Appendix C.2 - Air Conditioning Thermodynamics[1]

To aid in discussing the alternative technologies, it is helpful to have a basic description of how air conditioning systems work. Heat normally flows from hot regions to cold regions. To reverse this process in a system and move heat from a low temperature region to a higher temperature region requires that work be done on the system (this statement is a form of the second law of thermodynamics). Air conditioners and refrigerators are essentially the same in that the objective of their design and use is to utilize work to move heat from a cooled space and reject it to a hot space. Performance of these machines is usually characterized by a quantity known as the coefficient of performance (COP). Somewhat analogous to the efficiency of an engine, it is defined as

$$COP = \frac{heat\ removed\ from\ cooled\ space}{work\ input}$$

In words, the COP is the dimensionless ratio of how much heat is transferred out of the cooled space to the amount of work that is used to accomplish this task. Note that, unlike engine efficiency, the COP can be larger than unity. Higher values are better, indicating that more heat is removed for a given amount of work. COP is usually dependent on operating conditions, such as the temperatures of the cooled space and the hot space to which heat is to be rejected.

The theoretical maximum performance of a refrigerator under specific hot space and cooled space temperature conditions is given by the reversed Carnot cycle. This cycle consists of a gas that undergoes four ideal processes: a reversible adiabatic (no heat transfer) compression, a reversible isothermal (constant temperature) compression, a reversible adiabatic expansion and then a reversible isothermal expansion. The theoretical COP for a Carnot refrigeration machine can be shown to be:

$$COP_{Carnot} = \frac{1}{\left(\frac{T_{hot}}{T_{cooled}} - 1\right)}$$

where T_{hot} and T_{cooled} are the temperatures of the hot space and the cooled space, respectively. The restriction to ideal reversible processes means that this cycle cannot be achieved in a real machine, but it gives a yardstick for comparison of real refrigeration machines and processes. Any real refrigeration machine would have a COP less than COP_{Carnot}.

Note that COP_{Carnot} is a function of the external temperatures. For all refrigeration cycles, Carnot or otherwise, the numeric value of COP presented as the measure of a system's performance will depend upon the conditions under which the COP is measured or calculated. This is important to keep in mind when comparing COP values of various systems, i.e., COP comparison has significance only so far as the values under examination were determined under acceptably similar operating conditions (an "apples-to-apples" comparison, so to speak).

It is also important to distinguish the two types of COP values often presented in the literature. The "cycle COP" considers work input to be based upon measurements of the fluid state at the compressor inlet and exit. These values determine how much of the compressor work was actually delivered to the refrigerant (called the "enthalpy" increase) in useful form. The "system COP" is based on measurements of the work delivered to the compressor drive system, often by means of a torque measurement. This value essentially penalizes the system for the inefficiencies of the compressor drive system (belt drive losses, compressor mechanical friction, etc.), but is usually the easiest to measure experimentally.

Vapor Compression Refrigeration

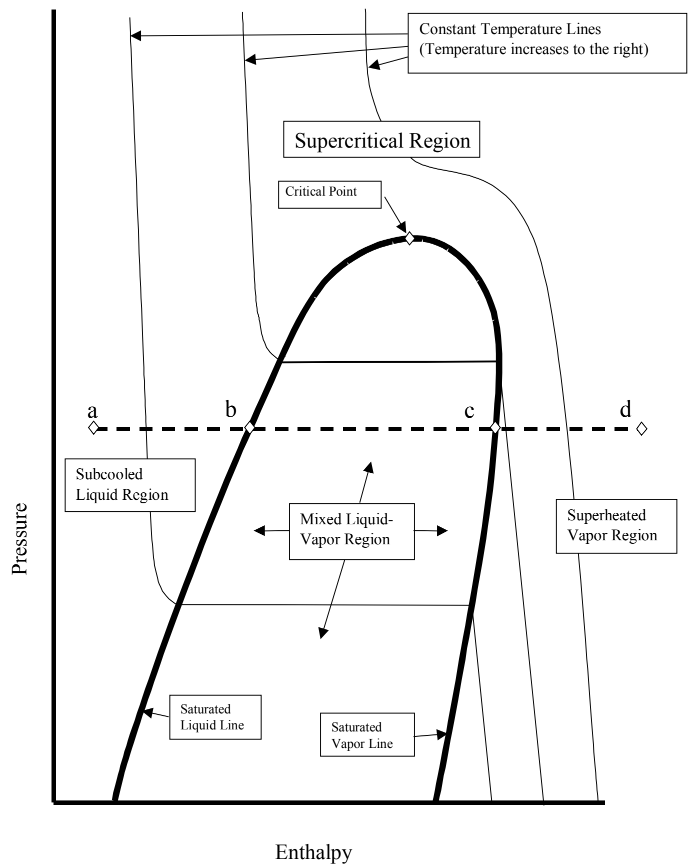
By far the most common mobile air conditioning cycle in use today is the vapor compression cycle. To understand the vapor compression cycle, and similar cycles, it is important to understand about the phase changes that a refrigerant goes through. This is best explained through the use of a pressure-enthalpy diagram, such as that in Figure A- 1. (For our purposes, enthalpy is a measure of the useable energy content of the refrigerant.) This diagram shows the important characteristics of a refrigerant at any likely combination of pressure and enthalpy.

In Figure A- 1, a refrigerant in the "subcooled liquid" region, point "a", is at a temperature that is below its boiling point. If one adds heat while maintaining constant pressure, the refrigerant's temperature will rise, it's enthalpy will increase and its state will approach the "saturated liquid" line at point "b", where it is just about to begin to vaporize. As one continues to add heat, the refrigerant will start to vaporize and its enthalpy will increase, but its temperature will remain constant as it moves through the "mixed vapor and liquid" range between "b" and "c". (In this "wet" region, the vapor fraction is termed the "quality", with a value between 0 at the saturated liquid line, and 1 at the saturated vapor line.) Soon, the refrigerant's state reaches the "saturated vapor" condition at point "c", where there is no more liquid and the refrigerant is said to be just completely vaporized (its quality is equal to 1). The heat that is absorbed in the saturated liquid to saturated vapor transition is called the "latent heat of evaporation" (the term "latent" implies that heat is absorbed without an increase in temperature). With still further heat addition, the refrigerant state moves into the "superheated vapor" region, point "d", where there is no more liquid, and temperature again increases with heat addition.

Note that the saturated liquid and saturated vapor curves on Figure 1 meet at a point called the "critical point", with corresponding "critical temperature" and "critical pressure". Above the critical pressure, a refrigerant's state is in the "supercritical region" where heat removal or addition does not cause a distinct liquid or vapor phase transition.

The next sections will describe how the refrigerant in the vapor compression cycle moves through these various states to accomplish the desired refrigeration effect.

Figure A- 1
Generalized Refrigerant
Pressure-Enthalpy Diagram



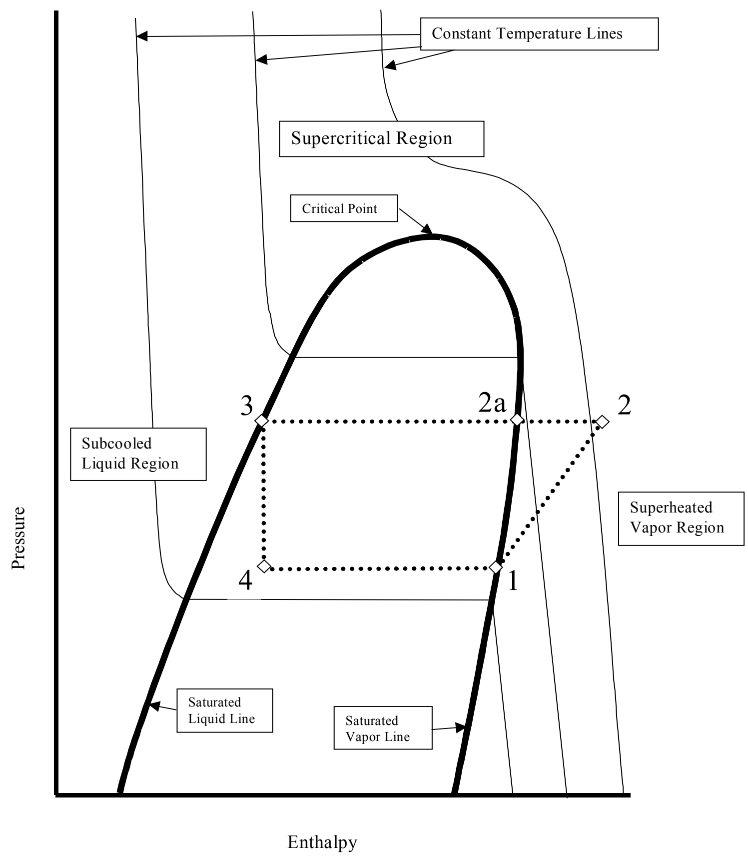
Ideal Cycle

Figure A- 2 illustrates the ideal vapor compression cycle on the pressure-enthalpy diagram. Starting at point 1 with a saturated vapor, the refrigerant enters a compressor and is compressed adiabatically (no heat is removed) from point 1 to a superheated state indicated by point 2. Note that this process significantly increases the pressure, temperature and enthalpy of the refrigerant. The fluid temperature at this point is significantly above that of the hot space.

Next, the refrigerant leaves the compressor and enters a condenser. A condenser is essentially a heat exchanger that transfers heat from the refrigerant and rejects it to the hot space. As heat removal from the refrigerant begins, the refrigerant cools until the saturated vapor state is reached, as denoted by point 2a. As heat continues to be removed, the enthalpy continues to decrease but the temperature and pressure remain constant. Instead, the vapor portion of the refrigerant begins to condense to the liquid phase (its quality is decreasing). Condensation continues until the saturated liquid line is reached at point 3, whereupon the refrigerant consists entirely of liquid with no vapor present. At this point, the refrigerant leaves the condenser as a saturated liquid.

Figure A- 2

Ideal Vapor Compression Cycle



Next, the refrigerant undergoes an isenthalpic (constant enthalpy) expansion process, usually in an expansion valve or capillary tube. This process dramatically reduces the temperature and pressure of the refrigerant while its enthalpy level remains unchanged. Some of the liquid vaporizes during the expansion process until the end of the process is reached at state 4, where the refrigerant is a low quality mixture of liquid and vapor at a temperature somewhat below the temperature of the space to be cooled.

Next, the refrigerant flows through an evaporator, which is a heat exchanger that transfers heat from the space to be cooled to the refrigerant. The refrigerant absorbs heat, increasing its enthalpy during this process, though its temperature and pressure remain constant. The liquid fraction gradually vaporizes until the saturated vapor line is reached at state 1, whereupon the refrigerant enters the compressor to begin the cycle anew.

Real vapor compression systems must deviate somewhat from this ideal cycle to allow for real-world operation. In particular, it is very difficult to make the condensation and evaporation processes end exactly on the liquid and vapor saturation curves, respectively, especially for a system that must operate under a wide range of temperature and heat transfer conditions. So condensers are usually designed to subcool the refrigerant a certain amount under most operating conditions to ensure that only liquid enters the expansion device for optimum expansion performance. Likewise, evaporators usually are designed to superheat the refrigerant by a small amount to ensure that no liquid enters the compressor, thereby avoiding possible compressor damage. Additionally, there are pressure decreases due to flow losses in the various components, which cause some of the processes not to be true constant pressure processes. Finally, there are pressure drops due to fluid friction in the flow passages connecting the components. Nevertheless, the ideal vapor compression cycle is a useful illustration and approximation of the real cycle.

Subcritical Systems

The ideal vapor compression cycle described above is a subcritical cycle, meaning that the condenser and evaporator operate at temperatures below the refrigerant's critical temperature. This allows the primary heat rejection (condensation) and heat absorption (evaporation) processes both to occur isothermally in the mixed liquid-vapor region of the pressure-enthalpy diagram. Isothermal heat absorption and rejection allow for more efficient system operation than processes that do not maintain constant temperature. Subcritical processes are made possible by refrigerants with critical temperatures high enough that they allow for mixed phase evaporation and condensing processes under the necessary temperature conditions throughout the entire cycle. Refrigerants such as CFC-12 and HFC-134a meet these requirements while operating under typical ambient conditions. Indeed, these substances were specifically invented to meet these conditions. However, other refrigerants that also meet these requirements are being investigated to replace these ozone-depleting and climate change gases.

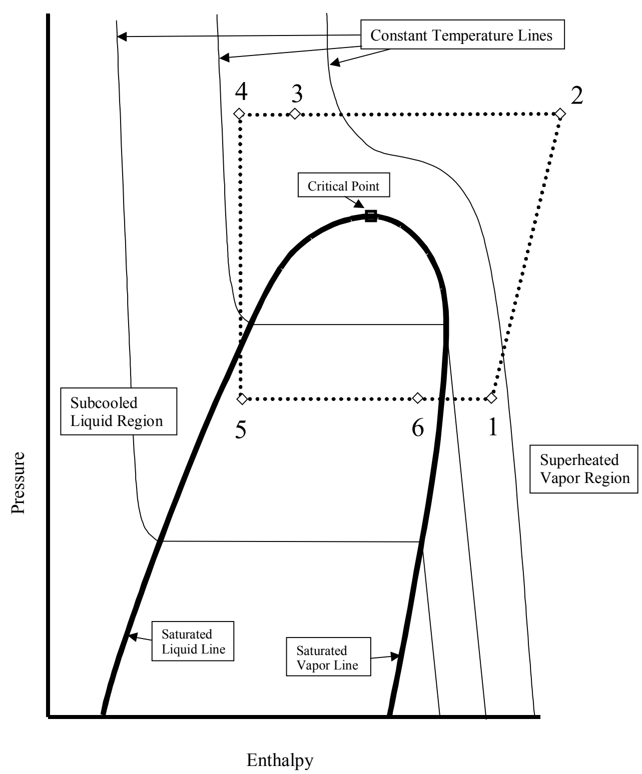
Transcritical Systems[2]

As described in the previous subsection, subcritical systems are possible when the critical temperature of the refrigerant is significantly above the temperature of the hot space to which heat is to be rejected. In another case, when the hot space temperature is at or significantly above the critical temperature, then the heat rejection process will occur with the refrigerant in the supercritical state. Refrigeration and air conditioning systems where the cycle incurs temperatures and pressures both above and below the refrigerant's critical levels are often called transcritical systems. Transcritical systems are somewhat similar to the subcritical systems described above though they do have some different hardware components.

Figure A- 3 illustrates the transcritical vapor compression process. It begins when the superheated refrigerant enters the compressor at point 1. Its pressure, temperature and enthalpy are increased until it leaves the compressor at point 2 located in the supercritical region. Next the refrigerant enters the gas cooler whose function is to transfer heat from the fluid to the hot space. Unlike the condensing process in the subcritical system, the refrigerant has not undergone a distinct phase change when it leaves the gas cooler at point 3. Note that this gas cooling process does not occur at constant temperature.

Figure A- 3

Transcritical Vapor Compression Cycle



The cooled gas then enters an internal heat exchanger (sometimes called a "suction line heat exchanger"), which removes heat and transfers it to that portion of the refrigerant that is just about to enter the compressor. This results in additional cooling of the refrigerant to point 4 on the figure, improving performance at high ambient temperatures. From there, the flow undergoes a constant-enthalpy expansion process that decreases its temperature and pressure until it exits at point 5 in the mixed liquid-vapor region, at temperature and pressure well below the critical values.

Next, the refrigerant enters an evaporator where it absorbs heat from the cooled space and its enthalpy and vapor fraction gradually increase until it exits at point 6. Finally, the flow enters the internal heat exchanger where it absorbs more heat, until it is ready to enter the compressor again at point 1 to repeat the cycle.

This transcritical process is necessitated by the use of a refrigerant with a low critical temperature, lower than the temperature of the hot space. This in turn requires the use of a gas cooler instead of a condenser, and the addition of the internal heat exchanger, both in contrast to the typical subcritical system. Also, in the case of carbon dioxide, the critical pressure is high enough that the maximum cycle pressures are well above those of a conventional subcritical system.

Other Cycles and Technologies

Though the vapor compression refrigeration cycle and its variants are by far the most popular approach to automotive air conditioning, other cycles have been proposed and some placed into use. For completeness, the next few sections will discuss some of these other technologies.

Gas Refrigeration Cycle

There are refrigeration cycles whose refrigerant remains in the gas phase throughout the cycle. These gas refrigeration cycle systems generally use air (designated as R-729), and are common on large aircraft, but occasionally have been advocated for use in automobiles.

Figure A- 4

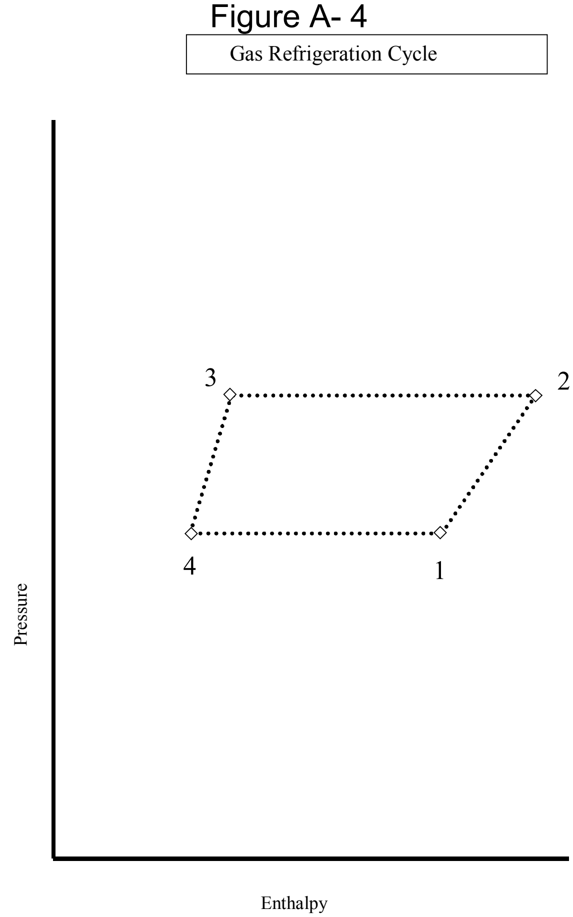


Figure A- 4 shows the pressure-enthalpy diagram for a closed gas refrigeration cycle in its simplest form. Note that the cycle operates at pressures and temperatures well outside of the phase transition area of the refrigerant and its components, so that the saturation curves do not appear on the diagram. At point 1, the gas refrigerant enters a compressor to raise its pressure and enthalpy to those at point 2. The gas then flows through a heat exchanger that rejects heat to the heated space at constant pressure.

The succeeding expansion process is somewhat different from that of most vapor-compression cycles. After leaving the heat exchanger, instead of entering an expansion valve or other device to accomplish an isenthalpic expansion, the gas expands through a turbine to reduce its enthalpy, temperature and pressure. The turbine shaft can be connected to a compressor to provide work to the compression process thus recovering some energy.

Upon leaving the turbine, if the cycle is “closed”, the gas flows through another heat exchanger to pick up heat from the cooled space, the flow then reenters the compressor to begin the cycle again. If the cycle is “open”, the reduced-temperature flow from the turbine is discharged directly to the cooled environment while the compressor takes in a fresh uncirculated flow. Most large aircraft cabin air conditioning systems are of the open type, utilizing compressed air bled from the turbofan engine compressor section and ultimately discharged to flow through the cabin to the outside, usually through a “dump valve” at the rear of the fuselage.

Gas refrigeration cycle systems usually have lower COP values than comparably sized vapor compression equipment. There are some indications this can be alleviated through the use of more precise, higher efficiency turbomachinery, though at higher cost.[3] Gas refrigeration equipment is usually lighter in weight and of lower complexity than other systems, making it quite suitable for applications such as aircraft.

Absorption Refrigeration

The absorption refrigeration cycle is attractive when there is a source of inexpensive or waste heat readily available. This cycle uses a refrigerant that is readily soluble in a transport medium. In brief, the condensation, expansion and evaporation processes are identical to those of the vapor-compression cycle. But instead of the latter’s compression process, the absorption cycle’s liquid transport medium absorbs the refrigerant vapor upon leaving the evaporator, creating a liquid solution. This solution is then pumped to a higher pressure, and then heat is used to separate the refrigerant from the solution, whereupon the high pressure refrigerant flows to the condenser to continue the familiar cycle. The equipment used to accomplish the solution-dissolution processes is complex and heavy, but the advantage lies in the low work input requirement to raise the pressure of a liquid solution as compared to that required for compressing a gas[4]. If the heat utilized is otherwise wasted heat, the low operating costs of absorption systems can be quite attractive.

The two most common refrigerants used in absorption systems are ammonia, with water as the transport medium, and lithium bromide in water. However, toxicity issues with ammonia require safeguards, adding to system cost and complexity. Lithium bromide can be corrosive to most common materials, adding to cost and complexity.[5] Absorption systems are used mostly in large non-vehicular building applications, though occasionally there has been advocacy of their use as mobile air conditioning systems.

Evaporative Cooling

The latent heat of vaporization of water can provide cooling to vehicle occupants. A crude approach is to spray one's face with a water mist, then place the head outside the window of a moving vehicle into the free air stream- the evaporating water carries away heat from the skin. There have been devices, mostly in the 1950s, akin to home "swamp coolers" that are placed hanging from a vehicle's side window, that utilize the evaporation of water in the free air stream to provide a cooling effect for vehicle occupants. At one time, they had a certain attractiveness, particularly in hot, low humidity regions like the U.S. Southwest. However, their performance compared to modern vehicular air conditioning systems is generally inadequate and they currently do not have significant popularity.[6]

Thermoelectric Refrigeration

When an electrical current is passed through a junction consisting of two dissimilar materials (usually metals or some types of semiconductors), the junction is cooled. This is called the Peltier effect. Unfortunately, at present this technology has a very low COP and therefore cannot compete directly with more conventional refrigeration cycles. It has been used in such devices as small food and beverage coolers, and as seat coolers in such high-end vehicles as the Lincoln Navigator and certain Lexus and Infiniti models[7].

Heat Pumps

Generally, some of the refrigeration cycles described above can be adapted to act as heat pumps, wherein the primary objective of a system's operation is not to remove heat from a cooled space but to add heat into a hot or warm space. Indeed, a heat pump can be thought of, at risk of oversimplification, as an air conditioner installed backwards.

In most current-day automobiles, raising the temperature of the passenger compartment air is usually accomplished by the simple use of a liquid-to-air heat exchanger to transfer heat from the engine coolant system to a flow of air forced into the passenger compartment. But with the increased use of highly efficient diesel engines, particularly direct injection models as presently occurring in Europe, and the anticipated increase in the use of hybrid vehicles, engine coolant will no longer have the customary temperatures and capacities for acceptable passenger compartment heating and window defrosting/demisting operations[8]. However, a heat pump can be used to convey this low-grade heat to the passenger compartment boosted to temperature levels to which vehicle occupants are accustomed. Proper design of vehicle air conditioning systems could allow them to be operated as heat pumps upon demand, with acceptable additional cost and complexity.

At present, some vehicles that require heating supplemental to the conventional engine coolant heater core approach currently utilize electric or fuel-fired heaters. Such systems at best have a COP of 1, whereas a well-designed heat pump will have a COP greater than 1, so it is easy to see the advantage of a heat pump system over these other heat source options.

For demisting of window and windshield interiors, heat pump systems could be at a disadvantage. Current automobiles often use the air conditioning system to first cool and dehumidify incoming air, then the engine coolant-based heating system raises the air's temperature just before it is directed at the window/windshield[9]. This combination of dehumidified-then-heated air is very effective in quickly removing mist and restoring clear visibility. Unfortunately, if the primary heating function is provided by the air conditioning system operating as a heat pump, then there is no separate air conditioning system to first provide cooling/dehumidification. This could adversely affect the speed, efficiency and safety with which the demisting process occurs.[10]

For California, it is unclear what the demand for vehicular heat pumps will be in the future. This report primarily addresses only the needs for the cooling performance from alternative systems.

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