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Air Products and Chemicals Inc., USA, explore liquefaction cycles for
floating LNG from concept to reality.

AN EVOLUTIONARY APPROACH



Selecting the optimal liquefaction cycle for floating LNG (FLNG) is key to project success. Factors such as sea motion, space limitations, feed gas compositions, and heightened safety concerns have driven the development of alternate liquefaction cycles for these unique challenges. This article will describe key features of different liquefaction cycles, and how leveraging relevant land-based and offshore experiences is essential in order to successfully implement new liquefaction technologies.

Leveraging LNG experience

While the AP-X® process has so far been implemented only on land, at the six mega trains in Qatar, many of the associated technology developments have proven essential to the development and commercialisation of liquefaction cycles for FLNG. The process builds on the AP-C3MR™ process to provide increased capacity while limiting the increase in equipment sizes (Figure 1).^{1,2} Propane pre-cools the natural gas and mixed refrigerant (MR). Sub-cooling LNG to the endflash temperature is performed by a nitrogen expander loop where cold nitrogen vapour provides

refrigeration for sub-cooling LNG in the sub-cooler, which is also a coil wound heat exchanger (CWHE).

Using nitrogen to sub-cool LNG reduces the total refrigeration load on the upstream C3MR section. The power per unit of LNG decreases by approximately 20% on the propane compressor and 40% on the MR compressors. This extra refrigeration power is then supplied by the nitrogen compressor. By shifting this power from the propane and MR compressors, those machines can remain within referenced limits while the overall plant capacity is increased.

Implementation of new technology

The biggest challenge of a sub-cooler design was the high pressure on the shellside – nominal operating pressure is greater than 20 barg. The most economical solution was to manufacture the shell from stainless steel rather than aluminium. However, design of the exchanger internals remained with the proven aluminium material to minimise bundle weight and provide strong heat transfer. Using two different metals created mechanical design challenges, because the steel and aluminium have different coefficients of expansion. The mechanical stresses were carefully analysed

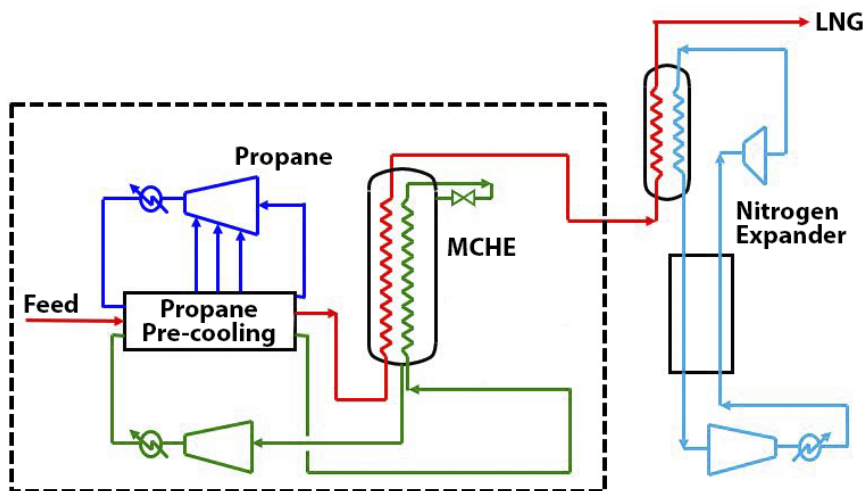


Figure 1. AP-X process.

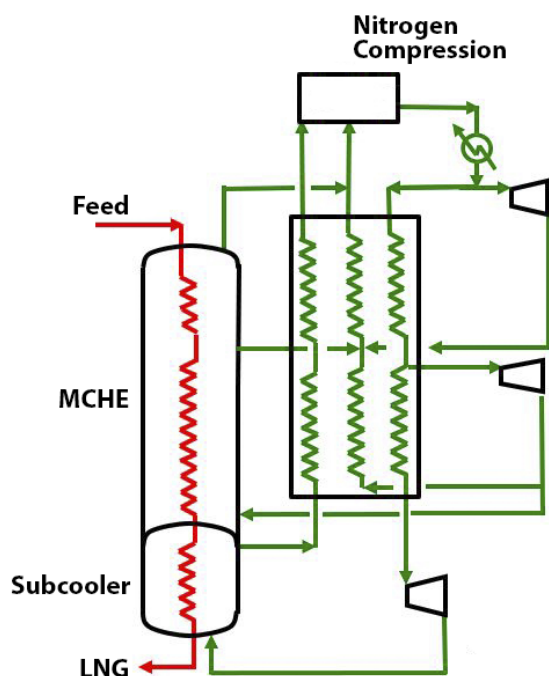


Figure 2. AP-N liquefaction process.



Figure 3. Petronas PFLNG Satu (image courtesy of Petronas).

throughout the entire heat exchanger, with a focus on the aluminium to stainless steel transition points.

The AP-X compressors were the largest cryogenic compressor loaded expanders (compressors) that have been constructed by Air Products in terms of power and mass flow, and each of the six trains uses four compressors. A rigorous qualification, testing, and risk management procedure was followed to ensure that the compressors performed as designed.

The project was a significant undertaking as trains had to be designed and constructed that were 55% larger than the previous design. A new process was used, and the

demonstrated limits of much of the equipment were significantly extended. GE Frame 9E gas turbines were used for the first time in mechanical drive service.

Leveraging experience

The AP-N™ process was developed by leveraging and extending experience with large compressors and stainless steel/aluminium exchangers gained from the AP-X process to make a complete LNG solution that does not require hydrocarbon refrigerants. A schematic of the process is shown in Figure 2.

The process uses nitrogen vapour as the refrigerant in a reverse Brayton expansion cycle. Refrigeration is generated by three high efficiency turboexpanders, operating with three temperature levels and at two pressure levels, which allow the process to precool, liquefy, and sub-cool the natural gas feed more efficiently than traditional nitrogen refrigerant processes.

As refrigeration is provided by vapour expanders, the process responds quickly to changes in refrigeration demand. Without the need to manage liquid refrigerant inventories, start-up and turndown are fast. Control of the process is provided by Air Products' control scheme, which keeps the liquefaction system operating efficiently with minimal operator interaction.

Key equipment for this process includes compressors, CWHEs and nitrogen economiser cold boxes.

The compressors chosen for the Petronas FLNG (PFLNG) Satu project were based on the large capacity machine design proven in the AP-X plants. Most of the major changes from the land-based machines to FLNG machines centred around reducing the size and weight of the compressor skid and associated lubrication oil and seal gas systems. The machines were designed to be integral, or skidded, with the machine support structure and the accessory system to minimise the footprint and eliminate the need for interconnecting piping which was present in the land-based design.

The development of CWHEs with a stainless steel shell and aluminium tubes for the AP-X sub-cooler has proven to be essential to the development of CWHEs for this project and for FLNG generally. For FLNG applications, CWHEs have

a distinct advantage due to their compactness and small footprint.

The AP-N process was successfully implemented in PFLNG Satu. The production vessel is currently located in the South China Sea at the Kanowit gas field, approximately 150 km off the shore of Sarawak, Malaysia, and has a production capacity of 1.2 million tpy. PFLNG Satu was started up in December 2016 and loaded its first cargo in April 2017 (Figure 3).

Overall, the logistical and design challenges were successfully met, resulting in successful commissioning and operation. A second production vessel using the AP-N process, Petronas PFLNG Dua, is currently under construction. It will have a nominal production capacity of 1.5 million tpy and is expected to be operational in 2020.

The next step

The AP-DMR™ process was developed by leveraging and extending experience in stainless steel/aluminium

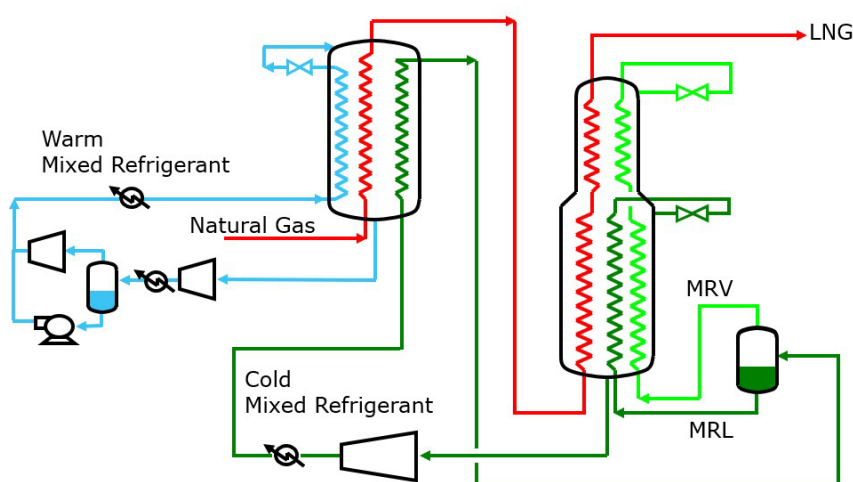


Figure 4. AP-DMR process.

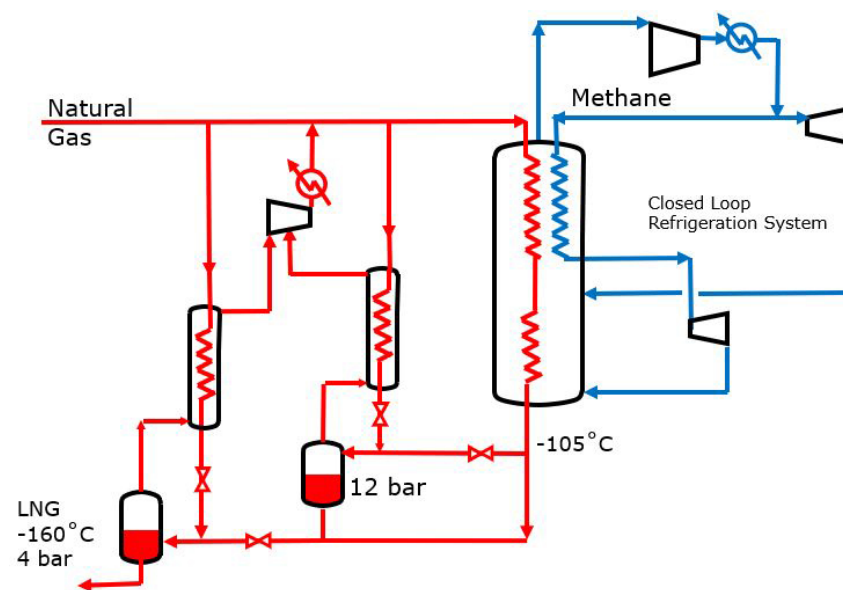


Figure 5. AP-C1 process for large-scale LNG.

exchangers gained from the AP-X process, experience with heavy mixed refrigerants in AP-SMR plants and the use of aeroderivative gas turbines for C3MR. The design also makes use of an extensive multi-year process and mechanical R&D programme to understand the potential effect of sea motion on the mechanical integrity and performance of the CWHEs.

The process differs from the C3MR process in that a single CWHE is used to pre-cool the LNG with a precooling (warm) MR. However, the process used to liquefy and sub-cool the natural gas is identical, using a second (cold) MR in a second CWHE (Figure 4).

The main differences between the process for FLNG applications compared to those that are land-based are the potential effects of motion on the performance and mechanical integrity of the exchangers.

Beginning in the late 1990s, Air Products completed a rigorous analysis of the effect of tilt and oscillatory motion on CWHE performance including laboratory-scale and pilot-scale testing. The results of these efforts allowed the company to incorporate the effects of shell-side flow distribution into established CWHE design methods.

The Air Products DMR process has been selected for the 3.4 million tpy Coral South FLNG project, which is currently under construction. The plant will include aeroderivative gas turbine drivers for both the warm and cold MR compressors, leveraging experience gained in compression in C3MR cycles with aeroderivative drivers for land-based plants.

Further evolution

The development of high capacity expanders and high pressure stainless steel CWHEs for the AP-X process along with the operational experience in the design of the AP-N process have been used to develop a new AP-C1™ process. As a gas phase reverse Brayton cycle, the process retains the advantages of the AP-N process: minimal liquid hydrocarbon inventory, sea motion insensitivity and operating simplicity, making it well-suited to FLNG applications.

Similarly, it also uses a gas phase reverse Brayton cycle for LNG precooling and liquefaction. Final sub-cooling of the LNG from a temperature of approximately -105°C is done in a series of flash steps (Figure 5).^{3,4} The flash steps are done using newly developed dual purpose CWHEs that provide heat exchange, warming the flash gas by liquefying feed, while also performing the vapour liquid separation of the

flushed LNG below the tube bundle inside the CWHE shell. By combining these functions into a single piece of equipment, plot space on the FLNG vessel is minimised.

The process employs a closed loop methane cycle. The use of methane in the closed loop process eliminates the logistical issues associated with the need to supply large quantities of refrigerant for start-up, since the refrigerant is taken from the feed gas. Additionally, by using primarily methane as the working fluid, the refrigerant heat capacity ratio, C_p/C_v , is lower than nitrogen, reducing the power consumption.

The refrigerant composition may also be optimised to improve performance. The process can be started up and operated using feed natural gas and the performance can be improved with the addition of approximately 10 – 40% of nitrogen. The nitrogen lowers the dew point of the refrigerant, which allows the expander discharge pressure to increase, reducing the sensitivity of the process to pressure drop. For nitrogen containing feeds, no additional nitrogen generation capability is typically needed to achieve the refrigerant composition.


For large and mid-scale LNG using AP-CI, CWHEs are used for all process heat transfer involving liquefaction of the natural gas feed. CWHEs are much less susceptible to blockage than brazed aluminium heat exchangers (BAHXs) because the inner diameter of the CWHE tubes are much larger than the fin spacing in a BAHX, greatly reducing the potential for blockage and the need for fine strainers.

A recently completed evaluation of the AP-CI process for an FLNG opportunity demonstrated the benefits

described above and its viability for mid-to-large capacity FLNG applications.

Summary

Traditionally, the baseload LNG industry has been risk averse, and justifiably so. The scale of these projects entailing multi-billion-dollar investment lowers the appetite of project owners and financiers for technical risk in all areas of the project including selection of the liquefaction cycle. This risk-aversion is particularly true for FLNG projects.

The inherent characteristics of FLNG projects including sea motion, space limitations, feed gas compositions, and heightened safety concerns along with technological advancements justify different liquefaction technology than is used for land-based plants. The developments described in this article show that new liquefaction cycle technology can be successfully implemented using an evolutionary approach that leverages proven technology combined with a rigorous qualification, testing, and risk management effort in partnership with plant owners and contractors. 

References

1. PILLARELLA, M., et al, 'The C3MR Liquefaction Cycle: Versatility for a Fast Growing, Ever Changing LNG Industry,' presented at the 15th International Conference and Exhibition on Liquefied Natural Gas, 2007, Barcelona, Spain.
2. ROBERTS, M. J., et al, 'AP-X™ LNG Process,' presented at Gastech 2002, Doha, Qatar.
3. ROBERTS, M. J., et al, 'Integrated methane refrigeration system for liquefying natural gas,' US Patent 9863697.
4. ROBERTS, M. J., et al, 'Innovative Liquefaction Technology for Floating LNG' presented at Gastech 2017, Tokyo, Japan.