Thermodynamics Labs
DT021 Year 4
Refrigeration Cycle

David Collins
C10736685
david.collins4@mydit.ie

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1 Objective

Goal The goal of this experiment was to determine the coefficients of performance of the R713 refrigeration system.

Coefficients of performance In this experiment we examine a very important thermodynamic cycle — the refrigeration cycle — with the aim of determining its coefficients of performance (a measure analogous to 'efficiency') as both a heat pump and a refrigerator.

Applications The refrigeration cycle is a ubiquitous thermodynamic cycle, used every day all over the world. The most obvious applications include fridge-freezers and air-conditioning units.

2 Theory

It is worth while to remind ourselves of some basic thermodynamic principles and definitions.

First law of thermodynamics The first law of thermodynamics is essential to understanding the processes taking place in a refrigeration cycle. Thus, we state it here for completeness.

$$\boxed{\Delta U = Q - W} \tag{1}$$

Enthalpy Enthalpy, which is a state variable in any thermodynamic system, is given by

$$\boxed{H = U + pV}. \tag{2}$$

(Note that enthalpy has the same units as the internal energy and the 'pressure-volume' work — i.e. *Joules*.) This definition will be used to determine values for the condenser and evaporator heats.

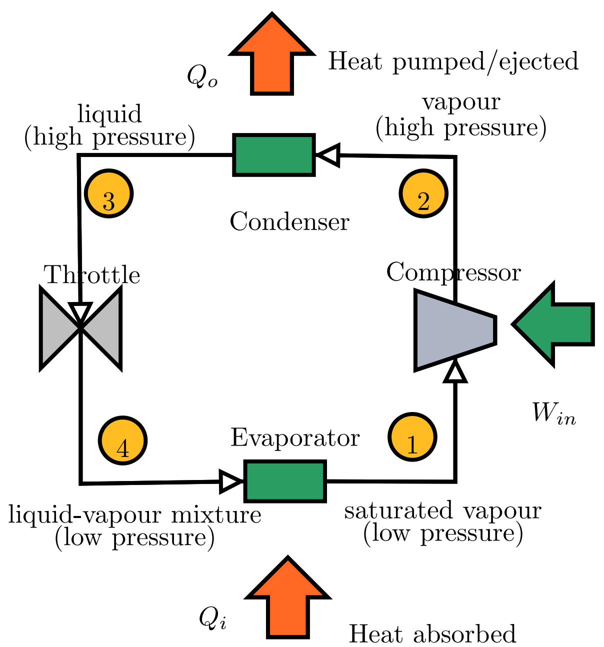

Figure 1: Refrigeration cycle

Refrigeration cycle Referring to Figure 1, we can identify four processes which yield four equations:

- **Compressor** This is assumed to be isentropic. Consequently,

$$\boxed{W_{in} = \Delta h = h_2 - h_1}. \tag{3}$$

- **Condenser** This takes place at constant pressure. $\Delta p = 0$ From the first law (Equation 1) and the definition of enthalpy,

$$H = U + pV, \qquad \Delta U = Q_o - p\Delta V.$$

$$\begin{aligned} \Delta H &= \Delta U + \Delta(pV) \\ &= Q_o - \cancel{p\Delta V} + \cancel{p\Delta V} + \cancel{\Delta p V} \because \Delta p = 0 \end{aligned}$$

$$\therefore \Delta H = Q_o$$

$$\boxed{Q_o = h_2 - h_3} \tag{4}$$

- **Throttle / Expansion valve** It is assumed that this process takes place very quickly and that, consequently, very little heat is lost to the environment. We say that the process is *adiabitic*. In this case,

$$\Delta H \approx 0.$$

- **Evaporator** This is the most important part of the cycle for a refrigerator, as this is responsible for the actual *cooling effect*. It can be shown, using a reasoning similar to that used in the case of the condenser, that the heat absorbed from the surroundings is given by

$$\boxed{Q_i = \Delta H = h_1 - h_4}. \tag{5}$$

Pressure-Enthalpy diagrams The refrigeration cycle could be viewed on a Temperature-Entropy (T-S) diagram rather than a Pressure-Enthalpy (P-H) diagram. One reason the latter is useful, however, is that the expansion in the throttle involves no change in enthalpy ($\Delta H = 0$), and can consequently be portrayed as simply a vertical line on the P-H diagram. Choosing the right diagram makes it easier to visualize (and to draw) the thermodynamic process that is occuring.

Coefficient of performance In a heat engine, one can refer to a 'thermal efficiency'. In a refrigeration cycle, we refer to a 'coefficient of performance instead'.

$$\boxed{COP_{HP} = COP_{cond} = \frac{Q_o}{W_{in}}} \tag{6}$$

However, from equations 3 and 4, we can represent this measure in terms of enthalpies directly:

$$\boxed{COP_{HP} = \frac{h_2 - h_3}{h_2 - h_1}}. \tag{7}$$

We also we want to know how the cycle performs as a refrigerator.

$$\boxed{COP_R = COP_{evap} = \frac{Q_i}{W_{in}}} \tag{8}$$

Again, we can represent this in terms of specific enthalpies instead:

$$\boxed{COP_R = \frac{h_1 - h_4}{h_2 - h_1}}. \tag{9}$$

It is the second form of these equations (i.e. 7 and 9) that we will use to actually calculate the coefficients of performance (cf. Appendix A).

Carnot cycle performance We can also consider the corresponding coefficients for a Carnot cycle. These are given by

$$\boxed{COP_{HP_{carnot}} = \frac{T_{high}}{T_{high} - T_{low}}} \tag{10}$$

and

$$\boxed{COP_{R_{carnot}} = \frac{T_{low}}{T_{high} - T_{low}}} \tag{11}$$

for the heat-pump and refrigerator performance respectively. Note that, as is the case with all temperature measurements, the values must be converted to *Kelvin* (K) before using these formula. Naturally, we expect the actual COP to be less than that of a Carnot cycle.

Actual performance and electrical power To determine the *actual performance* involves calculating the electrical power supplied to the compressor, and converting the specific heats (or enthalpies) into powers. In order to perform this latter conversion, we need to know the mass flow rate, $\dot{m}$. Once this is known, we can determine the *actual* coefficient of performance as a refrigerator, for example, according to

$$\boxed{COP_{R_a} = \frac{\dot{Q}_i}{P} = \frac{q_i \cdot \dot{m}}{P}}, \tag{12}$$

where q_i denotes the specific heat ($\mathrm{kJ\,kg^{-1}}$), $\dot{m}$ denotes the mass flow-rate, and the 'a' subscript denotes that this is the *actual* (rather than theoretical or Carnot-cycle) refrigerator performance. Note that the units for $\dot{Q}_i$ are

$$\frac{\mathrm{kJ}}{\mathrm{kg}} \times \frac{\mathrm{kg}}{\mathrm{s}} = \frac{\mathrm{kJ}}{\mathrm{s}} = \mathrm{W}.$$

I.e., we are dealing in units of power, as we expect.

Temperatures → enthalpies Note that we don't measure the enthalpies directly. We use the refrigeration charts to match temperature to enthalpy instead.

3 Procedure

For three sets of readings, with different compresser inputs in each case, proceed as follows.

1. **Turn on compressor** Switch on the compressor and note the voltage (V) and current (A).

2. **Measurements** Using the thermocouple selector, measure the temperatures for the relevant channels. Only T_1 and T_2 are really needed. Record, also, the pressures in the evaporator and condenser.[1]

3. **Determine specific enthalpies** Specific enthalpies were determined using the refrigeration charts. More specifically, the enthalpies were found by finding the intersection between the lines of constant temperature and constant pressure.

4. **Work done, evaporator heat, and condenser heat** Use equations 3 – 5, determine the work in, the heat .

5. **Coefficients of performance** Once we have the afore-mentioned values, the coefficients of performance can be determined using equations 6 and 8.

For the sake of comparison, the coefficients of performance for a Carnot cycle will be determined in each case also (using equations 10 and 11).

[1]Note that temperatures must be converted to Kelvin and gauge pressures must be converted to absolute pressures (in Bar).

4 Results

The results of measurements are shown in Table 1.

- p_{eva} — evaporation pressure
- p_{cond} — condensation pressure

The temperatures for all six thermocouple channels were recorded. Only T_1 and T_2 are actually needed for our purposes, however.

Units and conversions Note that we must convert our temperatures in to Kelvin, and our gauge pressures into absolute pressures in Bar. Also, for each of the specific enthalpies determined using the refrigeration charts (cf. Appendix B), we need to add 100 $\mathrm{kJ\,kg^{-1}}$.

5 Analysis

GNU Octave was used for the purpose of this analysis. Alternatively, Excel could be used. As mentioned in section 3, the specific enthalpies were determined using refrigeration charts. These charts are shown in Appendix B.

From analysis, the coefficients of performance shown in Table 2 were found. The notation is as follows:

- COP_R - Coefficient of performance for *refrigeration*;
- COP_{R_C} - same as above except for the corresponding *Carnot cycle*;
- COP_{HP} - Coefficient of performance for a *heat pump*;
- COP_{HP_C} - same as above except for the corresponding *Carnot cycle*;

In each case (for both the Carnot cycle and the realisable cycle) the coefficient of performance for the heat-pump is higher than that of the refrigerator. Not only this, but the relationship is highly predictable — as shown by equation 13:

$$COP_{HP} = COP_R + 1. \tag{13}$$

The reason for this is easy to understand.

$$\begin{aligned} COP_{HP} &= \frac{h_2 - h_3}{h_2 - h_1} = \frac{h_2 - h_4}{h_2 - h_1} \\ &= \frac{h_2 - h_1 + h_1 - h_4}{h_2 - h_1} \\ &= \frac{h_2 - h_1}{h_2 - h_1} + \frac{h_1 - h_4}{h_2 - h_1} \\ &= 1 + \frac{h_1 - h_4}{h_2 - h_1} \\ &= 1 + COP_R \end{aligned}$$

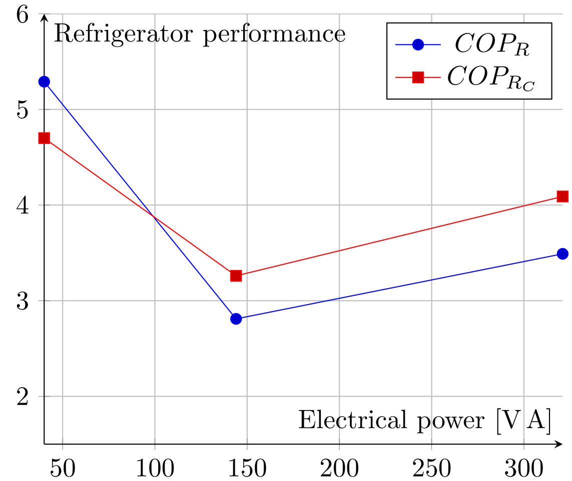

Figure 2: Refrigerator performance vs. compressor power

6 Conclusion

6.1 Summary

What we learned In addition to the general lessons discussed below, we learned the following key-points.

1. **Efficiency vs. coefficient of performance** Although the concepts of 'efficiency' and 'coefficient of performance' are analogous, there is an important distinction. While the efficiency of a thermodynamic cycle is necessarily a value between 0 and 1, the coefficient of performance is usually not.

	Temperatures [°]						Pressures [$kN\,m^{-3}$]			
	T_1	T_2	T_3	T_4	T_5	T_6	p_{eva}	p_{cond}	V [V]	I [A]
1)	-14.9	40	21.3	-34.9	24.7	25.4	-40	575	40	1
2)	-20.2	57.3	25.4	-26.3	26.3	28.6	-10	640	72	2
3)	-2.9	63.2	26.9	-17.3	26.1	30.6	40	710	107	3

Table 1: Results

Measurement set	P = VI [V A]	COP_R	COP_{R_C}	COP_{HP}	COP_{HP_C}
1	40	5.29	4.7	6.29	5.7
2	144	2.81	3.26	3.81	4.26
3	321	3.49	4.09	4.49	5.09

Table 2: Coefficients of performance

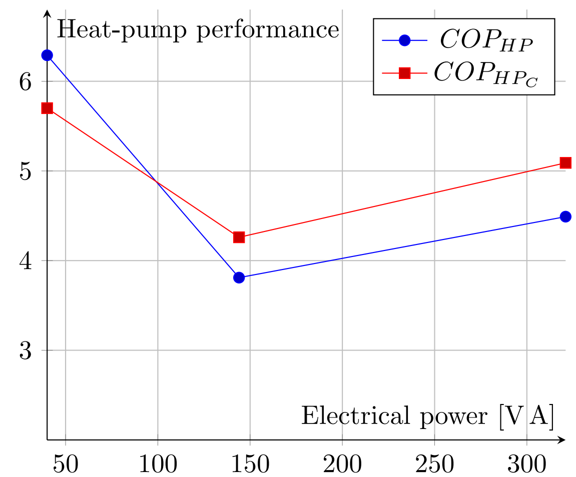

Figure 3: Heat-pump performance vs. compressor power

2. **Refrigerator vs. heat-pump performance**

$$COP_{HP} = COP_R + 1;$$

3. **Specific enthalpies** The coefficients of performance can be determined directly using specific enthalpies (once these are known).
4. **Carnot cycle performance** The performance of a Carnot cycle is the best we can achieve, but this is not viable in practice (it is not necessarily possible to compress a liquid-vapour mixture, for example).

Applications Although thermodynamics originally grew around the time of the industrial revolution and the development of the steam engine, the resulting theory has a wider scope. In this experiment we looked at a really widespread and important application — refrigeration. Without refrigeration and air-conditioning many of the comforts enjoyed in the modern civilized world would not be possible — and the theory of thermodynamics lies behind all of the technology responsible.

Choice of refrigerant Water is not a suitable refrigerant for common applications. We need a refrigerant which — while being liquifiable at moderate pressures — is a gas at room temperature. Water does not meet these criteria.

6.2 Assumptions

Compressor and entropy It was assumed, for the purpose of analysis, that the compression was isentropic (i.e. adiabatic and reversible). In reality, this is unlikely to be the case.

Constant pressure Note that, when deriving equations 4 and 5, we assumed that the pressure remained constant during these parts of the cycle.

Throttle We assumed, also, that no heat was lost to the surroundings while the liquid was expanding in the throttle, and that there was no chance in enthalpy during this process. If this was not the case, then $h_4 \neq h_3$, and the equations we used to determine the Coefficients of Performance would no longer be valid.

A Analysis procedure

The MATLAB / Octave script used for the analysis is shown in Listing 1.

Listing 1: GNU Octave / MATLAB code

```
% Refrigeration cycle calculations
% Author: David Collins

% Temperatures [degrees celcius]
T_low = [-14.9, -20.2, -2.9]
T_high = [40, 57.3, 63.2]
% Convert to Kelvin
T_low = T_low + 273;
T_high = T_high + 273;

% The Carnot performance can be calculated straight away
COP_HP_carnot = T_high ./ (T_high - T_low) % for the heat-pump performance
COP_R_carnot = T_low ./ (T_high - T_low) % for the refrigerator performance


% Pressures [kN / m^3]
P_low = [-40, -10, 40];
P_high = [575, 640, 710];
% Convert to absolute pressures (in bar!)
P_low = (P_low/100) + 1.0;
P_high = (P_high/100) + 1.0;

% Specific enthalpies [kJ / kg]
% These are determined from the refrigeraton charts, by
% finding the point of intersection between the isotherms and
% the isobars.

h_1 = [294, 288, 302];
h_2 = [325, 342, 349];
% Expansion in the throttle involves zero change in enthalpy.
% Thus, h_4 = h_3.
h_3 = [130, 136, 138];

% The specific enthalpies specified on the chart are relative.
% We need to add 100 kJ / kg.
h_1 = h_1+100;
h_2 = h_2+100;
h_3 = h_3+100;

% Corresponding work
mass_flow_rate = [1.2,2.0,2.7]; % g/s
mass_flow_rate = mass_flow_rate / 1000; % kg/s

% q_in: Heat absorbed in evaporator [kJ / kg]
q_in = h_1 - h_3;
```

```
p_in = q_in .* mass_flow_rate % kJ / kg -> kJ / s
% Work in: work done by compressor [kJ / kg]
w_in = h_2 - h_1;
% q_out: heat ejected by condensor [kJ / kg]
q_out = h_3 - h_2;

% Electrical measurements / Power
Voltage = [40,72,107];
Current = [1,2,3];
p_compressor = (Voltage.*Current) / 1000 % convert from W (J/s) to kJ / s

% COP [unitless]. This is just a ratio => no units
% Coefficient of performance (refrigerator)
COP_R = q_in ./ w_in

% Coefficient of performance (heat pump)
COP_HP = q_out ./ w_in

% Actual COPs
COP_R_a = p_in ./ p_compressor
```

B Charts

Three charts — one for each set of measurements are shown below.

1)

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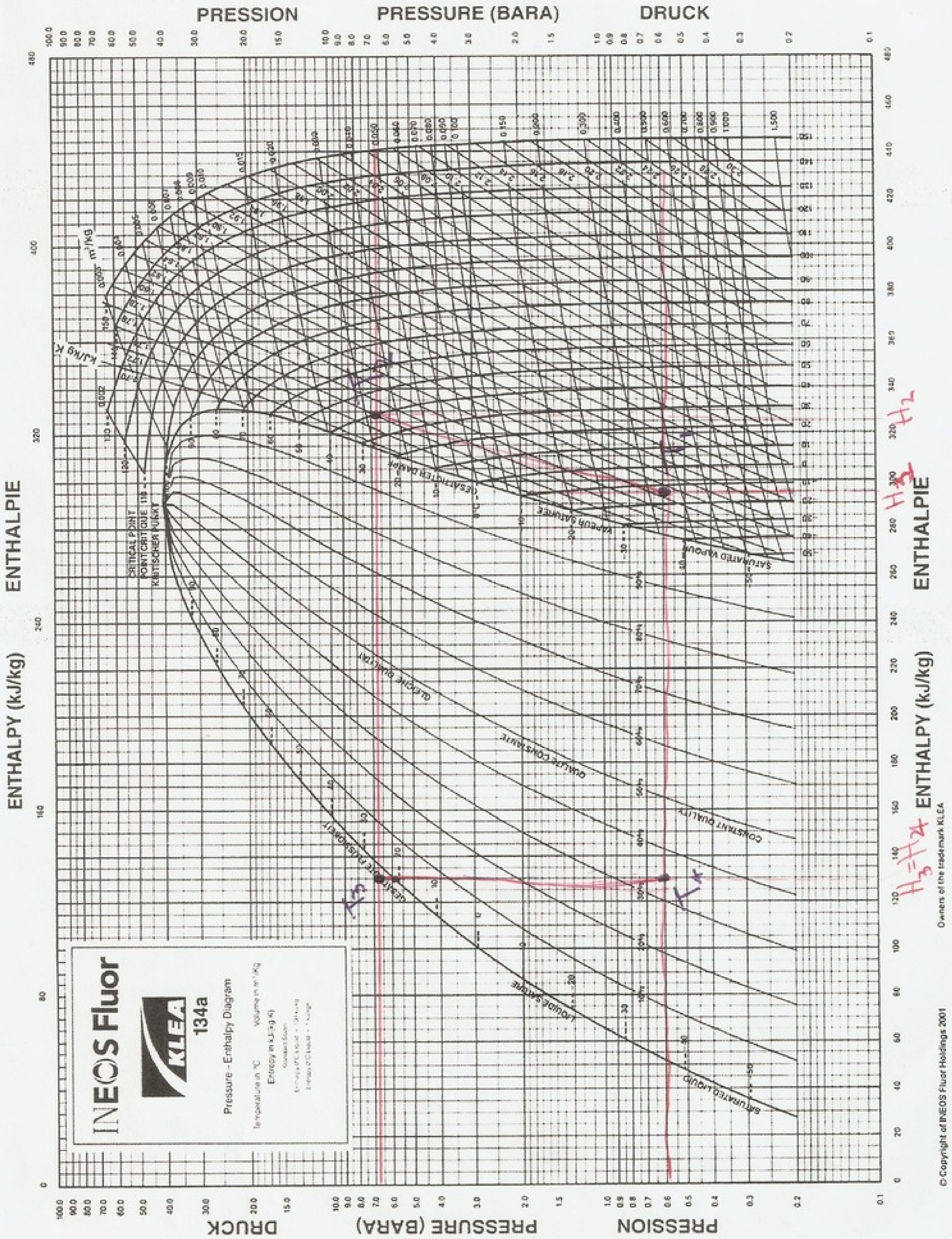

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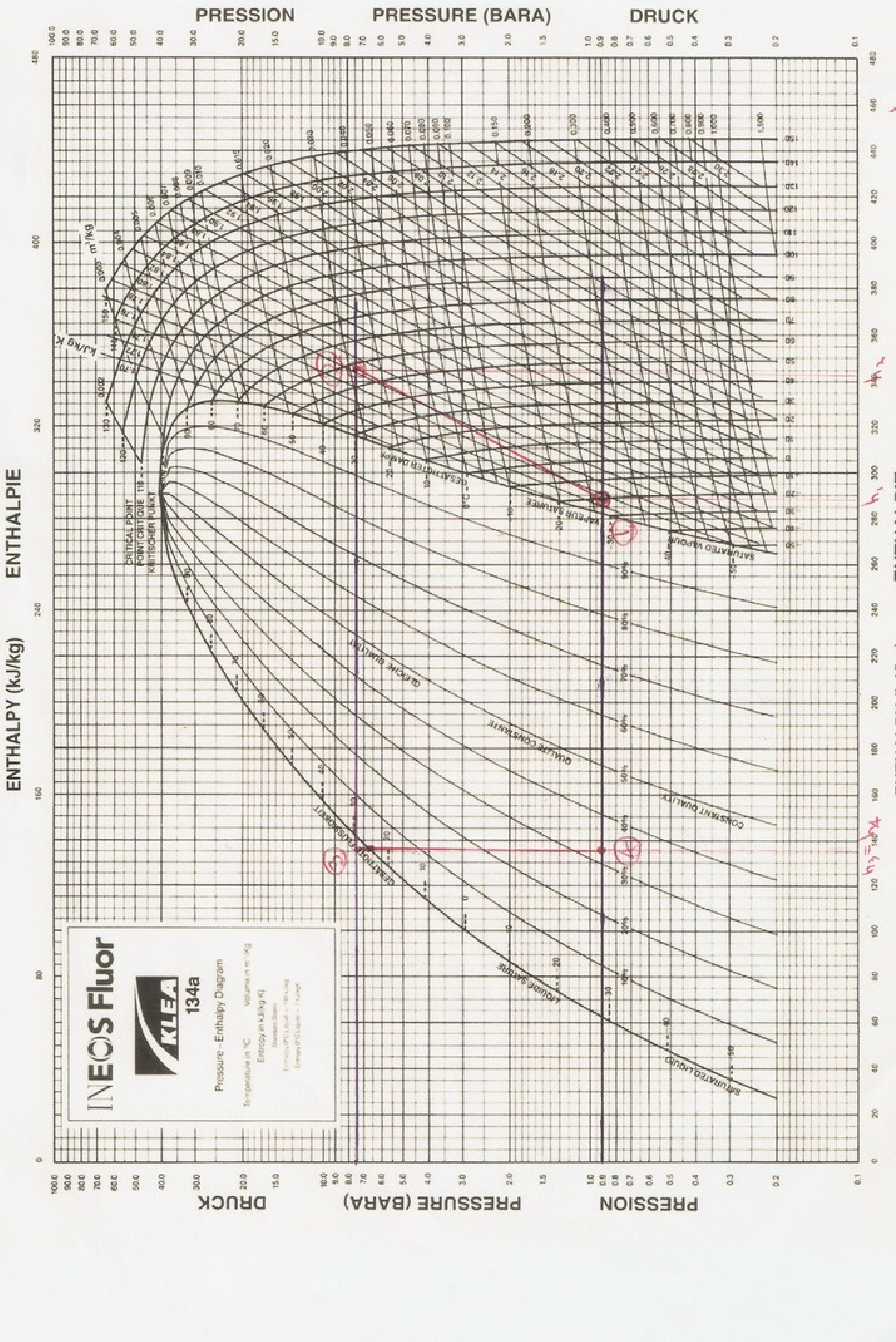

2)

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3)