

Process	**LNG 100 UA (KJ/C-h)**	**LNG 101 UA (KJ/C-h)**	**Total UA (KJ/C-h)**
CO_2 – N_2	613158.7493	610613.3171	1223772.066
N_2 – N_2	662947.0795	652306.448	1315253.527

Table 6 Comparison of Specific Power Consumption

Process	**Specific Power kWh/kg LNG**
CO_2 – N_2	0.440957327
CO_2 – N_2 (Khan et al 2014)[3]	0.494527778
N_2 – N_2	0.656884058

Table 7 Comparison of Liquefaction Power of both cycles

Process	**Compression Power (kW)**	**Expansion Power (kW)**	**Required Power (kW)**
CO_2 – N_2	759.299	211.63	547.669
N_2 – N_2	1139.15	323.3	815.85

Table 8 Comparison of production capacity

Process	LNG Production capacity (MTPA)
CO2 – N2	4904.38
N2 – N2	6945.6

4. Conclusion

Comparisons were made to justify which process is efficient regarding Power Consumption, production capacity, heat duty, and specific power. The CO_2- N_2 dual expander process was very efficient in terms of power consumption, specific power, total expander power, and compressor power compared to the N_2-N_2. The Coefficient of Performance of the CO_2-N_2 process has a higher COP than the N_2-N_2 process.

The same natural gas flow rate was used in both processes, but the liquefied natural gas (LNG) produced from the subcooling section has variations. The N_2-N_2 cycle has a higher LNG production rate than the CO_2-N_2 cycle of 13%. The production capacity was also calculated from the LNG output from the subcooling section, and it was deduced that the N_2-N_2 cycle has a higher production capacity than the CO_2-N_2 cycle.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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