All aboard the mega-train

Mark Roberts, Jeremy Beard, Chris Ott and William A. Kennington, Air Products and Chemicals, Inc., USA, look at advancements in LNG mega-train process technology.

It has been over 10 years since the six 7.8 million tpy large capacity liquefaction trains in Qatar were commissioned.[1] These projects represented a step change in single train liquefaction capacity from the prior maximum of 5 million tpy, and took advantage of economies of scale to lower unit production costs. This capacity increase was enabled by the new AP-X® LNG process technology, as well as new developments in turbomachinery and other equipment.

Recently, there has been renewed interest in large capacity trains and their potential unit cost reduction. Since the development of the original AP-X trains, however,

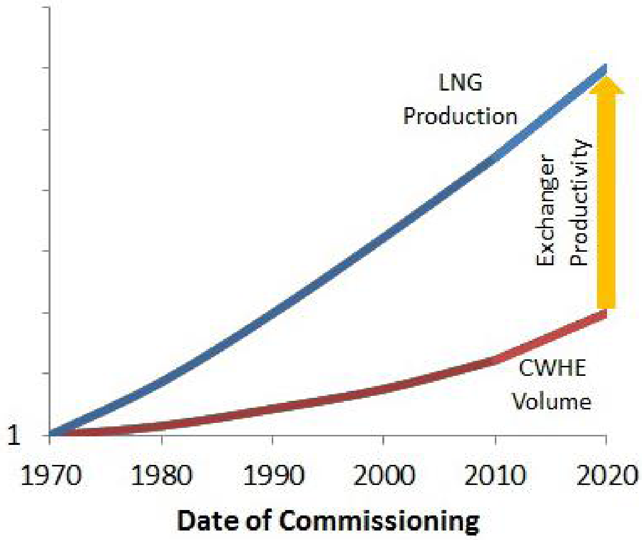

Figure 1. Exchanger productivity.

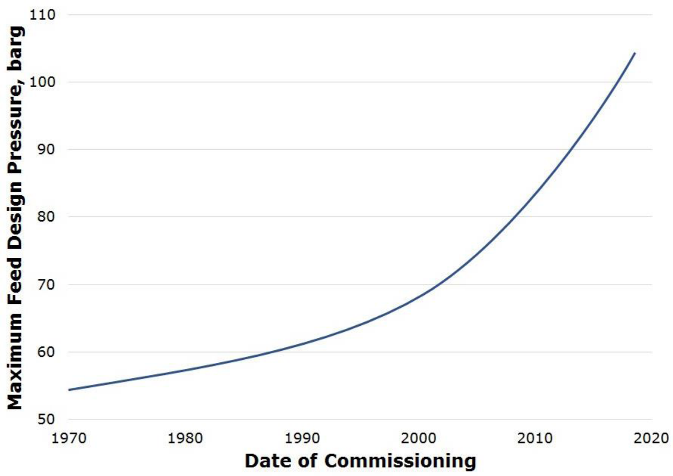

Figure 2. Increased feed pressure.

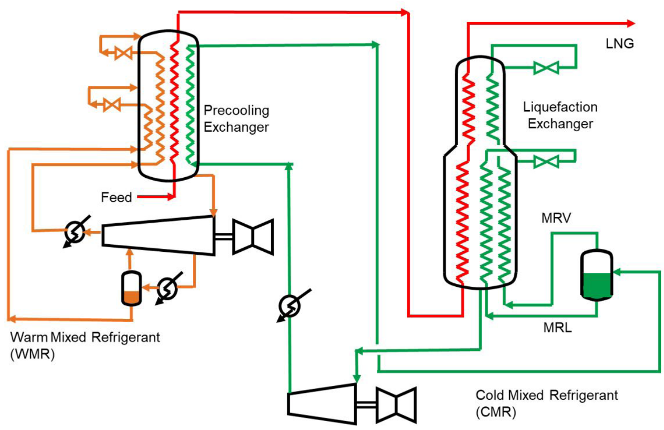

Figure 3. AP-DMR™ process with equal drivers.

there have been significant advancements in gas turbines, compression, coil wound heat exchangers (CWHEs) and other technologies. These advancements in LNG process technology enable new equipment arrangements for AP-X, AP-DMR™ and AP-C3MR™ technologies that offer benefits in liquefaction train availability, equipment count and operating cost.

Key process technology advancements

Larger capacity CWHEs

CWHE sizes have grown to meet market demands over the years for larger and larger LNG train sizes. Since the first CWHEs were delivered in the late 1960s, diameters have increased by 40%, volumes have tripled and weights have quadrupled. To keep up with projected market needs for even larger train sizes, continued growth in exchanger size is imperative. This required Air Products to build a new CWHE manufacturing facility with manufacturing equipment and infrastructure to handle larger and heavier CWHEs. In addition to this, it was strategically located immediately adjacent to a deepwater port in Manatee County, Florida, US, with accommodations to ship CWHEs by either a barge or a geared heavy lift vessel. Air Products' Port Manatee manufacturing facility began production in 2014, shipped its first CWHE in 2016, and has shipped several more since then, and one of those CWHEs has been in successful operation for over two years. This new facility allows fabrication and shipment of CWHEs up to 6 m in diameter and 60 m in length.[2]

Increasing exchanger productivity

Figure 1 shows how single train LNG production has increased over time, along with increases in CWHE volume. In a simple scale-up, one would expect that these variables would remain proportional. This plot, however, shows that the increase in production has outpaced the increase in exchanger volume, with the gap being made up by increasing exchanger productivity.

Increased feed pressure

One way of increasing single exchanger productivity is by increasing feed pressure. Increasing feed pressure allows for increased production without increasing the refrigeration power or refrigerant flow required. While the exchanger design must be modified to allow for the higher feed pressures, higher production rates can be achieved without an increase in exchanger volume. Figure 2 shows the evolution of liquefaction designs (including CWHEs) to accommodate higher feed pressures and enable increases in capacity.

Shifting refrigeration duty

Another way to increase single liquefaction exchanger productivity is to shift refrigeration duty. This can be done in two ways: by precooling deeper, thus decreasing the temperature of the fluid entering the main cryogenic CWHE (MCHE); or by increasing the temperature of the LNG exiting the MCHE. Both of these approaches decrease the refrigeration duty of the exchanger, allowing for higher throughputs.

Decreasing the inlet temperature

The AP-DMR process may be designed to efficiently shift heat duty from the MCHE to a precooling CWHE (PHE) by reducing the PHE outlet temperature. The process can be configured to efficiently provide precooling to a temperature of approximately -70°C by employing a two-bundle CWHE for precooling, as shown in Figure 3. The use of this precooling configuration results in high overall efficiency with a 50:50 precooling to liquefaction power split, allowing the use of identical gas turbine drivers for both services. With the deep precooling resulting from the 50:50 power split, for floating LNG (FLNG) applications, the cold mixed refrigerant can be fully condensed with only a small power penalty, eliminating the cold mixed refrigerant separator and reducing cost and plot space. Additionally, since the precooling refrigeration is supplied at a single pressure, the need for multiple precooling exchangers in series is eliminated, further minimising plot space.

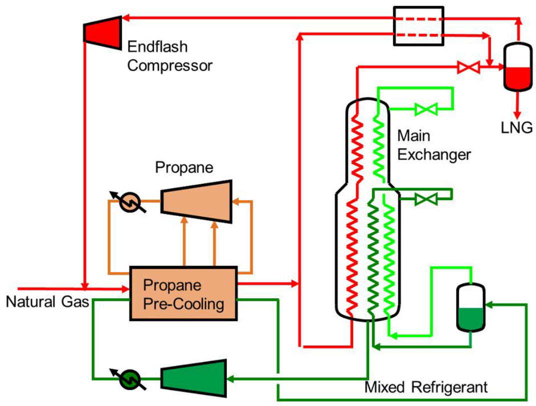

Figure 4. AP-C3MR™ process with end flash recycle.

Increasing the outlet temperature

Increasing the outlet temperature from the MCHE can debottleneck the exchanger, allowing increased production from the train while minimising specific power. Two proven methods for doing this are through recycling end flash and nitrogen subcooling.

Increasing the outlet temperature of the MCHE results in additional flash gas being formed when the LNG pressure is reduced to the storage tank pressure. Additional flash gas beyond what is required for plant fuel requirement can be warmed in an end flash exchanger, and then compressed and recycled to the feed using an end flash compressor as shown in Figure 4. Recycling end flash shifts power from the mixed refrigerant system to the end flash compressor. This debottlenecks the MCHE by reducing the amount of subcooling required, allowing for increased throughput.

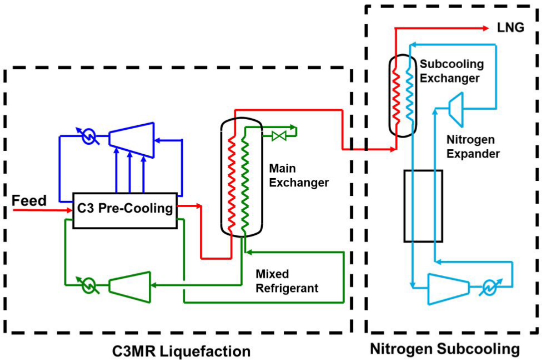

Figure 5. AP-X® process.

Air Products' AP-X liquefaction process, shown in Figure 5, employs a reverse Brayton nitrogen subcooling cycle to shift the entire subcooling duty to a separate nitrogen refrigeration loop. It employs the C3-MR cycle for precooling and liquefying natural gas. The LNG then enters the nitrogen expander cycle at approximately -115°C, where it is subcooled to a final temperature of -150°C. By using a separate cycle for LNG subcooling, the mixed refrigerant system is debottlenecked, reducing the mixed refrigerant flow by 40% per unit LNG produced.

The first AP-X trains, commissioned over a decade ago, had design capacities of 7.8 million tpy. Combining the AP-X cycle with currently available CWHE and machinery advancements enables LNG trains with production capacities of over 10 million tpy.

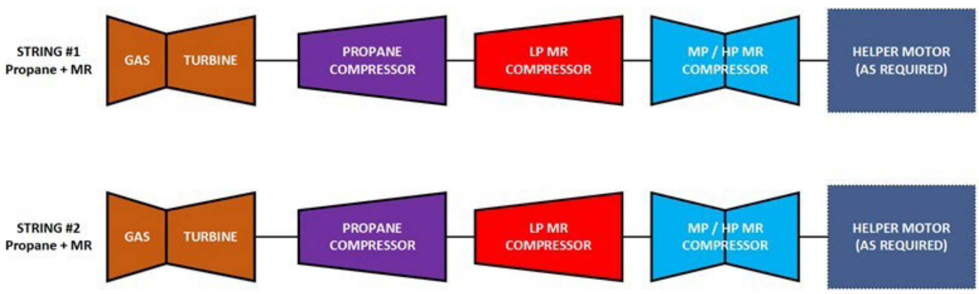

Figure 6. Parallel large gas turbine drivers for C3MR process.

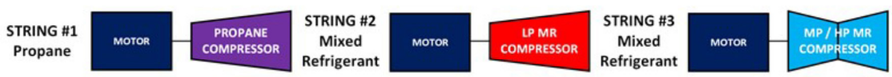

Figure 7. AP-C3MR configuration for electric motor drives.

Table 1. Recent large scale LNG train studies

Study	Cycle	Capacity (million tpy)	Driver configuration	End flash recycle	Feed pressure (Bara)	Climate
A	AP-C3MR	7.0	Parallel multi-shaft hybrid gas turbines	Yes	91	Warm
B	AP-C3MR	7.0	Parallel electric motors	Yes	88	Warm
C	AP-C3MR	6.7	Parallel aeroderivative gas turbines	No	82	Temperate
D	AP-DMR	7.1	Electric motors	Yes	95	Temperate
E	AP-X	7.8	Single-shaft heavy duty frame turbines	No	71	Hot
F	AP-X	8.7	Multi-shaft heavy duty frame turbines	No	83	Hot

Key machinery technology advancements

Along with process innovations that allow single train production beyond 5 million tpy, advancements in machinery technology and configurations also enable larger single train capacities.

Larger refrigeration compressor drivers

BHGE Frame 9E gas turbines were first used for mechanical drive service for the original six AP-X trains in Qatar. Since then, other driver options have become available for mechanical drive service.

One of the technology developments that has become available since the commissioning of the original AP-X trains is the use of multi-shaft gas turbine configurations for heavy duty frames in mechanical drive. The multi-shaft options offer several advantages, such as the following:

- Large helper motors are generally not required.
- Compared to single shaft gas turbines, multi-shaft gas turbines can be started under load, reducing or eliminating the need for flaring/loss/recovering of refrigerant components upon restart.
- Multi-shaft gas turbines offer the option of using a wide speed control range for additional process control and turndown capability.

Parallel compression

In scaling up the liquefaction process, refrigerant compressor aerodynamic and mechanical design considerations can become limiting. Specifically, compressor flow coefficients and Mach numbers may be beyond proven or feasible ranges. One solution to this problem is to use parallel compressor strings to remove aerodynamic constraints in the refrigerant compressors. With current gas turbine models available, two gas turbine driven compressor strings in parallel can provide enough refrigeration to produce approximately 6 million tpy of LNG while staying within referenced compressor design parameters. A parallel compression configuration for the AP-C3MR process is shown in Figure 6. This parallel driver configuration is now proven in operating AP-C3MR LNG plants with the successful commissioning of the Yamal[3] and Dominion Cove Point LNG facilities in 2017 and 2018.

Parallel compression can offer several other advantages to an LNG facility. One advantage of the compressor arrangement shown in Figure 6 is that as the power split between propane for precooling and MR for liquefaction changes because of changing process conditions, such as ambient temperature, load is automatically shifted between the MR and propane compressors to ensure the driver power is fully utilised. This is particularly useful in colder climates where the seasonal variation of ambient air temperature is large.

Electric motor drive

One final area of development to consider in refrigeration compression driver technology is the installation and commissioning of large electric motor drives for baseload LNG facilities. The largest electric motor drives in the LNG industry have recently been commissioned at the Freeport LNG facility. The AP-C3MR electric motor drive configuration is shown in Figure 7.

Recent mega-train examples

In recent years, there has been increasing interest in large trains, and Air Products has completed several studies on large 6 million tpy plus LNG trains in conjunction with engineering companies and facility owners.

All of the examples in Table 1, except for study 'E', require the enhanced capabilities of the Air Products CWHE manufacturing facility in Port Manatee, Florida. These studies show that advancements in process, CWHE and machinery technologies, as well as use of higher feed pressures, end flash recycle, and new compression driver configurations, have enabled significant increases in LNG train capacities. **LNG**

References

1. HAOURAI, A., 'Successful Start Up of QG Mega LNG Trains', 20th World Petroleum Congress, Doha, (2011).
2. SZATKOWSKI, A. and BUTLER, C., 'Coiled and Ready for Higher Capacity', *LNG Industry*, (April 2017), pp. 35 – 40.
3. 'Joint-Venture Makes Successful Contribution to Yamal LNG's First Cargo', *LNG Industry*, (April 2018), https://www.lngindustry.com/liquid-natural-gas/06042018/joint-venture-makes-successful-contribution-to-yamal-lngs-first-cargo/

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