ENHANCED SINGLE MIXED REFRIGERANT PROCESS FOR STRANDED GAS LIQUEFACTION

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ABSTRACT

This paper introduces an enhanced single mixed refrigerant process suitable for medium-scale (0.5-1.5 mtpa) and offshore natural gas liquefaction. The cycle fully utilizes two-phase expansion to achieve reasonable process efficiency with a single-cycle process. Two-phase expanders have been developed for commercial application and operated since 2004 to produce LNG at a nitrogen rejection unit site in Poland. Integration of two-phase expanders into mixed refrigerant processes offers the potential to decrease equipment footprint, installed compressor capacity, weight, complexity and flammable liquid inventory. However, these expanders are still new and have yet to be proven in a large capacity plant.

This paper includes potential results and discussion of mixed refrigerant processes using two-phase expanders. Taking full advantage of two-phase expanders can enable the use of single-cycle mixed refrigerant liquefaction process. Single-cycle processes use one working fluid as the refrigerant and have lower equipment, valve, line, instrument counts and complexity. The design can also be highly modular, allow the full utilisation of installed driver capacity, and shorten the time to market. These are advantages that are highly relevant to offshore and select onshore liquefaction facilities.

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 monetize 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
- lower LNG production costs
- monetize smaller or remote fields of non-associated gas

The realization 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)

LNG production for baseload consumption 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 either on cascaded refrigeration or single mixed refrigerant (SMR) 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 remains competitive in many cases today.

The number of cycles is a key factor in the success of liquefaction process. A cycle is shown in Figure 1. This cycle takes warm, pretreated feed gas and cools and condenses it into an LNG product. To make the cold temperatures required for the LNG, work must be put into the cycle through a refrigerant compressor, and heat must be rejected from the cycle through air or water coolers. The amount of work (size of refrigerant compressors, drivers and refrigerant flowrate) is a strong function of liquefaction process, feed gas conditions (liquefaction temperature), and cooler temperature. In the single cycle process, there is a single working fluid that can be compressed in a single set of compressors driven by a single driver. An example of a single cycle process is a propane refrigeration system.

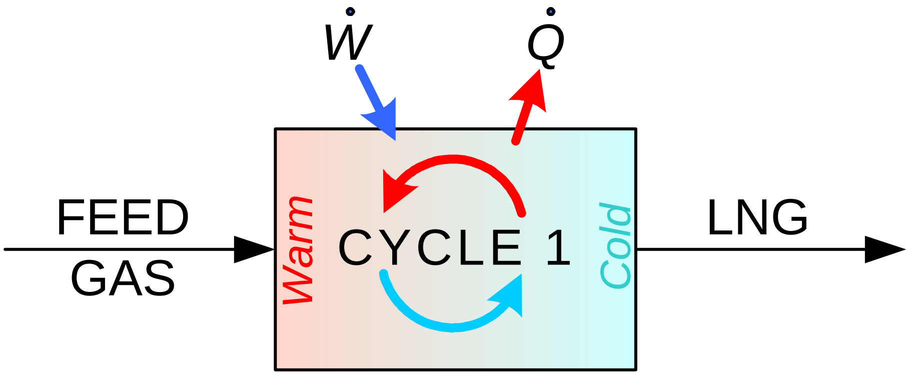

Figure 1. A Single Cycle Liquefaction Process

All modern baseload liquefaction facilities use either two or three cycles. The workhorse of the industry is the two-cycle C3MR. The first cycle is the propane cooling that precools the mix refrigerant and feed gas process. The second cycle is the mixed refrigerant that condenses and subcools the natural gas to very low temperatures. Because it is a two cycle process, it requires two separate refrigerants each with their own dedicated compressors, drivers, inter and aftercoolers, heat exchanger, etc.

Many of the liquefaction trains currently under development including RasGas, NLNG, Snøhvit, and Darwin feature three-cycle processes. Three-cycle processes include AP-X™, Shell PMR, Linde Mixed Fluid Cascade, and the ConocoPhillips Optimized Cascade. The third cycle on the AP-X™ process allows onshore train capacities to increase to approximately 7.5-10+ MTPA (5) and have thus circumvented the typical C3MR process bottlenecks, namely the main cryogenic heat exchanger diameter and propane refrigerant compressor capacity.

A high level representation of the number of cycles in various liquefaction processes is shown in Figure 2.

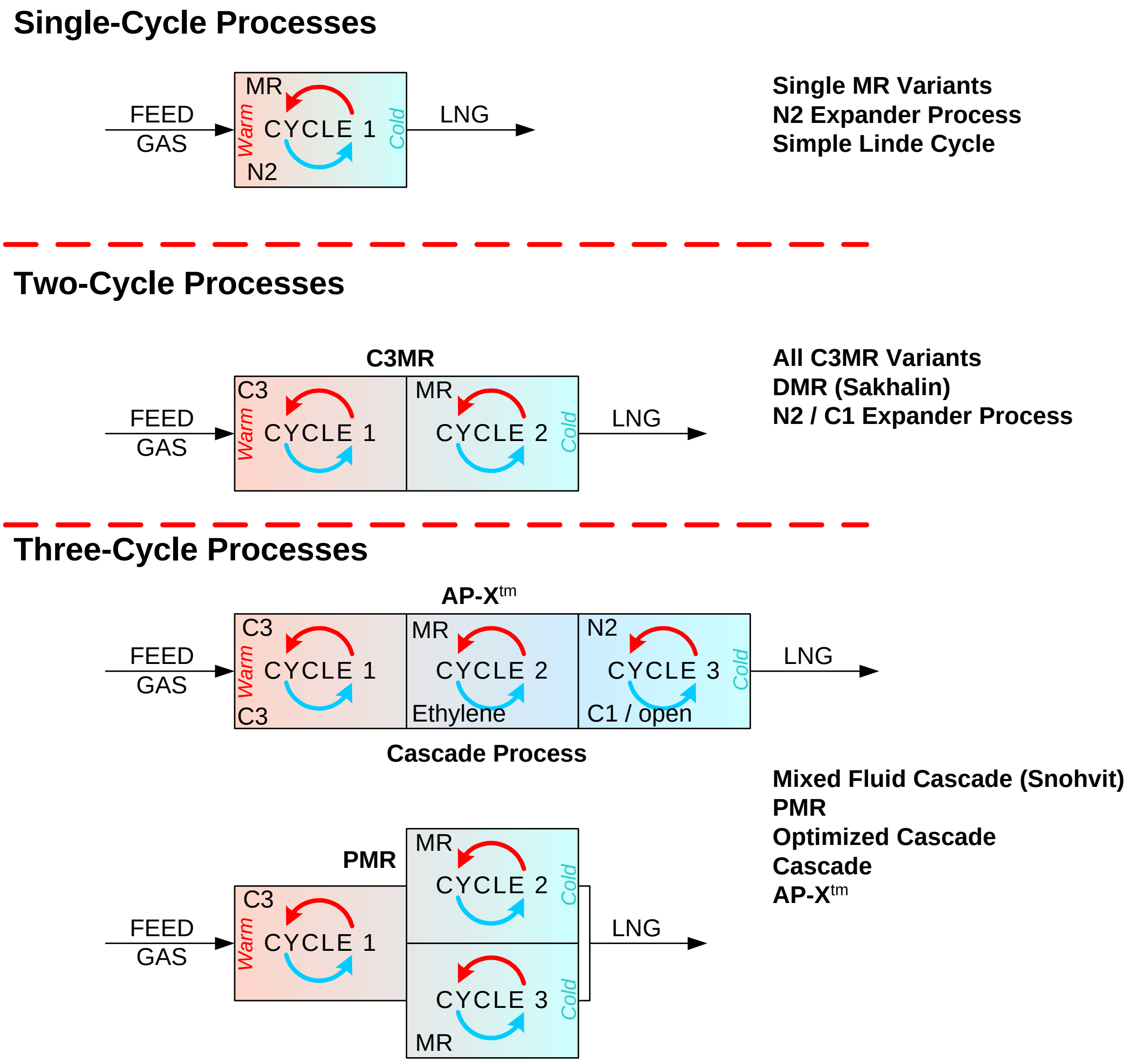

Figure 2. High Level View of Refrigeration Cycles within Processes

Generally speaking, economies-of-scale within the liquefaction train are realized when capacity can be increased without an increase in the number of cycles. When the required number of cycles increases, the equipment count, plot space, and complexity also increase such that liquefaction process cost savings are reduced or lost. LNG value chain economies-of-scale within other gas processing blocks, product storage, port facilities, utilities, and shipping remain so there is still a strong motivation to go to larger trains if sufficient gas is available.

Offshore Liquefaction State of Development

Many studies have discussed process requirements for offshore LNG facilities. Offshore liquefaction processes must be more compact and lighter 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 (6).

The concept of offshore LNG facilities has been around for many years. Early studies on the offshore LNG were conducted by Foster Wheeler over 25 years ago (7). Two processes that have been previously identified as offering potential for offshore liquefaction are nitrogen expander cycles and dual mixed refrigerant cycles (8, 9). 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 and easy to operate liquefaction process that can be effectively modularized and is indifferent to orientation. Expander cycles generally suffer from low efficiency and are thus only considered suitable for small fields (10). These factors have all been examined in various studies such as Project Azure and the Shell development work on floating and offshore concepts (9, 11).

Recently, Foster Wheeler has completed analysis that showed the introduction of the flashing expander, or full utilization of liquid expanders in a Single Mixed Refrigerant process offers potential for a compact, simple, and cost effective offshore liquefaction process(12). This type of expander enables more effective expansion of large-phase envelope fluids such as those utilized in the SMR process.

This paper presents the process design and performance results for a SMR process using liquid and flashing expander. The design supports a discussion of the potential benefit of improved expander operating range on the process and facility design. The SMR with the use of a flashing expansion has previously been identified as offering excellent potential for offshore liquefaction (12). This process offers reasonable efficiency and low flammable refrigerant inventory with the simplicity and low equipment count benefits of a single-cycle package.

Expansion Devices (13).

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 vapor 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 isentropically almost to its bubble point. The work of the expansion is extracted from the fluid as shaft power and 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 vapor dome and maximize work recovery and the reversibility of the expansion. Such expanders result in expanded fluids at either lower vapor 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 PROCESS

The Single Mixed Refrigerant Process

The process uses an aeroderivative gas turbine (GT) or two electric motors as the driver for a SMR liquefaction process. Although SMR processes have not received much attention for onshore large-scale LNG plants, they are highly suitable offshore primarily due to their simplicity, low equipment count, and reduced hydrocarbon inventory. Additionally, the SMR process can benefit by using a two-phase expander because the refrigerant can be isentropically expanded. This process is outlined below in Figure 3

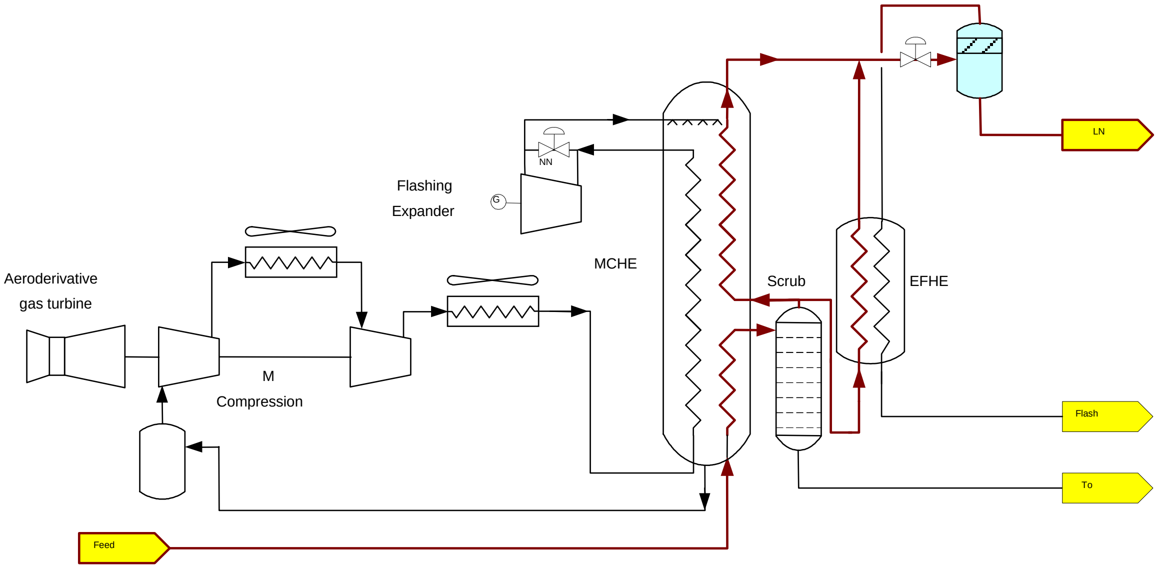

Figure 3. Simplified Single Mixed Refrigerant Liquefaction Process

The process will briefly be explained starting with the stream leaving the compressor suction drum. A warm, low pressure mixed refrigerant (MR) stream consisting of nitrogen (N2), methane (C1), ethane (C2), propane (C3), and normal butane (nC4) 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.

The MR is expanded through a flashing expander that isentropically expands the MR into the vapor region, thus recovering the work for both the subcooled liquid expansion as well as the phase change. Alternatively, using more proven equipment, the liquid could be isentropically expanded to the bubble curve in a liquid expander. 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.

In both cases, 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. In both cases, the process can operate in JT mode with the refrigerant flashing through a valve at limited LNG production capacity.

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.

An alternative that may be considered is the addition of a second MCHE and MR separator to allow operation of the MCHEs at two different pressures. This allows a decrease in the volumetric flow of refrigerant to the first stage of compression at the expense of increased equipment count, increased hydrocarbon inventories, and more complicated process control. The decision to add a second casing should consider the availability of centrifugal compressors for the duty and piping.

The process gas is shown entering a thermally integrated scrub column after partial condensation to separate the C5+ components that have condensed at warmer liquefaction temperatures. In most, if not all, cases a condensate product will need to be produced offshore. LNG is intolerant of benzene and other C5+ components that will form solids or waxes on cold liquefaction surfaces.

In the process illustrated, these components are removed in a scrub column. In other cases, a non-integrated NGL recovery process may be used upstream of liquefaction to recover addition LPG products. The decision on how many products to produce and how much processing offshore is required may be taken on a project specific basis. Typically, these decisions are a function of shipping distances, target market specifications, and facility capacity. Each product must be produced, stored, and offloaded from the production facilities. Small-scale liquefaction proposed in this paper is expected to favor production of a whole condensate product and rich LNG. The LNG is suitable for export to the major Asia-Pacific markets requiring high heating value LNG. The condensate can be further fractionated into LPG and condensate products locally using offshore infrastructure; such considerations are outside the scope of this paper.

The LNG leaving the MCHE is at high pressure and is expanded to a pressure suitable for transfer and storage through a JT valve and an end flash vessel. A flashing expander may also be considered for this application to increase production by a few percent at the expense of higher CAPEX and complexity. The liquid fraction (~90%) feeds the LNG transfer pump that sends the product to storage. The end flash vapor is enriched in N2 and is warmed in an end flash heat exchanger against a portion of the feed gas before it is compressed and used as fuel gas.

Cooling Media

There are two choices of cooling media used to reject heat from the process. Onshore plant conceptual design often considers the options of air cooling, seawater cooling, and seawater to closed-loop water cooling. The cooling media requirement for LNG is very large compared to normal cooler applications such as feed gas compressor aftercooling. This is because the refrigeration system needs to reject many times more heat to the heating medium than the refrigerated effect it produces and tight temperature approaches are desired because they improve process efficiency.

For floating applications, water cooling should be considered as the base case. Water cooling offers the most compact and efficient design of floating LNG facilities. The disadvantage is that titanium exchangers may be the longest lead time equipment item for the facility. Depending on the delivery schedule of titanium exchangers relative to the project schedule, a decision to use air cooling may be required to protect the project schedule. A FPSO shape lends itself to a bank of air coolers running near the long axis of the vessel as is common on air cooler baseload plants. In addition to thermal performance, the location of the air cooler bank must consider issues such as the location of other process equipment that are sensitive to vessel motion (columns, spiral-wound exchangers, etc.) and center of gravity.

Refrigeration Drivers and Power Generation

The preferred configuration uses aeroderivative GTs for power generation and as refrigeration system mechanical drives. Heat is recovered from the mechanical drive GT exhaust in a heat recovery unit and used as needed in various heat sinks as described below. Additional heat is recovered, and used as required. More complicated alternatives to this base design may be considered by a project as needed. Alternatives include combined cycle GT power generation, electric motor refrigeration compressor drive and the use of steam to drive smaller rotating equipment. This base configuration based on a Trent 60 mechanical drive can produce approximately 1.1 MTPA of LNG assuming reasonable feed conditions, cooling media temperature, etc.

The degree of heat integration is an important consideration as part of the driver and power generation design development. LNG facilities generally have excess heat available because of the large refrigeration power that is required to produce LNG. Early concept design determines the selection of heating media and the degree of heat integration. Heat may be recovered from the power generation and mechanical drive GTs using steam or hot water. The primary heating loads for the facility usually include the acid gas removal unit reboilers, mono-ethylene glycol regeneration, feed gas preheating, condensate stabilization, and dehydration regeneration.

The two centrifugal compressor casings may be driven by electric motors as an alternative to GTs. Electric motor drive offers several benefits that are already well-documented. The primary advantage of electric motor drive is that the availability of the facility may be increased because power generation can be spared so the maintenance required for the GTs need not set the plant availability. This increase in availability is offset against increased complexity and capital costs. The decision to proceed with electric drive should be taken as an integrated decision that includes power generation, and heat integration.

If electric motor driver is selected or increased process efficiency is an important project driver, CCGT power generation may be considered. In this case, heat is recovered from the power generation GTs and used to raise steam in an HRSG. This steam is then used to generate additional electrical power. The degree of heat integration is often primarily driven by economic considerations with due consideration of facility operability and emissions.

DISCUSSION AND CONCLUSIONS

The performance characteristics of the SMR process are seen below. A few key factors should be noted in this table. First, the basic SMR process (without flashing expansion) is a proven process with over 35 years of baseload LNG operational experience. Second, the efficiency of the SMR process with flashing expander is competitive with reported and simulated DMR and C3MR processes with liquid turbines. The SMR process is approximately 6% less efficient than the C3MR process reference point from Oman LNG train 1. When Chiyoda-Foster Wheeler completed the EPC of this project in 1997, it set a benchmark for train performance. Finally, the table should illustrate that the SMR process will have a lower equipment count as a single-cycle process. Major heat exchanger, compressor, and driver counts are included.

Table 1. Performance Characteristics of SMR and Other Cycles

Process	SMR	C3MR	DMR	AP-X
Year of First Start-up	1970	1972	Const.	Const.
Number of Cycles	1	2	2	3
Refrigerant Inventory	MR x 1	C3+MR	MR x 2	C3+MR
Efficiency (kW*day/tonne)	>13.5*	>12.2*	>12.8*	-
Typical Drivers	1 x Trent 60	*2 x FR7	2 x FR7	2 x FR9
Compressor Stages	2	4-5	4-5	6-7
Major Liquefaction Exchangers	2	4-6	3-5	7
Capacity (mtpa)	up to 1.3	up to 5.5	1-5	7.5-10+

*Barclay, M.A., Yang, C.C.: “Offshore LNG: The Perfect Starting Point for the 2-Phase Expander?”, Offshore Technology Conference, May 2006, paper number OCT 18012.

** McLachlan, G., Ayres, C., Vink, K., Al Mukhainy M.: “Efficient Operation of LNG from the Oman LNG Project”, Gastech 2002, Doha, Qatar, Oct. 2002.

Monetizing stranded gas requires novel solutions tailored to smaller fields, shorter project life, and variable marine and gas conditions. Foster Wheeler has developed a concept for a small-scale floating liquefaction process and novel value chain configuration that may offer the potential to monetize such challenging resources. This process is suitable for offshore floating LNG production solution suitable for LNG production rates up to ~1.3 MTPA supported by gas feed rates less than 200 million standard cubic feet per day. At the core of the concept is a robust single mixed refrigerant process based on a single aeroderivative GT, water cooling, and production of two products that make it suitable for offshore natural gas liquefaction and cost effective monetization of stranded gas resources.

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