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INNOVATIONS IN NATURAL GAS LIQUEFACTION TECHNOLOGY FOR FUTURE LNG PLANTS AND FLOATING LNG FACILITIES

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ABSTRACT

This paper discusses some of the challenges posed in the development of Floating LNG (FLNG) plants for the exploitation of offshore natural gas fields, and the work undertaken by Air Products to address these challenges. Specifically, we look at the LNG liquefaction process, the mechanical integrity of the coil wound heat exchanger (CWHE), and the impact of vessel motion on the CWHE performance for mixed refrigerant (MR) based liquefaction processes. The development of large compressor loaded expanders (companders) for nitrogen-refrigerant based liquefaction processes for FLNG will also be discussed.

A key decision in the development of an FLNG plant is the selection of a liquefaction process cycle that best meets the project objectives. Air Products has evaluated liquefaction process cycles for FLNG applications, including Single MR (SMR), Dual MR (DMR), Nitrogen (N_2) recycle, and N_2 recycle with Hydrofluorocarbon (HFC) precooling. These processes, as well as advantages and disadvantages of each, will be discussed.

Air Products is building on the success of the Air Products AP-X® LNG Process applied on the mega-trains in Qatar by leveraging the design of the AP-X stainless steel CWHE subcooler to serve as the basis for marinized exchangers for FLNG, and extending the development of large refrigeration companders to FLNG cycles.

In FLNG service, any two-phase process system, including a CWHE employing liquid refrigerants, may be subject to performance impacts due to the motion of the floating vessel. Air Products has completed an extensive research and development program to understand and predict these motion effects so that they may be adequately accounted for in the overall liquefaction system design.

TABLE OF CONTENTS

ABSTRACT
1 INTRODUCTION
2 CHALLENGES FOR FLNG
  Motion
  Flammable Components
  Weight and Space Limits
  Corrosion
3 PROCESS CYCLES
  C3MR
  DMR
  SMR
  N_2 Recycle
  N_2 Recycle/HFC
4 EXCHANGER MECHANICAL INTEGRITY
5 N_2 COMPANDER DESIGN
6 MOTION EFFECTS
  Fundamental Experiments
  Liquid Distribution Model and Pilot Scale Data
  Exchanger Design
  CFD
7 SUMMARY
8 REFERENCES

1 INTRODUCTION

Over the years since the first baseload LNG plant started up in Algeria in 1964, more than 90 LNG liquefaction trains have been built, today supporting a worldwide capacity of about 300 MTPA. The vast majority of these trains operate with one variation or another of the Propane-Precooled Mixed Refrigerant (C3MR) cycle, and all of the trains have been built on land. As the industry matured, the market has demanded trains with larger and larger capacity (Figure 1). This trend has been facilitated by developing larger gas turbines to drive larger refrigerant compressors and by improving the design of process cycles and CWHEs. The largest of these baseload trains are in Qatar. Each of these six trains utilizes the Air Products AP-X® LNG Process that combines a C3MR liquefier and N_2 recycle expansion process subcooler to make over 7.8 MTPA of LNG. All are running reliably with the first two in operation for over two years.

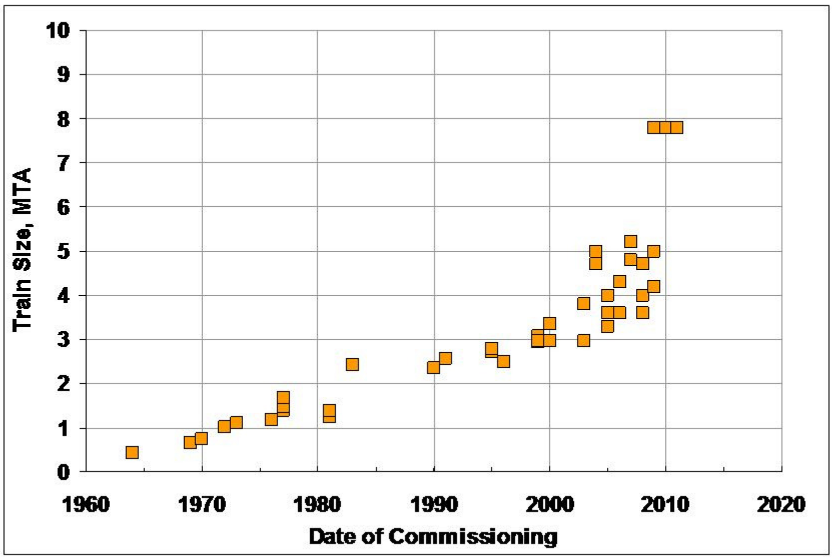

Figure 1 Progression of LNG train size over the past 50 years

Future growth in the LNG industry appears to be marked by an increasing interest in developing remote offshore gas fields. Although land-based plants are expected to continue to contribute to the increasing worldwide LNG capacity, there are many new gas fields slated for development which are located far enough offshore or in water too deep to make pipeline delivery to a land-based plant less attractive economically (Figure 2). FLNG projects are being developed to exploit these fields. Designing, constructing, and operating these plants pose a number of interesting challenges.

The oil and gas industry has operated offshore for many decades on fixed platforms as well as with Floating Production, Storage and Offloading (FPSO) vessels developed for oil production in deep water. As a consequence, there is a large experience base to draw upon to address many of the challenges of FLNG. However, there are some issues specific to LNG processing which required innovative problem solving.

Air Products has developed several liquefaction process cycles that offer various combinations of capital cost, efficiency, and features to allow the selection that best fits the needs of the Owner. Air Products has completed extensive research and development programs to marinize their liquefaction equipment. These programs confirmed the structural integrity and performance of Air Products equipment in the offshore environment, including motion induced forces. This paper will discuss how the past land-based successes have led to the development of efficient processes with attractive CAPEX and robust equipment designed for ship-board use.

Figure 2 Possible locations for land-based (circles) and offshore (stars) LNG

2 CHALLENGES FOR FLNG

Building and operating an LNG liquefaction plant on a floating platform will have some important differences from land-based LNG facilities.

Motion

A key issue is the motion of the production vessel. Motion is a consequence of the design and size of the vessel, as well as the sea conditions. During transit of the vessel to the production location, the ship motion will subject the installed equipment to mechanical stresses. At the production location, the operators will attempt to maintain the vessel steady and level, but stability control systems cannot eliminate all vessel motion. Process equipment with two-phase flow may therefore experience reduced performance due to liquid-vapor maldistribution, and liquid sloshing may cause additional mechanical stresses. At times of very heavy seas, the production operation may be shutdown. However, the equipment must be designed and constructed to survive the extreme forces from vessel motion caused by these heavy sea conditions. Higher strength materials may provide a benefit for equipment design.

Flammable Components

The most common liquefaction process currently used for land-based LNG plants is the C3MR process. Precooling of the natural gas feed is performed with propane refrigerant, and liquefaction and subcooling are completed with a mixed refrigerant composed of nitrogen, methane, ethane or ethylene, and propane. The C3MR process is well known, mature, and widely accepted. Some advantages of the process are high efficiency, high reliability, and ease of operation. Refrigerant components are typically readily available by extraction from the natural gas feed stream. For FLNG, some Owners have expressed concerns with the necessary inventory of flammable components in the refrigeration loops and associated storage. In particular, propane is considered the greatest concern because of its high volatility combined with its dense vapor which can accumulate at low elevations, in hull spaces, etc. As a result, refrigeration processes which minimize or eliminate either propane or all flammable components are of interest for some FLNG operators.

Weight and Space Limits

The plot space aboard an FLNG will be at a premium. Processes with reduced equipment count and size will be a benefit. The use of large diameter piping should be minimized. Weight is a concern because efficient and cost-effective construction techniques place equipment into modules, which have structural and weight limitations. Weight eventually affects the overall vessel size due to buoyancy and center of gravity considerations.

Corrosion

Any shipboard equipment installed on open decks will be subject to salt water spray. Uniform corrosion and stress corrosion cracking of piping and equipment are obvious concerns. Cryogenic equipment for land-based LNG plants is often constructed from aluminum which reduces weight. For FLNG, exposed equipment must use other materials, such as chloride resistant stainless steel.

3 PROCESS CYCLES

One key decision in the development of FLNG is the selection of a liquefaction process cycle that best meets the project objectives.[1] Although the design considerations and evaluation criteria are somewhat different from land-based facilities, the fundamental factors for land-based success can help to "pave the way" towards choosing the optimal cycle and key equipment for FLNG. Applying a similar methodology as used to successfully implement new processes and equipment for land-based facilities, Air Products has evaluated liquefaction process cycles for FLNG applications. The following discussion will focus only on the liquefaction step, starting with treated dry lean natural gas after the steps of acid gas removal, dehydration, mercury removal, heavy hydrocarbon removal, and optional feed recompression. The post liquefaction steps of pressure letdown, end flash gas recovery, and storage will not be discussed. All of those steps invite their own challenges for FLNG, but they are beyond the scope of this paper. The following processes involve the same three basic steps of precooling the treated gas to about -30 to -40C, liquefaction to about -120 to -135C, and subcooling the LNG to about -140 to -165C.

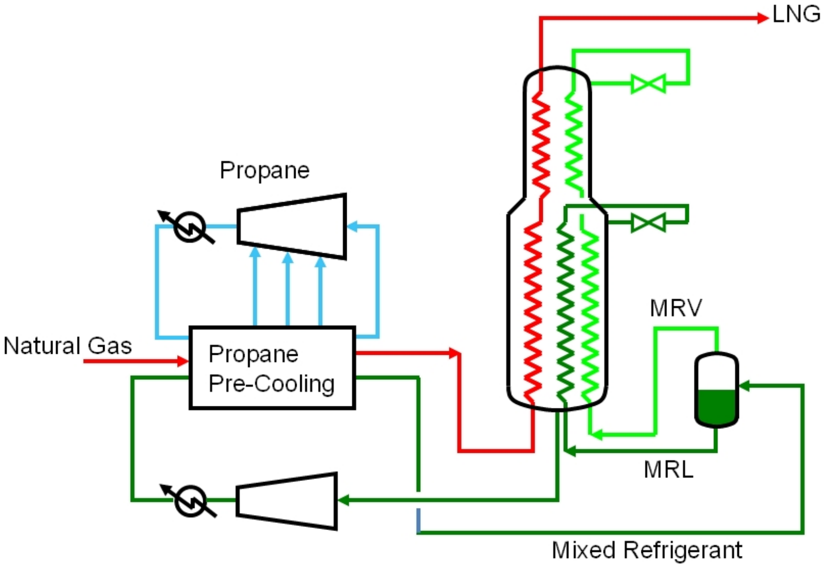

Figure 3 Air Products AP-C3MR™ LNG Process

C3MR

Most of the world's LNG is liquefied using the AP-C3MR process, using a CWHE (Figure 3). The basic process achieves precooling with a propane refrigerant loop, typically in kettle-type evaporators but other arrangements are possible and in operation. Liquefaction and subcooling are performed in the CWHE with a second refrigeration loop utilizing a mixed refrigerant composed of nitrogen, methane, ethane, and propane. The C3MR process achieves high efficiency due to the ability to match the MR boiling curve to the feed condensation curve. This process is well proven and widely accepted, and therefore might be expected to be the first choice for FLNG development. However, there are some conditions that make it less attractive. The most obvious is the use of propane refrigerant in the precooling loop, and the consequent large inventory of propane that is required, especially when kettle-type exchangers are used. A second issue is the relatively large plot space that is required for the propane evaporators. A side issue, which should be manageable with proper engineering, is sloshing of liquid propane in the large evaporators due to vessel motion, which could result in additional mechanical stresses and reduced process performance.

DMR

In the Dual MR cycle, the precooling propane refrigerant is replaced with a high boiling point Warm Mixed Refrigerant (WMR) containing methane, ethane, propane and butane. This significantly reduces the propane inventory in the vessel. Furthermore, the optimized WMR composition will frequently contain little or no propane, and the performance penalty to eliminate propane is typically minimal. Precooling is performed in a CWHE, which provides the proven mechanical performance of wound coil heat exchangers, countercurrent flow for better heat transfer performance and also may reduce the plot space required. The DMR process achieves an efficiency comparable to C3MR. It has also been used successfully in land-based LNG.[2] For these reasons, DMR has drawn considerable interest for FLNG.

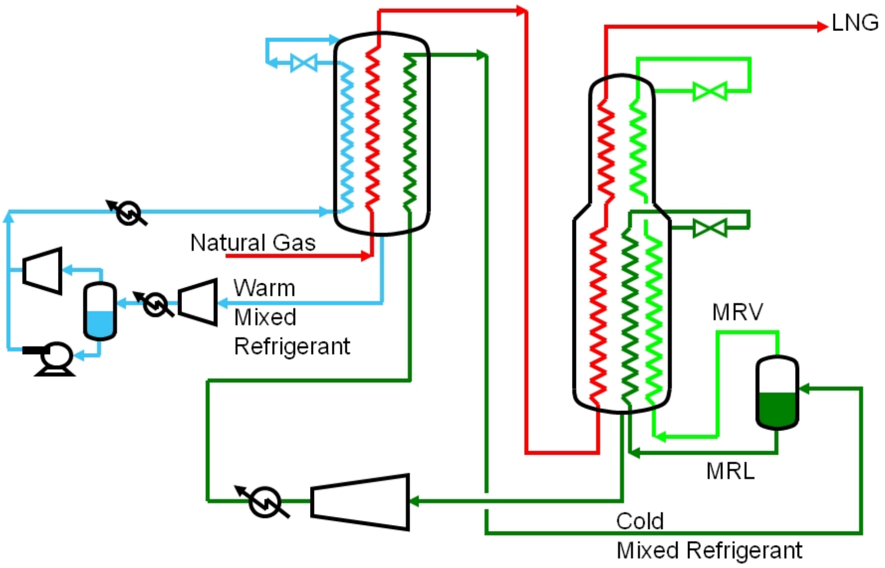

Figure 4 Air Products AP-DMR™ LNG Process

Figure 4 shows an AP-DMR process which uses two stages of WMR compression. The discharge from the first stage is partially condensed and the liquid portion is pumped around the second stage compression. The WMR is totally condensed after the second stage compression, cooled in the CWHE Precooler, and flashed to a single pressure level to provide precooling refrigeration. Other compression and Precooler configurations are possible, with various advantages and disadvantages. The process can therefore be configured and optimized to meet the project requirements.

SMR

The Single MR cycle uses only one MR loop for precooling, liquefaction, and subcooling (Figure 5). This provides the benefit of reduced equipment count, but comes at the cost of lower efficiency than C3MR and DMR. SMR has been used for land-based LNG plants, typically for capacities less than 1 MTPA. Air Products designed four 0.8 MTPA SMR trains for Libya, several LNG peakshaving trains, and two 0.4 MTPA SMR trains which are expected to start-up in China later this year. The SMR process requires a taller and larger liquefaction CWHE for a given LNG production than the DMR cycle, as it must handle all of the liquefaction duty including precooling. This can prove problematic for FLNG for both structural reasons and process reasons. In addition, at capacities approaching 2 MTPA, two CWHEs would likely be required.

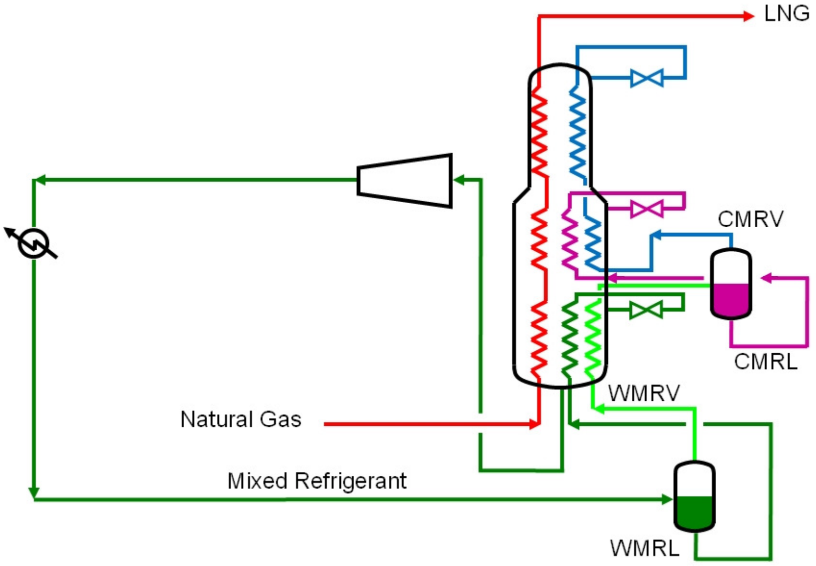

Figure 5 Air Products AP-SMR™ LNG Process with three bundles

A basic SMR process has a lower efficiency than a C3MR or DMR cycle. In addition to the configuration shown in Figure 5, Air Products has developed several variations of the AP-SMR process to enable increased efficiency, through the use of additional levels of compression and exchanger complexity.

N_2 Recycle

All of the foregoing process cycles use flammable refrigerants. Because the feed gas and product themselves are flammable, and LPG recovery may result in significant LPG storage, it is not possible to entirely eliminate risks due to hydrocarbon storage on an FLNG. However, minimization of flammable inventory drives interest in refrigeration cycles which contain no flammable components.

The nitrogen recycle expander plant is a well-known technology, used extensively in the air separation industry for producing liquid N_2 and O_2. The process uses the reverse Brayton cycle to create refrigeration by compressing nitrogen, removing the heat of compression, expanding the nitrogen through a turbo-expander to create a cold stream, and warming the stream against the heat load. The cycle has been used in hundreds of Air Separation Units as well as dozens of LNG peakshaver plants.

In the last decade, the AP-X® LNG Process increased baseload plant capacity by more than 50%, by adding a nitrogen refrigeration loop to the successful C3MR technology (Figure 6). The AP-X process utilizes propane for precooling, a mixed refrigerant for liquefaction, and a nitrogen refrigeration loop for subcooling. The nitrogen loop provides refrigeration that the C3MR portion of the liquefaction area would otherwise be required to provide and enables single train production greater than 8 MTPA. This new technology has been proven in six AP-X trains currently operating in Qatar. For the AP-X plants in Qatar, the N_2 recycle subcooling loop provides refrigeration equivalent to an LNG plant with capacity of 1-2 MTPA.

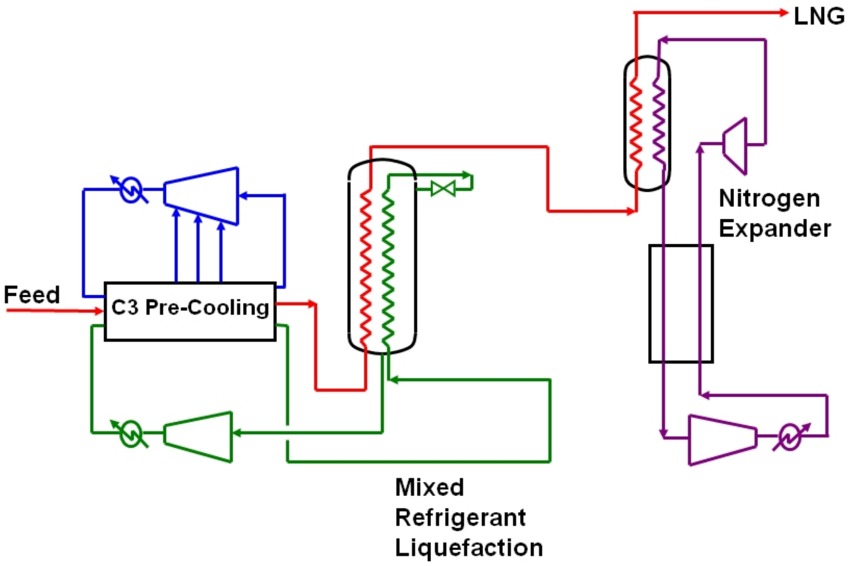

Figure 6 Air Products AP-X® LNG Process

However, the AP-X nitrogen loop as it stands would not be the optimum design to perform all three functions of precooling, liquefaction and subcooling. Air Products has developed several variations which are tailored to this purpose. These optimize the number of expanders, pressure and temperature levels along with process efficiency. Figure 7 shows an Air Products AP-N™ LNG process with a single pressure level and two expander temperatures. The nitrogen is compressed and enters an economizer in which it is cooled. Most of the nitrogen is withdrawn at an intermediate point, expanded through a turbo-expander to reduce the temperature, and enters the liquefaction exchanger to provide the majority of the refrigeration duty to liquefy the natural gas. The remaining nitrogen is further cooled in the economizer before being expanded to provide refrigeration to the subcooling portion of the main exchanger. Some of the nitrogen refrigerant is used to provide refrigeration in the economizer before all the refrigerant is returned to the compressor suction. The compression work is performed in several machines, with the first stage(s) driven by an external driver and the last stage driven by the turbo-expanders (companders). Note that the LNG is liquefied in a CWHE. The CWHE has a proven history of withstanding the high thermal stresses which can occur in liquefaction service.

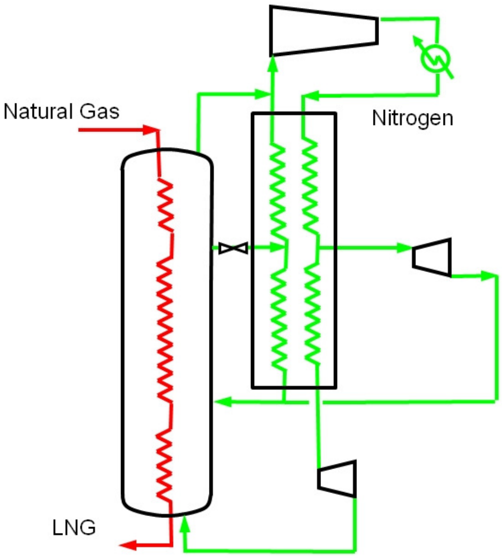

Figure 7 Air Products AP-N™ LNG Process with single pressure level

For FLNG, the N_2 recycle process has the obvious advantage of using a nonflammable refrigerant. However, the efficiency of the cycle is significantly lower than those which use a precooled

MR cycle. The N_2 refrigerant is entirely vapor and the heat transfer therefore entirely sensible. Because sensible heat produces less refrigeration per unit mass, the refrigerant flow rates are significantly higher for the N_2 recycle process. This results in larger heat exchanger and pipe sizes, often requires parallel rotating machinery, and limits single train N_2 recycle systems to between 1 and 2 MTPA.

N_2 Recycle/HFC

The reverse Brayton cycle is not the best option to create the warm refrigerant required for precooling, and therefore, using N_2 to provide precooling lowers the process efficiency. A way to improve the overall cycle performance is to use a second refrigerant loop for precooling. This approach can increase the efficiency of the process nearly to that of an SMR cycle. While propane would be a good choice based on efficiency alone, this obviously introduces a flammable refrigerant, which eliminates much of the advantage of the N_2 recycle process. Instead, the precooling can be performed by using a hydrofluorocarbon (HFC) refrigerant.[3] The HFC system is similar to a propane system, with the substitution of HFC-410A or another suitable refrigerant and a compressor designed for the heavier molecular weight of the HFC.

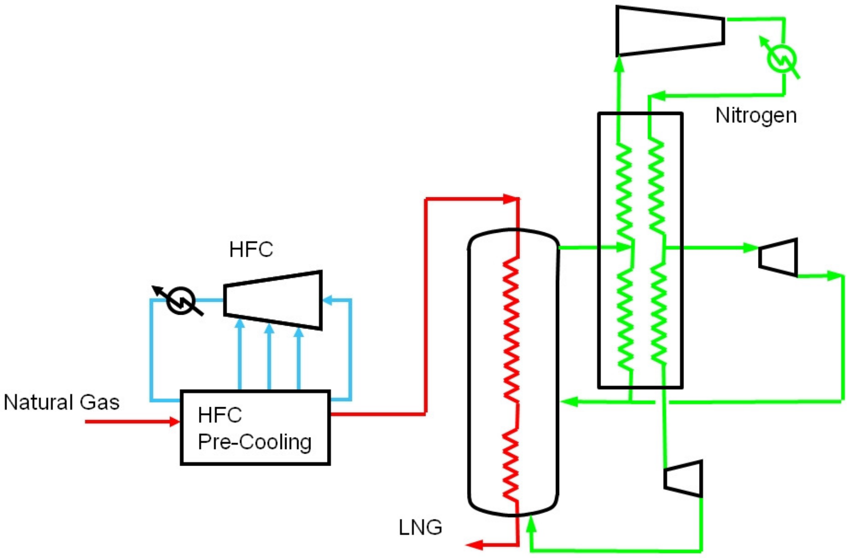

Figure 8 Air Products AP-HN™ LNG Process

Figure 8 shows an AP-HN process similar to the AP-N process of Figure 7, where an HFC precooling system has replaced the precooling bundle. HFC refrigerant systems are widely used in marine applications, as well as countless industrial and household functions. However, the scale of an FLNG precooling system with HFC may be a step-out from previous experience. The key consideration regarding the implementation of an HFC refrigerant loop is the question of refrigerant loss and makeup, since all the refrigerant would need to be imported to the FLNG vessel.

4 EXCHANGER MECHANICAL INTEGRITY

For both mixed refrigerant and nitrogen based processes, CWHEs are best suited for liquefaction for two reasons:

- In liquefying natural gas, the high heat transfer rate in areas where the NG is condensed can create high thermal stresses. CWHEs by their basic design are robust and have been proven to be able to tolerate these high thermal stresses.
- In the very rare case where tube leaks occur, the leak is fully contained. The leak would occur from a tube into the pressure vessel shell, and no refrigerant is leaked directly to the

environment. This allows the operator to continue to run for months or years before the leak needs to be repaired. This is different than other types of heat exchangers, which can leak directly to the environment. These external leaks require immediate repair, resulting in a significant unplanned outage. For FLNG, this dual containment provides an extra level of protection.

CWHE for FLNG are subjected to dynamic loads and stresses due to motions not present in land-based plants. The structural integrity necessary to withstand these dynamic loads and forces is provided by using stainless steel instead of aluminum for the shell. In the case of the CWHE Subcoolers associated with the AP-X trains, this was done in order to achieve greater mechanical design pressure while allowing for a thinner shell than would have been required had aluminum been used. The aluminum internals of the CWHE are retained, because they provide efficient heat transfer and reduce exchanger weight. In addition, as already mentioned, the stainless steel shell may allow for higher design pressures, which are necessary for the nitrogen refrigeration process.

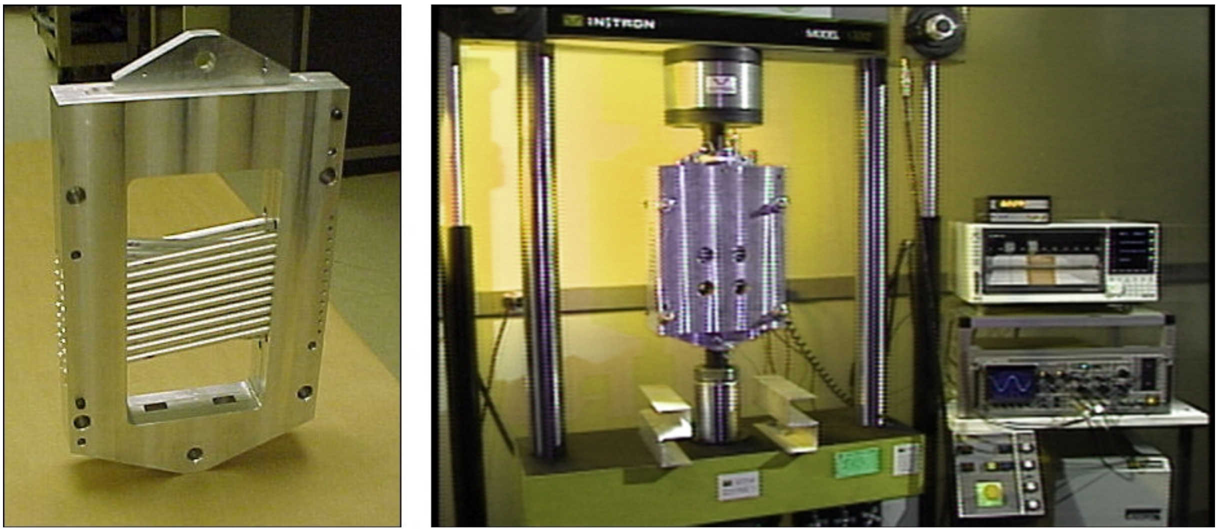

Figure 9 Tube support test assembly and tensile machine

Air Products' FLNG development program was conducted to confirm the structural reliability of CWHEs in an FLNG environment. The objectives of the analysis were to establish a basis for evaluating the structural integrity of the heat exchanger, define the mechanical design criteria for FLNG service, and determine the effects of the wave motion forces on (a) the pressure vessel and (b) the internal bundle support system.[4] The analysis assumed a conventional, steel hulled ship, and the wave motions were based on the North Sea due to its harsh conditions. The analysis confirmed that Air Products' CWHE design with a stainless steel pressure vessel and aluminum internals was acceptable for both strength and fatigue. Det Norske Veritas (DNV) reviewed the analysis and certified that the method and basic design were appropriate for an FLNG application. The behavior of the bundle support system under wave motions was also demonstrated.

(a) The analysis utilized the ship design and sea conditions by converting them into accelerations that are applied to the CWHE to determine loadings. The mechanical integrity of the pressure vessel shell subjected to these dynamic loads was then confirmed by analytical methods. The loadings used for the strength and fatigue analysis and the exchanger size evaluated were very conservative. The results showed that the shell will withstand the ship motions.

(b) The internal bundle support system is much more complicated and is not easily addressed by analytical methods. Therefore, Air Products developed a laboratory test to demonstrate the support systems ability to withstand the dynamic forces associated with wave motion. A model of the support system was subjected to millions of cycles to evaluate the effects of motion loads on the system. Figure 9 shows the test assembly and the tensile machine. The test loads and number of cycles were selected to exceed the expected load spectrum for the 100 year storm conditions. This experimental test program was highly successful, and showed that the support system will also withstand motions and loads which may occur at sea.

5 N_2 COMPANDER DESIGN

An FLNG plant using the N_2 recycle process requires large compressor-loaded expanders (companders), much larger than those typically used in most N_2 liquefaction processes such as Air Separation Units. However, the AP-X trains in Qatar required substantial scale-up of compander technology (Figure 10), with demonstrated powers up to approximately 8 MW. This proven technology can be applied to FLNG applications directly, with no need for further scale-up. For train capacities over 0.7 to 1 MTPA, the refrigeration loads are large enough to require parallel companders.

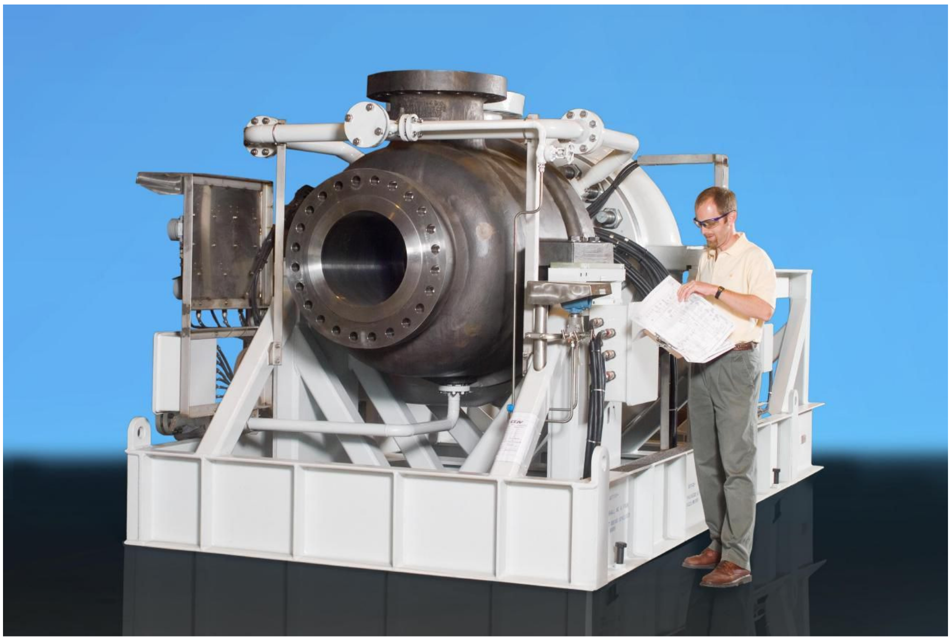

Figure 10 One of 24 AP-X® companders built for the six plants in Qatar

The Air Products compander design includes several features that are attractive for both FLNG and land-based applications. Bi-directional dry gas seals are used to minimize the loss of refrigerant to the atmosphere. High capacity oil thrust bearings allow application of a simple, intrinsically safe, passive thrust balance arrangement. Our testing facility can provide full-speed testing of all compander designs. Full-load testing can be performed either at our facility, or an outside facility, depending on the size.[5]

6 MOTION EFFECTS

An FLNG vessel in operation is subject to the motion of the sea. Stability control systems and vessel design are used to minimize, but do not eliminate, the consequent motion of the process decks. The motion and resultant acceleration can affect the flow of process liquid in the equipment.

The feed gas to be liquefied in a CWHE flows through the exchanger tubes, and the refrigerant flows through the shell in countercurrent direction. The tubes are each less than an inch in diameter. Because of the small dimensions, vessel motion does not have a significant effect on tubeside performance. For the Mixed Refrigerant cycles, the refrigerant is introduced to the shell at the top of the coil wound bundles. The exchanger has an internal liquid distributor to ensure that the refrigerant is distributed uniformly over the process tubes. The liquid refrigerant then flows downward over the tubes and boils to absorb heat from the feed gas. When the exchanger on an FLNG vessel undergoes motion, the distribution of liquid can change as the refrigerant flows downward, which can affect heat transfer.

Over the last 15 years, Air Products completed a rigorous analysis of the effect of tilt and oscillatory motion on wound coil exchanger performance. The analysis focused on liquid distribution on the shell-side of the exchangers and the effect on heat transfer performance. This work included fundamentally-based experiments, pilot scale test units, and dynamic simulation.

Fundamental Experiments

The fundamentally-based experiments investigated the flow of hydrocarbons across the tubes in a CWHE to quantify the flow behavior under various motion conditions. The experiments characterized the distribution of liquid flow over the outside of the tubes at various tube inclinations and tube spacing. Experiments were also performed to assess the effect of simultaneous vapor flow on the liquid distribution.

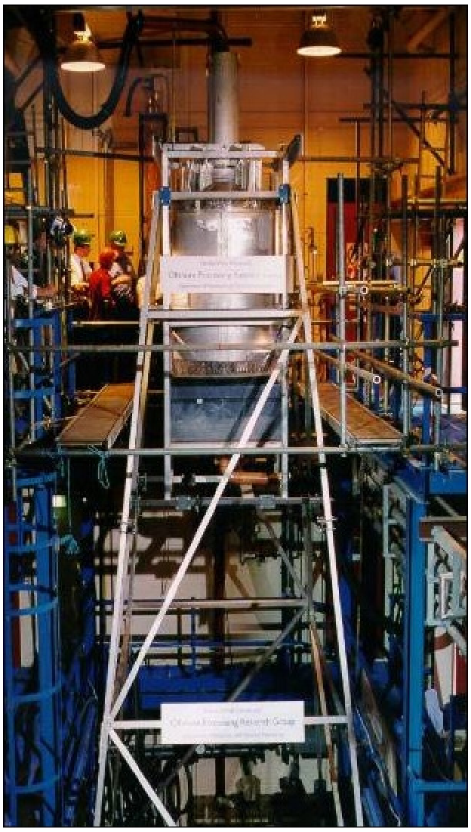

Figure 11 Pilot scale bundle for motion tests

Liquid Distribution Model and Pilot Scale Data

The experimental results were used to develop a proprietary model which predicts the shell-side liquid distribution as a function of heat exchanger geometry, motion conditions, elevation of the heat exchanger above the pivot point, and process conditions.

The model was validated in a pilot scale wound coil exchanger bundle. (Figure 11) This data was collected under various motion conditions, including both oscillations and permanent tilt. Flow distributions predicted by the model agree very well with the pilot scale data. Figure 12 shows the liquid distribution at an elevation in the bundle, as a function of circumferential position. The exchanger bundle is tilted, which causes an increase of liquid flow over the low side of the bundle. The Air Products proprietary model is able to accurately predict motion effects such as this.

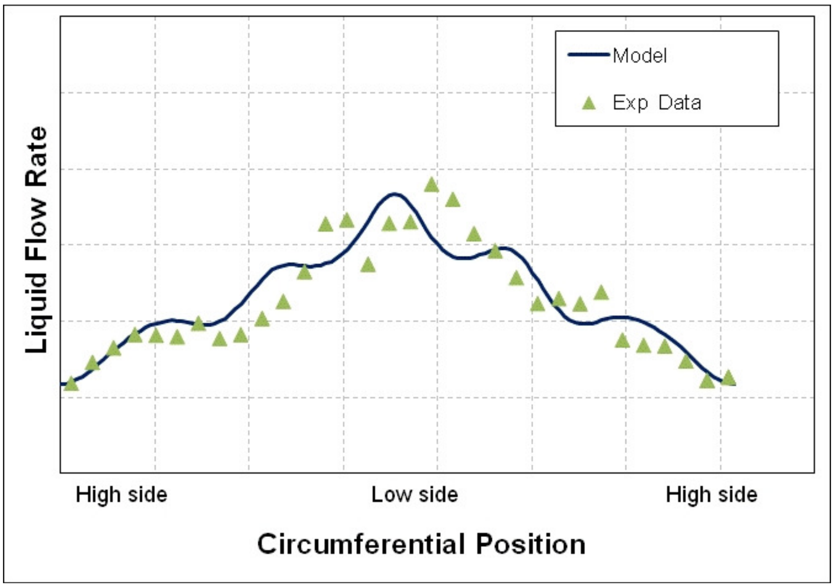

Figure 12 Experimental and predicted liquid distribution in tilted bundle

Exchanger Design

The final step incorporates the effects of shell-side flow distribution into Air Products' well established heat exchanger design methods. Air Products can use the computer models to predict the performance of a given design, when subjected to a specific level of motion. The design can then be adjusted to eliminate the effect of motion on the overall heat transfer performance. Note that if the vessel motion is larger than that considered in the process design, the process will still perform, but efficiency or production may be reduced.

CFD

Air Products has also used computational fluid dynamics (CFD) to assess the impact of motion on the hydraulic behavior of the internal distributors and separators in the CWHE. CFD has been used to model the sloshing dynamics and to assess the force amplification that may occur in areas where the resonant frequency is close to the motion frequency. Results demonstrated that the resonant period is much less than the ship motion period, indicating that the current design of the internal distributors and separators are suitable for FLNG applications.

7 SUMMARY

In summary, Air Products has developed efficient liquefaction processes and robust equipment for FLNG. This development builds on the many land-based successes and utilizes many years of research and development on the marinization of equipment for ship-board use. A wide variety of process cycles have been developed, with a range of equipment selections, refrigerants, process efficiencies, and other features to meet the particular needs of an opportunity. The Air Products coil wound heat exchanger offers exceptional mechanical strength and performance, and a detailed analysis and testing program has proven the ability of the mechanical design of the CWHE to meet the demanding conditions of FLNG service. For cycles using non-flammable nitrogen refrigerant, Air Products has developed large-scale companders with high efficiency and mechanical reliability. Finally, a rigorous research program spanning 15 years has provided the ability to predict and compensate for the effects of vessel motion on the CWHE performance in FLNG service.

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