What Every Energy Engineer Needs to Know about Thermodynamics and Liquefication Systems - Part 1

An Online Continuing Education Course for Engineers

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1. Learning Objectives

This course is the first in a 4-course series.

- Part 1 is based on understanding thermodynamic concepts and using pressure enthalpy charts.
- Part 2 builds onto Part 1 but uses thermodynamic software instead of pressure enthalpy charts for analysis and goes into additional depth.
- Part 3 (consisting of Parts 3A and 3B) builds on parts 1 and 2 to apply thermodynamics to understand air conditioning and refrigeration systems from ¼ hp size units to 300,000 hp size units. Part 3A focuses on pure substances and mixed refrigerant liquefaction systems. Part 3B focuses on nitrogen expansion liquefaction systems.

Note that each course in the series is a "stand-alone" course. It is not necessary to first complete Parts 1 and 2 to study Parts 3A & 3B, provided the learner already possesses the necessary prerequisite knowledge.

This course (Part 1) introduces the learner to natural gas's origins and the production of Liquefied Natural Gas (LNG). LNG is widely used around the world. It is a very compact form of natural gas in liquid form. It is used on very cold days to supplement gas coming from the interstate pipelines to supply gas load centers like New York, Boston, and other major load areas. Natural gas (essentially the same as vaporized LNG) is the cleanest burning fossil fuel as it contains the least amount of carbon of all the fossil fuels. Thus, many electric power plants now use natural gas or convert from dirtier fossil fuels to natural gas or vaporized LNG.

As part of this Part 1, an open expansion natural gas liquefaction system will be analyzed step-by-step to understand how it produces liquefied natural gas. The computations will use pressure enthalpy charts for methane.

This learning will focus on applying thermodynamics to understand liquefaction processes. A major part of this learning will be analyzing an open expansion natural gas liquefaction plant process, which applies all the learnings of this course.

2. A Safety Moment

This learning document is meant to be technical, mostly on refrigeration systems. The most important intention of every document I produce is to give you the basic technical knowledge that you need to start your study on how to continue to make the Liquid Natural Gas Industry a "Safe and Reliable Industry." You need technical knowledge to do that.

The image to the right reminds us that everyone has someone who loves and needs them to come home at the end of their shift.

Reliability is also related to safety. If the LNG plant cannot make LNG when needed, the consuming public may be out of gas during the worst cold weather, putting the public at a severe health risk.

As engineers, we need to ensure that our designs, plans, operations, and maintenance of LNG facilities help assure safety and reliability.

This will help ensure that everyone comes home at the end of their shift and that gas is supplied when needed by the end-user customers.

Figure 1: Beautiful Granddaughter
Source: Self-Made photo

3. Introduction

Two hundred years ago, ice was harvested from frozen rivers in the winter, and large chunks of it were stored in buildings insulated by large bales of hay and sawdust. During the spring and summer, that ice was consumed but those who could afford it, and once it ran out, there was no way to produce the heat extraction needed to make ice. The only source of that cold product was to wait for the winter weather to produce it!

In 1834, Jacob Perkins invented the first vapor compression system for refrigeration, and in 1876, Carl von Lined patented a new process for liquefying gases. Today, nearly every car and home is air-conditioned via various technologies; the most common is that of the vapor compression –

condensation – pressure drop evaporation system. This very same system is used in household refrigerators and massive liquefaction plants around the world. The massive systems used in LNG export facilities use the very same principles as most of the home refrigeration systems, except that some enhancements are used to make the large-scale systems more energy efficient. Also, the refrigerants needed to produce very cold temperatures are different from those used in the home air-conditioning and refrigeration systems.

We take for granted that when we want a cold soda, it is readily available from the refrigeration system in our house. The amazing thing is that the systems are so well perfected that typically, the only reason they are replaced is that they go out of style and not because they are malfunctioning. These systems run for many decades with little, if any, maintenance. One reason for these smaller systems being so reliable for so many years is that since the late 1920s these small-scale refrigeration systems have been hermetically sealed. That means the motor and compressor are in a sealed case without the need for shaft seals that could leak and without any possibility of refrigerant contamination.

Over the past 189 years, since Jacob Perkins invented the vapor compression refrigeration system, refrigerant technology has also developed significantly. In the 1800s, refrigerants were extremely toxic, and some were not efficient. These toxic refrigerants included ammonia, methyl chloride, and sulfur dioxide. Refrigeration systems were often installed outside to avoid death from a refrigerant leak.

I had chemical pneumonia for a month due to exposure to anhydrous ammonia from a small refrigeration system. Such exposures have killed many.

In 1928, halogenated hydrocarbons such as chlorofluorocarbons (Trade-named Freons) were invented. This revolutionized refrigeration, and various Freon compounds were developed for various temperature applications. However, in the late 1900s, as it became apparent that freons were harmful to the environment, legal restrictions were placed on the production, use, and reuse of Freons. Concurrent with the phasing out of older traditional Freons, newer refrigerants (hydrofluorocarbons, also trade name Freons) were introduced, such as R-134A for automobile applications and R-410a for home air conditioning applications. Even these refrigerants have environmental concerns associated with them, and newer refrigerants are under development.

For very low-temperature refrigeration systems (LNG production), Freons, cannot be used because they cannot achieve the very low temperatures needed to liquefy natural gas. Instead, mixtures of nitrogen, methane, ethane, propane, and iso-pentane are some of the most common refrigerant mixes used for attaining ~ -260° F. In a large size LNG production facility, the downside of these refrigerants is that tons of them are needed in these systems that cannot be hermetically sealed, and all but nitrogen are highly flammable. Any system that contains large quantities of pressurized flammable liquids and vapors poses a risk to the plant and its operators.

In this work, in Phases 1 and 2, we will start our study by understanding thermodynamics. Then, in Phase 3, we will apply this knowledge to include understanding simple systems like those in your automobile air conditioning system and your household refrigerator/freezer system. Finally, in Phase 3,

we will expand this learning to include understanding the ultra-large systems used to liquefy natural gas for export terminals (in the 300,000 hp range).

There are billions of small-size air conditioning/refrigeration systems in operation in the world today, but only a few hundred of the behemoth-size systems are used in the LNG Liquefaction Industry. There are many other gas liquefying industries, but we will limit our focus to understanding small simple systems and then learn about the larger systems used for liquefying natural gas.

Although the basic technology is the same between the small-size units and the large units, the complexity of the systems and the refrigerants used differs as the desired temperatures become colder and as the capacity of the units becomes larger.

If the outside environment is at 80 deg F, it takes little energy, and the technology is not complex enough to achieve the 35 deg F temperature needed to cool down a soda. If you want to store frozen food at 0 deg F, it takes more energy, but still, the technology is simple.

However, if the outside environment is 80 deg F, it will take a significantly large amount of energy and a more complex technology to achieve the ~ -260 deg F temperature needed to make Liquid Natural Gas (LNG). To achieve a temperature of ~ -424 deg F to liquefy hydrogen, the energy and technology required to increase many folds over that needed to make LNG. To take this to the extreme, liquid helium (the very coldest gas liquefied) can be produced at ~ -452 deg F and is extremely difficult and extremely power intensive. Keep in mind absolute zero temperature is -459.67 deg F.

To better respond to anomalies during plant operation, engineers need some understanding of thermodynamics. The thermodynamics presented in this publication are basic and based on application rather than theory. The cases studied are all steady-state (the properties of the fluid at any point do not change with time) and steady-flow (the flow rate does not change with time) type problems. All of the solutions are based on some simple calculations and or on the use of the pressure-enthalpy chart or thermodynamic software. A large-size pressure enthalpy chart for methane or thermodynamic software should be used in concern with this learning.

At the end of Phase 1, a thermodynamic overview of an open expansion gate station-type liquefaction plant process is studied. This open expansion plant overview study is not rigorous in that it is based on a simplified plant process without pressure drops, it does not take into account the pinch points of process heat exchangers, and it treats natural gas as a pure substance of 100% methane. Although this is not rigorous enough to depict the actual process, it serves the intent of this publication by exercising and reinforcing the concepts presented herein.

4. Cautionary Note

This document is intended to teach basic concepts. To accomplish this, it explains thermodynamic processes using a simplified approach.

Real plants have pressure drops, fluid velocity energy, head pressure due to elevation, unintended heat and mass leaks, etc., associated with flows through piping, exchangers, and other process equipment. Such effects are not taken into account in the simplified examples given herein. Parts of the plant, such as the CO_2 and water removal systems, were not included in the analysis because their study is outside the scope of this document.

Also, rounded-off numbers are often used throughout to allow the reader to focus on the concept and not get bogged down in numerical detail.

In this Phase 1 course, we will use a thermodynamic chart for methane for computations and illustrations. A separate copy of this chart accompanies this course to allow the learner to zoom in for better clarity and accuracy in reading the chart.

5. Facilities in the United States and Codes that Govern them

The Federal Energy Regulatory Commission (FERC) governs most permanent LNG facilities in the U.S. via the Federal Code of Regulations (code 49CFR193). This code requires the governed facilities to abide by the consensus code, National Fire Prevention Association (NFPA) 59A. Many countries around the world also conform to NFPA 59A.

The U.S. Pipeline and Hazardous Material Association (PHMSA) collects data on LNG facilities annually. According to PHMSA, the inventory of LNG facilities as of 10/1/2022 for the 2021 annual reporting year is as follows:

https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids

- 71 Peak Shaver (PS) LNG Facilities (48 with liquefiers)
- 23 Satellite (Sat) LNG Facilities (1 with liquefier – that is how it is reported)
- 26 Base Load LNG (liquefiers - not counted)
- 40 Mobile or temporary LNG facilities
- 8 Other LNG facilities
- Of the 94 Peak Shaver and Satellite LNG facilities, 44 (47%) facilities in the Northeast
- Of the 94 Peak Shaver and Satellite LNG facilities, 72(77%) 1960's – 1970's vintage
- Of the 48 PS and Sat in the Northeast U.S., 40 (83%) 1965 – 1975 vintage
- Of the 48 PS and Sat in the Northeast U.S, 12 (25%) have liquefiers

  The Northeast is emphasized because it is the country's area where local distribution companies (LDCs) are heavily dependent on LNG. Many of these facilities receive LNG via tanker truck from the Everett LNG import terminal.

6. Terms and Units of Measure for Natural Gas and LNG

6.1 Abbreviations

The following abbreviations, terms, and units will be used in this document for natural gas and LNG:

U.S.	United States
Peak Shaver	An LNG facility used to supplement the supply of natural gas during times of high gas demand
Satellite	An LNG facility used to
Sendout	Nat ia pipelines to customers
Boil-of	ed into the tank from the
F	
Psia	ero)
Psig	e
Lbm	
Lbf	t 32.2 ft./sec^2)
Cu. ft.	

s a volume 1' x 1' x 1'
Source: Self-Made

BOG	Boil-off gas
SCF	A standard cubic foot is a 1' x 1' x 1' volume of gas at a standard temperature and pressure. For this document, the American Gas Association (A.G.A.) definition of standard pressure and temperature of 14.73 psia and 60 F is used.
BTU	Btu is the amount of energy needed to raise 1 lbm of water 1 deg F. This is not a precise measure of energy because different industries and different countries use a different standard temperatures of the water being heated. The heat capacity of water differs with temperature.
HHV	Higher heating value is the amount of heat released from burning an SCF of natural gas at 60 F with air at 60 F and bringing the combustion products down to 60 F.
Therm	By definition, a Therm is 100,000 Btu.
Dekatherm	Deca means 10, so a dekatherm is 1,000,000 Btu.