HIGH CAPACITY
FLNG GAS EXPANDER PROCESS

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LNG plants with small-to-medium capacity rely frequently on refrigeration via work expansion of light gases like nitrogen, but also methane. To achieve a fair efficiency gas expander processes are designed with two or more expanders operating in different temperature ranges. The cooling duty for sub-cooling, liquefaction and in some cases, even pre-cooling of natural gas is provided by dedicated machines. As the duties are different in the respective cooling steps the expander operated at the cold end of the process will generate a small share to the overall duty. In a traditional dual gas expander process the warm expander establishes a capacity bottleneck, as it must provide 70-85% of the overall duty.

The objective of a joint development was to balance the duty of the warm and the cold expander without sacrificing thermodynamic efficiency. As this goal cannot be reached with pure nitrogen as working fluid a methane/nitrogen mixture was investigated. This paper will discuss in detail the features of the patented process (US patent 9,841,229).

The novel process can be used to design FLNG FPSOs with a total capacity of up to 2.5 mtpa, if two trains with 1.25 mtpa each are implemented. Thus, the equipment count (no parallel rotating equipment per train) and the plot requirement can be significantly reduced compared to competing technologies. The thermodynamic efficiency is on the same level as a well-designed N2 expander process. A major contribution to this concept is rotating equipment from Cryostar (e.g. TC600/130) and BHGE (e.g. LM9000 combined with 2BCL1406).
Introduction

Floating natural gas liquefaction (FLNG) projects\(^1\) are still exotic amongst more than hundred mid and World scale onshore LNG trains with at least 1 mtpa capacity. Only the Petronas floater #1 (PFLNG Satu) and SNH/Perenco's Kribi (Hilli Episeyo) project are in operation yet with Shell’s flagship ‘Prelude’ ready for start-up in 2018\(^2\). With reported specific CAPEX figures\(^3\) between 2,000 and 3,000 US$ per annual ton of LNG for realistic FLNG projects there is still room for cost reductions to get competitive with e.g. shale gas based LNG projects. A KPMG report\(^4\) provides further insight into crucial aspects of successful FLNG projects.

CAPEX reductions can be achieved by increasing the liquefaction capacity to improve the economy of scale. Not every time proven onshore concepts translate into optimal FLNG solutions. In many cases excellent operability is more important than outstanding efficiency. This offers new opportunities for expander based liquefaction processes.

State-of-the-art N2 expander processes

Generic process

![Diagram of a double N2 expander process (cLNG)](https://www.oilandgasiq.com/fpso-flng/news/top-10-flng-projects)

**Fig. 1** double N2 expander process (cLNG)

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\(^3\) Energy World Shipping, Gaffney, Cline & Associates; Excelerate Energy and Oxford Institute for Energy Studies, Infographic by Richard Neighbour

About 20 years ago BHP announced during LNG12 in Perth a new concept for World scale LNG production\(^5\). The first application of the cLNG process could have been a 2-3 mtpa gravity based facility, which should have produced gas from the Bayu-Undan field. BHP, however, was not successful to convince the other shareholders about the benefits of the new approach. BHP sold its interests to (Conoco)Phillips, which is producing nowadays the Bayu-Undan gas in Darwin/Australia.

What was new with the cLNG process (Figure 1)? Based on well-proven work expansion of nitrogen in the vapor phase only, the combination of two expanders operating in different temperature ranges reduced the energy consumption of the process to an acceptable level. In comparison to more efficient phase-change processes based on pure or mixed refrigerants the cLNG process does not require suction drums for compressors or pumps. Further, nitrogen is readily available also in remote locations and does not raise safety concerns.

A tight heat integration between warm and cold streams of the cLNG process requires a large duty of the warm expander, which acts as pre-cooling and liquefaction refrigerant provider, and a small duty of the cold expander, which serves as sub-cooling refrigerant generator. Depending on actual conditions like feed gas pressure and composition the duty of the warm expander may be as high as 70-85% of the overall duty causing a significant imbalance between the warm and the cold expander.

If the warm expander does not hit limits with respect to size and duty, the asymmetry between both expanders is not a big concern. LNG plants using this (meanwhile public domain) concept are widely used in the industry, mostly for small scale applications like the LNG facility\(^6\) for GazMétro in Montreal/Canada, which has been built and started-up in 2017 by Linde\(^7\) as EPC contractor.

*Petronas FLNG process*

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Fig. 2 enhanced N2 expander process (AP-N)

It took more than 20 years between filing the patent of the cLNG process and first LNG production of the Petronas floater #1 (PFLNG Satu). PFLNG Satu, however, does not use the process as originally invented by BHP, but applies a modified APCl design⁸ (Figure 2). Here up to three expanders are operating with two different ratios between inlet and outlet pressure. Even if a detailed comparison between cLNG and AP-N is not publicly accessible an efficiency improvement from cLNG to AP-N can be expected. A common feature, however, between cLNG and AP-N is the use of expanders with significantly different shaft power.

The two Petronas floaters Satu and Dua are not twins, rather sisters. PFLNG Satu uses BHGE PGT25+G4 gas turbines to produce 0.6 mtpa per train (1.2 mtpa in total) while PFLNG Dua applies BHGE LM6000PF as mechanical drives for a liquefaction process with 0.75 mtpa per train (1.5 mtpa in total)⁹.

So far, all FLNG projects are designed with at least two independent liquefaction trains. This concept provides more flexibility with respect to start-up and production quantities during scheduled and unscheduled plant outages.

Methane/nitrogen expander processes

As explained above nitrogen expander processes inherently require different expander sizes, if an acceptable thermodynamic efficiency is expected. Once the train capacity must be maximized new approaches need to be

⁸ http://www.airproducts.com/industries/energy/lng/~/media/0DEF92F964E04F2EAE5D39A9CD1AFFF2.pdf
taken to overcome prevailing design limits. Two dogmas of traditional nitrogen expander processes must be sacrificed to offer more headroom for design improvements

- Replace pure nitrogen by a methane containing mixture
- Accept condensation and vaporization (phase change) of the refrigerant

Even though other components might be conceivable the use of methane as partner of nitrogen is straight forward for an LNG plant with ample availability of high purity methane. Several process configurations with a CH4-N2 mixture have been discussed by Mokhatab et al.\textsuperscript{10}. Condensation of a portion of the HP refrigerant and re-vaporization at the cold end of the process allows to shift the operation of the cold expander to a warmer temperature range.

\textit{Single expander process}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{Fig_3.png}
\caption{LNG peak shaving plant Stuttgart/Germany}
\end{figure}

The use of a CH4-N2 mixture as refrigerant has been very popular for peak shaving LNG plants, where the ease of start-up and operation based on one single expander only was very much appreciated. One example of this technology is shown in Figure 3.

\textit{LIMEN™ (Linde Methane/Nitrogen) process}

The patented (US patent 9,841,229, patents pending in other countries) LIMEN™ process relies on proven building blocks, which are compiled in a novel and sophisticated manner. The simple and clean process layout quotes features from the cLNG process. The use of a methane/nitrogen mixture as refrigerant and a phase-change step in E3 (Figure 4) shows the following effects

\textsuperscript{10} Saeid Mokhatab, John Y. Mak, Jaleel V. Valapill, David A. Wood, Handbook of Liquefied Natural Gas, Elsevier, 2014, page 220 ff
• In E3 sub-cooling is provided by efficient condensation/vaporization like the sub-cooler design of well-known mixed refrigerant processes
• The operating range of the cold expander X2 is shifted from sub-cooling service to a warmer range where more refrigeration can be used efficiently
• With proper selection of the operating conditions of the feed gas similar or even identical shaft power of X1 and X2 can be achieved at the thermodynamic optimum (=minimum energy consumption) of the process

The LIMEN™ process does not contain liquid hydrocarbons except a minor volume at the cold end of E3, which is equivalent to the inventory of HP LNG upstream of the JT valve. The narrow range of flammable CH4/N2 mixtures and the absence of a BLEVE\textsuperscript{11} risk explains the excellent safety features, which are on the same level as a nitrogen expander process.

\textit{Rotating Equipment for the LIMEN™ process}

Smart process concepts are of little value, if suitable equipment is not available. While static equipment (mostly brazed aluminum plate-fin heat exchangers and compressor inter-/aftercoolers) are readily available the selection of appropriate rotating equipment is more challenging. Table 1 shows suitable equipment from Cryostar and BHGE.

\textsuperscript{11} https://en.wikipedia.org/wiki/Boiling_liquid_expanding_vapor_explosion
It should be mentioned that similar equipment is also available from other vendors avoiding a single sourcing situation.

<table>
<thead>
<tr>
<th>Capacity per train (mtpa)</th>
<th>Shaft power per expander (MW)</th>
<th>Expander model (Cryostar)</th>
<th>Gas turbine driver (BHGE)</th>
<th>GT power @ 7°C (MW)</th>
<th>Recycle compressor (BHGE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>7.4</td>
<td>TC400/90</td>
<td>LM2500+G4 or PGT25+G4</td>
<td>&gt;31</td>
<td>2BCL1006</td>
</tr>
<tr>
<td>0.95</td>
<td>11.6</td>
<td>TC500/110</td>
<td>LM6000PF+</td>
<td>52</td>
<td>2BCL1206</td>
</tr>
<tr>
<td>1.35</td>
<td>16.6</td>
<td>TC600/130</td>
<td>LM9000</td>
<td>70</td>
<td>2BCL1406</td>
</tr>
</tbody>
</table>

Table 1  selected rotating equipment for various plant sizes

**Turboexpander/Compressor (Cryostar)**

The industrial application of turboexpanders has been common since 1939 for cryogenic processes where expansion of a gas performing work results in a reduction in enthalpy of the working medium\(^\text{12}\). An expander is a machine that continuously expands a medium from a high pressure to a lower pressure resulting in an enthalpy drop. This drop in enthalpy corresponds to the increase in mechanical energy transferred (shaft power) from the expander to the power-consuming compressor. The expander is a reliable, compact and highly efficient machine, which can easily be scaled to cover a wide range of process conditions.

12 Klaus Reuter, Integrated Machinery Systems for Cryogenic Processes Consisting of Turboexpander, Compressor, High-Frequency Motor and Generator with Magnetic Bearings
A radial inflow turbine includes two steps of expansion, one stationary and one rotating. At peak efficiency, the stationary stage is responsible for about half the enthalpy drop and the remainder across the rotating stage. The stationary stage comprises converging nozzles mounted on an annular ring, known as inlet guide vanes or IGVs. The adjustable nozzles control the flow and respectively the cold production. The nozzles convert half of the enthalpy drop to kinetic energy in a near–isentropic expansion. The nozzles direct this high velocity flow into the rotating stage, called the impeller or wheel. The high velocity medium enters the wheel with relatively low angle of incidence, because the tip speed of the impeller approximately matches the velocity of the introduced medium. The blades extract energy when the medium enters the wheel in a radial direction and exits in an axial direction. The remaining energy can be recovered with a conical diffusor, contributing to cold production. The compressor stage should be designed to balance the power produced by the expander, acting as a brake. The absorbed power determines the operating speed of the turboexpander-compressor.

A single shaft connects the expander and the compressor wheel, supported by oil lubricated radial and axial bearings. A seal element provides a barrier between the process side and the oil bearing. Use of a dry gas seal design significantly reduces the leakage of the medium, if operation is in a closed loop. The specific design of the LIMEN™ process gives almost the same cold production in each of the warm and cold expanders. Similar speed and cold production of each expander allows operation the compressors in parallel, optimizing the performance. The stress in the wheel is governed by the transmission torque, centrifugal force at trip speed and the axial thrust. Finite element analysis (FEA) calculations are used to optimize the stress in the wheel and determine the maximum cold production of the expander.

Recycle compressor and gas turbine driver (BHGE)

The worldwide largest BHGE LM9000 aero-derivative gas turbine, the evolution of the highly successful GE90-115B turbofan used for Boeing™ 777 commercial aircraft, is chosen to maximize the single FLNG train production with the LIMEN™ process.

The LM9000 with 43% single cycle efficiency, delivers 67 MW ISO shaft power over a wide speed range and gives the flexibility to run the FLNG plant under any condition. The capacity to generate very high torque from start-up to full speed is also a key feature for LNG mechanical drive industry providing the capabilities to start from settle-out pressure without venting the refrigerant.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO performance</td>
<td>Power</td>
</tr>
<tr>
<td></td>
<td>Simple cycle efficiency</td>
</tr>
<tr>
<td></td>
<td>Operating speed</td>
</tr>
<tr>
<td>Emission</td>
<td>NOx</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Hot gas section</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Major overhaul</td>
<td></td>
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</table>

Table 2  
LM9000 performance summary table

The LM9000 has been designed for on-condition maintenance with boroscope ports for smart inspection while appropriate alloys selection throughout the engine allows longer running periods between maintenance actions. At the targeted temperatures for the combustor and turbine sections, the hot gas section exchange will be performed after 36,000 hours and the major overhaul after 72,000 hours.

The LM9000 package uses the proven LM6000 SeaSmart mini-skid concept to aid in maximum “safety in design” and ergonomics for technicians to provide a controlled engine removal and installation when the vessel is in motion. Either the supercore or entire gas turbine engine can be swapped in less than 24 hours to meet high availability requirements of LNG plants. The complete package especially designed for marine application, meets stringent space requirement of FLNG layout with compact package footprint, simple balance of plant and light weight. The LM9000 gas turbine available site power at 7°C ambient temperature of ~70 MW has been saturated to maximize the LNG production.

The recycle centrifugal compressor is optimized to match the process design point with state-of-the-art BHGE compressor efficiency using a two-stages single barrel compressor casing with intermediate external process gas cooler. The selected 2BCL1406 centrifugal compressor has two stages, with six three-dimensional impellers manufactured from single forging without welding back-to-back arranged and equipped with tandem dry gas seals. Top nozzles are envisaged. The compressor is directly connected to the gas turbine driver with flexible coupling and mounted on a single baseplate. Mineral lube oil system is integrated in the baseplate to allow single lift skid.
By removing the end cover it is possible to extract the rotor diaphragm bundle assembly and to gain access to the internal components without dismounting the outer casing which remains connected to the plant piping; seals and shaft ends can be inspected and removed without opening the compressor casing. Prior to shipment, the full speed/full load string tests is performed by BHGE at its testing facility in Massa (Italy).

This compression system solution is especially favourable as contribution to the outstanding FLNG capabilities of LIMEN™ process. All major components of the envisaged compressor concept have previously been supplied by BHGE on past LNG and FLNG projects.

The same compression train concept can be used for scaled-down LIMEN™ FLNG plant throughput using smaller gas turbines models like LM6000 PF+ or LM2500/PGT25+G4 gas turbine and lower centrifugal compressor sizes (see Table 1).

**Conclusions**

The novel LIMEN™ process can be used to design FLNG processes with a total capacity of up to 2.5 mtpa, if two trains with 1.25 mtpa each are implemented. Thus, the equipment count and plot requirement can be significantly reduced compared to competing technologies. The thermodynamic efficiency is on the same level as a well-designed N2 expander process. A major contribution to this convincing concept is rotating equipment from Cryostar (e.g. TC600/130) and BHGE (e.g. LM9000 combined with 2BCL1406).