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Offshore LNG: The Perfect Starting Point for the 2-Phase Expander?

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Abstract

Offshore natural gas liquefaction has become increasingly economically viable as the value of LNG has increased during the past few years. This has increased interest in both onshore and offshore liquefaction projects. Offshore liquefaction may facilitate the introduction of new technologies and processes because their project economics favour different criteria. For offshore applications, process design criteria such as compactness, weight, modular design, and process safety become more important.

This paper considers the potential process improvements that could be realised for mixed refrigerant-based processes using two-phase expander. This type of expander has recently been developed for commercial application and operated on a small-scale LNG project in Poland. Integration of two-phase expanders into mixed refrigerant processes offers the potential to decrease equipment footprint, installed compressor capacity, and flammable liquid inventory but these expanders are still new and have yet to be proven in a large capacity plant. This paper shares the simulation results for dual and single mixed refrigerant processes using three different expansion devices including two-phase expanders. These results support a discussion of the potential benefit of improved expander operating range on process and facility design. For onshore liquefaction, expanders would likely be used to boost efficiency to increased LNG production for a defined compressor and driver. Offshore however, two-phase expanders could enable use of single cycle mixed refrigerant liquefaction processes. Such processes benefit greatly from the use of two-phase expansions and may offer the potential to decrease footprint, weight, complexity, and flammable fluid inventor. All advantages that are highly relevant to offshore liquefaction facilities. The results encourage more detailed analysis of processes incorporating two-phase expanders for offshore liquefaction.

Introduction

Increasing global demand for natural gas is supporting the rapid growth of worldwide LNG production capacity. As demand continues to grow and the value of natural gas remains high, the impetus to monetise non-traditional gas resources also grows. Offshore floating LNG production has generated interest because it offers the potential to:

- avoid flaring or reinjection of associated gas
- monetise smaller or remote fields of non-associated gas
- reduce exposure to public and increase security of facilities
- lower LNG production costs

The realisation of large floating production, storage, and off-loading (FPSO) facilities for oil production and LPG production, use of barge transport for the Snøhvit LNG facility, and other developments demonstrate the potential for offshore LNG.

Liquefaction Cycle Development (1, 2, 3, 4).

The base-load LNG industry now has over 40 years of history starting with permanent operations of the Camel plant in Algeria in 1964. The earliest plants consisted of fairly simple liquefaction processes based on either cascaded refrigeration or single mixed refrigerant (MR) processes with train capacities less than one million tonnes per annum (MTPA). These were quickly replaced by the two-cycle propane pre-cooled mixed refrigerant (C3MR) process developed by Air Products and Chemicals Inc. (APCI). This process became the dominant liquefaction process technology by the late 1970s and is stillcompetitive in many cases.

Economies of scale, improved process simulation tools and equipment performance (e.g. liquid expanders and gas turbine drivers) have improved performance and increased the capacity of liquefaction trains. Recently, three-cycle processes such as the AP-X™ and the ConocoPhillips Optimised Cascade have been selected for new projects. The third cycle on the AP-X™ process allow onshore train capacities to climb to approximately 7.5-10+ MTPA (5) and have thus circumvented the typical process bottlenecks like the main cryogenic heat exchanger diameter and propane refrigerant compressor capacity.

Expansion Devices (6).

Liquid refrigerant-based liquefaction processes until the 1990s were based exclusively on isenthalpic expansion through JT valves. These valves expand a liquid stream to a two-phase stream at reduced pressure and temperature. Since they feature no work recovery, the expansion is irreversible and pressure availability is destroyed through viscous dissipation such that the end state for the fluid is either at higher temperature and/or vapour fraction.

During the past decade liquid expanders have been introduced and become widely accepted in both new liquefaction plants as well as a common retrofit of existing facilities starting with MLNG Dua in 1996. These expanders are essentially a pump run backwards that allow a subcooled liquid to be expanded almost to its bubble point isentropically. The work of the expansion is extracted from the fluid as shaft power than may be used to drive a centrifugal compressor or electrical generator elsewhere in the process. The recovery of power is valuable, especially offshore, but more importantly, when the fluid does work (by expansion) it lowers the fluid temperature. This is particularly important when the fluid, either refrigerant or LNG, is at very low temperature as more power is required to reject heat at a lower temperature. By doing work at a very low temperature, it is the most efficient way of rejecting heat.

Recently two-phase or flashing expanders have become available. These expanders are able to isentropically expand a liquid into the vapour dome and maximise work recovery and the reversibility of the expansion. Such expanders result in expanded fluids at either lower vapour quality or lower temperature and thus can serve as the basis for more efficient liquefaction. The two-phase expanders have not yet been proven at large scale. In all cases, where liquid or two-phase expanders are used in the production of LNG, they have a JT valve by-pass.

Offshore Liquefaction.

Many studies have discussed process requirements for offshore LNG. Offshore liquefaction processes must be more compact and light weight, support modular design, and offer higher inherent process safety than traditional onshore processes. Offshore processes must also consider deployment and operation in a marine environment where vessel motion, ease of operation, low equipment count, quick start-up, process simplicity, and high availability are important (7).

Early studies on the offshore LNG were conducted over 25 years ago (8). N2 expander cycles for offshore liquefaction were discussed and studied by Foster Wheeler and others in the 1980s (9) and recent studies have considered both expander-based as well as dual MR processes. Two processes that have been previously identified as offering potential for offshore liquefaction are nitrogen expander cycles and dual mixed refrigerant cycles (10). The C3MR cycle that has dominated onshore applications is generally discounted because of the large propane inventory and weight associated with the propane precooling system. Nitrogen expander processes attract attention because they offer the potential for an extremely safe easy to operate liquefaction process that can be effectively modularised and is indifferent to orientation. These expander cycles generally suffer from low efficiency and are thus only considered suitable for small fields (11). These factors have all been examined in various studies such as Project Azure and the Shell development work on floating and offshore concepts (10, 12).

The Present Work.

This paper shares the simulation results for dual and single mixed refrigerant processes using the three different expansion devices described above. These results support a discussion of the potential benefit of improved expander operating range on process and facility design. Included in the analysis is one process, the single MR with the use of 2-phase expansion, that has not been rigorously examined for off-shore liquefaction. The development of the two-phase expander has enabled more effective expansion of large-phase envelope fluids such as those required to cover the entire temperature range for a LNG process.

Simulation Work

The dual MR and single MR (SMR) processes were simulated because they feature flashing liquid expansion. Each MR process was simulated with three different types of fluid expansions to generate a total of six liquefaction process simulations. Simulated expansion options were expansion valves only (isenthalpic), liquid turbine expansion followed by expansion valve (isentropic /isenthalpic), or two-phase turbine expanders (isentropic). This generated a total of six different liquefaction processes that were simulated using Hysys process simulation software to benchmark relative performance.

The dual and single MR processes were chosen because they offer good potential for offshore liquefaction and the potential to realise some benefits offered by two-phase expansion. The dual mixed refrigerant process has been previously identified as offering promise for off-shore liquefaction because it offers efficiencies comparable to the C3MR but decreases the large propane inventory required for the multiple stage propane refrigeration system that precools the MR. The dual MR also allows balancing of the compressor and driver loads to maximise LNG production and increase train capacity. Simplified process descriptions and diagrams of both the SMR and dual MR processes follow starting with the simpler SMR.

Single Mixed Refrigerant Process.

SMR processes have not received much attention for large-scale natural gas liquefaction because they are less efficient than their two-cycle (i.e. the C3MR) counterparts. The SMR process was selected because it required a wide phase-envelope working fluid and thus is expected to show dramatically improved performance with a two-phase expander. This process is seen below in Figure 1.

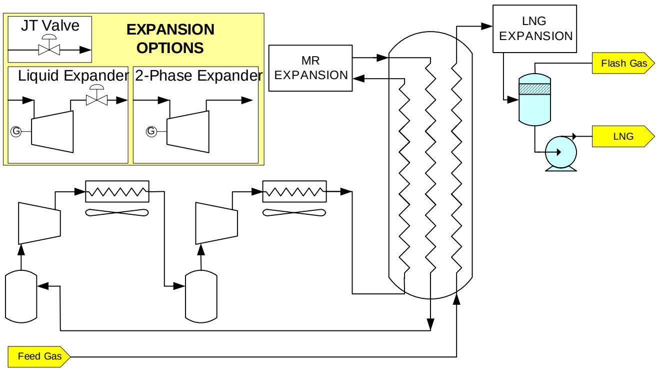

Figure 1. Single Mixed Refrigerant Liquefaction Process

The process will briefly be explained starting with the stream leaving the compressor suction scrubber. A warm, low pressure MR stream consisting of nitrogen (N_2), methane (C_1), ethane (C_2), propane (C_3), and normal butane (nC_4) is compressed in two stages. This compression requires an intercooler and aftercooler, shown pictorially as air coolers, to reject the heat from the liquefaction cycle to the environment. The high pressure MR is partially condensed in the aftercooler before flowing into the spiral wound main cryogenic heat exchanger (MCHE). In this exchanger this stream is continuously cooled and condensed tube-side against the cold, LP mixed refrigerant stream. Once condensed the cool high pressure MR is expanded in MR expansion. Three options where considered for expanding the cool high pressure MR.

The MR could be expanded through a JT expansion valve, the oldest, most robust, and cheapest expansion device that is simulated as an isenthalpic expansion such that the stream does work on itself and pressure availability is converted to heat through turbulent dissipation. This offers the least efficient process.

The second option considered is to isentropically expand the liquid to the bubble curve. Liquid expanders are commonly used on new build and many retrofit large scale LNG facilities. Up to 2 MW of power is often recovered in these turbines in electrical generators. The electrical power recovery is a benefit but is small compared to the decrease in compressor power input and liquefaction load. The extracted power is a reduction in load at very low temperature from a liquefaction process with a finite efficiency. For instance, 1 MW of power extracted from a LNG stream at -160^{o}C may decrease refrigerant driver power by a further 5 MW. Recovered power is limited by the degree of subcooling since currently used liquid expanders cannot tolerate vapour forming and care must be taken to avoid entering the vapour envelope of the LNG. The expansion is finished in a JT valve designed for flashing flow.

The third expansion option considered is two-phase expansion using a new liquid exducer type expansion engine. These expanders can isentropically expand a liquid into the vapour dome thus recovering the work for both the subcooled liquid expansion as well as the phase change.

Returning to the process description, the cold expanded MR returns to the MCHE as the cold stream and continuously cools the warm refrigerant stream and cools, condenses, and subcools the incoming high pressure, dry natural gas. The warmed, vaporized, LP MR then leaves the MCHE and returns to the first stage of the refrigerant compressor to complete the cycle.

The LNG leaving the MCHE is at high pressure and is expanded to a pressure suitable for transfer and storage in an end flash. This expansion occurs through one of the three previously explained expansion configurations and then flows to a separator. The liquid fraction (~90%) feeds the LNG transfer pump that sends the product to storage. The vapour is enriched in N_2 and is warmed in a separate exchanger against a portion of the feed gas before it joins the boil-off gas (BOG) from storage and offloading operations and is compressed and used as fuel gas. The heat recovery exchanger is not shown in the schematic (Figure 2) for simplicity.

Dual Mixed Refrigerant Process.

The dual MR process simulated is similar in concept with the SMR and will not be explained in great detail. The dual MR features a high temperature (HT) and low temperature (LT) refrigeration circuit that each operates over a smaller temperature range and thus requires a different refrigerant. The HT circuit consists of a refrigerant including nC_4, C_3, C_2, and C_1 and operates at temperatures between the hot heat sink and approximately -45^{o}C. This circuit is identical to the SMR except that the exchanger has an additional pass that cools the LT refrigerant. Most of the heat of the liquefaction cycle is rejected through the HT MR circuit. The HT MR circuit also continuously cools the process gas.

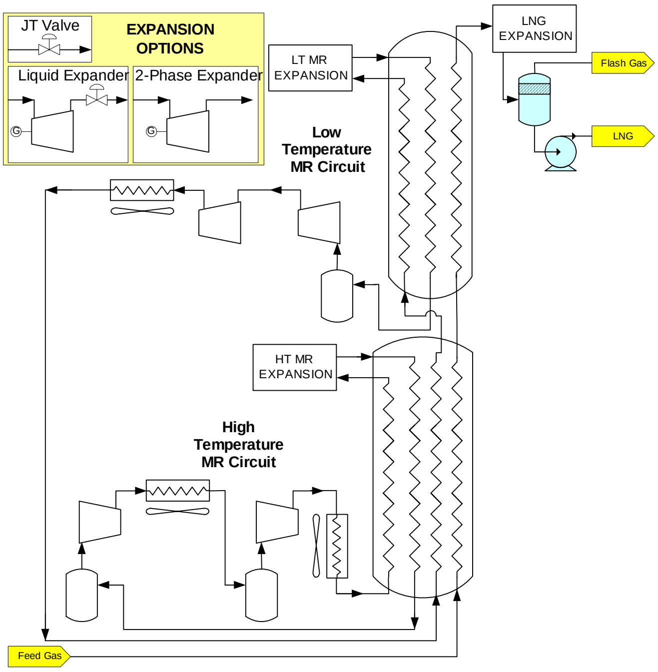

Figure 2. A Dual Mixed Refrigerant Process

The LT circuit is precooled by the HT MR circuit and is again similar to the SMR except that it rejects most of the process heat to the HT MR refrigerant and cools, liquefies, and subcools a precooled process gas.

The dual MR features four compression stages, and three expansions. All the expansions were simulated with the three options previously discussed. The LNG end-flash was simulated as described in the SMR section.

Simulated Conditions.

As in all complex systems, key liquefaction system performance metrics are strong functions of feed gas, ambient conditions, and equipment performance. To allow meaningful comparison of the processes, the same set of conditions and constraints were applied to all processes.

Natural Gas Feed and Product Conditions.

Details of the feed gas that were used for all simulations are seen below in Table 1. Since the simulation focused on the liquefaction process and the impact of two-phase expansion, the feed gas is free of water, acid gas components, and has a tail consistent with a natural gas with the C3+ components recovered in an upstream NGL recovery plant.

Table 1. Feed and Product Conditions

	Feed Gas	LNG
Methane	0.92	0.93
Ethane	0.07	0.06
Propane	0.01	0.01
Butanes+	0.00	0.00
N_2	0.00	0.00
CO_2	0.00	0.00
H_2S	0.00	0.00
H_2O	0.00	0.00
Pressure	63 bar	1 bar
Temperature	48 ^oC	-160 ^oC
Flow rate	2985 Nm^3/hr	~2.1 MTPA
Vapour quality	1	0

The simulation's objective target was to produce approximately 2 MTPA LNG. This was accomplished in an end-flash that produced roughly 10-12% cold vapour for recompression. The temperature of the LNG entering the end-flash was adjusted to ensure that approximately 2.1 MTPA LNG product flow rate was achieved. This meant that the LNG that was finished through a JT valve-based end-flash was cooled to a lower temperature by the liquefaction process. The relative effects of the two phase and liquid expanders in the mixed refrigerant circuit and the LNG stream were also quantified and are discussed later in the paper.

Standard Simulation Assumptions.

Care was taken to ensure that the comparison was completed on a reasonable and consistent basis. All major constraints and assumptions were kept consistent across the six simulated processes as seen in Table 2.

Table 2. Simulation Conditions and Assumptions

Equipment	Value
Compressor efficiency	82% Adiabatic
Expander efficiency	90% Adiabatic
After coolers (discharge)	52 ^oC / 0.7 bar pressure drop
Suction piping	0.5 bar pressure drop
MCHE minimum temperature approach of 2.5 ^oC.	
1% maximum vapour in liquid expander discharge	
Neglect heat leak into the system	
Pressures in both circuits kept within 600 # pipe class	
Electrical generator loaded expanders	
Consistent / reasonable pressure profiles for all simulations	

Simulation Details	Value
Mixture tuning resolution	0.5% molar composition
Single MR composition	N_2, C_1, C_2, C_3, nC_4
Dual MR compostion	C_1, C_2, C_3, nC_4 in HT circuit
	N_2, C_1,C_2, C_3 in LT circuit
Simulation package	HYSYS Plant v3.2
Equation of state	Peng-Robinson (Hysys)
Enthalphy model	Equation of State (Hysys)
Vapour fraction in end-flash	~12%

Most of the constraints and assumptions listed in Table 2 are considered reasonable. Mixed refrigerant processes are challenging to simulate because of the multiple degrees of freedom within the refrigerant composition, added to pressure and temperatures throughout the system. Optimisation tends to focus on the MCHE minimum temperature approach's response to refrigerant composition and flow rate. Mixture composition is adjusted to avoid a pinch in the MCHE. Reasonable system pressures were used through the process considering pipe flange classes limits, volumetric flow in suction lines, literature, and simulated performance. Care was taken to ensure that the simulation optimisation methodology was used across all six simulations.

The detail present in the simulation was kept to a minimum to facilitate rapid evaluation of the six schemes. The same assumptions and basic simulation conditions were maintained for all six processes to ensure that a meaningful comparison can be made between them. The absolute process performance is a function of many variables including feed gas conditions, ambient temperature, and system design. The process efficiencies for the dual mixed refrigerant process with liquid expansion can be roughly benchmarked against actual plant performance to verify the assumptions and degree of optimisation are reasonable.

Results

Shaft power from the compressor (input) and expanders (output) are shown as positive numbers in Table 3. Compressor power is the shaft power required to drive the compressor and is the sum of all energy streams (two compressor stages for the single MR and four for the dual MR). Expander power sum is the shaft power extracted from the process stream in each MR circuit and the LNG end flash. Total power is the compressor power required minus the expander power recovered.

Table 3. Simulation Results

	Single MR		
	JT Valve	Liquid Only	2-Phase
Compressor Power (kW)	108735	88413	84447
Expander Power (kW)	0	2712	6279
Total Power (kW)	108735	85701	78167
Efficiency (kW/TPD)	18.8	14.8	13.5
Added Power Recovered (kW)		2712	3567
Relative Efficiency	160%	126%	115%
Process Improvement			8.8%
	Dual MR		
	JT Valve	Liquid Only	2-Phase
Compressor Power (kW)	81501	76402	75138
Expander Power (kW)	0	2094	7061
Total Power (kW)	81501	74308	68077
Efficiency (kW/TPD)	14.1	12.8	**11.7**
Added Power Recovered (kW)		1256	4639
Relative Efficiency	120%	109%	**100%**
Process Improvement			8.5%

LNG liquefaction process efficiency may be expressed as thermal efficiency, specific power, or figure of merit. Table 3 expresses the thermodynamic efficiency as specific power, the power consumed per unit of LNG production, in units of kW/tonnes per day (TPD) of LNG produced. This metric, along with some other simulation outputs are also included in the table. Added power recovered is the power extracted by the expander relative to the process with less expansion. For example, the Added power recovered of a single MR with liquid expansion is 2.7 MW more than the single MR with JT valves only due to the expander electricity generation.

The most efficient process was the dual MR process deploying the two-phase expander with a total power consumption of approximately 68 MW for the simulated 2.1 MTPA production rate. The other process efficiencies are reported relative to this process and range up to 60% less efficient for the single MR using only JT expansion valves. The single MR processes are less efficient than the dual MR processes using the same expansion devices. The efficiency of the single MR process using the 2-phase expander is roughly between that of a dual MR and dual MR with liquid expander processes.

The use of two phase expanders in either the SMR or dual MR process result in a power saving of approximately 8.5% over the liquid-only expander.

Discussion

The efficiencies of the single MR processes using either liquid expanders or possibly two-phase expanders are considerably higher than the cycle using only JT valve expansion. With an 8.5-8.8% improvement in liquefaction process efficiency, liquid expanders should be considered, further developed, and eventually work their way into baseload liquefaction facilities. Onshore, this will allow increase process efficiency and a resultant increase in LNG production for a given compressor-driver capacity. Offshore however, the two-phase expanders may facilitate the development of less efficient single-cycle processes that are more compact, easier to operate, safer, and more reliable.

Two-phase expanders facilitate the use of a refrigerant with a wider phase envelope and a larger, more reversible, temperature drop across the expansion device(s). The process efficiencies of these single cycle processes is approaching the JT valve and liquid-expander only process efficiencies of the dual cycle process. Although a single-cycle process has not been designed for an onshore baseload facility for over 30 years, they may be acceptable offshore because of improved performance and different process selection criteria. Generally speaking, onshore process efficiency and very large train capacity is more important than process simplicity, footprint, and flammable fluid inventories. The efficiency of the two-phase expander-based SMR process between that of a traditional C3MR and a C3MR with liquid expansion is considered very good considering the increased process simplicity, decreased equipment count, and reduced flammable refrigerant inventories this process could offer.

The absolute process efficiency for the dual MR is reasonable compared to published baseload process efficiencies. Onshore baseload liquefaction facility efficiency values range widely and are not reported on a consistent basis. A reasonable range for MR based processes is 11.5-13 kW/TPD of LNG produced (13). The dual MR with liquid expansion efficiency result of 12.8 kW/TPD of LNG is approximately 5% less efficient than a published value for the Oman LNG C3MR Train 1 of 12.2 kW/TPD (14). This plant (EPC phase completed by Foster Wheeler and Chiyoda) featured liquid expansion as well as other design features such as axial compression boosting efficiency.

The simulation absolute process efficiencies benchmark well against published values but must be used with caution. They are best used to assess the potential of two-phase expander-related process improvements and to gain insight into which conditions two-phase expansion will be most beneficial. Process performance is a strong function of simulation assumptions, pressure profile, equipment performance, ambient temperatures, feed gas, and other variables.

Conclusions

The analysis supports three basic conclusions relating to two-phase expander use in offshore liquefaction processes:

1. When proven and optimally designed into liquefaction processes, the two-phase expander process should offer significant efficiency improvements. Further design and study work is required to quantity the performance of two-phase expander processes but the current simulation results indicate a ~8.5% efficiency improvement relative to liquid expanders.

2. The performance of the single MR processes using either liquid or two-phase expanders is sufficiently high that they will likely be suitable in some offshore applications given their simplicity, size, and safety advantages.

3. Processes using two-phase expanders should be carefully optimised to ensure they fully utilise the potential offered by these newly available machines. These expanders maximise the utilisation of large phase envelope refrigerants in simple cycles.

Future work should consider in more detail the relative contribution of the two-phase expander in the LNG stream and the refrigerant cycle. This is strongly dependent on the N_2 content in the feed gas and the vapour fraction downstream of the end-flash. Additional study work should focus on the optimisation of a two-phase expander based process with possible multiple expansions.

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