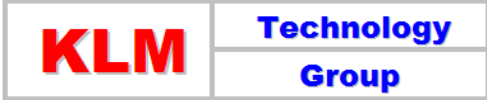


KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	 Solutions, Standards and Software www.klmtechgroup.com	Page : 1 of 69
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TABLE OF CONTENT

INTRODUCTION	1
Scope	6
General Design Consideration	8
DEFINITION	12
NOMENCLATURE	13
THEORY	14

KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 2 of 69
		Rev: 01
		August 2014

Low temperature In Science and Technology	14
Cryogenic Fluid	18
Cryogenic Fluid Mechanics	18
Properties of Cryogenic Fluids	25
Thermophysical Properties	26
Liquid Boil-Off	27
Cryogenic Usage for Equipment Cooldown	28
Phase Domains	29
Heat Transfer and Thermal Design	31
Properties of Solids	32
Structural Properties at Low Temperatures	32
Thermal Properties at Low Temperatures	33
Electrical Properties at Low Temperatures	34
Superconductivity	35
Refrigeration and Liquifaction	36
Expansion Types of Refrigerators	38
Liquefaction	44
Application: Cryogenic Heat Exchangers	47
Challenges in the Modeling of CHE	48
Change in Fluid Properties	52

These design guideline are believed to be as accurate as possible, but are very general and not for specific design cases. They were designed for engineers to do preliminary designs and process specification sheets. The final design must always be guaranteed for the service selected by the manufacturing vendor, but these guidelines will greatly reduce the amount of up front engineering hours that are required to develop the final design. The guidelines are a training tool for young engineers or a resource for engineers with experience.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 3 of 69
		Rev: 01
		August 2014

Heat in Leakage	52
Longitudinal Thermal Conduction	52
Flow Maldistribution	52
Effect Pressure Drop on Heat Transfer	53
Present Models for Heat Exchanger Design	55
Lumped Parameters Models (LPM)	57
Distributed Parameters Models (DPM)	60
Stream Evolution Models (SEM)	61
Scope of The Work	63
Heat Exchanger in Cryogenic Processes	64
High Effectiveness HE are Required	65
Etymology	67
Industrial Applications	67
Cryogenic Processing	68

APPLICATION

REFERENCES

These design guideline are believed to be as accurate as possible, but are very general and not for specific design cases. They were designed for engineers to do preliminary designs and process specification sheets. The final design must always be guaranteed for the service selected by the manufacturing vendor, but these guidelines will greatly reduce the amount of up front engineering hours that are required to develop the final design. The guidelines are a training tool for young engineers or a resource for engineers with experience.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 4 of 69
		Rev: 01
		August 2014

LIST OF TABLE

Table 1. Comparison of Plate Fin and Coil Wound Heat Exchanger	11
Table 2. Characteristic Temperatures of Cryogenics Fluid [K]	15
Table 3. Properties of Helium and Nitrogen Compared to Water	27
Table 4. Volume [1] of liquid cryogenics required to cool down 1 kg of iron	29
Table 5. Review of HE models and their evaluation of interesting effects for cryogenic and LNG applications.	56
Table 6. Normal Boiling Point (NBP) and Critical Point for Cryogenic Fluids	61
Table 7. Normal Boiling Point (NBP) and Critical Point for Cryogenic Fluids	63
Table 8. Thermodynamic minimum input of mechanical power unit of thermal power removed for selected cryogenic fluids	66

These design guideline are believed to be as accurate as possible, but are very general and not for specific design cases. They were designed for engineers to do preliminary designs and process specification sheets. The final design must always be guaranteed for the service selected by the manufacturing vendor, but these guidelines will greatly reduce the amount of up front engineering hours that are required to develop the final design. The guidelines are a training tool for young engineers or a resource for engineers with experience.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 5 of 69
		Rev: 01
		August 2014

LIST OF FIGURE

Figure 1. Heat Exchanger Geometries used for LNG Processes	10
Figure 2. Rockets Using Cryogenic Liquid Propellants	16
Figure 3. Phase Diagram of Helium, Showing Typical Operating Domains	31
Figure 4. Refrigerator Using Simple J-T Cycle	39
Figure 5. Cold-Gas Refrigerator	40
Figure 6. Claude Cycle Refrigerator Utilizing Both Expansion Processes	42
Figure 7. Mixed-Refrigerant Cycle	43
Figure 8. Schematic Representation of a MCHE	45
Figure 9. Forced Flow Single Phased Fluid-Fluid	47
Figure 10. Forced Single Phase Flow-Boiling Liquid (Tube in Shell HX)	47
Figure 11. Static Boiling Liquid-Liquid	47
Figure 12. LNG Processes	49
Figure 13. Relevant Physical Effects for a Given Design Effectiveness. The color Bars Indicate if The Effect Can Be Neglected or Not	51
Figure 14. Summary of models for sizing heat exchangers	53
Figure 15. Ideal Isothermal Compression and Isoentropic Expansion Process in T-S Diagrams for Air and Natural Gas	65
Figure 16. Cycle for Liqueaction of Air	65

These design guideline are believed to be as accurate as possible, but are very general and not for specific design cases. They were designed for engineers to do preliminary designs and process specification sheets. The final design must always be guaranteed for the service selected by the manufacturing vendor, but these guidelines will greatly reduce the amount of up front engineering hours that are required to develop the final design. The guidelines are a training tool for young engineers or a resource for engineers with experience.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 6 of 69
		Rev: 01
		August 2014

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 °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°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°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°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 °C, -238 °F or 123 K). A person who studies elements that have been subjected to extremely cold temperatures is called a cryogenicist.

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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 7 of 69
		Rev: 01
		August 2014

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°C (123 K; -238°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°C or -292.00°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°C while the Freon refrigerants, hydrogen sulfide, and other common refrigerants have boiling points above -180°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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 8 of 69
		Rev: 01
		August 2014

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.

Cryogenics, 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°C (-148°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°F (140 °R; 78 K; -196°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

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 9 of 69
		Rev: 01
		August 2014

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 area 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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 10 of 69
		Rev: 01
		August 2014

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.

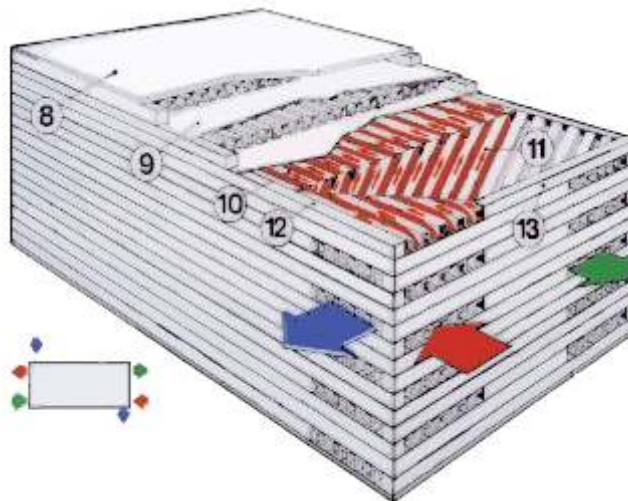


Figure 1. Heat Exchanger Geometries used for LNG Processes

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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 11 of 69
		Rev: 01
		August 2014

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 <i>T</i> or <i>p</i> 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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 12 of 69
		Rev: 01
		August 2014

Their main advantages are given by the very high area density, as large as $6500 \text{ m}^2/\text{m}^3$, 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 $-196 \text{ }^\circ\text{C}$) 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.

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 13 of 69
		Rev: 01
		August 2014

Liquefied natural gas (LNG) – is natural gas (predominantly methane, CH₄) 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)

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 14 of 69
		Rev: 01
		August 2014

THEORY

Low Temperatures in Science and Technology

Cryogenics is defined as that branch of physics which deals with the production of very low temperatures and their effect on matter, a formulation which addresses both aspect of attaining low temperatures which do not naturally occur on Earth, and of using them for the study of nature or the human industry. In a more operational way, it is also defined as the science and technology of temperatures below 120 K.

The reason for this latter definition can be understood by examining characteristic temperatures of cryogenic fluids (table 2): the limit temperature of 120 K comprehensively includes the normal boiling points of the main atmospheric gases, as well as of methane which constitutes the principal component of natural gas.

Today, liquid natural gas (LNG) represents one of the largest – and fast-growing – industrial domains of application of cryogenics (Figure 2), together with the liquefaction and separation of air gases (Figure 2). The densification by condensation, and separation by distillation of gases was historically – and remains today – the main driving force for the cryogenic industry, exemplified not only by liquid oxygen and nitrogen use in chemical and metallurgical processes, but also by the cryogenic liquid propellants of rocket engines (Figure 3) and the proposed use of hydrogen as a “clean” energy vector in transportation (Figure 4).

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KLM Technology Group Practical Engineering Guidelines for Processing Plant Solutions	Kolmetz Handbook Of Process Equipment Design Cryogenic Heat Exchanger Selection and Sizing (ENGINEERING DESIGN GUIDELINE)	Page 15 of 69
		Rev: 01
		August 2014

Table 2. Characteristic Temperatures of Cryogenics Fluid [K]

Cryogen	Triple point	Normal boiling point	Critical point
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2*	4.2	5.2

*λ point

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