

Expanding nitrogen at sea

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processes suitable for floating LNG.

There are many challenges when designing a floating LNG (FLNG) vessel. A process designer will divide these challenges into three main categories. The first category concerns the size and weight of each piece of equipment because these have a more significant impact on the overall project economics for a floating plant than they have for a land-based plant. Consequently, the liquefaction cycle selection will have to consider the production capacity and equipment count for each train.

The second challenge involves the vessel motion due to wind and waves. The mechanical design of the equipment will need to account for these added stresses,

and the process design will need to consider possible effects of the motion on two-phase fluid flow.

Finally, the inventory of flammable material is a concern for a seagoing vessel. Due to space limitations, it is difficult to provide separation between the process areas and living quarters. For some owners, liquid propane inventory causes particular concern due to its combination of volatility and heavy vapour.

These three challenges can be addressed by choosing the appropriate liquefaction process cycle and using robust equipment. The choice of process cycle is important, since it determines the equipment

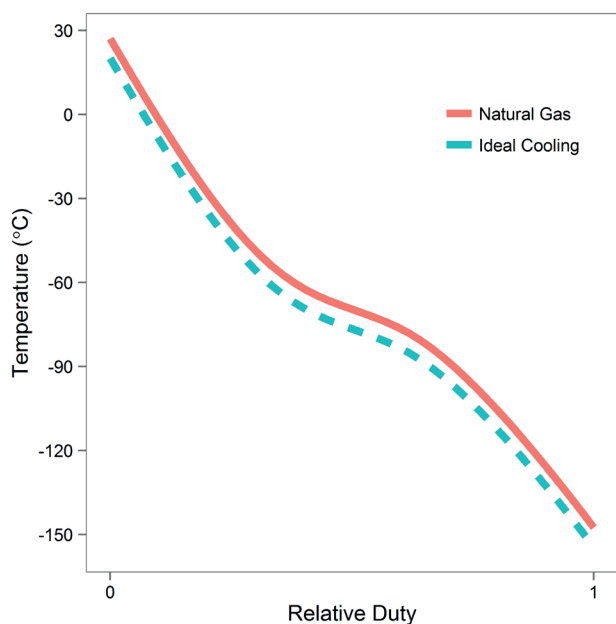


Figure 1. Ideal cooling curve.

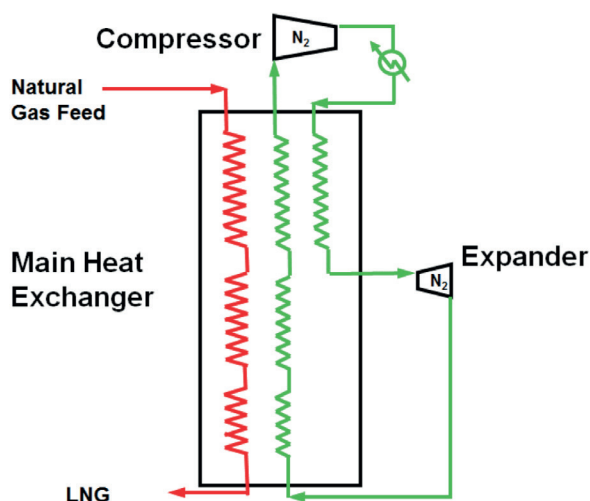


Figure 2. Standard nitrogen cycle.

Table 1. Air Products' natural gas liquefaction processes for FLNG applications				
Process	Relative efficiency	FLNG train capacity (million tpy)	Type of refrigerant	Feature
AP-DMR	1	3 – 4	Boiling hydrocarbon mixture	High capacity
AP-SMR	0.88	<2	Boiling hydrocarbon mixture	Simple layout
AP-N	0.72	<2	Gaseous N ₂	Non-flammable refrigerant

requirements for a large section of the FLNG facility and will have a great impact on the overall vessel design.

There are a number of liquefaction process cycles that are suitable for FLNG application.¹ These include the AP-SMR™ single mixed refrigerant process, the AP-DMR™ dual mixed refrigerant process and the AP-N™ nitrogen recycle process. Some key features of these processes are summarised in Table 1. The AP-SMR and AP-DMR processes utilise hydrocarbon refrigerants and have been presented previously in *LNG Industry*.²

Comparing liquefaction processes: cooling curves

Process engineers often use cooling curves as one measure to optimise and compare liquefaction processes. An ideal cooling curve is given in Figure 1. The horizontal axis for this plot is the fractional amount of duty removed from the natural gas. The vertical axis is the temperature of the process stream. In Figure 1, the feed stream is the hot side; the natural gas stream and its temperature is shown by the red solid line. The refrigerant stream temperature, which is the cold side of the main exchanger, is shown by the blue dashed line.

For the process given in this example, the natural gas enters the exchanger as a gas at ambient temperature. At first, sensible heat is removed from the natural gas and the resulting cooling curve is relatively straight and the slope is proportional to the heat capacity of the feed gas. After the dew point is reached, the slope flattens and the feed liquefies as latent heat is removed from the natural gas. Once liquefied, the change in natural gas temperature increases as sensible heat is removed to subcool the LNG.

The blue dashed line is an ideal cooling curve for an ideal refrigerant system, or combination of systems. It is considered as ideal because the shape of the curve closely follows that of the natural gas cooling curve. The temperature difference between these two curves are related to the efficiency of the process. For a given liquefaction process, the closer these curves are to each other, the more efficiently refrigeration is supplied to the natural gas, reducing the refrigerant compression power requirement. Also, the closer these curves are to each other, the more heat exchanger surface area is needed. For a given process, the optimal heat exchange surface area and compression power is determined by the project specifics and the trade-off between CAPEX and OPEX.

Cooling curves can also be used as an aid in liquefaction cycle development by identifying areas for improvement, and to compare liquefaction cycles.

Nitrogen recycle expander process

The nitrogen recycle expander process is based on a Brayton refrigeration cycle, which uses gaseous nitrogen as refrigerant. The simplest nitrogen expander cycle has only one expander, as shown in Figure 2. In this process, nitrogen is compressed to high pressure and heat is rejected into the

atmosphere through the compressor intercoolers and aftercooler. The refrigerant is further cooled in the main cryogenic heat exchanger (MCHE) and then expanded to cryogenic temperature in a turboexpander. Once expanded, the nitrogen enters the cold side of the MCHE, where it pre-cools, liquefies and sub-cools the feed, as well as initially cools the warm nitrogen. After leaving the MCHE, the low pressure refrigerant returns to the compressor suction.

The cooling curves for this process are given in Figure 3. In this figure, the hot side temperature, shown in red, is the temperature of the natural gas feed as it is pre-cooled, liquefied and sub-cooled. The curvature in temperature line is due to the latent heat removal from the condensing mixture. The temperature profile for the nitrogen, cold side, is straight without any curvature. This is because warming of the cold nitrogen vapour is all sensible heat as there is no phase change.

The bend in the nitrogen line is where the 'hot side' nitrogen exits the main exchanger and enters the expander. Notice that the difference between these two cooling curves changes through the exchanger. The larger gaps show that there is underutilised refrigerant, which translates to inefficiencies in the process or, conversely, represents room for process improvements.

This standard process is simple with minimal equipment. It is often used in small plants, such as peak shavers where the production is only a few hundred tons per day.³ However, as this process is scaled up to capacities relevant for FLNG, it becomes less simple, since the expander duty will increase to the point where multiple units in parallel will be needed, as well as their associated piping. In addition, the number of brazed aluminium heat exchangers will increase such that multiple cold boxes and the associated piping will be required.

Another factor to be considered is thermal stresses on the heat exchange equipment. The cold side of the exchanger will have cryogenic liquid and the hot side will have cryogenic vapour. During upset conditions it will be quite easy to get an imbalance in duty, creating large thermal gradients in the exchanger because the refrigerant flow is independent of the natural gas feed flow. The likelihood of these gradients occurring also increases with the size of the piping system and number of cores and cold boxes in parallel. Coil wound heat exchangers have years of operating experience, demonstrating that they can withstand these stresses. In addition, the process tube bundles in the coil wound heat exchanger are enclosed within a pressure vessel shell, providing an additional level of containment in the unlikely event of a leak due to maloperation.

Case study

Two FLNG projects that are in construction, Petronas FLNG *Satu* and Petronas FLNG *Dua*, will use the AP-N liquefaction process.

For these large capacity liquefiers, the patented AP-N liquefaction process⁴ takes advantage of the multiple expanders required and coil wound exchangers to improve the robustness and efficiency of the process for FLNG service. As shown in Figure 4, the natural gas, shown in

red, is liquefied in a coil wound exchanger. The gas is pre-cooled in the top section (often termed 'bundle'), liquefied in the middle section and, lastly, sub-cooled in the bottom section. Those familiar with the use of coil wound heat exchangers in land-based mixed refrigerant (MR) cycle plants will notice that the coil wound heat exchangers for the N₂ cycle are 'cold end down' rather than the typical 'cold end up' configuration. This is because the refrigerant, being all vapour, does not need to make use of gravity as in processes where the warmed refrigerant condenses to a liquid. The nitrogen economiser, which has nitrogen vapour on both the hot side and cold side, can be brazed aluminium exchangers, since the fluids are all gas phase and the hot and returning cold flow are inherently balanced.

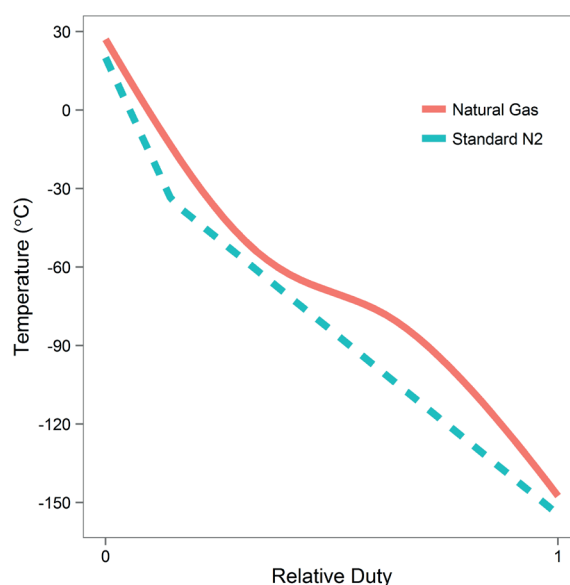


Figure 3. Cooling curves for standard nitrogen cycle.

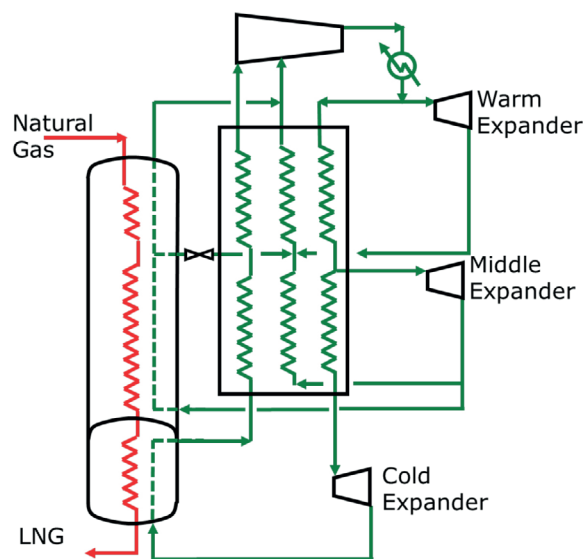


Figure 4. AP-N liquefaction process.

Instead of simply scaling up the standard nitrogen process by placing the three expanders in parallel, they are arranged to optimise the cooling curves for both the liquefaction exchanger and the economiser exchangers. The cooling curve for the AP-N liquefaction cycle is given in Figure 5. The arrangement of the expanders allows for two bends in the refrigerant cooling curve, such that this refrigerant curve follows more closely with the feed cooling curve, creating a more efficient process.

One expander is used on warm nitrogen to provide precooling refrigeration and another larger expander is used on colder nitrogen to provide the refrigeration for the liquefaction. The third remains on the coldest nitrogen to provide refrigeration for subcooling.

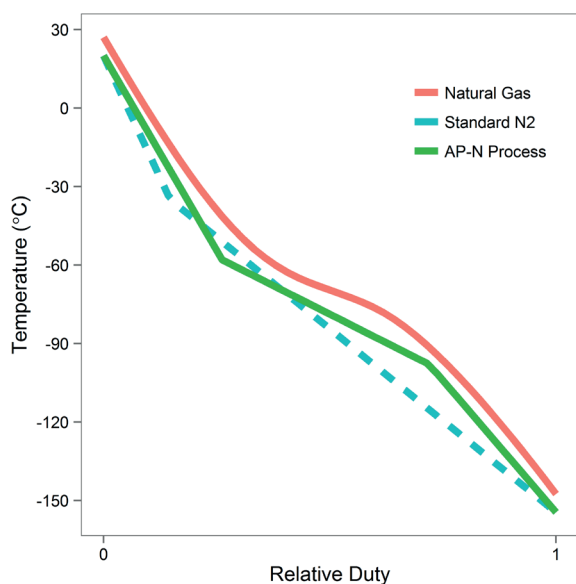


Figure 5. Cooling curves for AP-N liquefaction process.



Figure 6. Turboexpander for FLNG service.

Turboexpanders

The expander arrangement in the AP-N liquefaction process is such that each has a separate refrigeration duty. Although not shown in Figure 5, the work generated by the expanders is used to provide the final stage of compression in a parallel compressor arrangement. This arrangement requires that the expander-compressor (compander, Figure 6) units work harmoniously together while providing the individual adjustability to properly balance and regulate the refrigeration for each service. Therefore, the compander design team must work closely with the process engineering team to ensure that the companders will be able to provide the required refrigeration and compression, as well as the operational flexibility and durability required for all steady state and transient operating conditions.

As with all shipboard equipment, there are challenges and trade-offs with respect to weight, deck space, maintainability, operability and reliability. The Air Products compander design package utilises rugged oil bearing technology and robust passive thrust balancing systems to enhance reliability and limit operational constraints for a compact, robust and maintainable package.

Conclusion

There are additional challenges when designing an LNG plant for floating applications. A number of liquefaction processes are available (each with their own unique features) to address these challenges. AP-SMR and AP-DMR are efficient liquefaction processes that use boiling hydrocarbon refrigerants. The AP-N liquefaction process uses a non-flammable single-phase refrigerant and the rotating machinery is highly integrated for increased efficiency. One similar aspect of each of these three processes is that the natural gas is liquefied in a robust coil wound heat exchanger for safety and reliability. All are suitable for floating plant service and each has its own attributes, which project developers may find attractive for their specific application. **LNG**

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