# The First Law of Thermodynamics for Control Volumes Part III

## Refrigerators and Heat Pumps

### Introduction and Discussion

In the early days of refrigeration the two refrigerants in common use were ammonia and carbon dioxide. Both were problematic - ammonia is toxic and carbon dioxide requires extremely high pressures (from around 30 to 200 atmospheres!) to operate in a refrigeration cycle, and since it operates on a transcritical cycle the compressor outlet temperature is extremely high (around 160°C). When Freon 12 (dichloro-diflouro-methane) was discovered it totally took over as the refrigerant of choice. It is an extremely stable, non toxic fluid, which does not interact with the compressor lubricant, and operates at pressures always somewhat higher than atmospheric, so that if any leakage occured, air would not leak into the system, thus one could recharge without having to apply vacuum.

Unfortunately when the refrigerant does ultimately leak and make its way up to the ozone layer the ultraviolet radiation breaks up the molecule releasing the highly active chlorine radicals, which help to deplete the ozone layer. Freon 12 has since been banned from usage on a global scale, and has been essentially replaced by chlorine free R134a (tetraflouro-ethane) - not as stable as Freon 12, however it does not have ozone depletion characteristics.

Recently, however, the international scientific consensus is that Global Warming is caused by human energy related activity, and various man made substances are defined on the basis of a Global Warming Potential (GWP) with reference to carbon dioxide (GWP=1). R134a has been found to have a GWP of 1300 and in Europe, within a few years, automobile air conditioning systems will be barred from using R134a as a refrigerant.

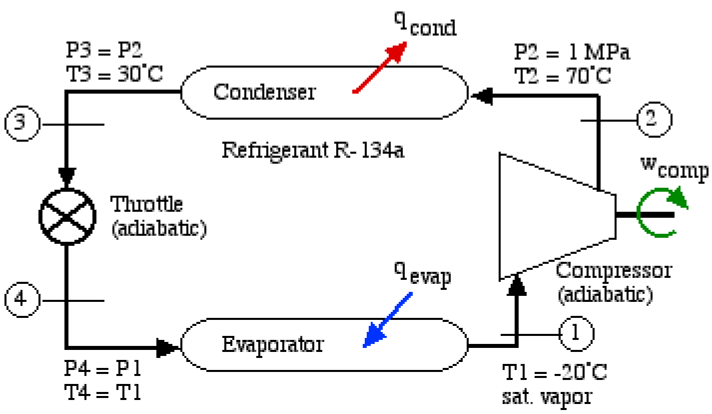
The new hot topic is a return to carbon dioxide (R744) as a refrigerant (refer for example to the website: R744.com). The previous two major problems of high pressure and high compressor temperature are found in fact to be advantageous. The very high cycle pressure results in a high fluid density throughout the cycle, allowing miniturization of the systems for the same heat pumping power requirements. Furthermore the high outlet temperature will allow instant defrosting of automobile windshields (we don't have to wait until the car engine warms up) and can be used for combined space heating and hot water heating in home usage (refer for example: Norwegian IEA Heatpump Program Annex28.

In this chapter we cover the vapor-compression refrigeration cycle using refrigerant R134a, and will defer coverage of the carbon dioxide cycle to Chapter 9.

## A Basic R134a Vapor-Compression Refrigeration System

Unlike the situation with steam power plants it is common practice to begin the design and analysis of refrigeration and heat pump systems by first plotting the cycle on the *P-h* diagram.

The following schematic shows a basic refrigeration or heat pump system with typical property values. Since no mass flow rate of the refrigerant has been provided, the entire analysis is done in terms of specific energy values. Notice that the same system can be used either for a refrigerator or air conditioner, in which the heat absorbed in the evaporator ($q_{evap}$) is the desired output, or for a heat pump, in which the heat rejected in the condenser ($q_{cond}$) is the desired output.

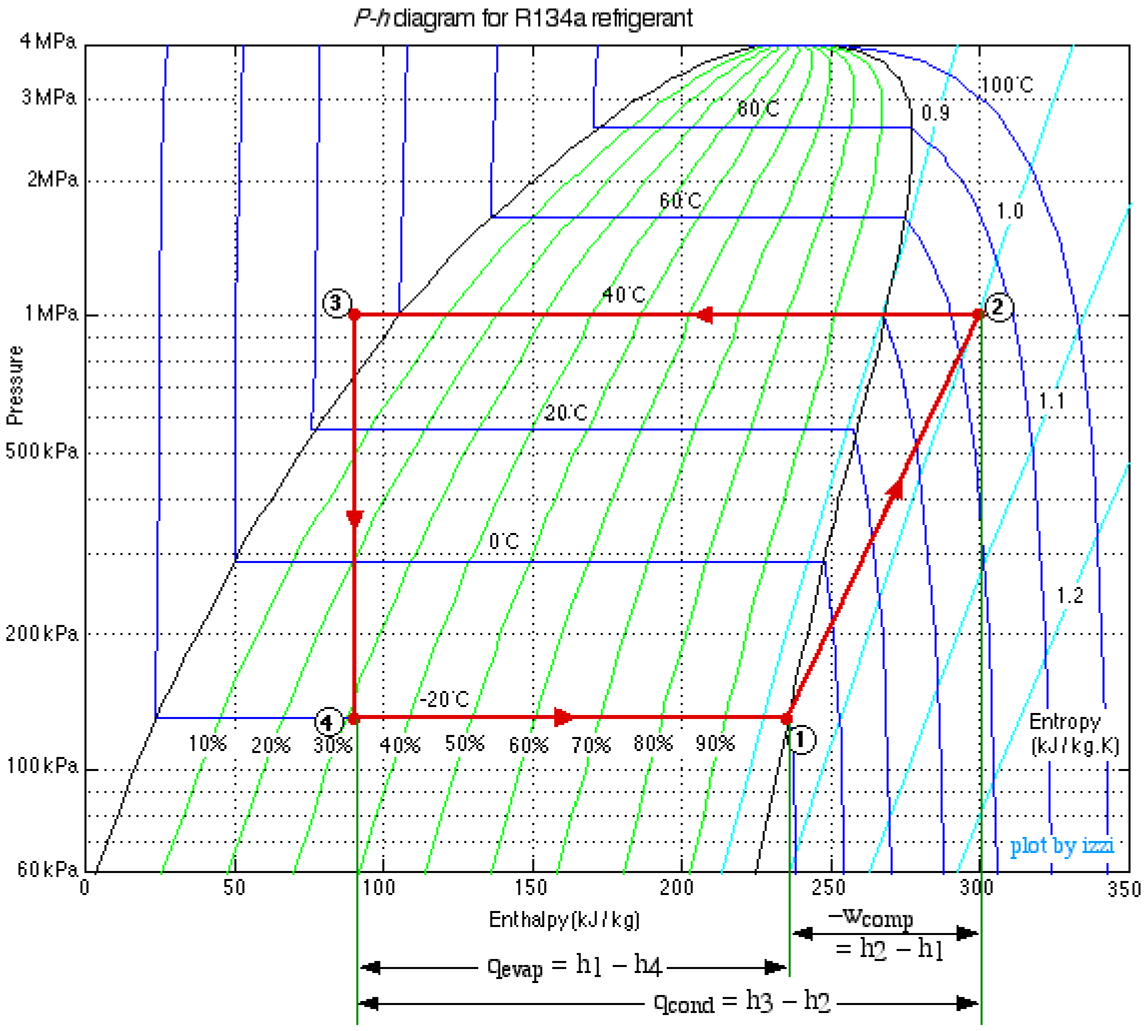



In this example we wish to evaluate the following:

- Heat absorbed by the evaporator ($q_{evap}$) [kJ/kg]
- Heat rejected by the condenser ($q_{cond}$) [kJ/kg]
- Work done to drive the compressor ($w_{comp}$) [kJ/kg]
- Coefficient of Performance (COP) of the system, either as a refrigerator or as a heat pump.

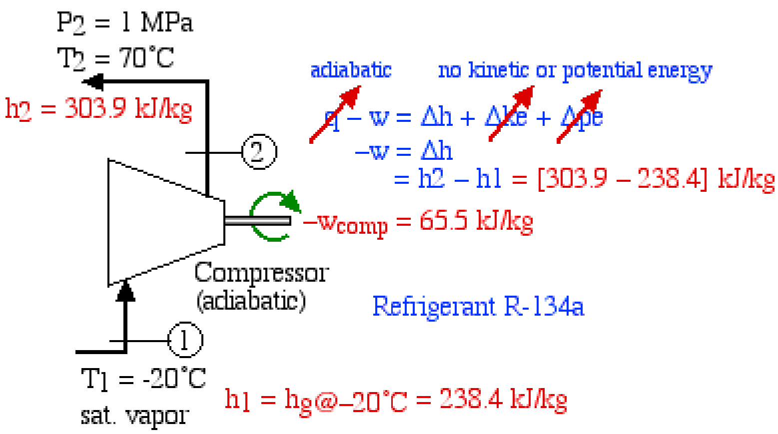
As with the Steam Power Plant, we find that we can solve each component of this system separately and independently of all the other components, always using the same approach and the same basic equations. We first use the information given in the above schematic to plot the four processes (1)-(2)-(3)-(4)-(1) on the *P-h* diagram. Notice that the fluid entering and exiting the condenser (State (2) to State (3)) is at the high pressure 1 MPa. The fluid enters the evaporator at State (4) as a saturated mixture at -20°C and exits the evaporator at State (1) as a saturated vapor. State (2) is given by the intersection of 1 MPa and 70°C in the superheated region. State (3) is seen to be in the subcooled liquid region at 30°C, since the saturation temperature at 1 MPa is about 40°C. The process (3)-(4) is a vertical line ($h_3 = h_4$) as is discussed below.

In the following section we develop the methods of evaluating the solution of this example using the R134a refrigerant tables. Notice that the refrigerant tables do not include the subcooled region, however since the constant temperature line in this region is essentially vertical, we use the saturated liquid value of enthalpy at that temperature.

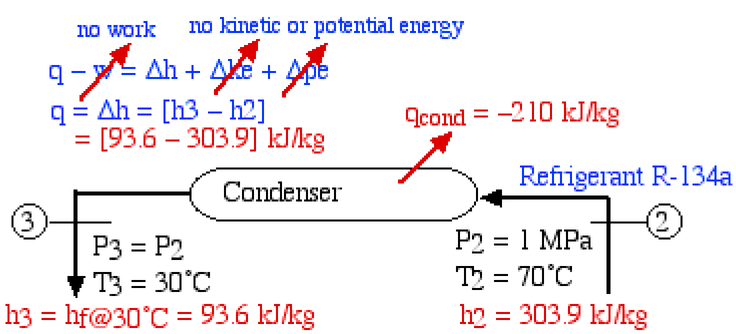



Notice from the *P-h* diagram plot how we can get an instant visual appreciation of the system performance, in particular the Coefficient of Performance of the system by comparing the enthalpy difference of the compressor (1)-(2) to that of the evaporator (4)-(1) in the case of a refrigerator, or to that of the condenser (2)-(3) in the case of a heat pump.

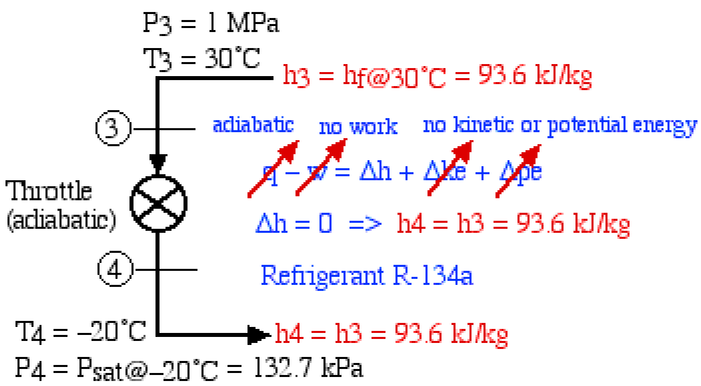
We now consider each component as a separate control volume and apply the energy equation, starting with the compressor. Notice that we have assumed that the kinetic and potential energy change of the fluid is negligeable, and that the compressor is adiabatic. The required values of enthalpy for the inlet and outlet ports are determined from the R134a refrigerant tables.



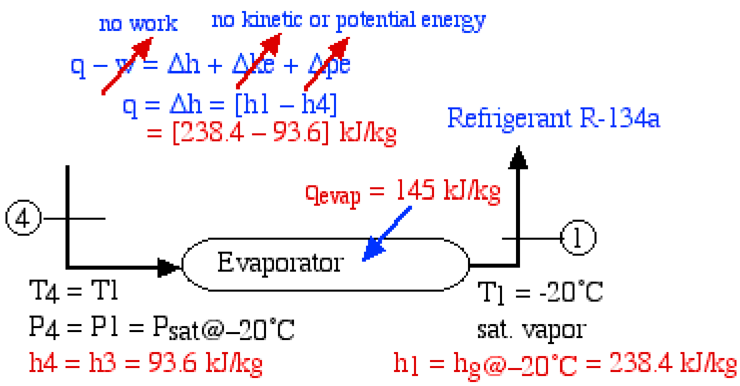

The high pressure superheated refrigerant at port (2) is now directed to a condenser in which heat is extracted from the refrigerant, allowing it to reach the subcooled liquid region at port (3). This is shown on the following diagram of the condenser:




The throttle is simply an expansion valve which is adiabatic and does no work, however enables a significant reduction in temperature of the refrigerant as shown in the following diagram:




The final component is the evaporator, which extracts heat from the surroundings at the low temperature allowing the refrigerant liquid and vapor mixture to reach the saturated vapor state at station (1).




In determining the Coefficient of Performance - for a refrigerator or air-conditioner the desired output is the evaporator heat absorbed, and for a heat pump the desired output is the heat rejected by the condenser which is used to heat the home. The required input in both cases is the work done on the compressor (ie the electricity bill). Thus

$COP_R = q_{evap} / w_{comp} = 145 / 65.5 = 2.2$

$COP_{HP} = q_{cond} / w_{comp} = 210 / 65.5 = 3.2$

Notice that for the same system we always find that $COP_{HP} = COP_R + 1$.
Notice also that the COP values are usually greater than 1, which is the reason why they are never referred to as "Efficiency" values, which always have a maximum of 100%.

Thus the *P-h* diagram is a widely used and very useful tool for doing an approximate evaluation of a refrigerator or heat pump system. In fact, in the official Reference Handbook supplied by the **NCEES** to be used in the Fundamentals of Engineering exam, only the *P-h* diagram is presented for R134a. You are expected to answer all the questions on this subject based on plotting the cycle on this diagram as shown above.

Source: http://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/Chapter4c.html