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KLM Technology Group P. O. Box 281 Bandar Johor Bahru, 80000 Johor Bahru, Johor, West Malaysia	**Kolmetz Handbook Of Process Equipment Design** **CRYOGENIC HEAT EXCHANGER SELECTION, SIZING AND TROUBLESHOOTING** **(ENGINEERING DESIGN GUIDELINES)**	Co Authors Rev 01 – Mela Widiawati Author / Editor **Karl Kolmetz**

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INTRODUCTION

Scope

Cryogenic is the science that addresses the production and effects of very low temperatures. The word originates from the Greek words 'kryos' meaning "frost" and 'genic' meaning "to produce". Under such a definition it could be used to include all temperatures below the freezing point of water (0 ^{o}C). The techniques employed in producing such low temperatures were quite different from those used somewhat earlier in the production of artificial ice. In particular, efficient heat exchangers are required to reach very low temperatures. Over the years the term cryogenics has generally been used to refer to temperatures below approximately -150^{o}C.

According to the laws of thermodynamics, there exists a limit to the lowest temperature that can be achieved, which is known as absolute zero. Molecules are in their lowest, but finite, energy state at absolute zero. Such a temperature is impossible to reach because the input power required approaches infinity.

However, temperatures within a few billionths of a degree above absolute zero have been achieved. Absolute zero is the zero of the absolute or thermodynamic temperature scale. It is equal to -273.15^{o}C or -459.67 F. The metric or SI (International System) absolute scale is known as the Kelvin scale whose unit is the kelvin (not Kelvin) which has the same magnitude as the degree Celsius. In terms of the Kelvin scale the cryogenic region is often considered to be that below approximately 120 K (-153^{o}C).

The measurement of cryogenic temperatures requires methods that may not be so familiar to the general public. Normal mercury or alcohol thermometers freeze at such low temperatures and become useless. The platinum resistance thermometer has a well-defined behavior or electrical resistance versus temperature and is commonly used to measure temperatures accurately, including cryogenic temperatures down to about 20K.

In physics, cryogenics is the study of the production and behavior of materials at very low temperatures (below -150 ^oC, -238 ^oF or 123 K). A person who studies elements that have been subjected to extremely cold temperatures is called a cryogenicst.

Rather than the relative temperature scales of Celsius and Fahrenheit; cryogenicists use the absolute temperature scales. There are Kelvin (SI units) or Rankine scale (imperial units). The term cryogenics is often mistakenly used in fiction and popular culture to refer to the related cryonics.

Etymology

The word cryogenics stems from Greek and means “the production of freezing cold”, however, the term is used today as a synonym for the low temperature state. It is not well defined at what point on the temperature scale refrigeration ends cryogenics begins, but most scientists assume it starts at or below -150^{o}C (123 K; -238^{o}F).

The National Institute of Standards and Technology at Boulder, Colorado has chosen to consider the field of cryogenics as that involving temperatures below -180^{o}C or -292.00 ^{o}F or 93.15 K. This is a logical dividing line, since the normal boiling points of the so called permanent gases (such as helium, hydrogen, neon, nitrogen, oxygen, and normal air) lie below -180^{o}C while the Freon refrigerants, hydrogen sulfide, and other common refrigerants have boiling points above -180^{o}C.

Industrial applications

Liquefied gases, such as liquid nitrogen and liquid helium, are used in many cryogenic applications. Liquid nitrogen is the most commonly used element in cryogenics and is legally purchasable around the world. Liquid helium is also commonly used and allows for the lowest attainable temperatures to be reached.

The liquids may be stored in Dewar flasks, which are double-walled containers with a high vacuum between the walls to reduce heat transfer into the liquid. Typical laboratory Dewar flasks are spherical, made of glass and protected in a metal outer container.

Dewar flasks for extremely cold liquids such as liquid helium have another double-walled container filled with liquid nitrogen. Dewar flasks are named after their inventor, James Dewar, the man who first liquefied hydrogen. “Thermos” bottles are smaller vacuum flasks fitted in a protective casing.

Cryogenic barcode labels are used to mark dewar flasks containing these liquids, and will not frost over down to -195 degree Celsius. Cryogenic transfer pumps are the pumps used on LNG piers to transfer liquefied natural gas from LNG carriers to LNG storage tanks, as are cryogenic valves.

Cryogenic processing

The field of cryogenics advanced during World War II when scientists found that metals frozen to low temperatures showed more resistance to wear. Based on this theory of cryogenic hardening, the commercial cryogenic processing industry was founded in 1966 by ED Busch. With a background in the heat treating industry, Busch founded a company in Detroit called CryoTech in 1996 which merged with 300 below in 1999 to become the world's largest and oldest commercial cryogenic processing company.

Busch originally experimented with the possibility of increasing the life of metal tools to anywhere between 200%-400% of the original life expectancy using cryogenic tempering instead of heat treating. This evolved in the late 1990s into the treatment of other parts.

Cryogens, such as liquid nitrogen, are further used for specialty chilling and freezing applications. Some chemical reactions, like those used to produce the active ingredients for the popular statin drugs, must occur at low temperatures of approximately -100^{o}C (-148^{o}F).

Special cryogenic chemical reactors are used to remove reaction heat and provide a low temperature environment. The freezing of foods and biotechnology products, like vaccines, requires nitrogen in blast freezing or immersion freezing systems. Certain soft or elastic materials become hard and brittle at very low temperatures, which makes cryogenic milling (cryomilling) an option for some materials that cannot easily be milled at higher temperatures.

Cryogenic processing is not a substitute for heat treatment, but rather an extension of the heating – quenching – tempering cycle. Normally, when an item is quenched, the final temperature is ambient. The only reason for this is that most heat treaters do not have cooling equipment. There is nothing metallurgically significant about ambient temperature down to -320^{o}F (140 ^{o}R; 78 K; -196^{o}C).

In most instances the cryogenic cycle is followed by a heat tempering procedure. As all alloys do not have the same chemical constituents, the tempering procedure varies according to the material's chemical composition, thermal history and/or a tool's particular service application.

A heat exchanger for vaporizing a cryogenic fluid comprises a conduit through which the fluid is passed and a heat transfer sleeve surrounding the conduit. The sleeve is comprised of two heat transfer sections, each having a central arcuate portion in close partial circumferential contact with the conduit, a plurality of radially extending heat transfer fins, and a pair of interlocking members located on the fins at a predetermined distance from the central portion for assembling the two sections together around the conduit.

In the assembled state, the resiliency of the fins on which the interlocking members are located provides a continuous clamping for which permits the two central portions to maintain intimate contact with the conduit as it undergoes thermal contraction, while also facilitating assembly and disassembly of the two sections. Each heat transfer fins is also provided with a corrugated or rippled surface near its tip to increase its surface area and the rate of heat transfer and vaporization.

General Design Consideration

Cryogenic Heat Exchanger for LNG

For small scale and laboratory applications, simple geometries such as concentric tubes Heat Exchanger can be used with the advantages of building and maintenance simplicity. However, for larger scale applications, the high effectiveness requirement for Cryogenic Heat Exchanger and the use of complex processes for LNG, including multiple streams exchanging heat simultaneously, result in development of complex equipment.

The selection of the main Cryogenic Heat Exchanger for LNG processes is currently dominated by the use of plate fin and spiral wound geometries. They are illustrated in and compared in the following subsections.

Coil-wound Heat Exchanger (CWHE)

The coil wound heat exchanger (CWHE), also known as Giauque-Hampson Heat Exchanger, was first used by Linde in 1895 in Germany and shortly thereafter by Hampson in England. Layers of tubes are coiled around a central mandrel, which provides mechanical stability. Several tube-side streams can be used in the different layers (two or three being common in LNG processes), exchanging heat with a common shell side stream.
They are used as main Cryogenic Heat Exchanger in most of the present LNG production plants, and their selection is based on the advantages of multi-stream capability, high are to volume ratio, efficient heat transfer and mechanical robustness considering fast transients in temperature and pressure. They can be constructed in very large units, only limited in size by transportation issues. The main disadvantage is that they are proprietary and expensive equipment.

Plate Fin Heat Exchanger (PFHE)

Plate fin heat exchanger (PFHE) are very compact equipment, with the possibility of handling up to 10 streams in the same unit. In addition, very low temperature differences can be achieved. This results in lower capital and operating costs compared to traditional shell and tube type Heat Exchanger. For this reason they are in several industries, covering large ranges of temperature and pressure.

The use of fins results in a large density of heat transfer area although their mechanical stability is more sensitive to operational transients.

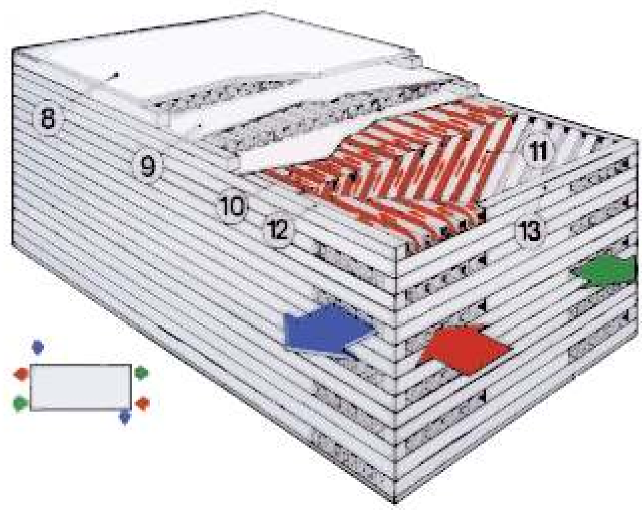

Figure 1. Heat Exchanger Geometries used for LNG Processes

Both geometries are used in LNG processes. A comparison between them given is presented in **Table 1.** It is worth mentioning that the reported cost for Plate Fin Heat Exchanger does not include the installation of manifolds and connecting equipment. Plate Fin Heat Exchanger are more limited in size than Coil Wound Heat Exchanger, making necessary the use of parallel units with the corresponding mani-folding and assembly, that can represent more than double the cost of the actual Heat Exchanger cores.

Table 1.Comparison of Plate Fin and Coil Wound Heat Exchanger.

	PFHE	CWHE
Main feature	Extremely compact	Extremely robust
Heating surface density	300-1000 m^2/m^3	50-150 m^2/m^3
Fluid conditions	Very clean, non-corrosive	Less restrictive
Applications	Smooth operation	High *T* or *p* gradients
Relative price	25-35%	100%

Cryogenic Heat Exchanger for small scale/laboratory applications

Small scale equipment is usually on a different basis than for larger scale applications. Simplicity and maintenance issues are sometimes more important than the relative cost per unit heat removed, since the amount of heat is small. Two main types are described: perforated plate and regenerators.

Perforated plate heat exchangers (PPHE)

The periodic disruption of the flow gives a high heat transfer coefficient but also a relatively large pressure drop.

Heat exchange between the usually counter current streams occurs laterally through the high conductivity plates (usually copper or aluminum) which act as fins. Axial heat condition is avoid, to some extent, with the use of low conductivity material, such as stainless steel, for the spacers.

Regenerators

The design of a regenerator is conceptually different from all the other geometries, which can be grouped under the name of recuperators. In a regenerator, both fluids occupy alternately the same space and the heat is transferred in and out of a packing material, called the matrix.

Their main advantages are given by the very high area density, as large as 6500 m^2/m^3, relatively low cost and simplicity to build and maintain. The major limitations consist on their maximum size, and the residual amount of mixing between streams.

DEFINITION

Condensation – is the change of the physical state of matter from gas phase into liquid phase, and is the reverse of evaporation.

Coolant – is a fluid which flows through or around a device to prevent it's overheating, transferring the heat produced by the device to other devices that use or dissipate it. An ideal coolant has high thermal capacity, low viscosity, is low cost, nontoxic, and chemically inert, neither causing nor promoting corrosion of the cooling system.

Cooling down – is an easy exercise that will allow the body to gradually transition to a resting or near-resting state.

Cryogenics – The branches of physics and engineering that involve the study of very low temperatures, how to produce them, and how materials behave at those temperatures.

Cryobiology – The branch of biology involving the study of the effects of low temperatures on organisms (most often for the purpose of achieving cryopreservation).

Cryosurgery – The branch of surgery applying very low temperatures (down to -196 ^{o}C) to destroy malignant tissue, e.g. cancer cells.

Cryonics – The emerging medical technology of cryopreserving humans and animals with the intention of future revival. Researchers in the field seek to apply the results of many sciences, including cryobiology, cryogenics, rheology, emergency medicine, etc. "Cryogenics" is sometimes erroneously used to mean "Cryonics" in popular culture and the press.

Entropy – is a measure of the number of specific ways in which a thermodynamic system may be arranged, commonly understood as a measure of disorder.

Liquefaction – is a term used in materials sciences to refer to any process which either generates a non-liquid from a solid or a gas, or generates a non-liquid phase which behaves in accordance with fluid dynamics.

Liquefied natural gas (LNG) – is natural gas (predominantly methane, CH_4) that has been converted to liquid form for ease of storage or transport.

NOMENCLATURE

A	Cross sectional area (m^2)
C	Heat capacity flow rate (WK^{-1})
C_p	Specific heat capacity at constant pressure ($J\ kg^{-1}\ K^{-1}$)
d	Droplet diameter (m)
D_t	Inner diameter (m)
D_o	Outer diameter (m)
D_{eq}	Equivalent diameter (m)
D_h	Hydraulic diameter (m)
F	Correction factor for mean temperature difference
$\dot{m}$	Mass flow rate ($kg\ s^{-1}$)
MW	Molecular weight ($kg\ mol^{-1}$)
N	Number of nodes/elements
p	Pressure (Pa, bar)
U	Overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
u	Fluid velocity (ms^{-1})

Abbreviations and acronyms

CHE	Cryogenic heat exchanger
CWHE	Coil-wound heat exchanger
HE	Heat exchanger
NTU	Number of thermal units
NG	Natural gas
PFHE	Plate fin heat exchanger

Greek letters

α	Volume/void fraction
Δh_{LV}	Specific heat of evaporation
ΔT	Local temperature difference (K)
ΔT_m	Effective mean temperature difference (K)
ΔT_{lm}	Logarithmic mean temperature difference (K)