REFRIGERATION AND CRYOGENIC SYSTEMS

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Contents

Summary

The aim of this article is to provide the the basic information needed to understand the technology of producing low and very low temperatures, i.e., refrigeration and cryogenics. The article addresses the refrigeration, absorption, and liquefaction processes from the engineering point of view. It avoids a purely theoretical approach and it is not presenting technologies of limited, state of the art applications.

In order to enable the comprehension of these applications, a brief presentation of the thermodynamics of the respective processes is also given.

Emphasis is placed on the main technologies applied in contemporary refrigeration practice, like heat pump systems, single and multistage compression refrigerating systems, Lithium Bromide and Aqueous Ammonia absorption systems, and gas refrigeration systems.

The Linde and the Claude gas liquefaction systems are presented as the most interesting cryogenic processes, as well as the heat exchangers used in those processes.

For the reader who may be interested in a more detailed and in-depth knowledge of refrigeration and cryogenics technologies, the references mentioned in the bibliography will be helpful.

1. General Characteristics of Refrigeration and Cryogenic Installations

It is a natural phenomenon that heat flows in the direction of decreasing temperature, i.e., from high temperature to low temperature regions. The reverse process, however, can take place, not in violation of the second law of thermodynamic but by the addition of work.

The heat transfer from a low-temperature region to a high-temperature one requires therefore, intermediate devices and systems called refrigerators. The difference between a refrigeration and a cryogenic system lies in the achievable temperatures, with the dividing line being set at –100°F or –74°C.

The methods used and the physical principles applied to achieve low temperatures are shown in Table 1.

Method	Physical principle
Cyclic processes	
Vapor compression cycle	Evaporation
Steam ejection	Evaporation
Absorption cycle	Evaporation
Gas refrigeration cycle	Adiabatic expansion
Open processes	
Linde liquefaction	Joule Thompson effect
Claude liquefaction	Joule Thompson effect and adiabatic expansion

Table 1. Methods and principles for low temperature achievement

Refrigerators are systems that operate on a cyclic principle involving a working fluid called a refrigerant. The working principle of a refrigerator is shown schematically in Figure 1.

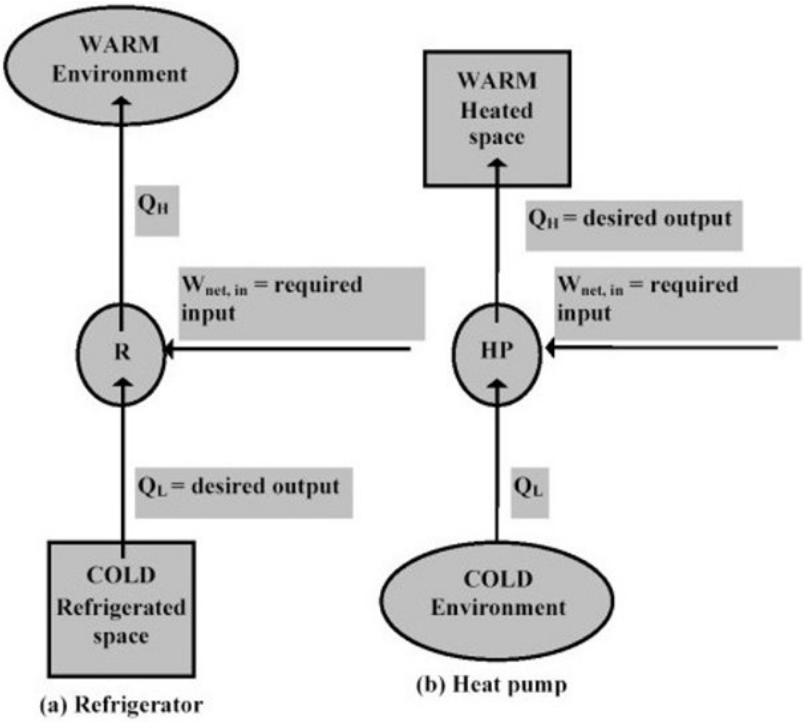

Figure 1. Refrigerator and heat pump working principle

In this scheme Q_L is the magnitude of the heat removed from the refrigerated space at a given temperature T_L, Q_H is the magnitude of the heat rejected to the warm environment at a temperature T_L, and $W_{net,in}$ is the net work input needed to the refrigerator. Q_L and Q_H represent magnitudes and thus are positive quantities.

In the same scheme, a heat pump is shown, in order to demonstrate the relation between the two applications, which is the inversion of the same function. The objective of the refrigerator is to remove heat from the cold medium, whilst the objective of the heat pump is to supply heat to a warm one. Both of these systems transfer heat from low to high temperature media with the input of work.

The objective of the refrigerator is to maintain the refrigerated space at a low temperature by removing heat from it. Discharging this heat to a higher temperature medium is only a necessary part of the operation, not an aim on its own.

The objective of a heat pump, however, is to maintain a heated or cooled space at a given temperature. This is accomplished by absorbing heat from an energy source, such as the ground, water, or ambient air, and supplying this heat to a warmer or colder medium, such as a building, in winter or summer respectively.

The performance of refrigerators and heat pumps is expressed in terms of the *coefficient of performance (COP)*, which is defined as

$$COP_R = \frac{desired\_output}{required\_input} = \frac{cooling\_effect}{work\_input} = \frac{Q_L}{W_{net,in}} \qquad (1)$$

$$COP_{HP} = \frac{deisired\_output}{required\_input} = \frac{heating\_effect}{work\_input} = \frac{Q_H}{W_{net,in}} \quad (2)$$

These relations can also be expressed in the rate form by replacing the quantities Q_L, Q_H and $W_{net,in}$ by $\dot{Q}_L$, $\dot{Q}_H$ and $\dot{W}_{net,in}$ respectively. Notice that both the COP_R and COP_{HP} can be greater than 1. A comparison of the equations (1) and (2) reveals that for fixed values of Q_L and Q_H:

$$COP_{HP} = COP_R + 1 \quad (3)$$

This relation implies that COP_{HP} >1 since COP_R is a positive quantity. That is, a heat pump will function in the case of heating a space, at worst, as a resistance heater, supplying as much energy to the house as it consumes. In reality, however, part of Q_H is lost to the outside air through piping and other devices, and COP_{HP} may drop below unity when the outside air temperature is too low. When this happens the system normally switches to a resistance heating mode.

The cooling capacity of a refrigeration system—that is, the rate of heat removal from the refrigerated space—is often expressed in terms of tons of refrigeration or in British Thermal Units (BTUs). The capacity of a refrigeration system that can freeze 1 ton of liquid water at 0°C into ice at 0°C in 24 hours is said to be 1 ton. One ton of refrigeration is equivalent to 211 kJ/min or 200 Btu/mon.

1.1 The Ideal Vapor-Compression Refrigeration Cycle

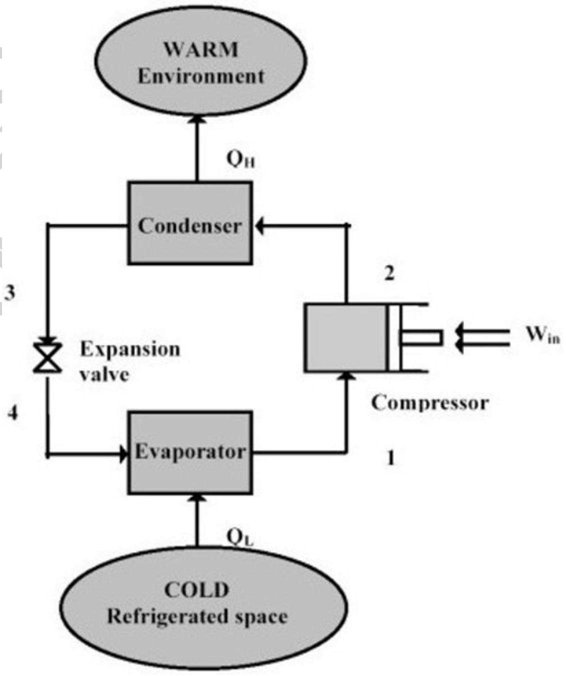

Figure 2. Schematic representation of the ideal vapor compression refrigeration cycle

Many of the impracticalities associated with the reversed Carnot cycle can be eliminated by vaporizing the refrigerant completely before it is compressed and by replacing the turbine with a throttling device, such as an expansion valve or capillary tube. The cycle that results is called the *ideal vapor-compression refrigeration cycle*, and it is shown schematically in Figure 2 and on a T-S diagram in Figure 3. The vapor-compression refrigeration cycle is the most widely used cycle for refrigerators, air conditioning systems, and heat pumps.

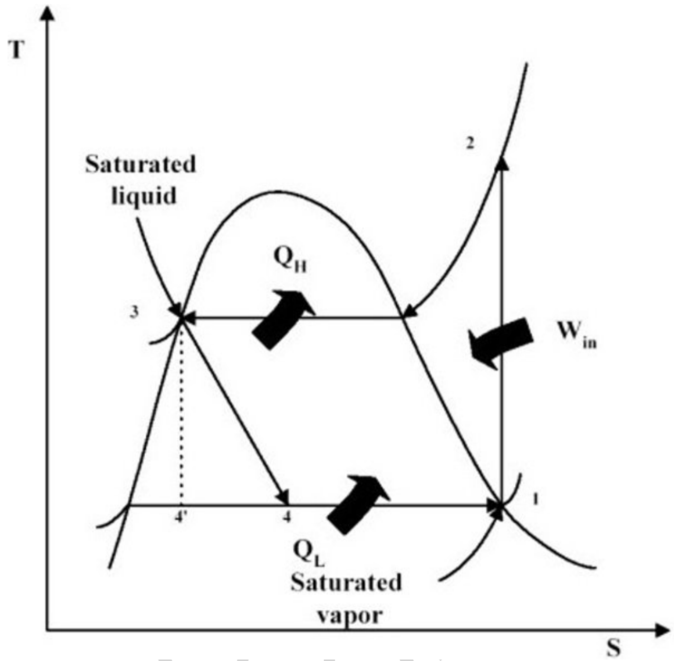

Figure 3. Temperature versus entropy diagram of the ideal vapor compression refrigeration cycle

This cycle consists of four processes:

1–2: Isentropic compression
2–3: Heat rejection in a condenser at constant pressure
3–4: Throttling in an expansion device
4–1: Heat absorption in an evaporator at constant pressure

The cycle can be well described in five steps.

Step 1: The refrigerant leaves the evaporator at state 1 as a low pressure, low temperature, saturated vapor. In an ideal cycle, the refrigerant enters the compressor without heat gain/loss from the environment.

Step 2: The compression process compresses the refrigerant reversibly (without losses), leaving the refrigerant in a high temperature, high pressure, superheated vapor state.

Step 3: Condensing brings the refrigerant out of superheated state and condenses it at a constant pressure. The refrigerant becomes a high pressure, medium temperature, saturated liquid.

Step 4: Once condensed, the refrigerant expands adiabatically (without heat transfer) and reversibly (i.e., at constant enthalpy) in the expansion valve. The refrigerant leaves the expansion valve as a low pressure, low temperature, low enthalpy vapor.

Step 5: At constant pressure and in an adiabatic fashion, the refrigerant enters the evaporator and evaporates. It is during the evaporation that heat transfer occurs from the refrigerated space to the refrigerant.

2. Actual Vapor-Compression Refrigeration Cycles

An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components. Two common sources of the irreversibilities are fluid friction (which causes pressure drops) and heat transfer to or from the surroundings. The T-S diagram of an actual vapor compression refrigeration cycle is shown in Figure 4.

In the ideal cycle, the refrigerant leaves the evaporator and enters the compressor as *saturated vapor*. This cannot be accomplished in practice, however, since it is not possible to control the state of the refrigerant so precisely. Instead the system is designed so that the refrigerant is slightly superheated at the compressor inlet.

This slight overdimensioning ensures that the refrigerant is completely vaporized when it enters the compressor. Also, the line connecting the evaporator to the compressor is usually very long, thus the pressure drop caused by fluid friction and heat transfer from the surroundings to the refrigerant can be very significant.

The result of superheating, heat gain in the connecting line, and the pressure drops in the evaporator and the connecting line, is an increase in the specific volume. This leads to an increase in the power-input requirements to the compressor, since steady-flow work is proportional to the specific volume. The compression process, however, will involve frictional effects that increase the entropy, and heat transfer which may increase or decrease the entropy, depending on the direction. Therefore the entropy of the refrigerant may increase (process 1-2), or decrease (process 1-2') during the actual compression process, depending on which effect dominates.
The compression process 1-2 may be even more desirable than the isentropic compression process since the specific volume of the refrigerant and thus the work input requirements are smaller in this case. Therefore, the refrigerant should be cooled during the compression process whenever it is practical and economical to do so.

In the ideal case, the refrigerant is assumed to leave the condenser as *saturated liquid* at the compressor exit pressure. In actual situations, however, it is unavoidable to have some pressure drop in the condenser as well as in the lines connecting the condenser to the compressor and to the throttling valve.

Also, it is not easy to execute the condensation processes with such precision that the refrigerant is saturated liquid at the end and it is undesirable to route the refrigerant to the throttling valve before the refrigerant is completely condensed. Therefore the refrigerant is subcooled somewhat before it enters the throttling valve.

The refrigerant enters the evaporator with a lower enthalpy and thus can absorb more heat from the refrigerated space. The throttling valve and the evaporator are usually located very close to each other, so that the pressure drop in the connecting line is small.

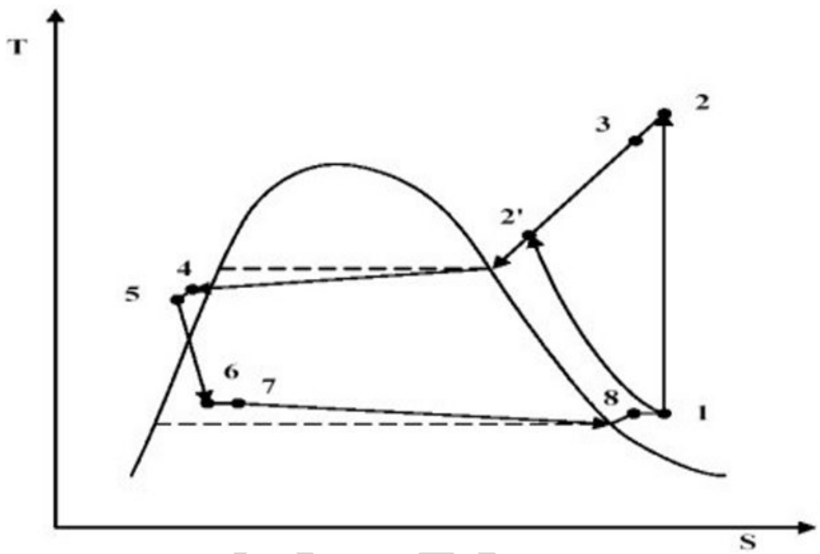

Figure 4. Temperature versus entropy diagram of the actual vapor compression refrigeration cycle

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Biographical Sketches

Agis M. Papadopoulos. Born in Thessaloniki (GR) in 1966, he graduated as a Diploma Mechanical Engineer (Dipl.-Eng.) from the Aristotle University of Thessaloniki in 1989. After a Master of Science in Energy Conservation and the Environment at the School of Mechanical Engineering of Cranfield University (UK) in 1990, he earned his Doctorate on the feasibility of solar systems at the Department of Mechanical Engineering at the Aristotle University of Thessaloniki in 1994.

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Christopher J. Koroneos studied Chemical Engineering in Columbia University where he also earned his Doctorate. His research interests are in the areas of Environmental Engineering, Energy Engineering, Process Engineering, Environmental Process Synthesis, and Life Cycle Analysis.

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