History of the Development of LNG Technology

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Introduction

Liquefied Natural Gas (LNG) started in the USA as a peak-shaving measure. International interest in transporting LNG across the ocean for energy utilization soon developed. Baseload LNG plant capacity has expanded from about 1.0 MTPA to a 4.0 MTPA and recently, up to 7.5 MTPA. The compressor drivers have increased from Frame-5, to single Frame-6 & Frame-7 and now, Frame-9s.

The drivers have evolved from steam to gas and electrical, or a combination of them. There have also been the challenges of using plate-fin heat exchangers versus spiral wound exchangers, coupled with the development of cascade, mixed refrigerant, expander cycles and various hybrids of them.

New energy-saving developments across the LNG value chain include the use of cryogenic liquid expanders, larger LNG storage tanks, and bigger LNG ships with alternate propulsions. New concepts include floating LNG plants, Gravity Based Structures (GBS) and floating LNG receiving terminals. There is also Energy Bridge, reduction of Greenhouse Gas (GHG) emissions, etc.

This paper addresses the development of LNG technology in the transportation and utilization of natural gas in the 21st century [1, 2].

Early Development

Cryogenic industry has its early start since Dr. Carl von Linde developed air and gas separation technologies in the nineteenth century in Munich, Germany. The LNG industry started its early development by using LNG technology for natural gas peak shaving. Peak shaving is a strategy used by the power industry to store natural gas for peak demand that can not be met by their typical pipeline volume. Utility companies liquefy natural gas during low demand and re-gasify it during peak demand to augment available supply.

Cascade cycle was used in LNG plant in the beginning. Later, A. Klimenko presented the mixed refrigerant concept [3] at the LNG-1 Conference. Air Products applied its all mixed refrigerant cycle in the Libya Marsa El Brega LNG plant. Afterwards, Air Products improved it with the propane precooled mixed refrigerant (C3-MR) cycle, which is being used in more than 80% of the LNG plants globally.

Phillips Petroleum invented the cascade liquefaction cycle [4]. This cascade cycle is a closed loop cycle of propane, ethylene, and methane refrigerants. Interestingly, at the time the C3-MR cycle was built in Brunai LNG plant, the cascade cycle was built for Kenai LNG plant in Alaska and Prichard's all MR cycle was built later in Africa. A newer version of Phillips open loop cascade cycle has been built in Trinidad and several other places such as Egypt, Darwin, and Equatorial Guinea.

Early contributors to LNG industry include Lee Gaumer and Chuck Newton who invented the all mixed refrigerant cycle [5] and the C3-MR cycle [6] for Air Products LNG process. The Wilkes Barre cryogenic facility has manufactured the coil wound LNG Main Cryogenic Heat Exchangers (MCHE) since late 1960s. Ludwig Kniel of Lummus invented a cascade cycle and regasification plant synergy with ethylene plant. Ludwig introduced a nitrogen expansion cycle as a subcooling section for LNG process [7].

Dr. C. M. "Cheddy" Sliepcevich pioneered and managed the research, development and implementation of the first commercial process for liquefaction and LNG ocean transport during his work with Chicago Stock Yards and Continental Oil Company, at the University of Oklahoma [8, 9]. For his pioneering research in LNG technology, Cheddy – also referred to as the "Father of LNG", received the Gas Industry Research Award by the American Gas Association Operating Section in 1986 in Seattle. The award, sponsored by Sprague Schlumberger, honored his scientific achievement in LNG research and his contribution to LNG safety. Some of his students, Dr. Hardi Hashemi, Dr. Harry West and Dr. Jerry Havens have further developed his work in LNG safety [10, 11].

Developments in Drivers and Coolers

In the beginning, steam turbines were preferred for LNG plant application because of its prevalence in the oil refineries. Steam turbines were applied at Bontang LNG plant in Badak, Brunei and Das Island LNG plants. Later it was discovered that gas turbines can be more economically applied in LNG plant and therefore new LNG plants started using gas turbines.

Compressor and gas turbine drivers adapted from the electrical industry were the first on the scene. Thereafter, the Frame-5 was redesigned with a split-shaft configuration suitable for mechanical service driver service. This change underlie the shift from GE Frame-5 split-shaft turbine to GE Frame-6, Frame-7 and recently Frame-9 single shaft gas turbines, with power range of 30 to 123 MW. These large turbines are driving large axial and centrifugal compressors. Also, LM-2500 aero-derivative gas turbines have been used in the direct drive application at the Darwin LNG plant in Australia, and the LM-6000 have been used to generate electricity to drive the electric motors which in turn, drive the compressors. This has influenced the application of all electric drivers for more LNG plants in the future.

As the gas turbine drivers are being improved, the water cooled exchangers have been changed to ambient air cooled heat exchangers. This is attributed to two factors: one is the concern over water temperature changes and secondly, due to simple and more efficient usage of large ambient air cooled exchangers.

Heat Exchangers for Liquefaction

Heat exchangers used in LNG are classified into the coil wound heat exchangers and the plate-fin core exchangers.

Coil wound heat exchangers have evolved from smaller sizes to about 15 feet diameter and approximately 200 feet in height and weighs up to 300 metric tons, including thousands of tubing capable of holding internal pressure up to 1,100 psig. Currently Air Products and Linde manufacture this kind of cryogenic heat exchangers, and it can take up to 25 months to complete one exchanger.

Plate-fin exchangers are manufactured by several vendors and are much cheaper than the coil wound heat exchangers. Variations include core-in-kettle exchangers. These exchangers are manufactured by vacuum brazing the aluminum components into the whole exchanger and require shop testing for high pressure performance.

Liquefaction Cycle and Economies of Scale

Phillips Petroleum developed the close loop optimized LNG cascade cycle and improved it in the early 90s to what is known today as the open loop process cycle. For mixed refrigerant cycle - there is the Pritchard Prico cycle, and Air Products all MR and C3-MR cycles. There are also other cycles by some French companies. Conoco Phillips' optimum cascade cycle can be built in large LNG plants up to 8+ MTPA [12]. This process is being used in LNG plants built in Darwin, Egypt and Equatorial Guinea and will be used in the Angola LNG plant.

There have been tremendous developments in liquefaction technology in recent years. In mixed refrigerant cycle, there is the single mixed refrigerant cycle and double mixed refrigerant cycles developed by Shell. Shell also developed the Parallel MR cycle [13], which utilizes the split casing propane compressor arrangement. The Axen's Liquefin cycle, is essentially a dual mixed refrigerant cycle. Air Products has developed the AP-X™ cycle to plant capacity up to 8+ MTPA [14]. Linde and Statoil invented the mixed fluid cascade cycle which is being applied to the Snohvit LNG plant in the Arctic region of Norway [15].

All electric drive configuration is being used in Snohvit LNG to increase overall liquefaction efficiency. Furthermore, cryogenic liquid expanders are now commonly used in liquefaction processes to increase liquid production.

LNG Ships

Newer LNG storage tanks of 160,000 M^3 are in use. In the near future 200,000 m^3 tanks will be deployed above ground. Similarly, larger LNG ships called Q-Flex and Q-Max ships are being built and deployed. The Q-Max has the capacity for about 266,000 m^3 of LNG, with a length of 345 m, a breadth of 53.8 m, and a height of 34.7 m. These new vessels are expected to ship LNG to the US and Europe from Qatar.

Q-Flex LNG ships were previously the world's largest LNG carriers. The Q-Max vessels now feature slow-speed diesel engines that are more fuel and thermal efficient than steam turbine drivers, with a 30% reduction in overall emissions. It also reduces the shipping costs by 30%. Shipping by conventional vessels typically accounts for a third of the LNG price. High efficient propulsion systems and ship board re-liquefaction have helped to achieve further operational efficiencies and a reduction in greenhouse gas (GHG) emissions. 14 Q-Max and 31 Q-Flex LNG ships have been ordered.

Offshore FPSO and Receiving Terminals

There are exciting developments in the offshore liquefaction [16]. Offshore floating LNG studies were performed by Air Products in 1970s. Mobil published their work in 1998 with a moon-pool layout and used the single mixed refrigerant process. Shell is working on Greater Sunrise, offshore Australia and Kudu, offshore Namibia. Statoil and others have worked on Nnwa-Doro, offshore Nigeria, and several Japanese and French outfits have worked on various offshore LNG production schemes. Floating offshore LNG production can eliminate the flaring or re-injection associated with crude production if sufficient gas quantities are available. Recent developments have seen Flex LNG, SBM and Linde, and Teakay working with Mustang on floating LNG concepts.

An offshore LNG receiving terminal was constructed on a Gravity-Based Structure (GBS) and installed offshore Italy. ExxonMobil announced plans to seek regulatory approval for BlueOcean Energy, a floating LNG receiving terminal to supply natural gas to New Jersey and New York.

There are two different locations in America that use the Energy Bridge™ concept. One is the Gulf Gateway and the other is the Northeast Gateway. Excelerate Energy uses fleet of Energy Bridge Regasification Vessels (EBRVs) to dock to these offshore gateways, regasify LNG on board the ship and then transport the re-gasified natural gas onshore by pipelines.

Conclusions

Historically, development of LNG technology has responded to growing LNG demand with new innovation in liquefaction technology, coupled with energy integration of the LNG chain. In the near future, we can envisage an increase in global liquefaction capacity, LNG storage and LNG ship size. The sites for LNG liquefaction plants or receiving terminals will expand to include offshore.

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References

1. S. Huang, C.-H. Chiu and D. Elliott, “LNG: Basics of Liquefied Natural Gas”, A book published by *the University of Texas Continuing Education*, Petroleum Extension Service, Austin, Texas, 2007.
2. C.-H. Chiu and C. L. Newton, “Second Law Analysis in Cryogenic Processes”, *Energy*, Volume 5, Pergamon Press Limited, 1980.
3. A. P. Klimenko, *First International LNG Conference*, Chicago, April, 1968.
4. J. H. Hughes, US Patent 3,581,510, June 1, 1971. Also J. T. Karbosky and E. A. Harper, *US Patent* 3,408,824, November 5, 1968.
5. L. S. Gaumer, Jr, and C. L. Newton, *US Patent* 3,593,535, December 22, 1969.
6. G. E. Kinard and L. S. Gaumer, “Mixed Refrigerant Cascade Cycles for LNG”, *Chemical Engineering Progress*, January 1973.
7. L. Kniel, *US Patent* 3,362,173, January 9, 1968.
8. *The Norman Transcript*, “Endowed OU Professorship Honors Sliepcevich”, February 14, 1992. Also, *OU College of Engineering*, “Dr. C.M. Sliepcevich was elected to the Distinguished Graduates Society in 1993”, the Board of Regents of the University of Oklahoma.
9. *OKChE, Winter 1988-1989* by School of Chemical Engineering and Material Science, University of Oklahoma: http://cbme.ou.edu/alumni/okchearchive/OKChE_1988_Winter.pdf
10. H. H. West and C.-H. Chiu, “LNG Safety: An Issue of Increasing Importance”, *Process Safety Progress*, 24 (3), 2005.
11. J. Havens and T. Spicer, “LNG Vapor Cloud Exclusion Zones for Spills into Impoundments”, *Process Safety Progress*, 24 (3), 2005.
12. A. Avidan, W. Varnell and B. Martinez, “Study Evaluates Design Considerations of Larger, More Efficient Liquefaction Plants”, *Oil & Gas Journal*, August 18, 2003.
13. B. Pek, E. de Jong, A, van Driel and R. K. Nagelvoort, “Large Capacity LNG Plant Development”, *LNG 14 Conference*, Doha, Qatar. March 2004.
14. M. J. Roberts, Y.-N. Liu, J. C. Bronfenbrenner and J. M. Petrowski, “The AP-X™ LNG Process: A Flexible Approach for Reducing LNG Unit Cost”, *AIChE Spring Conference*, New Orleans, April, 2004.
15. W. Forg, et al, “A New LNG Baseload Process and Manufacturing of the Main Heat Exchanger”, *Reports on Science and Technology* 61, 1999.
16. C.-H. Chiu and L. D. Quillen, “A New Frontier! Offshore Natural Gas Liquefaction”, *Gastech 2008*, Bangkok, Thailand, March 2008.