Vapor-Compression Refrigeration Cycle

Thermal, Fluids, and Energy Systems Lab

(ME EN 4650)

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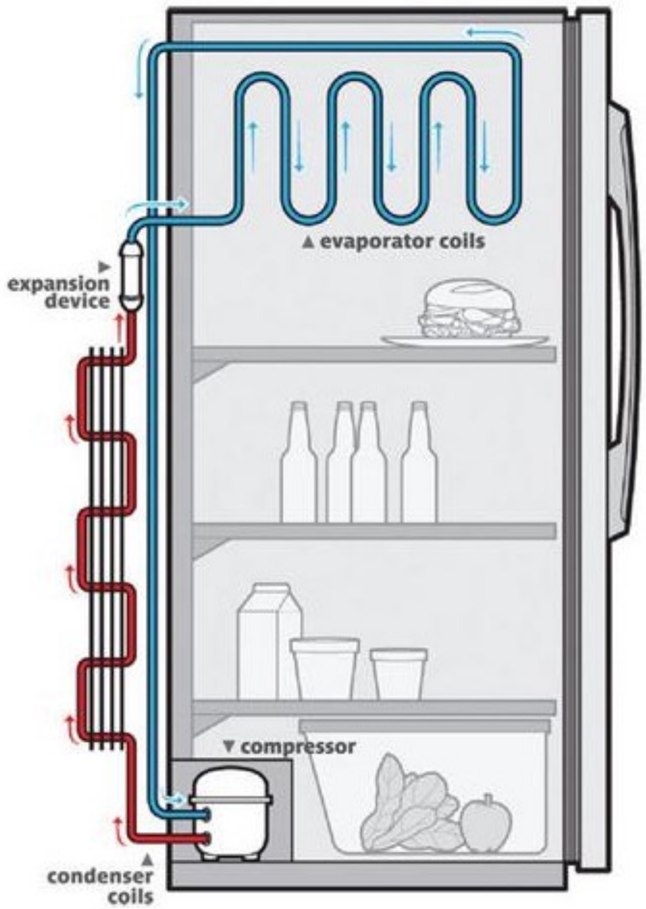
Based on Prof. M's slides

THE UNIVERSITY OF UTAH

Objectives

- Measure temperatures and pressures in a refrigeration system designed on the vapor-compression cycle
- Determine the coefficient of performance COP_R using the First Law of Thermodynamics as a function of refrigerant ow rate
- Determine the amount of heat rejected from the refrigerant as a function of refrigerant flow ow rate, and calculate the isentropic compressor efficiency as a function of refrigerant flow rate

Vapor-Compression Refrigeration Cycle Lab Overview



$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}}$$

What we want to know:

- Temperature in the refrigerated space as a function of mass flow rate
- Heat rejected to from the refrigerated space (Q_L)
- Coefficient of performance (COP_R)
- Compressor efficiency (η_C)

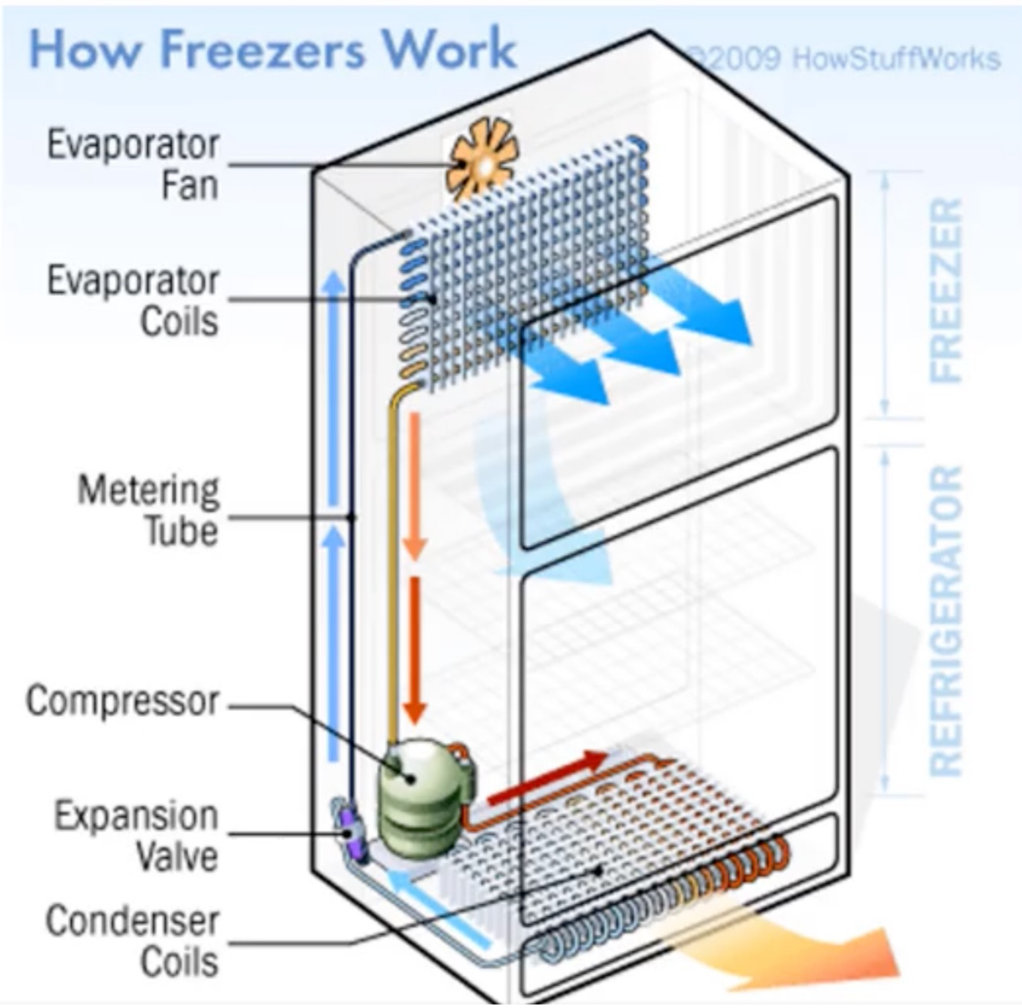
What we can measure:

- Temperature and pressure (dial gauges)
- Refrigerant volume flow rate (rotameter)
- Air temperatures T_c, T_e (thermocouples)
- Electrical power supplied to system (total and fan power)

Outline

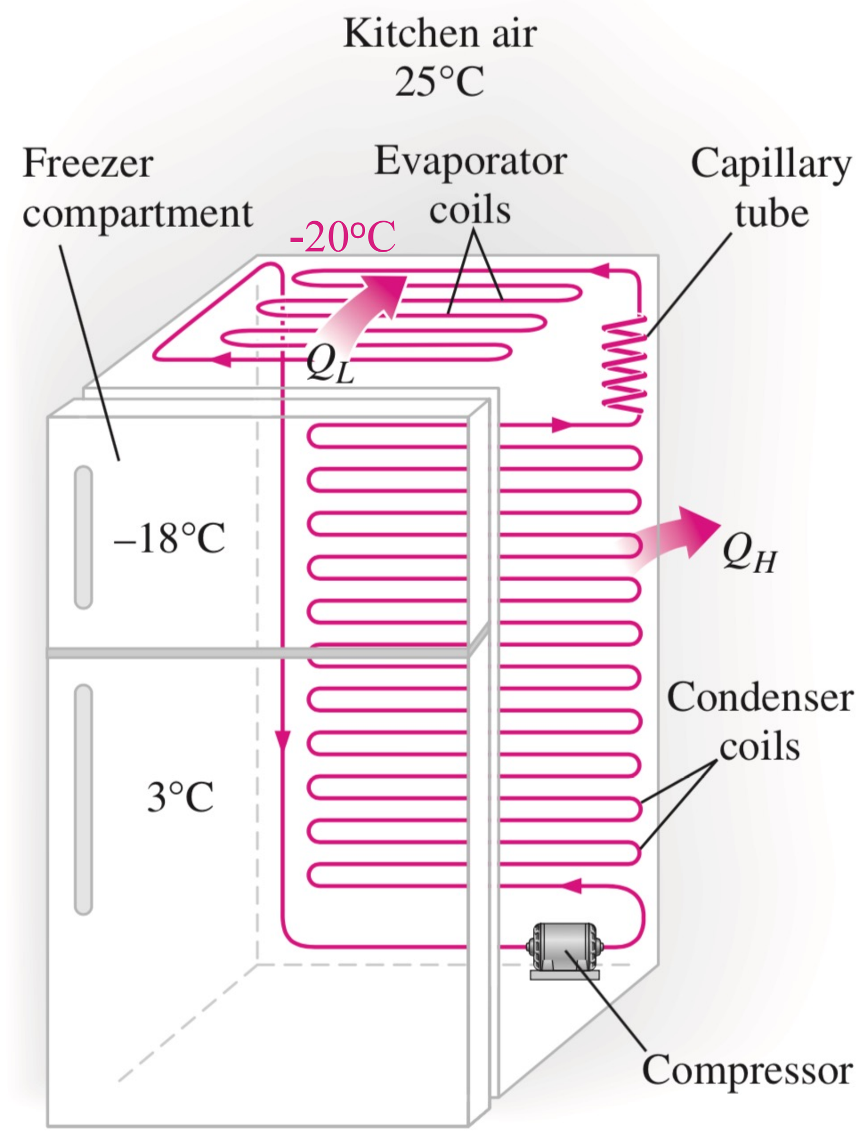
- Background (Thermodynamics)
- Experimental Setup
- Measurements and Instrumentation
- Required Figures
- Data Analysis

Refrigerator Components



- Removes heat from refrigerated medium
- Maintains refrigerated medium at a low temperature
- Does not care about discharged heat
- Closed system
- Hydrofluorocarbon refrigerant
- Low power consumption

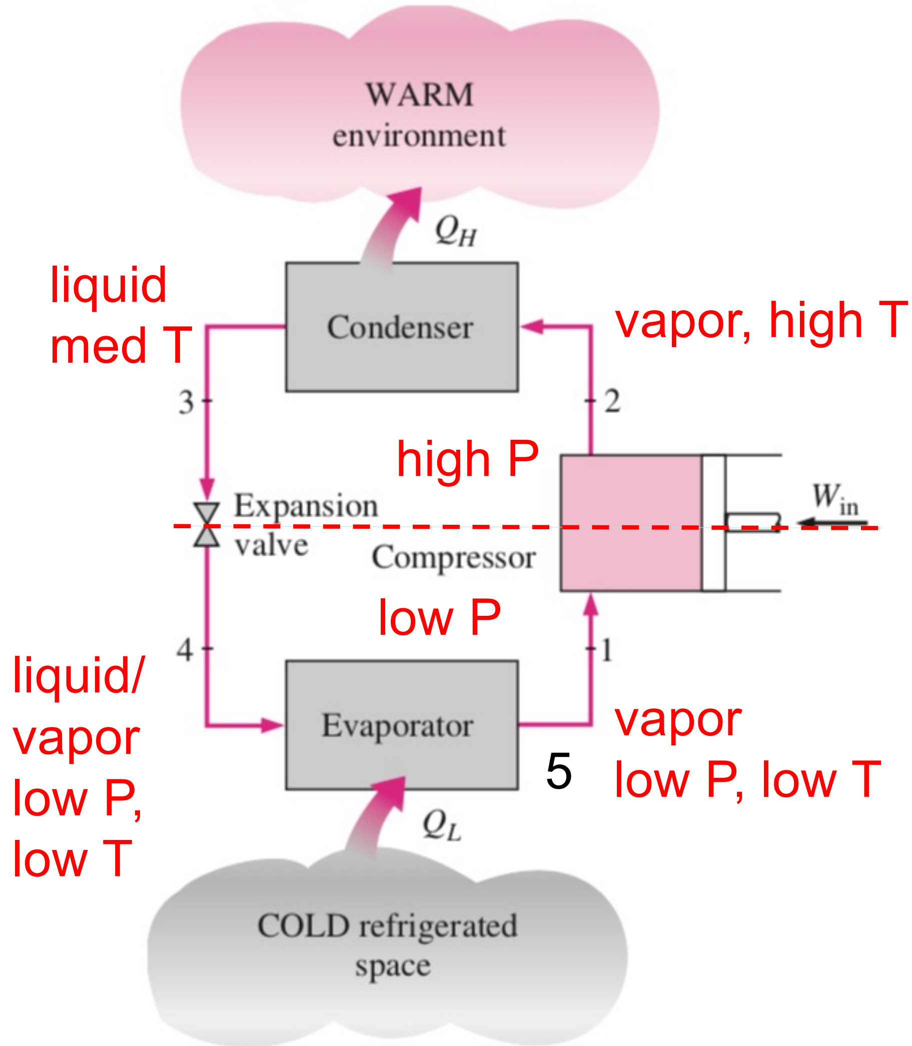
Refrigerator Temperatures



Ideal Schematic

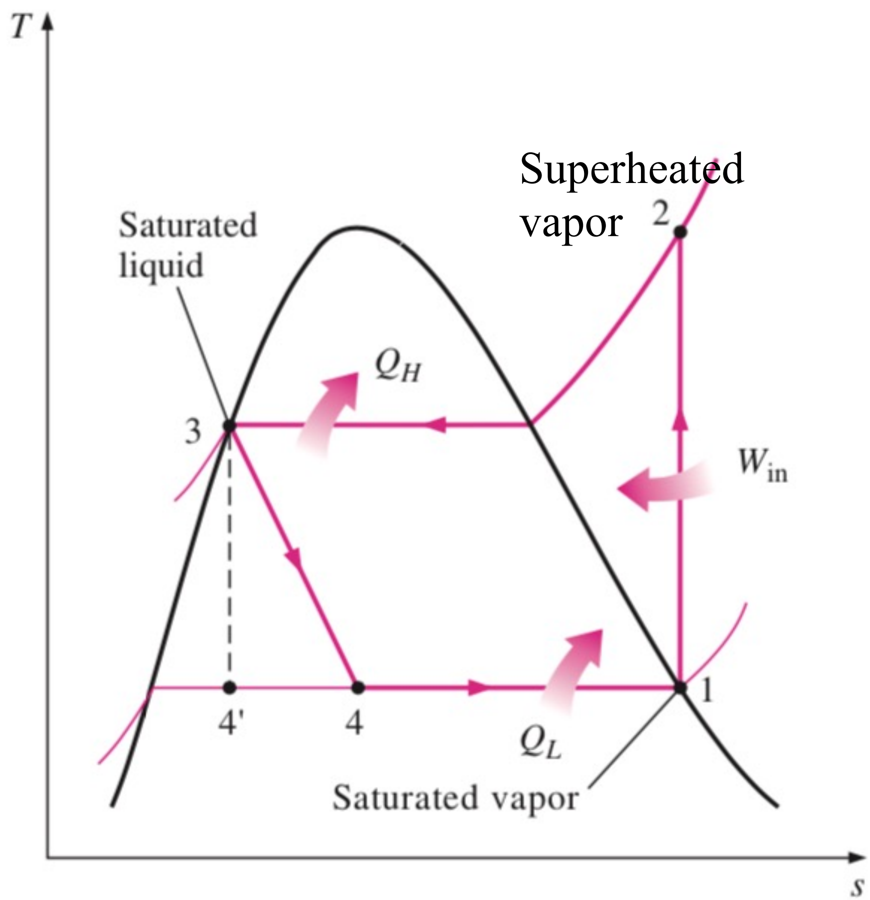
T_h ~25 C

T_c ~ 3 C

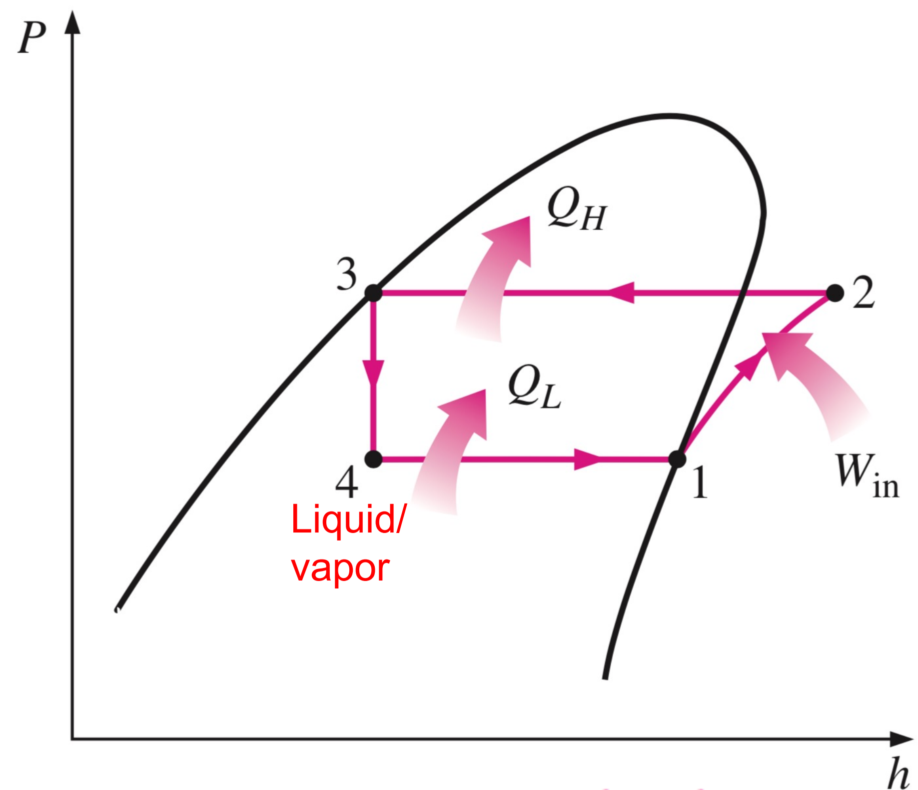


Ideal Cycle

T-s Diagram

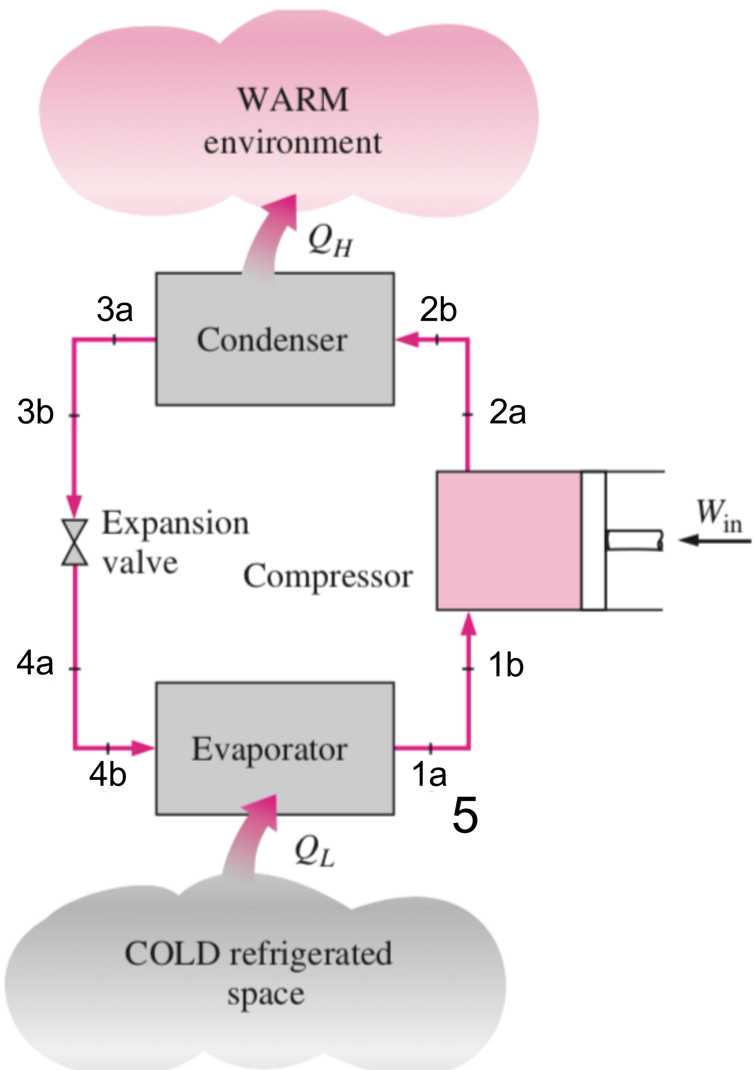


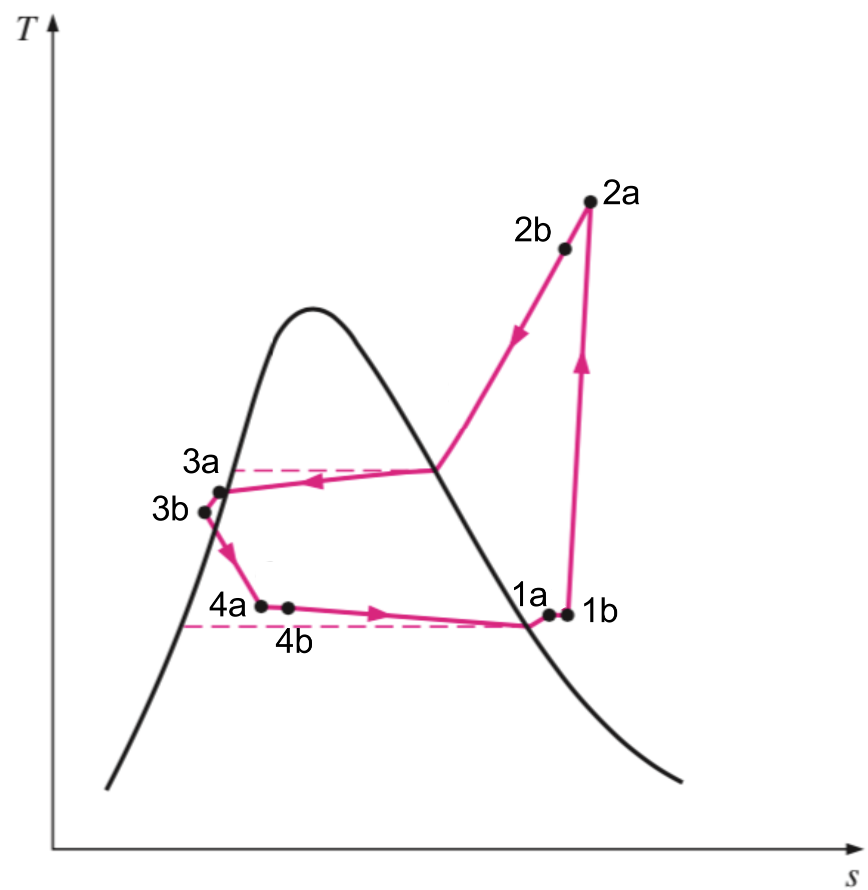
P-h Diagram



$$\mathrm{COP_R} = \frac{q_L}{w_{\mathrm{net,in}}} = \frac{h_1 - h_4}{h_2 - h_1}$$

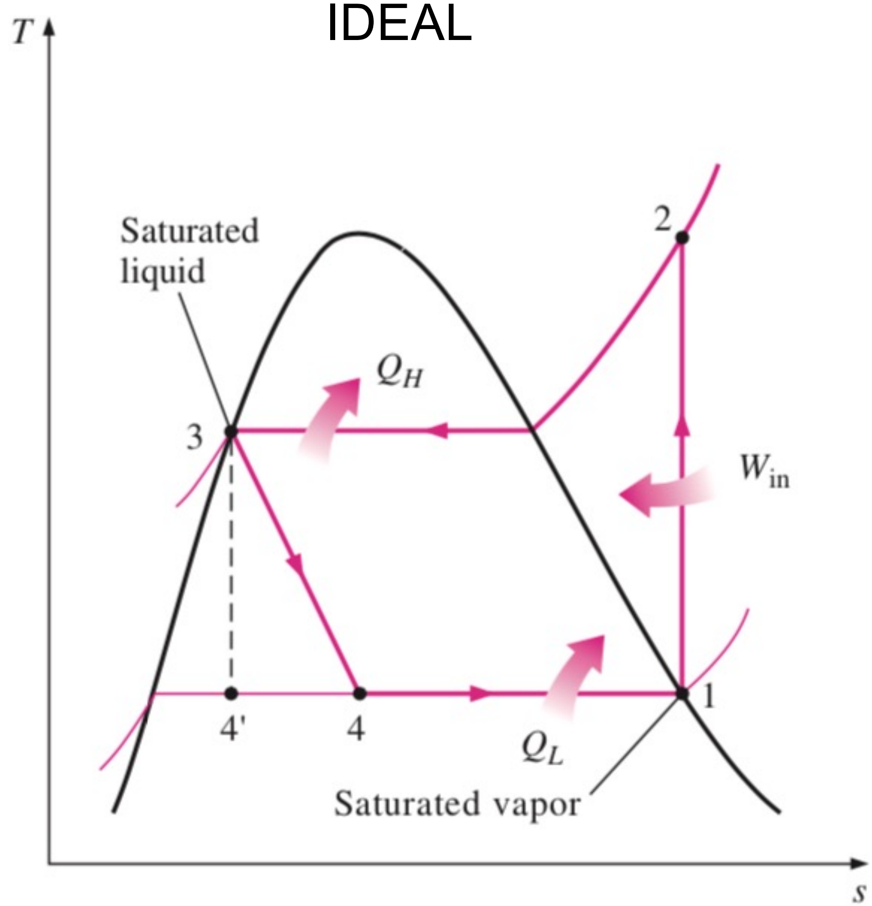
Actual Cycle



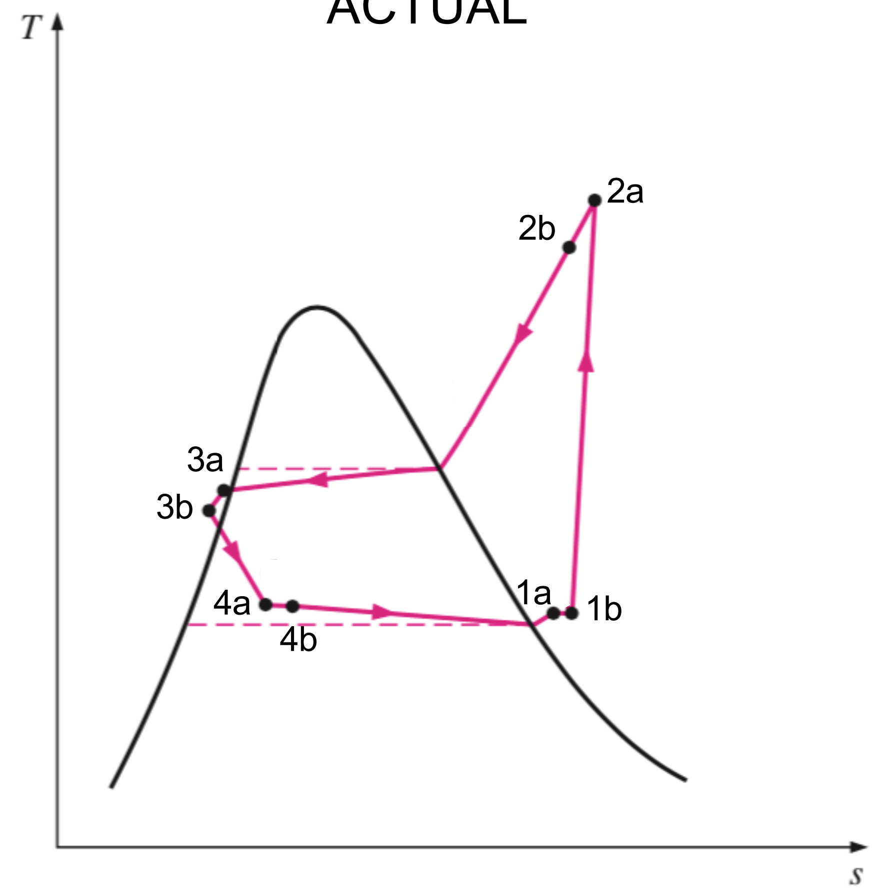


Ideal vs Actual Cycle

IDEAL



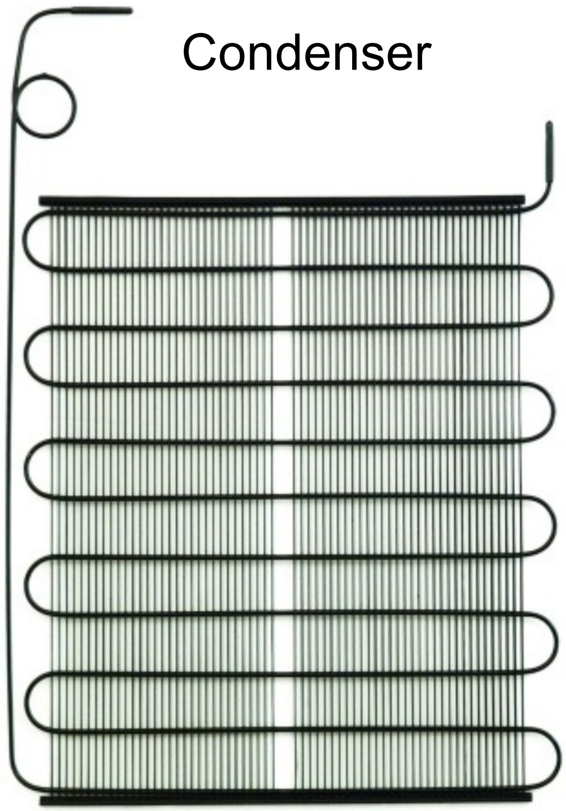
ACTUAL



Refrigerator Components

Compressor

Condenser

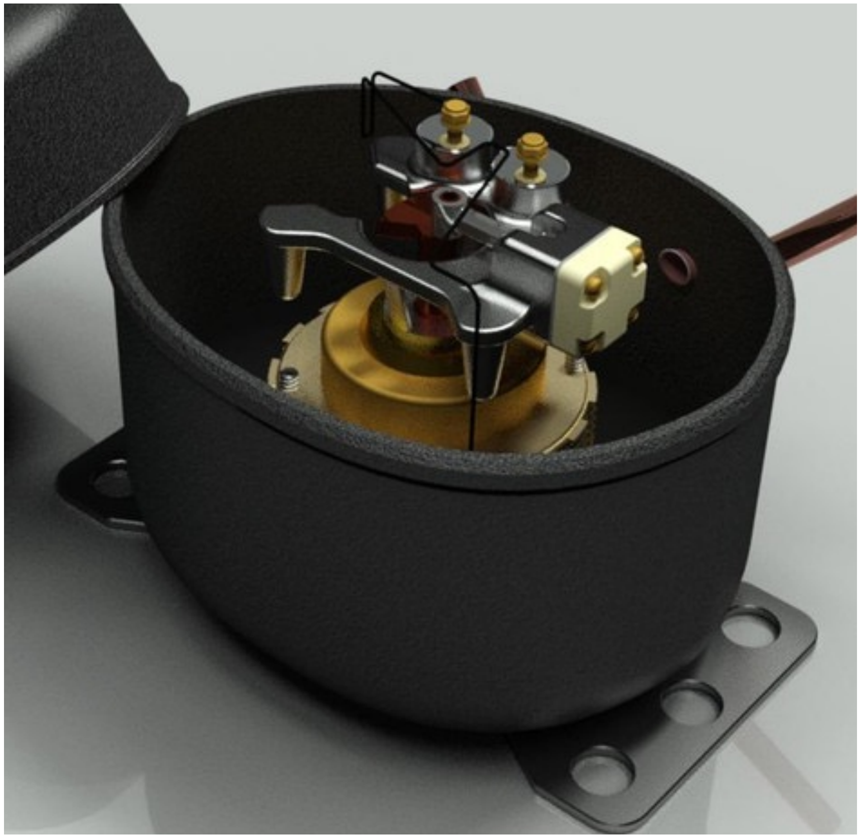


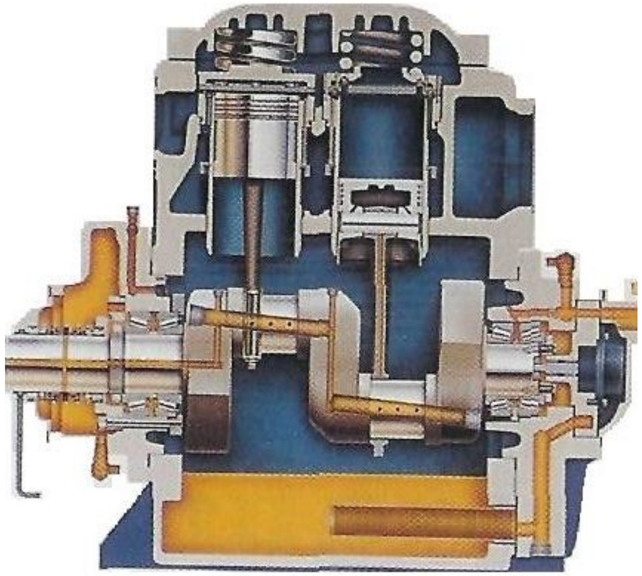
Evaporator

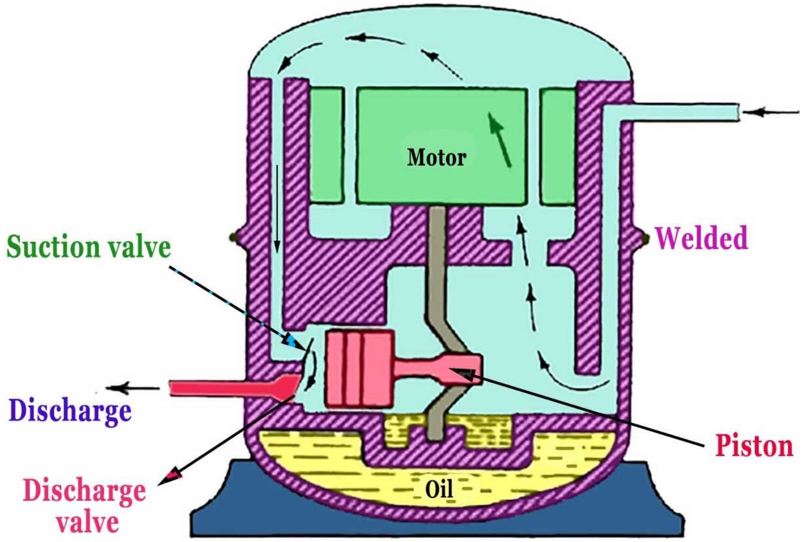
Refrigerant
(working fluid)

Throttling valve

Compressor





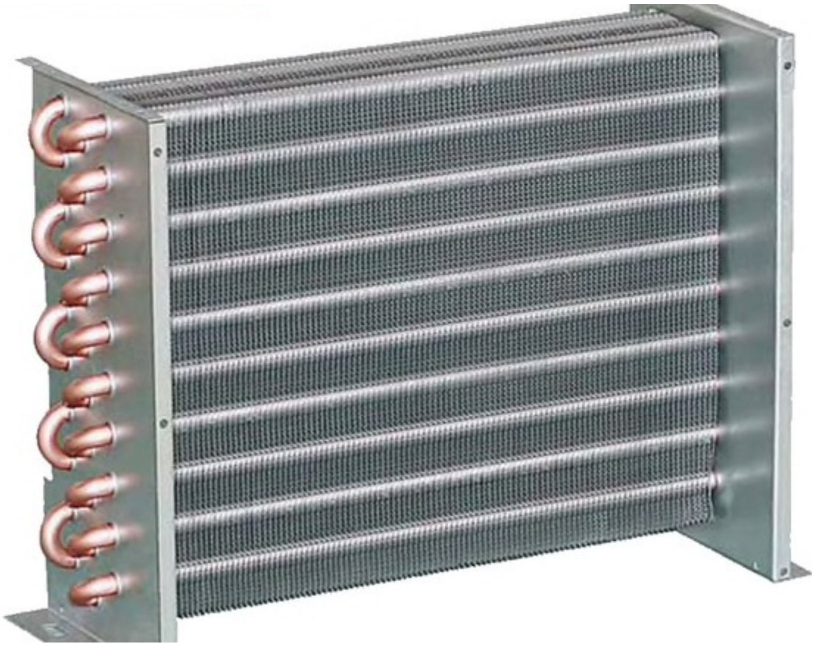

Motor
Suction valve
Welded
Discharge
Piston
Discharge valve
Oil

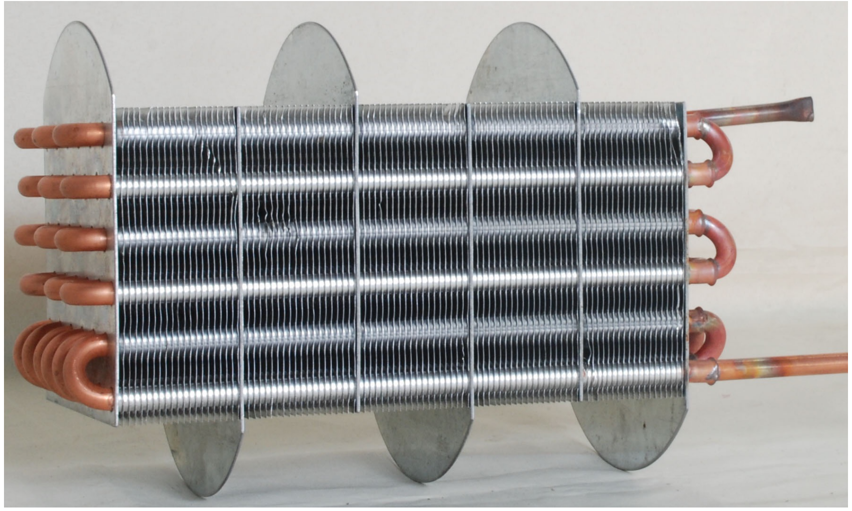
Condenser Coils

Located in **back** of unit

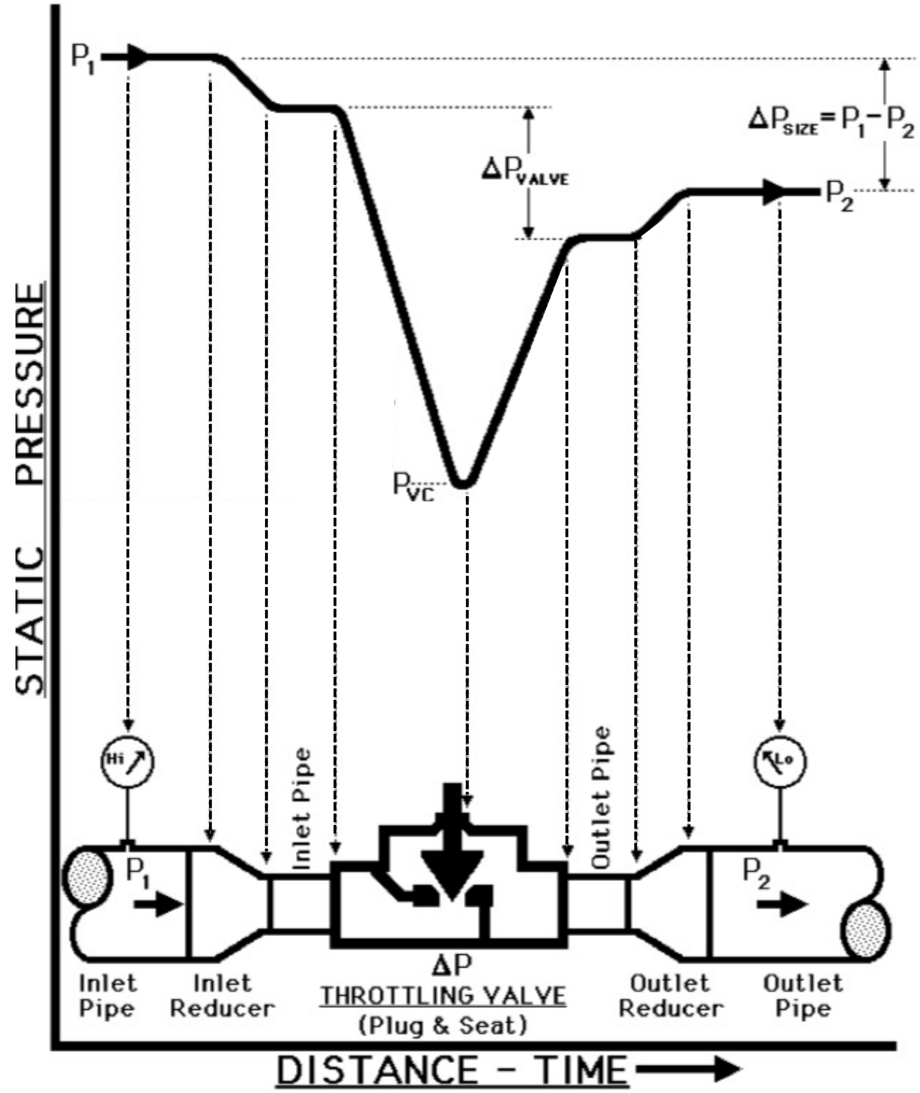
Located in **bottom** of unit

Fin-and-Tube Heat Exchangers



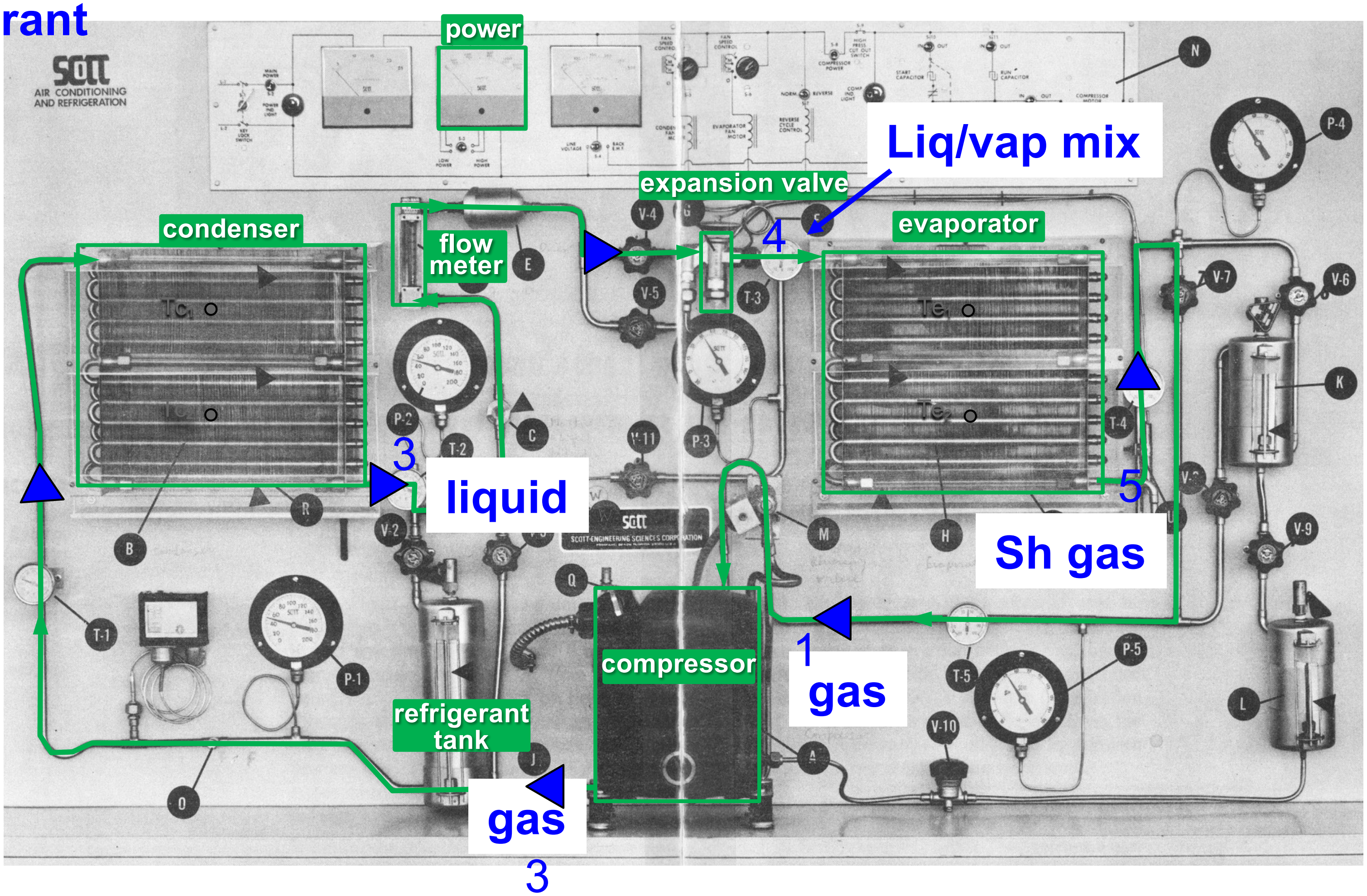


Throttling Valve

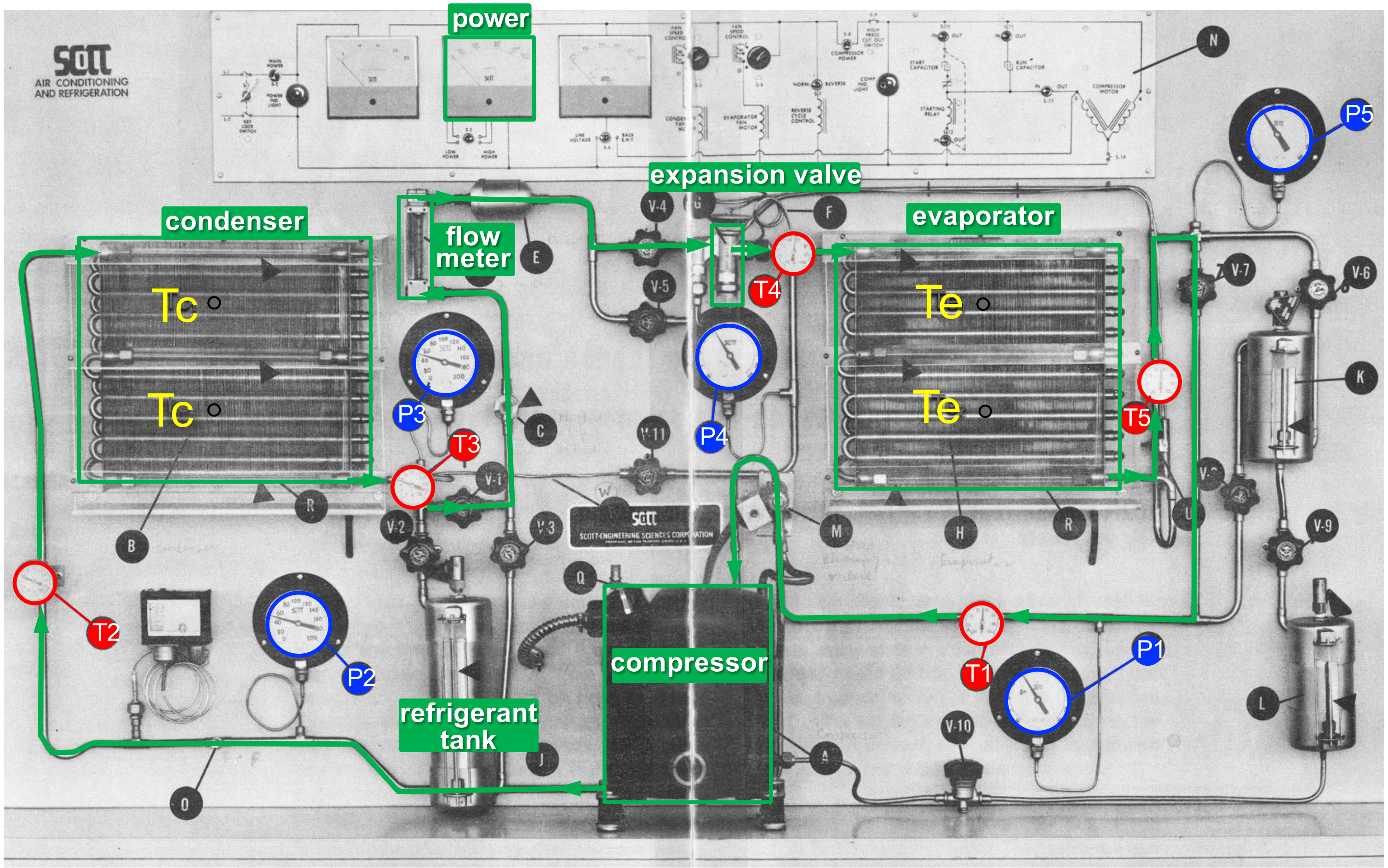


Experimental Setup

R134a refrigerant



Experimental Setup Measurements



State T in ^oF, state P in psig, and flow rate gpm; Tc, Te in ^oC; Power in W

Experiments

- 4 experiments will be run by adjusting the flow rates of the refrigerant with a needle valve of approximately: 0.07, 0.1, 0.15, 0.2 gpm
- Read the pressure, temperature, thermocouples, and power meter from the gauges

Measurements

Table 2. List of measured state points in the experiment.

	Pressure	Temperature
compressor inlet	P_1	T_1
compressor outlet (condenser inlet)	P_2	T_2
condenser outlet (expansion valve inlet)	P_3	T_3
expansion valve outlet (evaporator inlet)	P_4	T_4
evaporator outlet	P_5	T_5

Table 3. List of measurements acquired in the experiment with their native units.

Quantity	Symbol	Units	Instrument
Refrigerant temperature	T	°F	dial gauge
Refrigerant pressure	P	psig	dial gauge
Air temperature	T_e, T_c	°C	thermocouple
Refrigerant volume flow rate	$\dot{V}$	gpm	rotameter
Electrical power	$\dot{W}_{\text{total}}$	W	analog meter

Need to convert everything to SI units

Data Analysis

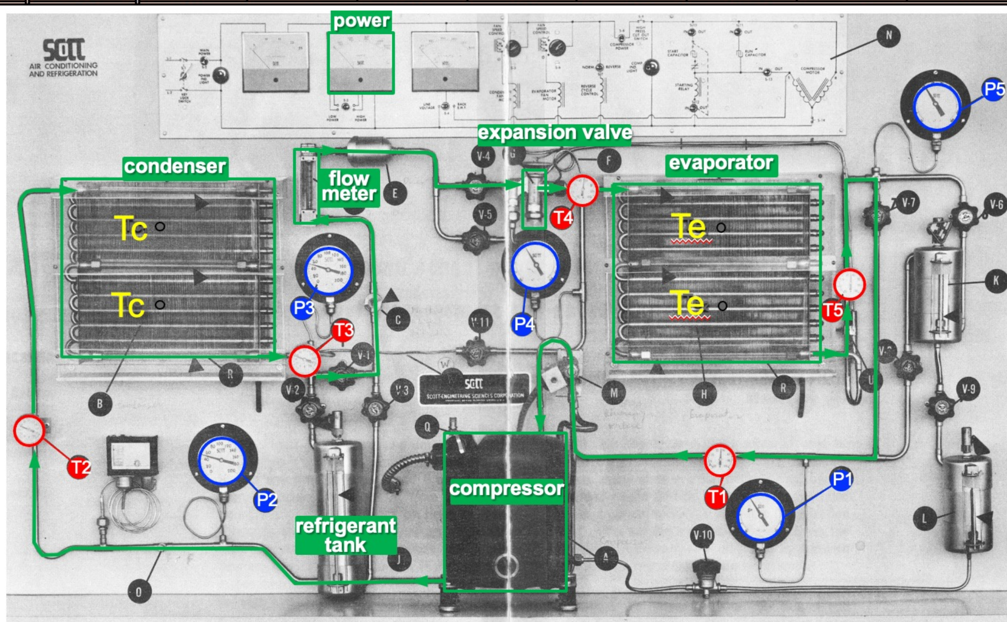
Your Data!

TFES Lab (ME EN 4650)

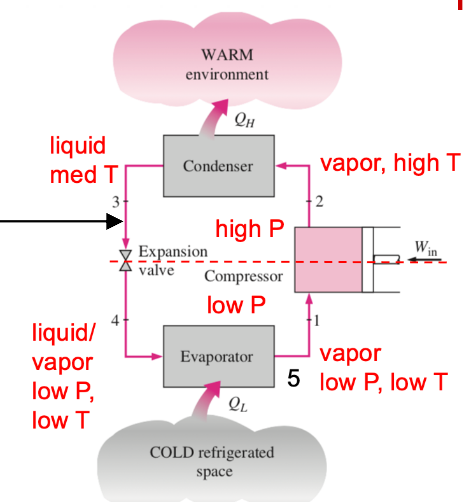
Vapor-Compression Refrigeration: Raw Data Sheet

Ambient Temperature, T_{amb} :	23.5	(°C)
Barometric Pressure, P_{amb} :	651.4	(mm Hg)
Electrical Power to Fans Only, W_{fan}:	130	(W)

Flow Rate (gpm)	Total Power (W)	Refrigerant State Points										Air Temperatures			
		T1 (oF)	P1 (psig)	T2 (oF)	P2 (psig)	T3 (oF)	P3 (psig)	T4 (oF)	P4 (psig)	T5 (oF)	P5 (psig)	Tc1 (oC)	Tc2 (oC)	Te1 (oC)	Te2 (oC)
0.2	840	62	31	120	147	98	145	39	40	62	35	35.3	34.3	15.7	18.9
0.15	680	63	20	140	135	82	135	24	27	68	23	32.8	29.7	11.7	22.5
0.1	570	69	10	135	136	72	114	2	13	70	12	29.5	25.7	11.7	23
0.07	515	70	5	132	108	75	105	-5	8	70	9	28.2	25	12.2	23



Flow meter

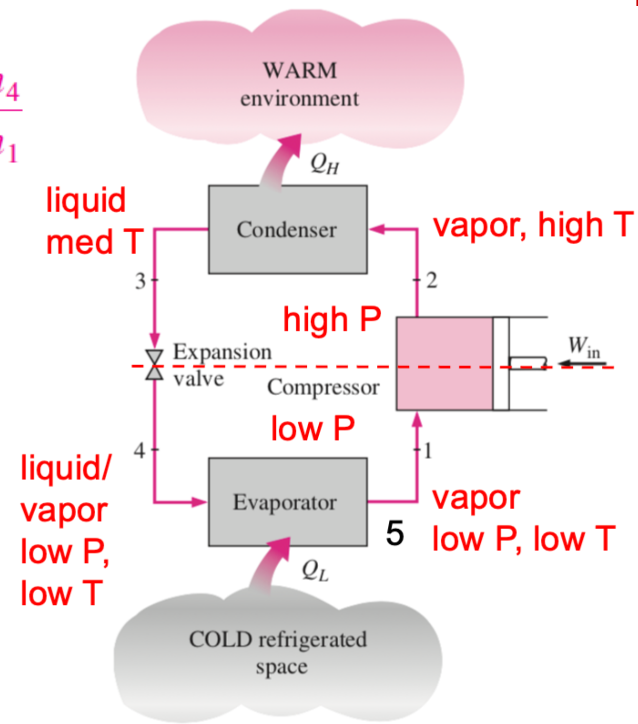


Required Figures

- $T_3, T_4, \overline{T_c}, \overline{T_e}, T_{\text{amb}}$ (°C) vs $\dot{m}$ (kg/s)
- $q_L, q_H, q_{\text{loss}}, w_{\text{in}}$ (kJ/kg) vs $\dot{m}$ (kg/s)
- COP_R vs $\dot{m}$ (kg/s)

$$\text{COP}_\text{R} = \frac{q_L}{w_{\text{net,in}}} = \frac{h_1 - h_4}{h_2 - h_1}$$

- η_c and $\dot{W}_{\text{total}}$ (W) vs $\dot{m}$ (kg/s)
- P (MPa) vs h (kJ/kg)



Thermodynamic properties

$$\underbrace{(T, P)}_{\text{data}} \implies \rho \text{ and } h$$

We'll use CoolProp (free python package) instead of the tables in the back of your book

Using CoolProp in Matlab to get Thermodynamic Properties

CoolProp is an open-source database of fluid and humid air properties (www.coolprop.org), formulated based on the most accurate state equations available in the literature. The CoolProp package has already been installed on the CADE LAB machines. It can be accessed via Python, and imported into Matlab. To do this, type the following line into the Matlab Command Window upon startup of the program:

```
>> pyversion C:\Anaconda3\python.exe
```

This command tells Matlab where to find the CoolProp library. Note, you only need to type this command ONCE per Matlab installation. If you quit Matlab and restart it, you do not need to type in this command again. Then, at the top of your Matlab script for the Refrigeration Lab analysis, include the following line in order to import the CoolProp library into Matlab:

```
% load the CoolProp package into Matlab
import py.CoolProp.CoolProp.PropsSI
```

Since enthalpy is a relative property (only changes in enthalpy represent the important physical characteristic of a system), we need to set the reference state. We will utilize a standard reference state where h=200 kJ/kg and s=1.0 kJ/kg·K for saturated liquid at T=0°C. To do this, add the following line to your Matlab script:

```
% set reference state to match that in provided P-h diagram
py.CoolProp.CoolProp.set_reference_state('R134a','IIR')
```

Using CoolProp in Matlab

You should be able to import a couple of commands, set the reference state and then use the code directly. Note: you can't send in arrays (use a loop).

```
%import so that you don't have to type the full command out
import py.CoolProp.CoolProp.PropsSI %you can just type PropsSI now
import py.CoolProp.CoolProp.set_reference_state %you can just type set_reference_state now

%set reference state (only do this one time at the beginning)
%the for IIR it is: h = 200 kJ/kg, s=1 kJ/kg/K at 0C saturated liquid
%Recall, entropy and enthalpy are relative
set_reference_state('R134a','IIR')

T1 = 36 + 273.15; %T should be in Kelvin
P1 = 912.35e3 %Pressure in Pa

% You need to provide 2 state variables (e.g. T and P)
%Compute the density of the refrigerant (kg/m^3)
D1 = PropsSI('D','T',T1,'P',P1,'R134a')

%Compute the enthalpy of the refrigerant (J/kg)
H1 = PropsSI('H','T',T1,'P',P1,'R134a')

%Compute the entropy of the refrigerant (J/kg/K)
S1 = PropsSI('S','T',T1,'P',P1,'R134a')
```

See appendix in lab

density 1163.42 (kg/m^3)
enthalpy 250477.28 (J/kg)
entropy 1171.70 (J/kg/K)

Data Analysis

- T_1, T_2, T_3, T_4, T_5 : convert °F to K
- $\overline{T_c} = \frac{1}{2}\left(T_{c_1} + T_{c_2}\right)$ and $\overline{T_e} = \frac{1}{2}\left(T_{e_1} + T_{e_2}\right)$
- $P = P_{\text{g}} + P_{\text{atm}}$: convert to Pa

Data Analysis

- Determine refrigerant density and enthalpy from "CoolProp"

```
%TinK(i,j) -> i is the row, j is the column
%TinK(i,j) -> i mass flow rate, j is the state
for i = 1:height(TinK) %mass flow rate (1 to 4)
  for j=1:length(TinK) %state location (1 to 5)
    %Compute the density of the refrigerant (kg/m^3)
    D(i,j) = PropsSI('D','T',TinK(i,j),'P',PabsPa(i,j),'R134a');
    %Compute the enthalpy of the refrigerant (J/kg)
    H(i,j) = PropsSI('H','T',TinK(i,j),'P',PabsPa(i,j),'R134a');
  end
end
```

TinK =

	T_1	T_2	T_3	T_4	T_5
$\dot{m} - \exp 1$	289.8167	322.0389	309.8167	277.0389	289.8167
$\dot{m} - \exp 2$	290.3722	333.1500	300.9278	268.7056	293.1500
$\dot{m} - \exp 3$	293.7056	330.3722	295.3722	256.4833	294.2611
$\dot{m} - \exp 4$	294.2611	328.7056	297.0389	252.5944	294.2611

- $\dot{m} = \rho_3 \dot{V}$ Determine the mass flow rate from state 3 were the rotometer was located

Your Data!

TFES Lab (ME EN 4650)

Vapor-Compression Refrigeration: Raw Data Sheet

Ambient Temperature, T_{amb}:	23.5	(°C)
Barometric Pressure, P_{amb}:	651.4	(mm Hg)
Electrical Power to Fans Only, W_{fan}:	130	(W)

Flow Rate	Total Power	Refrigerant State Points										Air Temperatures			
		T1 (oF)	P1 (psig)	T2 (oF)	P2 (psig)	T3 (oF)	P3 (psig)	T4 (oF)	P4 (psig)	T5 (oF)	P5 (psig)	Tc1 (oC)	Tc2 (oC)	Te1 (oC)	Te2 (oC)
(gpm)	(W)														
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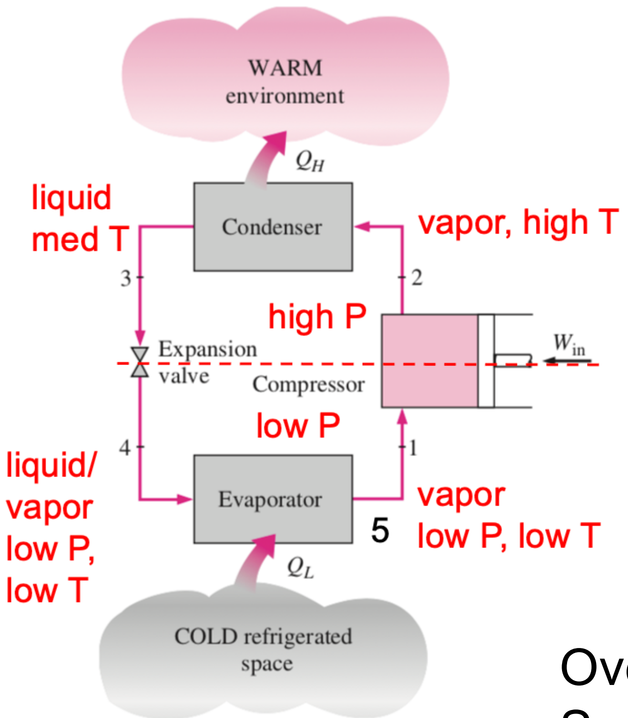
0.1	570	69	10	135	136	72	114	2	13	70	12	29.5	25.7	11.7	23
0.07	515	70	5	132	108	75	105	-5	8	70	9	28.2	25	12.2	23

Specific Energy Terms



heat rejected by system: $q_H = -(h_3 - h_2)$

heat absorbed by system: $q_L = h_1 - h_4$

work done by compressor: $w_c = h_2 - h_1$

work done on system: $w_{in} = \dot{W}_{in}/\dot{m}$

$$\dot{W}_c = \dot{W}_{total} - \dot{W}_f$$

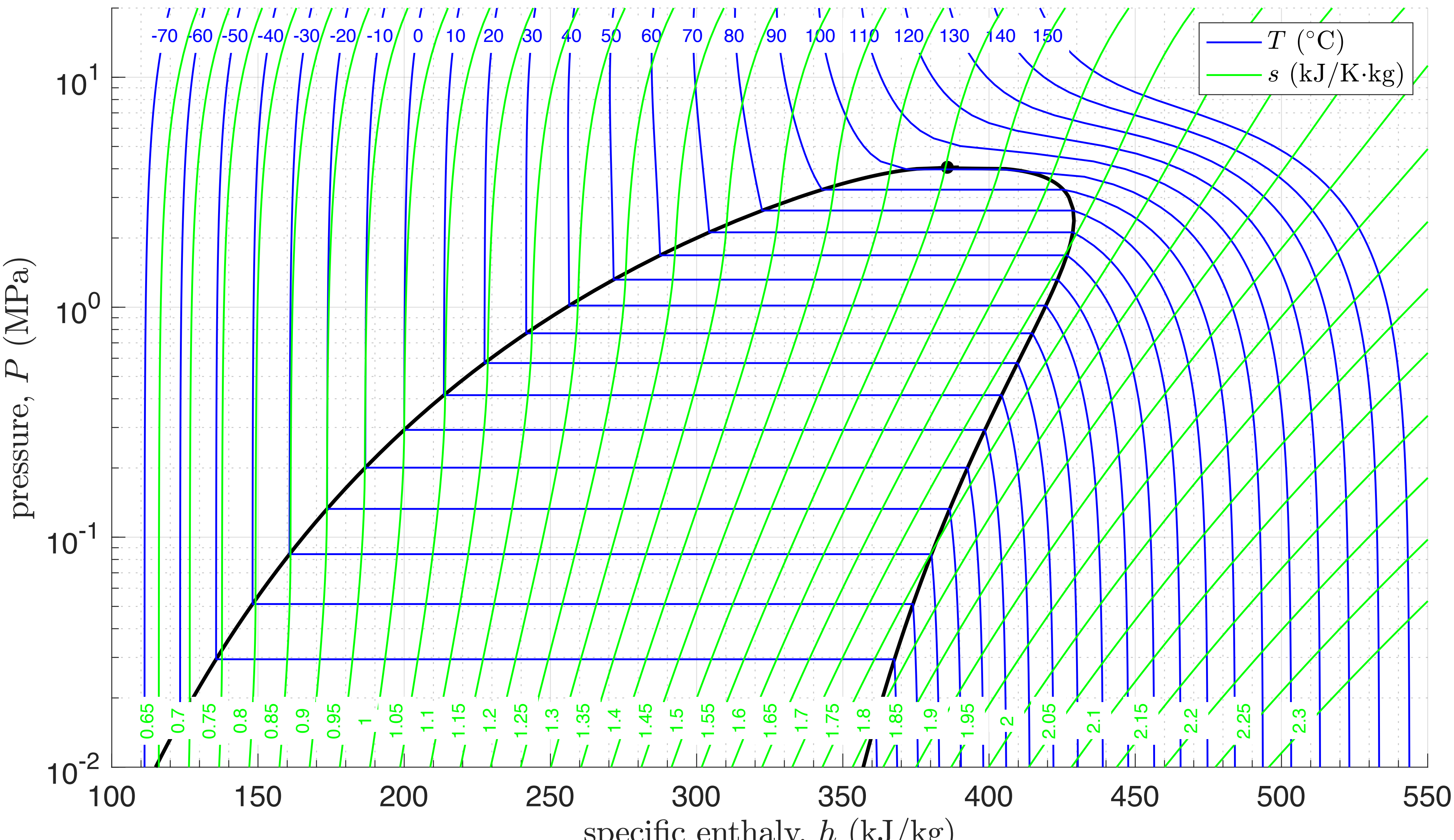
$$\dot{W}_{in} = \eta_M \, \eta_H \, \dot{W}_c$$

Overall efficiency of the compressor
Specified by the manufacturer $\longrightarrow$ $\eta_M \, \eta_H = 78\%$

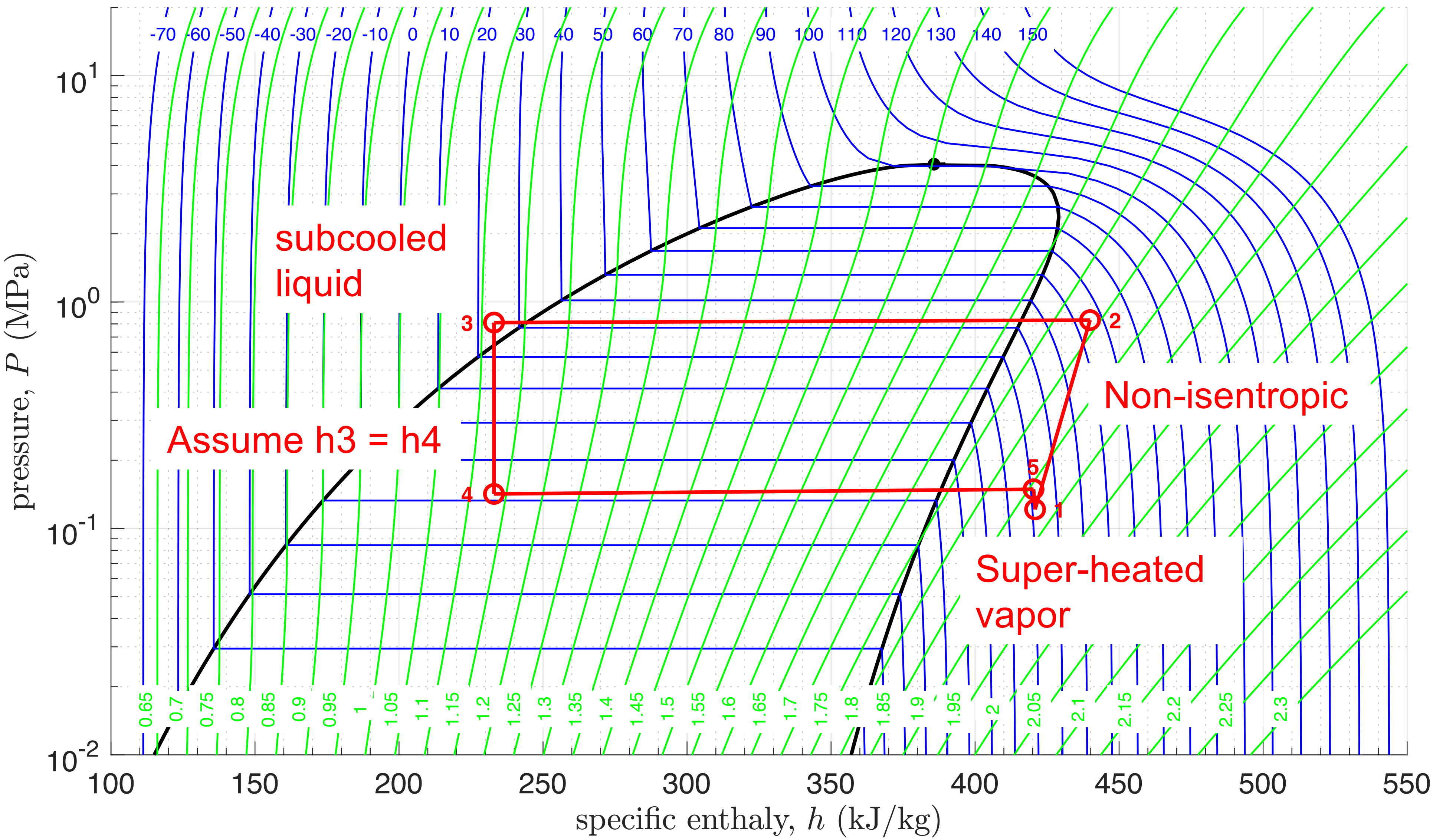
heat loss: $q_{loss} = w_{in} - w_c$

coefficient of performance: $\mathrm{COP_R} = \dfrac{q_L}{w_{in}}$

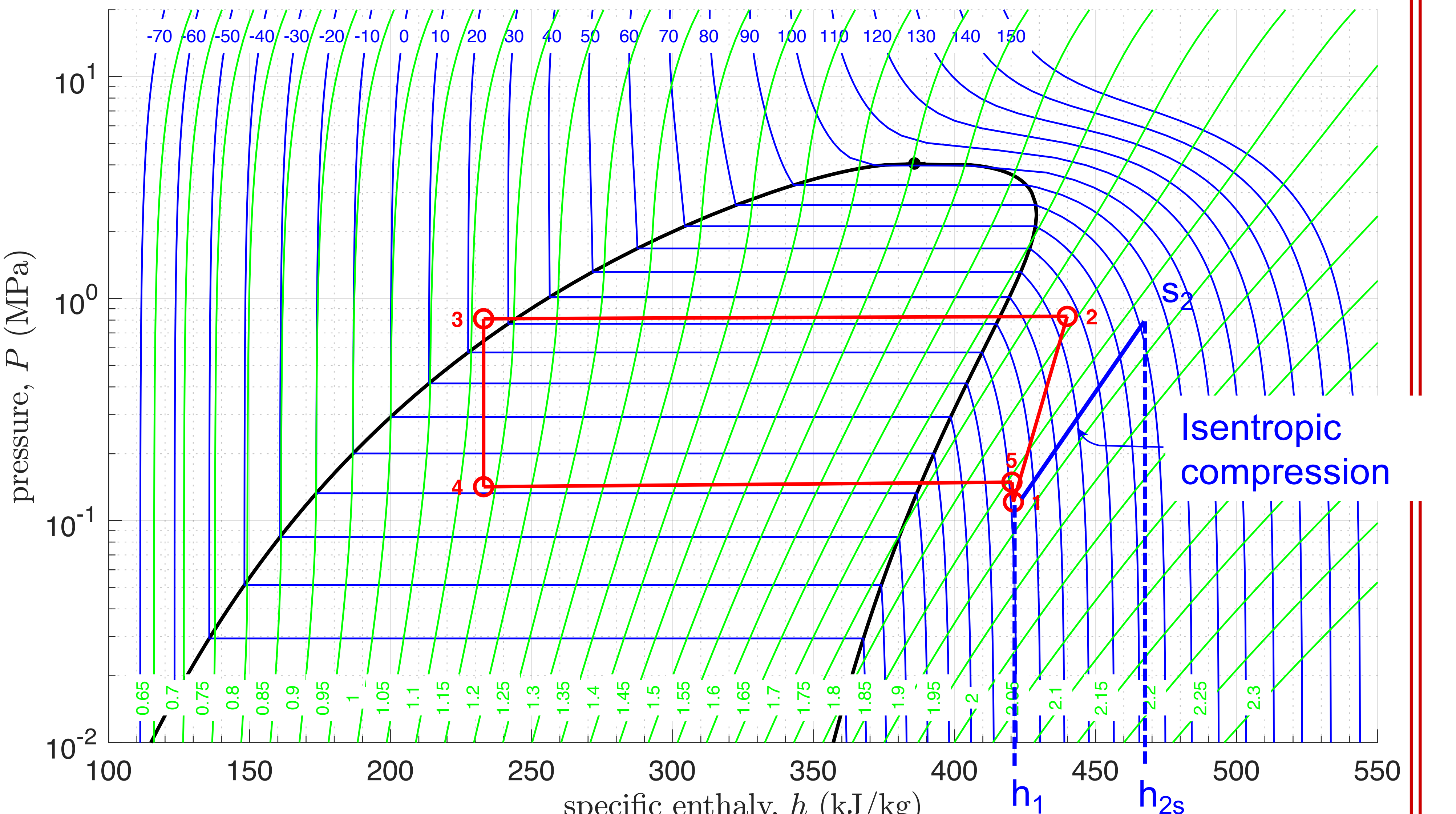
P-h Diagram for R-134a



P-h Diagram for R-134a



P-h Diagram for R-134a



Isentropic Efficiency

Find the entropy at state 1

```
S1 = PropsSI('S','T',T1,'P',P1,'R134a')
```

Determine the enthalpy at state 2 if we had isentropic compression

```
H2s = PropsSI('H','T’,T2,’S’,S1,'R134a')
```

Compute the isentropic efficiency:

$$\eta_c = \frac{w_{\text{isen}}}{w_{in}} \cdot 100\%$$

$$\eta_c = \frac{h_{2s} - h1}{w_{in}} \cdot 100\%$$