Evaluation of Membrane desalination schemes in desert oil field with emphasis on membrane separation technologies

Comparative Study of Turbine based Small Scale Natural Gas Liquefaction

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Abstract

Expansion-based liquefaction packages are used for stranded gas liquefaction due to their compact size and the possibility to construct these packages as skid-mounted. Three typical turbine-based liquefaction processes for small-scale natural gas are optimized based on power consumption using Hysys Optimizer. Mixed method is used as the optimization configuration. Single nitrogen expansion process is tested for various feed conditions of temperature, pressure and compositions as being the base case for all expansion-based processes.

The results show the superiority of dual nitrogen expansion process over single mixed refrigerant (MR) and single nitrogen expansion process. Dual N2 process requires much less power to bring the natural gas to the liquefaction conditions. Also, heat exchanger duty for dual N2 is much lower than MR process which leads to smaller heat exchangers.

Keywords

Multi-variable optimization, Hysys Optimizer, Natural gas, Liquefaction and cryogenics.

1. Introduction

Due to the increased energy demand with an average rate of 0.9-1.6% per year and the world act towards decreasing CO_2 emissions, natural gas is still the main preferred energy source with increased consumption rate of 1.4-1.6% per year (Wonsub Lim, 2013)**.** The main reason behind this increase is the lower environmental impact of natural gas than other fossil fuels such as oil and coal. Natural gas has a lower percent of carbon dioxide emissions of 28.6% and 43.7% compared to oil and coal respectively. (Natural Gas Issues and Trends, 2010).

In view of the above, venting and flaring of natural gas produced from scattered onshore and offshore fields, associated gas from oil wells in addition to coal-bed methane from mines besides wasting the resource it drastically affects the environment (Zongming Yuan, 2014).

Stranded gas sources are defined as gas resources remote from market or pipelines or those resources that are close to market however, produced gas throughputs are low or the lifetime of producing wells is very short (J.S. Gudmundsson, 2002).

The estimated volume of stranded gas reserves is 6,000 trillion cubic feet. This volume is considered half of the volume of gas reserves in the world (L. Castillo). The estimated recoverable stranded gas in Middle East reaches 888 Tcf with 304 Tcf for stranded gas in gas fields and 584 Tcf for stranded gas in oil fields (L. Castillo)**.**

Gas producers have four options for making use of the stranded gas resources. These options are; gas to transit by volume reduction such as LNG (Liquefied Natural gas), CNG (Compressed Natural Gas), and NGH (Natural Gas Hydrate), gas to other valuable liquid products (GTL), gas to other form of energy such as power and transmission by subsea cables to shore (GTW) and gas to export via gas pipelines (Zongming Yuan, 2014).

Construction of gas pipelines for these low productivity and fast depleted wells is time consuming and expensive which makes the fourth alternative uneconomic in most of stranded gas recovery.

In this paper, the first option of liquefaction of stranded gas is studied to choose the most suitable process to be applied for remote sites.

Several processes for natural gas liquefaction have been proposed and applied on commercial scale. Based on capacity, LNG plants are; base load plants with capacity up to 3.4 MMTPA of LNG per single production train. The aim of base load LNG plants is to maximize the amount of exported LNG per cargo. Base load LNG producers target countries with unavailability of large domestic gas reserves or supply. The second category of LNG plants are the peak shaving LNG plants with capacity up to 0.9 MMTPA of LNG per single production train. Peak shaving LNG plants are used to liquefy excess natural gas to be used in peak periods. The smallest and the final category of LNG plants are the small-scale LNG plants with lower capacities (Wen-sheng Cao, 2006).

Small-scale LNG plants were introduced as a solution to recover stranded gas in addition to the re-liquefaction of boil off gas from floating, production, storage and off-loading (FPSO). Because of the compact size required for small-scale LNG plants, the manufacturers are able to install these plants as skid mounted packages. By this installation, small-scale plants can be used for various stranded gas sources because of the ease of fabrication, mobilization, installation and demobilization.

Many researchers studied the design, simulation and optimization of small-scale LNG packages. Michael. B and Noel. D compared various natural gas liquefaction processes to select the most suitable process to be used for offshore fields and FPSOs (floating, production, storage and off-loading) (Michel Barclay, 2005). The research showed efficiency and power consumption of various nitrogen expansion processes relative to propane pre-cooled process licensed by Air Products and Chemical. Inc (APCI). Dual nitrogen expansion process with propane pre-cooling showed close results compared to APCI process with an advantage of having low flammability refrigerant.

Wen-sheng Cao et al simulated two small-scale liquefaction processes utilizing two different refrigerants; typical single mixed refrigerant (SMR) and new mixture of nitrogen and methane. The results showed the superiority of the new N2/CH4 refrigerant to ordinary SMR when propane pre-cooling is excluded from the liquefaction process (Wen-sheng Cao, 2006). Remeljej and Hoadley performed exergy analysis for four different liquefaction processes including single mixed refrigerant process (SMR), two stage nitrogen expansion process in addition to two open-loop expander processes (C.W. Remeljej, 2006) . P. Neksa et al proposed a patented small-scale liquefaction plant concept to be installed on multi-gas carriers for re-liquefaction of boil-off gas. The usage of hydrocarbon mixed refrigerant in combination with lubricant injected screw compressor contributes in increasing energy efficiency and decreasing specific suction volume requirements (P.Neksa, 2010). L. Castillo and C.A. Dorao studied the effect of the available plot area in selecting the most suitable small-scale LNG technology for remote gas production areas including offshore production facilities (L. Castillo).

Q.Y.Li and Y.L. Ju compared propane pre-cooled mixed refrigerant cycle (C_3/MRC), mixed refrigerant cycle (MRC) and nitrogen expander cycle (N_2

expander) based on various comparison criteria including performance parameters, economics, layout, sensitivity to motion, safety and flexibility for different feed gas resources. Although N_2 expander cycle showed lower economic performance and higher energy consumption, nitrogen expansion was advantageous for offshore applications for being more simple, safe and easier in operation (Q.Y.Li, 2010). Maoqiong. G et al designed and tested a portable small trailer-mounted liquefier for natural gas based on mixed refrigerant cycle (MRC) with R22 pre-cooling (Moaqiong. Gong, 2012). Knut M et al compared five expansion-based liquefaction cycles; single N_2 expander, dual N_2 expander (BHP), N_2 and CH_4 expander (Niche), Statoil dual N_2 expander and dual N_2 expander with CO_2 pre-cooling. A comparison was also made with three mixed refrigerant cycles; PRICO, Linde LiMuM and Shell DMR. Production from each process in addition to energy consumption were assessed based on the maximum duty of the same gas turbine driver. Heat exchangers were preliminary designed using ASPEN MUSE (PFIN) for the five expander cycles. The diameter of suction lines of compressors were also compared (Knut Marak).

Zongming et al simulated and optimized single nitrogen expansion cycle with carbon dioxide pre-cooling with liquefaction rate as a constraint and energy consumption as objective function. Also, the flexibility of the proposed cycle was tested for different feed pressure, temperature and compositions (Zongming Yuan, 2014). Tianbiao and Yonglin designed and optimized a conceptual design of new parallel nitrogen expansion liquefaction process. Genetic algorithm was used to optimize the Hysys simulation of the proposed process based on energy consumption. The optimized parallel configuration had lower energy consumption compared to the base case. Also, the adaptability of the process was tested against two different gas feeds (Tianbiao He). Tianbiao and Yonglin introduced an optimized small-scale LNG plant integrated with NGL recovery. The novel process was based on mixed refrigerant cycle (MRC). Since LNG process is a non-linear system with possibility of many local optimal solutions, global optimization using genetic algorithm was performed for the Hysys simulation case. The optimized process showed lower energy consumption and refrigerant flow rate compared to the base case. Because of the advantage of NGL recovery, the novel process demonstrated good profitability and short payback period (Tianbiao He).

2. Design of Liquefaction Processes

2.1. Single N_2 Expander Process

After being compressed, N_2 is pre-cooled then expanded to a lower pressure causing further drop in its temperature. The expander produced work can be used to drive the N_2 compressors. Cold N_2 refrigerant cools the natural gas in a Plate Fin Heat Exchanger (PFHE) to the required liquefaction temperature (-161 °C at 1 atm). The main drawback of this process is that all the refrigerant is expanded to the lowest temperature, even though most of it is needed at high temperature. This results in increasing the temperature difference between hot and cold sides of LNG heat exchangers which increases the compressor work.

2.2. Single Mixed Refrigerant (MR) Expander Process

The concept of MR expander process is the same as the N_2 expander process. It differs only in that phase change takes place for the refrigerant. This feature is considered as a disadvantage since the heat exchange duty is much higher than the N_2 expansion process because part of this duty goes to condense the refrigerant.

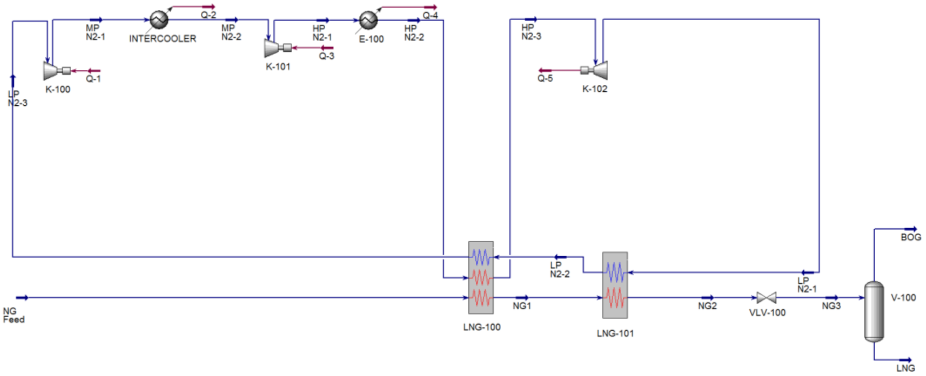


Figure 1. Single N_2 expansion process

2.3. Dual N2 Expander Process

To solve the problem of high compressor work for the single N_2 process, a second stage expander is introduced. This makes most of N_2 refrigerant to expand at an intermediate pressure to a warmer temperature and only the required small portion of refrigerant expands at a lower pressure to the lowest temperature to sub cool the natural gas.

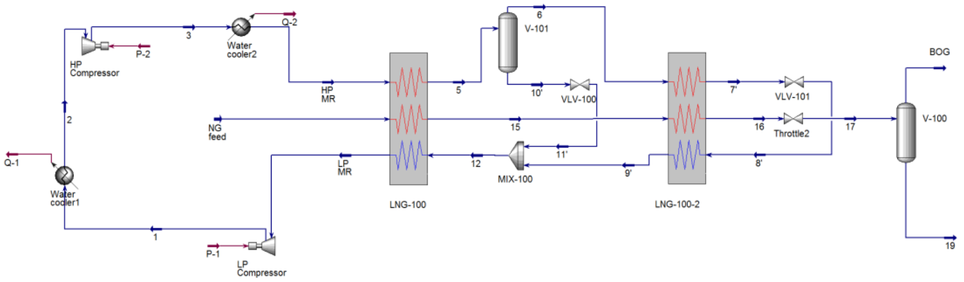
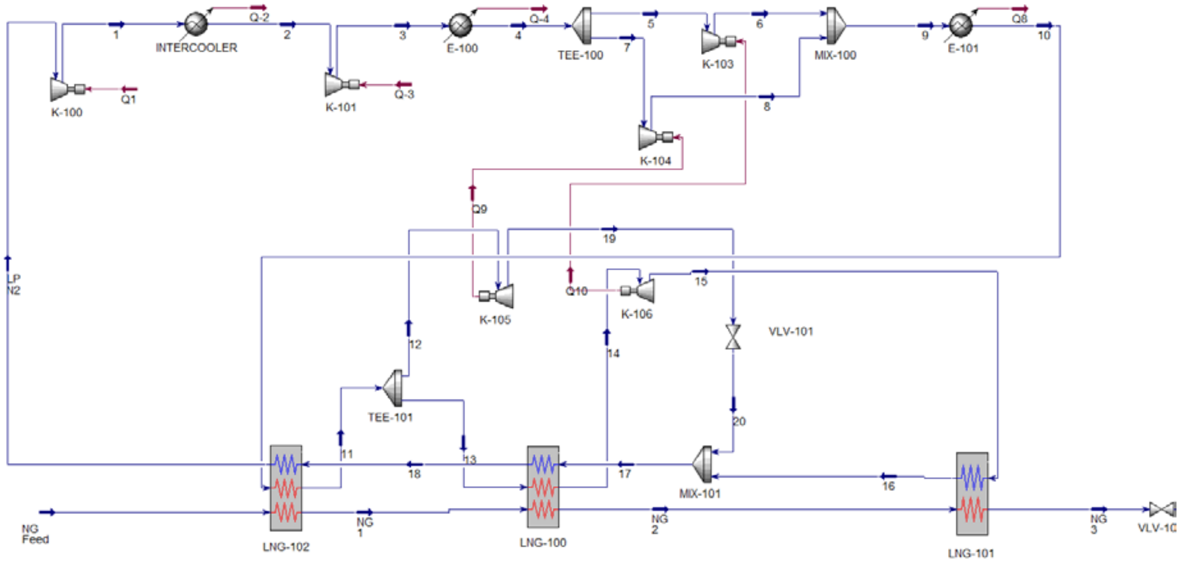


Figure 2. Single MR expansion process

3. Methodology

3.1. Optimization Using Hysys Optimizer (Hysys Operations Guide, 2004)

Simulation and optimization of the expansion-based processes are performed using Hysys ® V7.2. Hysys can be used to optimize single objective function which contains multi-variables using Hysys Optimizer tool. In order to use Hysys optimizer, the process flow sheet has first to be converged.



Hysys optimizer enables the user to find the operating conditions which minimize or maximize a certain objective function. All decision variables, constraints and objective functions are defined using the optimizer spreadsheet.

Hysys Optimizer has different configurations depending on the selected optimization mode. In this paper, original optimizer configuration is selected. Original optimizer configuration contains five schemes. Only BOX, SQP and Mixed schemes are discussed in this paper. The BOX, Mixed and SQP methods allow for inequality constrained problems. Only the SQP can handle equality constrained problems.

BOX method is based on the complex method of BOX. BOX method is a sequential search technique which handles non-linear objective functions subjected to non-linear inequality constraint. The main draw back with BOX method is the large time it requires to converge as it requires a large number of objective function evaluations.

The Sequential Quadratic Programming method (SQP) is based on the algorithm of Powell. SQP is considered one of the most efficient methods for equality constrained problems with either linear on non-linear equality constraints. On the other hand, SQP requires a good initial guess in addition and a small number of decision variables.

Mixed method combines the advantages of BOX and SQP methods. It starts with using BOX method with loose convergence tolerance that may reach 10 to 50 times of the desired tolerance. After convergence, SQP method is used to determine the final solution with the desired tolerance. In this paper, Mixed method is used to optimize the proposed cycles. Also, Peng-Robinson equation of state is used as it accurately predicts the thermodynamic properties especially for applications in natural gas processing and liquefaction.

3.2. Optimization of N_2 and MR Expansion Processes Using Hysys Optimizer

As the operating cost is the first parameter which defines the feasibility of a given cycle, the objective function of the proposed cycle is only based on minimization of power consumption. The objective function is;

$min\ f(X) = W_{net}/m_{LNG}$

Where:

X is the vector of decision variables

W_{net} = Power required by compressors (W_{comp}) – Power generated by turbines (W_{turb})

m_{LNG} is the molar flow rate of liquefied natural gas

The vector of decision variables *(X)* should be properly defined in order to avoid large time for objective function convergence. Vector of decision variables *(X)* used to minimize the objective function in this paper includes (A) molar flow rate of the refrigerant, (B) Outlet pressures of refrigerant compressors, (C) Outlet temperatures of the natural gas from each LNG heat exchanger. Lower and higher bounds for each decision variable are properly defined to avoid large time for objective function convergence.

The constraints are; (A) Pressure ratio of compressors is 2 up to 3, (B) Temperature approach for LNG heat exchangers is 3 °C, and (C) 0.95 of the feed gas is liquefied. Tables (1) and (2) present the process conditions used as optimization basis.

Table 1. Feed gas and mixed refrigerant mole fraction

	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	nC_4H_{10}	N_2
Natural gas	0.82	0.112	0.04	0.012	0.009	0.007
MR (Wen-sheng Cao, 2006)	0.40	0.40	0.19	-	-	0.01

Table 2. Feed gas inlet conditions

	Pressure, bar	Temperature, °C	Flow rate, kgmole/hr
Natural gas	50	32	507.5

4. Results and Discussion

4.1. Effect of Operating Conditions on Power Consumption for Single Nitrogen Expansion Cycle

The optimizer tool is used to test the sensitivity of the single nitrogen expansion cycle by changing feed conditions of temperature, pressure and composition. After changing one of the feed conditions, while the other two conditions remain constant, the optimizer tool is used to minimize the objective function which is subjected to the set of constraints by changing the vector of decision variables as previously mentioned.

4.1.1. Effect of feed temperature

As seen from Figure (4), as the feed temperature increases, the power consumption increases due to the additional amount of refrigerant required to bring down the hot feed to the liquefaction temperature. The circulation of more refrigerant requires more compression power.

4.1.2. Effect of feed composition

The power consumption for natural gas liquefaction increases with the increase of methane percentage. This is well explained by observing the amount of condensed heavy hydrocarbons.

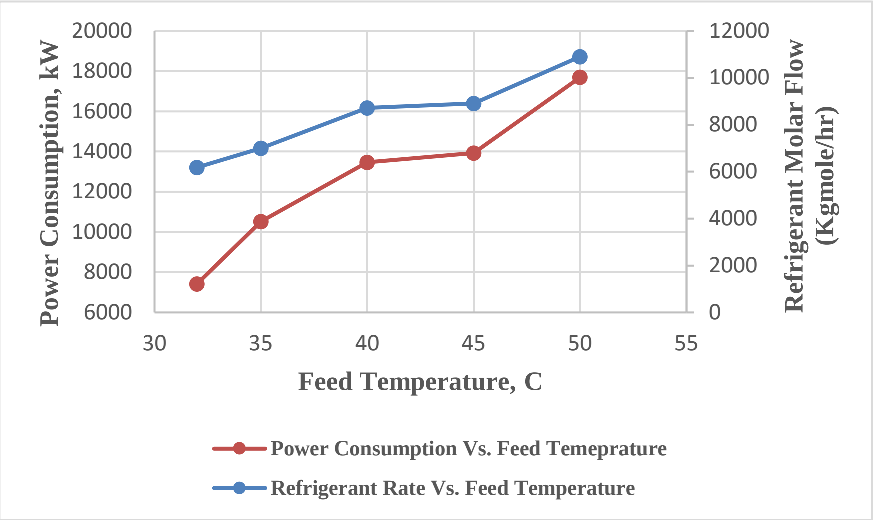


Figure 4. Effect of feed gas temperature on power consumption

As the methane percentage increases, the amount of heavy hydrocarbon decreases which leads to more uncondensed gas passing through the liquefaction heat exchangers. Heat transfer through gaseous media involves a higher thermal resistance which means that more refrigerant is required. As a result, compression power increases leading to more energy consumption of the proposed liquefaction cycle as shown in Figure (5).

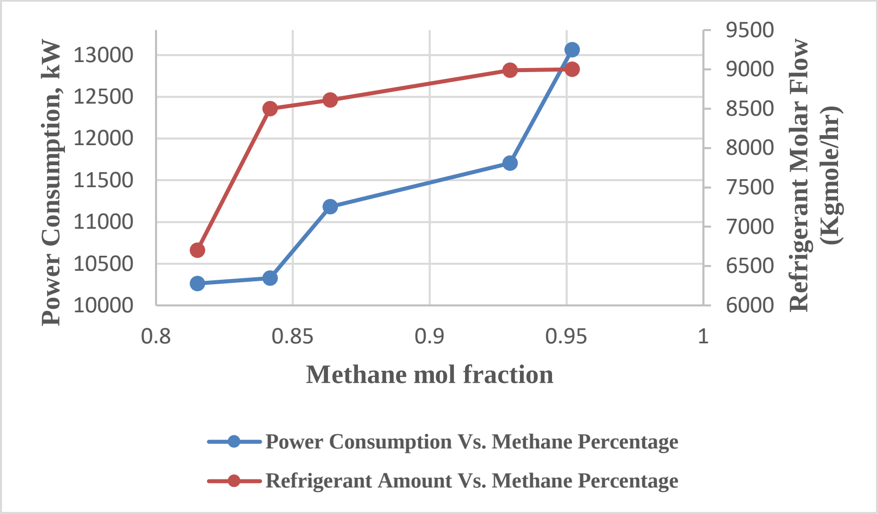


Figure 5. Effect of feed gas composition on power consumption

4.1.3. Effect of Feed Pressure

Feed gas pressure does not have a significant effect on power consumption as demonstrated in Figure (6), and as a result, has no effect on the amount of the required refrigerant. This is because most of the cooling is supplied by the refrigerant not by pressure drop through throttling valves for the feed gas.

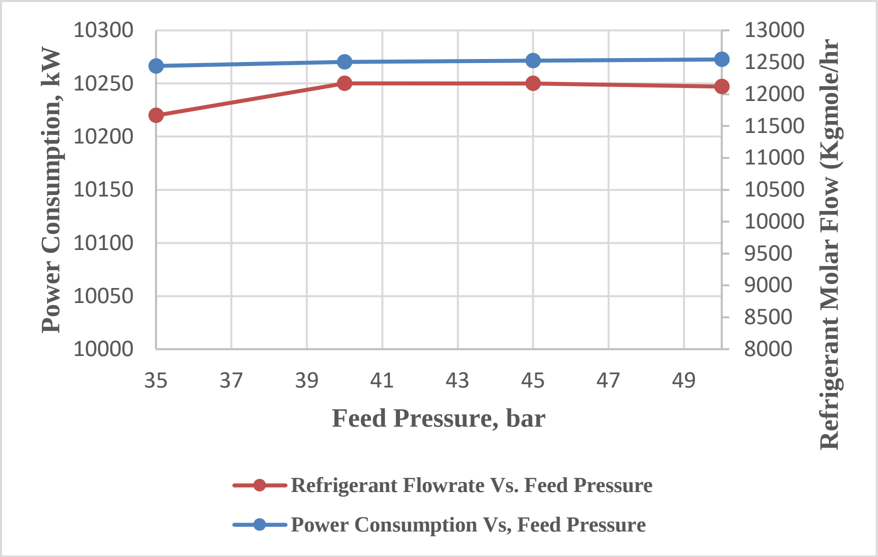


Figure 6. Effect of feed gas pressure on power consumption

4.2. Comparison results for single N_2, single MR and dual N_2 expansion processes

Figure (7) summarizes the optimization results for minimization of power consumption. It is clear that MR process requires higher power consumption because no turbines are used in the process. It is also clear that single N2 process has lower power consumption due to the produced electricity from using a turbine. In dual N2 process, less refrigerant is required due to the increased efficiency resulting from the incorporation of an intermediate pressure reduction turbine. As a result, the dual N_2 process consumes less power than the single N_2 expansion process. The optimization results identified the minimum amount of refrigerant required to achieve a given liquefaction rate subject to the minimum approach constraint. The required refrigerant flow rate in kgmole/hr was 7500, 6180 and 5970 for MR, single N_2 and dual N_2 respectively.

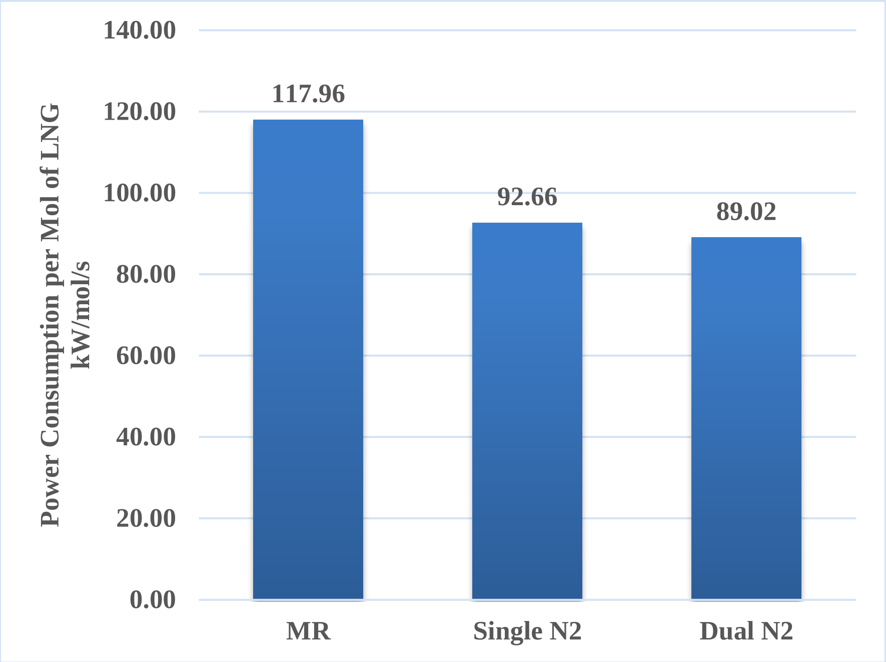


Figure 7. Power consumption for MR, single N2 and dual N2 processes

Figure (8) shows the difference in the required liquefaction duty for each liquefaction process. The large duty for MR is explained by that a part of this duty goes to condense the refrigerant since MR does not utilize one phase refrigerant like N_2 processes.

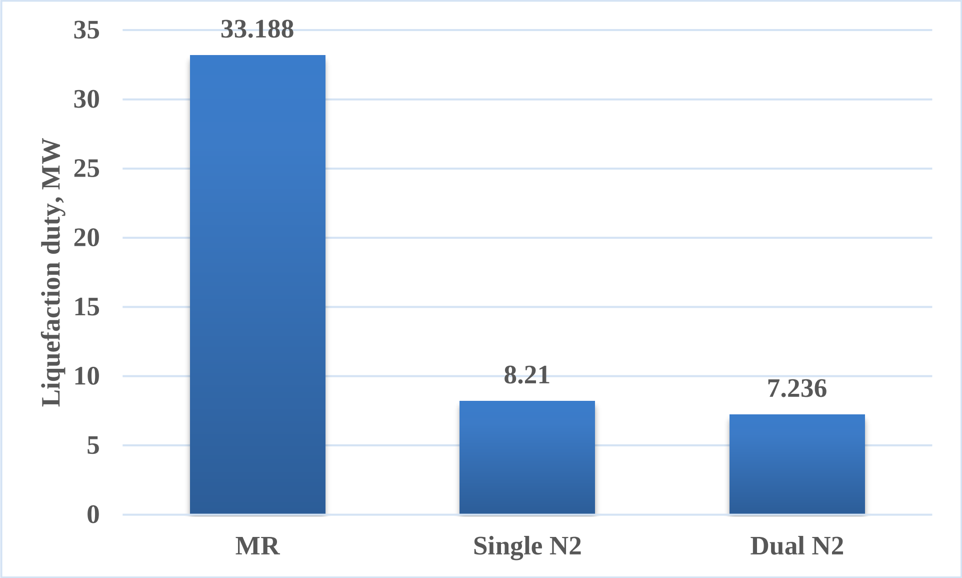


Figure 8. Liquefaction duty for MR, single N2 and dual N2 processes

5. Conclusion

Three expansion-based processes were simulated and optimized. Hysys Optimizer tool was used to minimize an objective function of minimum power consumption required to liquefy 1 mole/s of LNG. Optimizer tool was used to test the sensitivity of single N2 expansion process against change in feed temperature, pressure and composition. An increase in feed temperature and methane content in natural gas feed leads to higher power requirements. The increase in feed pressure does not have a significant effect on power consumption.

The optimization results show the advantages of dual N_2 process over MR and single N_2 processes. Dual N_2 process requires lower energy requirements, much lower cooling duty compared to MR process in addition to smaller refrigerant flow rate.

References

C.W. Remeljej, A. H. (2006). An exergy analysis of small-scale liquefied natural gas (LNG) liquefaction processes. *Energy, 31*, 2005-2019.

Hysys Operations Guide. (2004). 1253-1309.

J.S. Gudmundsson, M. M. (2002). Hydrate non-pipeline technology. *Proceedings of 4th International Conference on Gas Hydrates*, (pp. 19-23). Yokohama.

Knut Marak, B. N. (n.d.). Comparrison of Expander Processes for Natural Gas Liquefaction. Trondheim, Norway: Statoil Research Center.

L. Castillo, C. D. (2010). Influence of the plot area in an economical analysis for selecting small scale LNG technologies for remote gas production. *Journal of Natural Gas Science and Engineering*, 302-309.

L. Castillo, C. D. (2010). Influence of the plot area in an economical analysis for selecting small scale LNG technologies for remote gas production. *Journal of Natural Gas Science and Engineering*, 302-309.

Michel Barclay, N. D. (2005, October). Selecting offshore LNG processes. *LNG Journal*, 34-36.

Moaqiong. Gong, J. W. (2012). Development and performance test of a small trailer-mounted moveable natural gas liquefier. *Energy Conversion and Management*(57), 148-153.

(2010). *Natural Gas Issues and Trends.* U.S: International Energy Agency (IEA).

P.Neksa, E. M. (2010). Development and analysis of a natural gas reliquefaction plant for small gas carriers. *Journal of Natural Gas Science and Engineering, 2*, 143-149.

Q.Y.Li, Y. J. (2010). Design and analysis of liquefaction process for offshore associated gas resources. *Applied Thermal Engineering*(30), 2518-2525.

Tianbiao He, Y. J. (2014). A novel conceptual design of parallel nitrogen expansion liquefaction process for small-scale LNG (liquefied natural gas) plant in skid-mount packages. *Energy*(75), 349-359.

Tianbiao He, Y. J. (2014). Design and optimization of a novel mixed refrigeration cycle integrated with NGL recovery process for small-scale LNG plant. *Industrial and Engineering Chemistry Research*(53), 5545-5553.

Wen-sheng Cao, X.-s. L.-s.-z. (2006). Parameter comparison of two small-scale natural gas liquefaction processes in skid-mounted packages. *Applied Thermal Engineering, 26*, 898–904.

Wonsub Lim, K. C. (2013). Current Status and Perspectives of Liquefied Natural Gas (LNG) Plant Design. *Industrial & Engineering Chemistry Research, 52*, 3065−3088.

Zongming Yuan, M. C. (2014). Design and analysis of a small-scale natural gas liquefaction process adopting single nitrogen expansion with carbon dioxide pre-cooling. *Applied Thermal Engineering, 64*, 139-146.