Question 1 (30 points)

Select the most correct answer and circle it in the provided answers sheet. More than one answer may be correct, make your choices carefully and wisely.

1. The latent heat of vaporization for a liquid with a normal boiling point temperature of 300 K according to Trouton's rule is

a) 25 kJ/kg [✓ b) 25 kJ/mole] c) 25 J/mole d) 25 J/kg

2. The device in which an irreversible process in which a fluid, flowing across a restriction, undergoes a drop in its pressure is called

a) porous plug b) nozzle c) orifice [✓ d) a and c]

3. The Joule-Thomson coefficient is defined as

a) $\left(\frac{\partial \underline{V}}{\partial P}\right)_{\underline{H}}$ b) $\left(\frac{\partial T}{\partial P}\right)_{\underline{V}}$ [✓ c) $\left(\frac{\partial T}{\partial P}\right)_{\underline{H}}$] d) $\left(\frac{\partial P}{\partial T}\right)_{\underline{H}}$

4. The value of the specific heat at constant pressure of nitrogen assuming it to be an ideal gas

a) 1.5R b) 2.5R [✓ c) 3.5R] d) 4.5R

5. The term used to denote a phase change from vapor to solid is called

a) evaporation b) melting [✓ c) deposition] d) vaporization

6. The compressibility factor for an ideal gas is

a) 0 [✓ b) 1] c) ∞ d) -1

7. The natural thermodynamic variables for the Helmholtz free energy are

[✓ a) $T,\underline{V}$] b) T,P c) $\underline{H},P$ d) $\underline{S},P$

8. For an incompressible liquid, the value of the isothermal compressibility κ_T is

a) 1 [✓ b) 0] c) -1 d) ∞

9. Typical pressure ratios in a standard Brayton cycle are

a) 1-5 b) 1-10 c) 1-20 [✓ d) 5-20]

10. Differences between the PR and SRK EOS are mainly in

a) Repulsive term [✓ b) Attractive term] c) κ d) b and c

11. If the Mach number of the shockwave accompanying a mechanical explosion is greater than one; then the shockwave is classified as?

[✓ a) Supersonic] b) Sonic c) Subsonic d) Ultrasonic

12. The energy released when 10 kg of TNT explode is

[✓ a) 46 kJ] b) 0.46 MJ c) 4.6 MJ d) None of these

13. The efficiency in the Linde process compared to the simple liquefaction process at the same operating conditions is

[✓ a) Greater for Linde] b) Greater for simple c) Equivalent d) May vary

14. Based on its origin, oil shale is classified as

a) an alternative fuel b) biomass [✓ c) fossil fuel] d) electrochemical

15. The refrigeration vapor compression cycle differs from the refrigeration Rankin cycle by replacing the turbine with

a) a nozzle b) piston-cylinder [✓ c) throttling valve] d) None of these

Student name:
Registration number:

	(A)	(B)	(C)	(D)
⓿❶	○	●	○	○
⓿❷	○	○	○	●
⓿❸	○	○	●	○
⓿❹	○	○	●	○
⓿❺	○	○	●	○
⓿❻	○	●	○	○
⓿❼	●	○	○	○
⓿❽	○	●	○	○
⓿❾	○	○	○	●
❶⓿	○	●	○	○
❶❶	●	○	○	○
❶❷	●	○	○	○
❶❸	●	○	○	○
❶❹	○	○	●	○
❶❺	○	○	●	○

Fill the circles completely.
Don’t fill more than one circle for each question. If there are more than one circles filled, you will get a zero for that question.
No answers on the questions sheet will be accepted.
Use a black/blue pen not a pencil.

Question 2 (15 points)

Two kilograms of water at 90˚C are mixed with 5 kg of ice at 0˚C in an isolated system. The specific heat for water and ice can be taken as 4.18 kJ/kg.K, and the latent heat of melting the ice is 333.5 kJ/kg.

1. Calculate the entropy change and the final temperature.
2. Calculate the entropy change and the final temperature if one instead of 5 kilograms of ice were present.

Solution

The first step is to find the temperature after the mixing process. Two cases can arise:

a) The decrease in the internal energy of the water is less than the latent heat of melting the ice. This case will produce a final temperature of 0˚C and an ice-water mixture.
b) The decrease in the internal energy of the water is more than the latent heat of melting the ice. This case will produce a final temperature between 0˚C and 90˚C and liquid water is produced.

To find the final temperature, formulate the energy balance for this isolated system assuming all the ice is melted to water, subscript *w* refers to water and *s* to ice,

Heat lost by water = Heat gained by ice

$$m_w c_{P,w}(T_{w,i} - T_f) = m_s c_{P,s}(T_f - T_{s,i}) + m_s \Delta \underline{H}_{\text{Fusion}}$$

$$T_f = \frac{m_w c_{P,w} T_{w,i} + m_s c_{P,s} T_{s,i} - m_s \Delta \underline{H}_{\text{Fusion}}}{m_w c_{P,w} + m_s c_{P,s}}$$

$$= \frac{(2)(4.18)(90) + (5)(4.18)(0) - (5)(333.5)}{(2)(4.18) + (5)(4.18)} = -31.275^{\circ}\text{C}$$

Clearly, this is unrealistic since the minimum temperature of the system can only be 0˚C. Therefore, the ice did not melt completely and the temperature of the mixture is 0˚C. The amount of ice that melted can be found from the same energy balance taking into consideration that ice remains at 0˚C

Heat lost by water = Heat gained by ice

$$m_w c_{P,w}(T_{w,i} - T_f) = m_{s,\text{melted}} \Delta \underline{H}_{\text{Fusion}}$$

$$m_{s,\text{melted}} = \frac{m_w c_{P,w}(T_{w,i} - T_f)}{\Delta \underline{H}_{\text{Fusion}}} = \frac{(2)(4.18)(90-0)}{(333.5} = 2.256 \text{ kg.}$$

The entropy change for the ice is associated with the latent heat of melting. Also, water did not have a phase change which enables us to calculate the entropy change using the standard formula

$$\Delta S_s = \frac{Q}{T} = \frac{m_{s,\text{melted}} \Delta \underline{H}_{\text{Fusion}}}{T_{\text{Fusion}}} = \frac{(2.256)(333.5)}{(273.15)} = 2.754 \text{ kJ/K.}$$

$$\Delta S_w = m_w c_{P,w} \ln \frac{T_f}{T_{w,i}} = (2)(4.18) \ln \frac{273.15}{363.15} = -2.381 \text{ kJ/K.}$$

$$\Delta S_{\text{Total}} = \Delta S_s + \Delta S_w = 2.754 - 2.381 = 0.373 \text{ kJ/K.}$$

The second part is the same as the previous. However, the amount of ice is not enough to remain as ice. Consequently, we can find the temperature from the general energy balance as

$$T_f = \frac{m_w c_{P,w} T_{w,i} + m_s c_{P,s} T_{s,i} - m_s \Delta \underline{H}_{\text{Fusion}}}{m_w c_{P,w} + m_s c_{P,s}}$$
$$= \frac{(2)(4.18)(90) + (1)(4.18)(0) - (1)(333.5)}{(2)(4.18) + (1)(4.18)} = 33.4^\circ\text{C}.$$

The final temperature is between the two initial temperatures of the water and ice. This implies that all the ice is melted and its temperature rose to 33.4°C, while the water cooled to this temperature.

$$\Delta S_s = \frac{m_{s,\text{melted}} \Delta \underline{H}_{\text{Fusion}}}{T_{\text{Fusion}}} + m_s c_{P,w} \ln \frac{T_f}{T_{s,i}}$$
$$= \frac{(1)(333.5)}{(273.15)} + (1)(4.18) \ln \frac{33.4 + 273.15}{273.15} = 1.703 \text{ kJ/K}.$$
$$\Delta S_w = m_w c_{P,w} \ln \frac{T_f}{T_{w,i}} = (2)(4.18) \ln \frac{33.4 + 273.15}{363.15} = -1.417 \text{ kJ/K}.$$
$$\Delta S_{\text{Total}} = \Delta S_s + \Delta S_w = 1.703 - 1.417 = 0.286 \text{ kJ/K}.$$

The entropy change is smaller in this case. This is due to the final temperature being higher than the first case. The higher final temperature implies more available work can be obtained from the system.

Question 3 (30 points)

A 16.9 m^3 process vessel containing liquid petroleum fraction that may be approximated by n-hexane is subjected to sudden rise in pressure and temperature that led to BLEV explosion. The temperature is 420 K at the vessel pressure which is 10 bars. The liquid heat capacity for n-hexane may be assumed constant at 200 J/mol.K. Also, the vapor pressure for n-hexane is given by Antoine's equation

$$\ln P(\text{bar}) = 9.2164 - \frac{2697.55}{T(\text{K}) - 48.78}$$

Solution

1. Use the Peng-Robinson EOS to find the mass of the liquid in the vessel. Use a proper initial guess and carry out 3 iterations.
   Obtain the critical constants for n-hexane: T_c = 507.4 K, P_c = 29.69 bar, and ω = 0.296. Subsequently, apply the Peng-Robinson EOS at the given conditions. I used the Newton-Raphson method to obtain the final answer of $Z = 0.0484$.

$$b = 0.07779 \frac{RT_c}{P_c} = 0.07779 \frac{(8.314)(507.4)}{(2.969 \times 10^6)} = 0.00011053$$
$$\kappa = 0.37464 + 1.5422\omega - 0.26992\omega^2 = 0.80748$$
$$\alpha(T) = \left[1 + \kappa\left(1 - \sqrt{\frac{T}{T_c}}\right)\right]^2 = \left[1 + 0.80748\left(1 - \sqrt{\frac{420}{507.4}}\right)\right]^2 = 1.15096$$
$$a(T) = 0.45724 \frac{(RT_c)^2}{P_c} \alpha(T) = 0.45724 \frac{(8.314 \times 507.4)^2}{(2.969 \times 10^6)} (1.0728) = 3.1544$$

$$A=\frac{aP}{(RT)^2}=\frac{(3.1544)(1\times10^6)}{(8.314\times420)^2}=0.25870$$

$$B=\frac{bP}{RT}=\frac{(11.053\times10^{-5})(1\times10^6)}{(8.314\times420)}=0.031653$$

$$f(Z)=Z^3+(-1+B)Z^2+(A-2B-3B^2)Z+(-AB+B^2+B^3)=0$$

$$f(Z)=Z^3-0.96835Z^2+0.19239Z-0.0071550=0$$

$$f'(Z)=3Z^2-(2)(0.96835)Z+0.19239$$

$$Z^{(n)}=Z^{(o)}-\frac{Z^3-0.96835Z^2+0.19239Z-0.0071550}{3Z^2-(2)(0.96835)Z+0.19239}$$

```
i      xold          xnew          f(x)          f'(x)
1      0.03200000    0.04064491    -0.00195734   0.22641560
2      0.04064491    0.04432859    -0.00086790   0.23560773
3      0.04432859    0.04617536    -0.00044235   0.23952459
4      0.04617536    0.04715905    -0.00023755   0.24148826
5      0.04715905    0.04769826    -0.00013078   0.24253422
6      0.04769826    0.04799825    -0.00007293   0.24310756
7      0.04799825    0.04816648    -0.00004095   0.24342653
8      0.04816648    0.04826125    -0.00002309   0.24360542
9      0.04826125    0.04831476    -0.00001304   0.24370618
10      0.04831476    0.04834502    -0.00000738   0.24376308
11      0.04834502    0.04836215    -0.00000417   0.24379526
12      0.04836215    0.04837184    -0.00000236   0.24381347
13      0.04837184    0.04837733    -0.00000134   0.24382378
14      0.04837733    0.04838044    -0.00000076   0.24382962
15      0.04838044    0.04838220    -0.00000043   0.24383292
16      0.04838220    0.04838320    -0.00000024   0.24383480
Converged with the following results:Iterations 16
Root (x value) =       0.04838320
Function value at the root f(x) value =      -0.00000024
Derivative value at the root f'(x) value =      0.24383480
```

2. The compressibility factor at the initial conditions is $Z = 0.0484$. What is the mass in the vessel?
   The molar volume is found from the compressibility factor, then the mass is found.
   $$\underline{V}=\frac{ZRT}{P}=\frac{(0.0484)(8.314)(420)}{(1\times10^6)}=0.000169\text{ m}^3\text{/mol.}$$
   $$n=\frac{V}{\underline{V}}=\frac{16.9}{0.000169}=100{,}000\text{ mol.}$$
   $$m=n(MW)=(1\times10^5)(0.086178)=8617.8\text{ kg.}$$
3. Find the fraction of vapor that caused the explosion.
   Solution to this part and the next part requires the knowledge of the latent heat of vaporization for n-hexane. You may solve this by estimating using Riedel's equation, or differentiating the Antoine equation and using the Clapeyron equation to find an estimate of the latent heat of vaporization
   $$\frac{d\ln P^{\text{vap}}}{dT}=\frac{\Delta\underline{H}^{\text{vap}}}{RT^2}=\frac{2697.55}{\left(T(\text{K})-48.78\right)^2}$$
   $$\Delta\underline{H}^{\text{vap}}=(8.314)(420)^2\frac{2697.55}{\left(420-48.78\right)^2}=28{,}709\text{ J/mol.}$$
   Also, we need the normal boiling point temperature. This can be obtained from the

Antoine equation by solving for T using $P = 1$ bar.

$$\ln P(\text{bar}) = 9.2164 - \frac{2697.55}{T(\text{K}) - 48.78}$$

$$T(\text{K}) = 48.78 + \frac{2697.55}{9.2164 - \ln P(\text{bar})} = 341.47\text{K}.$$

Now, we can apply the simplified analysis of BLEV as

$$X_f = 1 - \exp\left[\frac{C_P^L}{\Delta \underline{H}^{\text{vap}}}(T_b - T_i)\right]$$

$$= 1 - \exp\left[\frac{200}{28709}(341.47 - 420)\right] = 0.4214.$$

4. What is the TNT equivalent for this BLEV explosion?

$$-W = M\left[C_P^L(T_i - T_b) - X_f\left(\Delta \underline{H}^{\text{vap}} - RT_b\right)\right]$$

$$= (1\times 10^5)\left[200(420 - 341.47) - 0.4214\left(28709 - 8.314\times 341.47\right)\right]$$

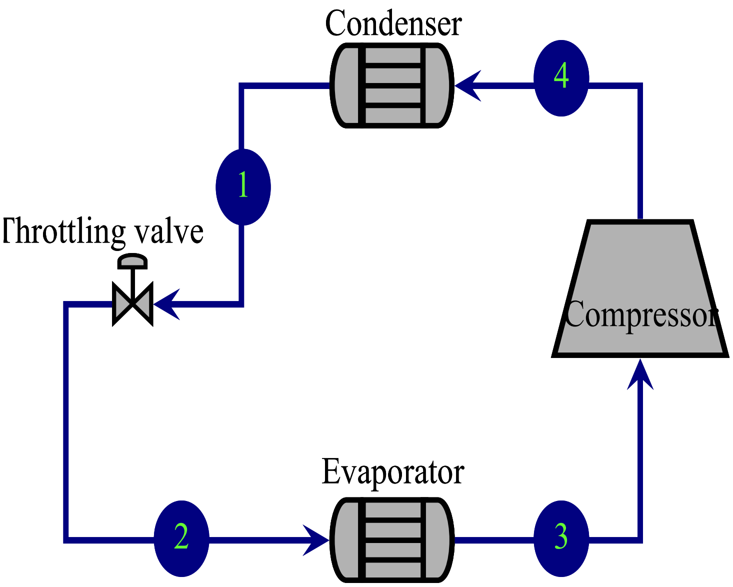
$$= 4.8044\times 10^8 \text{ J}.$$

$$\text{TNT equivalent} = \frac{4.8044\times 10^8}{4.6\times 10^6} = 104.4 \text{ kg TNT}.$$

Question 4 (25 points)

An air conditioner uses vapor-compression refrigeration cycle with the environmentally friendly refrigerant HFC-134a as the working fluid. The cycle operates between 70˚C and -10˚C.

Solution

Sketch	**Assumptions**
	Cyclic process described by the refrigeration vapor compression cycle. Properties obtained from the supplied HFC-134a chart. Isenthalpic throttling valve. Isobaric evaporator and condenser. Isentropic compressor.

1. Supply the missing temperatures and pressures at each location in the provided table. Provide the vapor fraction if there are vapor-liquid mixtures.

Location	State	Process Path	T(˚C)	P (kPa)	$\underline{H}$ (kJ/kg)	$\underline{S}$ (kJ/kg.K)
1	Saturated liquid	Isenthalpic	70	2000	304	1.33
2	Vapor-Liquid ($x = 0.56$)	Isobaric	-10	200	304	1.40
3	Saturated vapor	Isentropic	-10	200	395	1.73
4	Superheated vapor	Isobaric	80	2000	444	1.73
1	Saturated liquid	Isenthalpic	70	2000	304	1.33

2. Determine the COP for the cycle.

$$COP = \frac{Q_{\text{Evaporator}}}{W_{\text{Compressor}}} = \frac{H_3 - H_2}{H_4 - H_3} = \frac{395-304}{444-395} = \frac{91}{49} = 1.86$$

3. What is the efficiency of a Carnot cycle operating at the temperatures in the evaporator and condenser?

$$\eta_{\text{Carnot}} = \frac{1}{T_H / T_C - 1} = \frac{1}{343.15/263.15 - 1} = 3.29$$

This indicates that this vapor compression cycle operates at only 57% of the maximum attainable value as indicated by the COP for the Carnot's cycle.

4. If the AC is rated at 20 kW, what is the power input to the compressor?

The rating refers to heat supplied to the evaporator. Mass flow rate can be obtained from the given rating, and then the power to the compressor can be calculated.

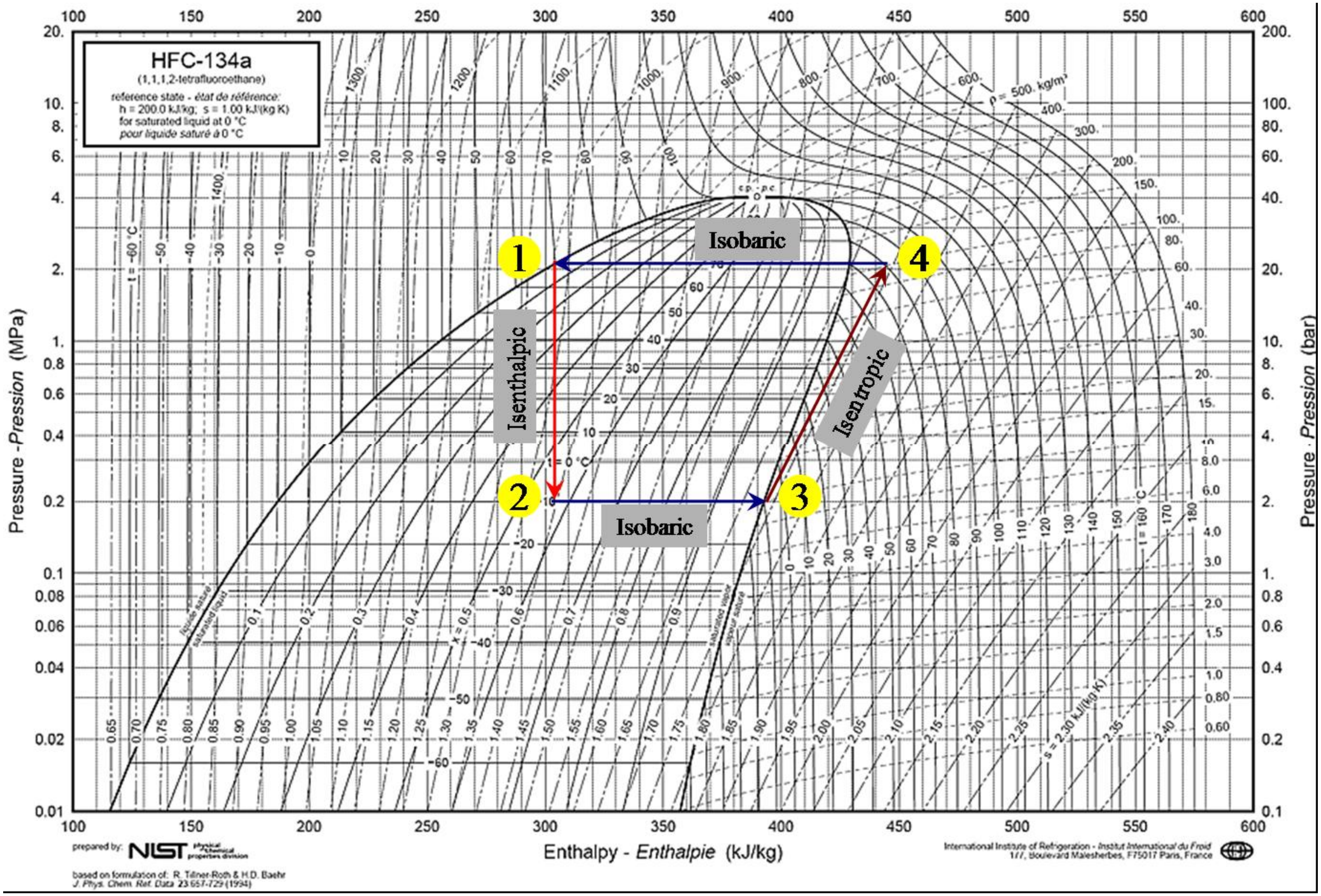
$$\dot{m} = \frac{20\text{kW}}{91\text{kJ/kg}} = 0.2198 \text{ kg/s}$$

$$\text{Power input to the compressor} = (0.2198 \text{ kg/s})(49\text{kJ/kg}) = 10.77 \text{ kW.}$$

5. Find the volumetric flow rate for the refrigerant entering the compressor.

This requires finding the specific volume at the suction of the compressor (point 3). From the chart $\rho = 11$ kg/m^3.

$$\text{Volumetric flow rate} = \dot{m}/\rho = (0.2198 \text{ kg/s})/(11\text{kg/m}^3) = 0.020 \text{ m}^3\text{/s.}$$


HFC-134a
(1,1,1,2-tetrafluoroethane)
reference state - état de référence:
h = 200.0 kJ/kg; s = 1.00 kJ/(kg K)
for saturated liquid at 0 °C
pour liquide saturé à 0 °C
1
2
3
4
Isobaric
Isenthalpic
Isobaric
Isentropic
Pressure - Pression (MPa)
Pressure · Pression (bar)
Enthalpy - Enthalpie (kJ/kg)
ρ = 500. kg/m³
s = 2.30 kJ/(kg K)
x = 0.5
t = 0 °C
t = -60 °C
t = 160 °C
saturated liquid
liquide saturé
saturated vapor
vapeur saturée
c.p. - p.c.
100
150
200
250
300
350
400
450
500
550
600
20.
10.
8.
6.
4.
2.
1.
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
200.
100.
80.
60.
40.
20.
10.
8.
6.
4.
2.
1.
0.8
0.6
0.4
0.2
0.1
prepared by: NIST physical & chemical properties division
based on formulation of: R. Tillner-Roth & H.D. Baehr
J. Phys. Chem. Ref. Data 23:657-729 (1994)
International Institute of Refrigeration - Institut International du Froid
177, boulevard Malesherbes, F75017 Paris, France