Thermodynamics
Professor Anand T N C
Department of Mechanical Engineering
Indian Institute of Technology, Madras
Lecture 89
Tutorial problem (1 number)

(Refer Slide Time: 00:12)

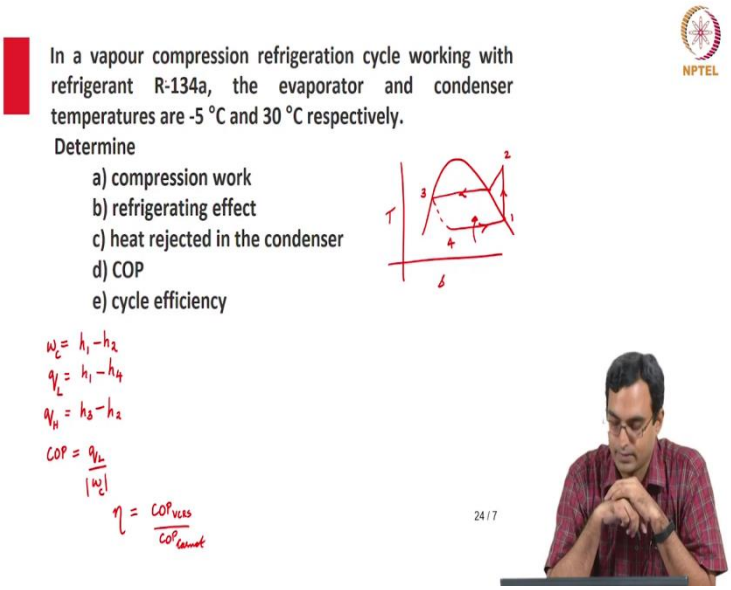


Figure 1.

Solution of the problem in Fig. 1.

The VCRS cycle is shown on the T-S diagram in Fig. 1.

Compression work = $w_c = h_1 - h_2$

Refrigerating effect = heat received by the refrigerant in the evaporator = $q_L = h_1 - h_4$

Heat rejected in the condenser = $h_3 - h_2$

$COP_{VCRS} = \frac{q_L}{|w_c|}$

Cycle efficiency = $\eta = \frac{COP_{VCRS}}{COP_{Carnot}}$ (COP_{Carnot} is the COP of the reverse Carnot's cycle operating between the same two temperature reservoirs as the given VCRS cycle)

We can obtain enthalpy values in the above formulae from the tables for the refrigerant R134a. R134a stands for 1, 1, 1, 2- tetrafluoroethane.

Different tables have different fixed reference points. Properties at other conditions are measured with respect to this reference point. At the same condition, the properties may be different in different tables because the reference points are different for different tables. However, the difference between a property at two different conditions is the same irrespective of the table used. It is recommended that the students continue using one table throughout.

We need enthalpy values at states 1, 2, 3 and 4.

We have saturated vapor at state 1. Hence, $h_g\ (at - 5℃) = h_1 = 395.9 \frac{kJ}{kg}$

We know that states 2 and 3 lie on an isobar. State 2 is in superheated zone. At 30 ℃, the saturation pressure p_{sat}=771 kPa. The process 1-2 is isentropic. Hence, $s_2 = s_1 = s_g(at - 5℃) = 1.7308 \frac{kJ}{kg \cdot K}$. Now, we need enthalpy (h_2) at the state where p=771 kPa and s=1.7308 $\frac{kJ}{kg \cdot K}$.

If we have table with better resolution for pressure and temperature values, it would be easy to get enthalpy value at p=771 kPa and s=1.7308 $\frac{kJ}{kg \cdot K}$, which is in the superheated zone. However, we do not have such table here. In such a case, we can do interpolation and calculate values at the required condition or use the value at the condition which is closest to the required condition and listed in the table. In the table we have for superheated refrigerant, at p=750 kPa and T=35 ℃, the entropy value is very close to s=1.7308 $\frac{kJ}{kg \cdot K}$. Hence, we will use enthalpy value at p=750 kPa and T=35 ℃, which is h_2 = 420.8 kJ/kg.

At state 3, we have saturated liquid at 30 ℃. Hence, $h_3 = h_f(at\ 30\ ℃) = 241.8 \frac{kJ}{kg}$

Throttling is an isenthalpic process. Hence, $h_4 = h_3 = 241.8 \frac{kJ}{kg}$

Now, we have the values of enthalpy at all the states.

Hence, Compression work = $w_c = h_1 - h_2 = -24.9 \frac{kJ}{kg}$

Refrigerating effect = heat received by the refrigerant in the evaporator = $q_L = h_1 - h_4 = 154.1 \frac{kJ}{kg}$

Heat rejected in the condenser = $h_3 - h_2 = -179 \frac{kJ}{kg}$

$\text{COP}_{\text{VCRS}} = \frac{q_L}{|w_c|} = 6.2$

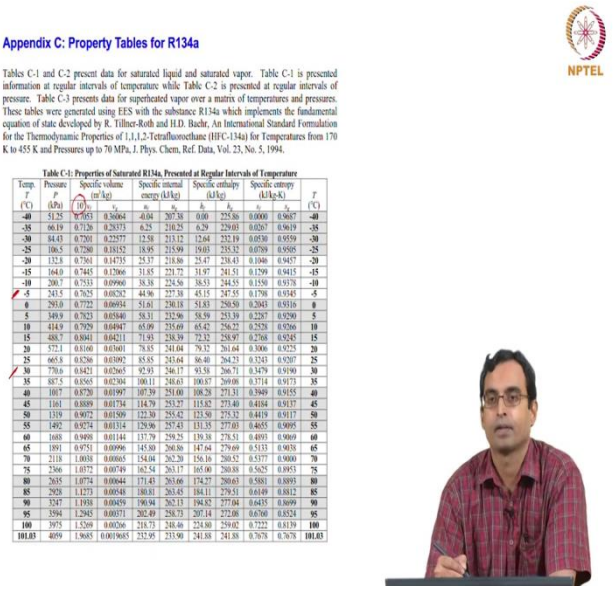
For calculating cycle efficiency, we need COP_{Carnot}.

$COP_{Carnot} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1} = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{T_L}{T_H - T_L} = \frac{268}{303 - 268} = 7.66$ (This is the maximum COP achievable between the temperature reservoirs at -5 ℃ and 30 ℃.)

Hence, cycle efficiency = $\eta = \frac{COP_{VCRS}}{COP_{Carnot}} = \frac{6.2}{7.66} = 0.81$

Hence, the VCRS cycle in the problem is around 81 % as efficient as the Carnot's cycle. In reality, the COP of the VCRS cycle is even lower as the process in the compressor is also irreversible.

(Refer Slide Time 05:27)



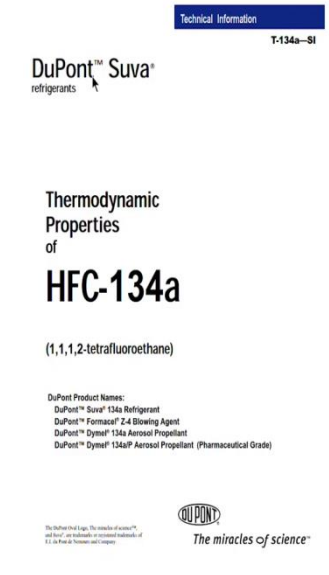
Appendix C: Property Tables for R134a

Tables C-1 and C-2 present data for saturated liquid and saturated vapor. Table C-1 is presented information at regular intervals of temperature while Table C-2 is presented at regular intervals of pressure. Table C-3 presents data for superheated vapor over a matrix of temperatures and pressures. These tables were generated using EES with the substance R134a which implements the fundamental equation of state developed by R. Tillner-Roth and H.D. Baehr, An International Standard Formulation for the Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (HFC-134a) for Temperatures from 170 K to 455 K and Pressures up to 70 MPa, J. Phys. Chem, Ref. Data, Vol. 23, No. 5, 1994.

Table C-1: Properties of Saturated R134a, Presented at Regular Intervals of Temperature

Temp. T (°C)	Pressure P (kPa)	Specific volume (m^3/kg) v_f	v_g	Specific internal energy (kJ/kg) u_f	u_g	Specific enthalpy (kJ/kg) h_f	h_g	Specific entropy (kJ/kg-K) s_f	s_g	T (°C)
-40	51.25	0.7055	0.36064	-0.04	207.38	0.00	225.86	0.0000	0.9687	-40
-35	66.19	0.7126	0.28373	6.25	210.25	6.29	229.03	0.0267	0.9619	-35
-30	84.43	0.7201	0.22577	12.58	213.12	12.64	232.19	0.0530	0.9559	-30
-25	106.5	0.7280	0.18152	18.95	215.99	19.03	235.32	0.0789	0.9505	-25
-20	132.8	0.7361	0.14735	25.37	218.86	25.47	238.43	0.1046	0.9457	-20
-15	164.0	0.7445	0.12066	31.85	221.72	31.97	241.51	0.1299	0.9415	-15
-10	200.7	0.7533	0.09960	38.38	224.56	38.53	244.55	0.1550	0.9378	-10
-5	243.5	0.7625	0.08282	44.96	227.38	45.15	247.55	0.1798	0.9345	-5
0	293.0	0.7722	0.06934	51.61	230.18	51.83	250.50	0.2043	0.9316	0
5	349.9	0.7823	0.05840	58.31	232.96	58.59	253.39	0.2287	0.9290	5
10	414.9	0.7929	0.04947	65.09	235.69	65.42	256.22	0.2528	0.9266	10
15	488.7	0.8041	0.04211	71.93	238.39	72.32	258.97	0.2768	0.9245	15
20	572.1	0.8160	0.03601	78.85	241.04	79.32	261.64	0.3006	0.9225	20
25	665.8	0.8286	0.03092	85.85	243.64	86.40	264.22	0.3243	0.9207	25
30	770.6	0.8421	0.02665	92.93	246.17	93.58	266.71	0.3479	0.9190	30
35	887.5	0.8565	0.02304	100.11	248.63	100.87	269.08	0.3714	0.9173	35
40	1017	0.8720	0.01997	107.39	251.00	108.28	271.31	0.3949	0.9155	40
45	1161	0.8889	0.01734	114.79	253.27	115.82	273.40	0.4184	0.9137	45
50	1319	0.9072	0.01509	122.30	255.42	123.50	275.32	0.4419	0.9117	50
55	1492	0.9274	0.01314	129.96	257.43	131.35	277.03	0.4655	0.9095	55
60	1683	0.9498	0.01144	137.79	259.25	139.38	278.51	0.4893	0.9069	60
65	1891	0.9751	0.00996	145.80	260.86	147.64	279.69	0.5133	0.9038	65
70	2118	1.0038	0.00865	154.04	262.20	156.16	280.52	0.5377	0.9000	70
75	2366	1.0372	0.00749	162.54	263.17	165.00	280.88	0.5625	0.8953	75
80	2635	1.0774	0.00644	171.43	263.66	174.27	280.63	0.5881	0.8893	80
85	2928	1.1273	0.00548	180.81	263.45	184.11	279.51	0.6149	0.8812	85
90	3247	1.1938	0.00459	190.94	262.13	194.82	277.04	0.6435	0.8699	90
95	3594	1.2945	0.00371	202.49	258.73	207.14	272.08	0.6760	0.8524	95
100	3975	1.5269	0.00266	218.73	248.46	224.80	259.02	0.7222	0.8139	100
101.03	4059	1.9685	0.0019685	232.95	233.90	241.88	241.88	0.7678	0.7678	101.03

(Refer Slide Time 08:00)



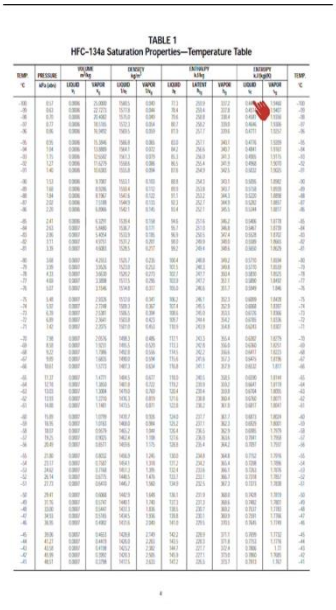
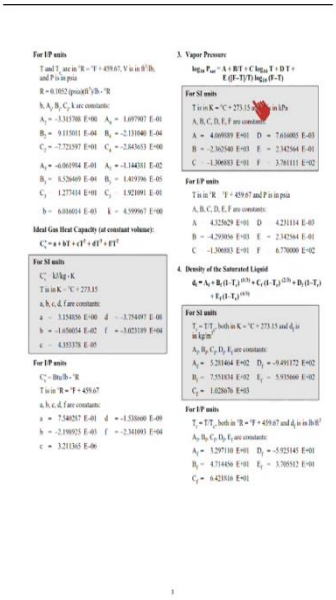


TABLE 1
HFC-134a Saturation Properties—Temperature Table

(Refer Slide Time 08:44)



For I/P units

T and T_c are in °R = °F + 459.67, V is in ft^3/lb, and P is in psia

R = 0.1052 (psia)ft^3/lb - °R

b, A_1, B_1, C_1, k are constants:

A_1 =	−3.315708 E+00	A_2 =	1.697907 E-01
B_1 =	9.115011 E-04	B_2 =	−2.131040 E-04
C_1 =	−7.721597 E+01	C_2 =	−2.843653 E+00
A_3 =	-0.1661954 E-01	A_4 =	-1.144381 E-02
B_3 =	8.526469 E-04	B_4 =	1.419396 E-05
C_3 =	1.277414 E+01	C_4 =	1.921091 E-01
b =	0.016014 E-03	k =	4.599967 E+00

Ideal Gas Heat Capacity (at constant volume):

$C_v^o = a + bT + cT^2 + dT^3 + fT^4$

For SI units

C_v^o - kJ/kg - K

T in K = °C + 273.15

a, b, c, d, f are constants:

a =	3.154856 E+00	d =	−3.754497 E-08
b =	-1.656054 E-02	f =	+3.023189 E+04
c =	4.353378 E-05		

For I/P units

C_v^o - Btu/lb - °R

T in °R = °F + 459.67

a, b, c, d, f are constants:

a =	7.540257 E-01	d =	-1.538660 E-09
b =	-2.198925 E-03	f =	−2.341093 E+04
c =	3.211365 E-06		

3. Vapor Pressure

$\log_{10} P_{sat} = A + B/T + C \log_{10} T + D\,T + E\,(F-T)/T) \log_{10}(F-T)$

For SI units

T in K = °C + 273.15 and P in kPa

A, B, C, D, E, F are constants:

A =	4.069589 E+01	D =	7.616055 E-03
B =	−2.302540 E+03	E =	2.342564 E-01
C =	−1.306083 E+01	F =	3.761111 E+02

For I/P units

T in °R - °F + 459.67 and P in in psia

A, B, C, D, E, F are constants:

A	4.325629 E+01	D	4.231114 E-03
B	−4.293056 E+03	E	2.342564 E-01
C	-1.306083 E+01	F	6.770000 E+02

4. Density of the Saturated Liquid

$\rho_f = A_1 + B_1(1-T_r)^{0.35} + C_1(1-T_r)^{2/3} + D_1(1-T_r) + E_1(1-T_r)^{4/3}$

For SI units

$T_r = T/T_c$, both in K = °C + 273.15 and ρ_f is in kg/m^3

A_1, B_1, C_1, D_1, E_1 are constants:

A_1 =	5.281464 E+02	D_1 =	-9.491172 E+02
B_1 =	7.551834 E+02	E_1 =	5.935660 E+02
C_1 =	1.028676 E+03		

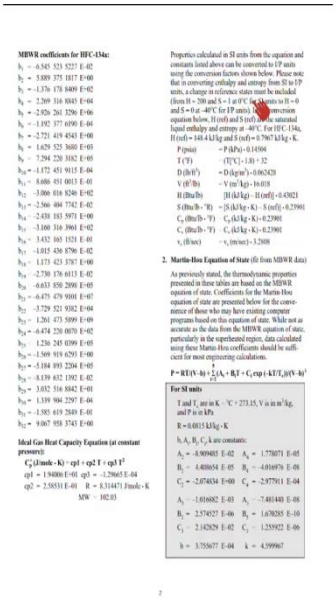
For I/P units

$T_r = T/T_c$, both in °R = °F + 459.67 and ρ_f is in lb/ft^3

A_1, B_1, C_1, D_1, E_1 are constants:

A_1 =	3.297110 E+01	D_1 =	-5.9225145 E+01
B_1 =	4.714456 E+01	E_1 =	3.705512 E+01
C_1 =	6.421816 E+01		

1



MBWR coefficients for HFC-134a:

b_1 =	-0.545 523 522? E-02		
b_2 =	5.889 375 1817 E+00		
b_3 =	-1.376 178 8409 E+02		
b_4 =	2.269 316 8843 E+04		
b_5 =	-2.926 261 3296 E+06		
b_6 =	-1.192 377 6190 E-04		
b_7 =	-2.721 419 4543 E+00		
b_8 =	1.629 525 3680 E+03		
b_9 =	-7.294 220 3182 E+05		
b_{10} =	-1.172 451 9115 E-04		
b_{11} =	8.686 451 0013 E-01		
b_{12} =	-3.006 016 8240 E+02		
b_{13} =	-2.566 404 7742 E-02		
b_{14} =	-2.438 183 5973 E+00		
b_{15} =	-3.160 316 3961 E+02		
b_{16} =	3.432 165 1521 E-01		
b_{17} =	-1.015 436 8796 E-02		
b_{18} =	1.173 423 3787 E+00		
b_{19} =	-2.730 376 6113 E-02		
b_{20} =	-0.633 850 2090 E+05		
b_{21} =	-0.475 479 9301 E+07		
b_{22} =	-3.729 521 9382 E+04		
b_{23} =	1.261 473 5099 E+09		
b_{24} =	-0.474 220 0070 E+02		
b_{25} =	1.230 245 0399 E+05		
b_{26} =	-1.569 919 6293 E+00		
b_{27} =	-5.184 893 2204 E+05		
b_{28} =	-0.139 632 1392 E-02		
b_{29} =	3.052 516 8842 E+03		
b_{30} =	1.339 904 2297 E-04		
b_{31} =	-1.585 619 2849 E-01		
b_{32} =	9.067 958 3743 E+00		

Ideal Gas Heat Capacity Equation (at constant pressure):

C_p^o (J/mole - K) = cp1 + cp2 T + cp3 T^2

cp1 = 1.94006 E+01 cp3 = -1.29665 E-04

cp2 = 2.58531 E-01 R = 8.31447 J/mole - K

MW = 102.03

Properties calculated in SI units from the equation and constants listed above can be converted to I/P units using the conversion factors shown below. Please note that in converting enthalpy and entropy from SI to I/P units, a change in reference states must be included (from H = 200 and S = 1 at 0°C for SI units to H = 0 and S = 0 at -40°C for I/P units). Use the conversion equation below. H (ref) and S (ref) are the saturated liquid enthalpy and entropy at -40°C. For HFC-134a, H (ref) = 148.4 kJ/kg and S (ref) = 0.7967 kJ/kg - K.

P (psia)	= P (kPa) - 0.14504
T (°F)	= (T[°C] - 1.8) + 32
D (lb/ft^3)	= D (kg/m^3) - 0.062428
V (ft^3/lb)	= V (m^3/kg) - 16.018
H (Btu/lb)	= [H (kJ/kg) - H (ref)] - 0.43021
S (Btu/lb - °R)	= [S (kJ/kg - K) - S (ref)] - 0.23901
C_p (Btu/lb - °F)	= C_p (kJ/kg - K) - 0.23901
C_v (Btu/lb - °F)	= C_v (kJ/kg - K) - 0.23901
v_s (ft/sec)	= v_s (m/sec) - 3.2808

2. Martin-Hou Equation of State (fit from MBWR data)

As previously stated, the thermodynamic properties presented in these tables are based on the MBWR equation of state. Coefficients for the Martin-Hou equation of state are presented below for the convenience of those who may have existing computer programs based on this equation of state. While not as accurate as the data from the MBWR equation of state, particularly in the superheated region, data calculated using these Martin-Hou coefficients should be sufficient for most engineering calculations.

$P = RT/(V-b) + \sum_{i=1}^{5} (A_i + B_i T + C_i \exp(-kT/T_c))/(V-b)^i$

For SI units

T and T_c are in K = °C + 273.15, V is in m^3/kg, and P is in kPa

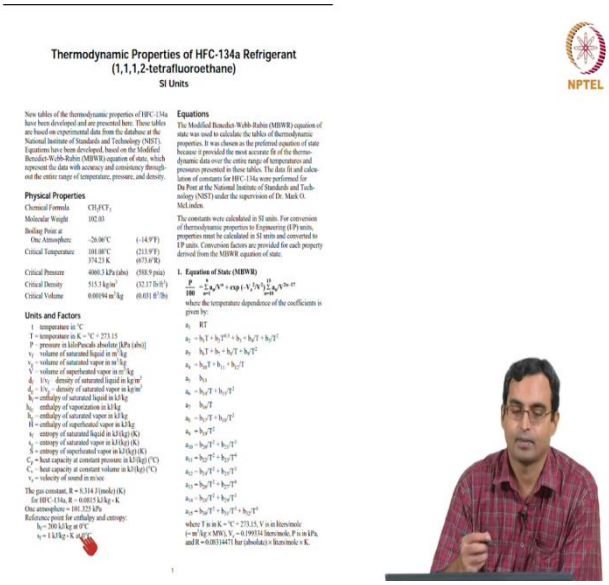
R = 0.4615 kJ/kg - K

b, A_1, B_1, C_1, k are constants:

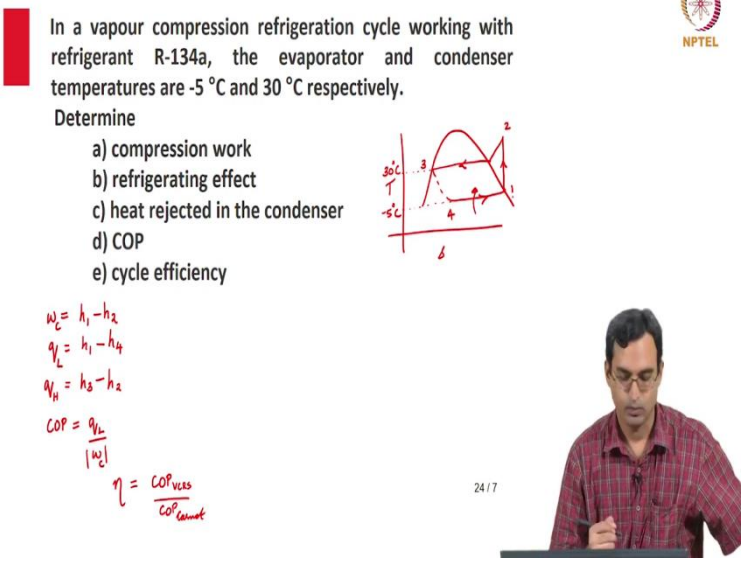
A_1 =	-8.909485 E-02	A_4 =	1.778071 E-05
B_1 =	4.408654 E-05	B_4 =	-4.016976 E-08
C_1 =	-2.074834 E+00	C_4 =	-2.977911 E-04
A_2 =	-1.016882 E-03	A_5 =	-7.481440 E-08
B_2 =	2.574527 E-06	B_5 =	1.670285 E-10
C_2 =	2.142929 E-02	C_5 =	1.255922 E-06
b =	3.755677 E-04	k =	4.599967

2

(Refer Slide Time: 09:03)



(Refer Slide Time 09:57)



(Refer Slide Time 10:38)

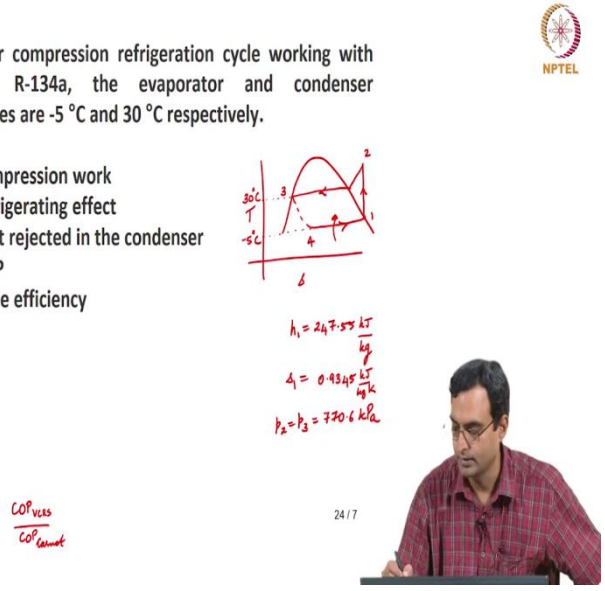
Appendix C: Property Tables for R134a

Tables C-1 and C-2 present data for saturated liquid and saturated vapor. Table C-1 is presented information at regular intervals of temperature while Table C-2 is presented at regular intervals of pressure. Table C-3 presents data for superheated vapor over a matrix of temperatures and pressures. These tables were generated using EES with the substance R134a which implements the fundamental equation of state developed by R. Tillner-Roth and H.D. Baehr, An International Standard Formulation for the Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (HFC-134a) for Temperatures from 170 K to 455 K and Pressures up to 70 MPa, J. Phys. Chem, Ref. Data, Vol. 23, No. 5, 1994.

Table C-1: Properties of Saturated R134a, Presented at Regular Intervals of Temperature

Temp. T (°C)	Pressure P (kPa)	Specific volume v (m³/kg)			Specific internal energy (kJ/kg)			Specific enthalpy (kJ/kg)			Specific entropy (kJ/kg·K)			T (°C)
		v_f	v_{fg}	v_g	u_f	u_{fg}	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
-40	51.25	0.7053	0.3604	0.4604	-0.04	207.38	0.00	225.86	0.0000	0.9667				-40
-35	66.19	0.7120	0.2833	0.3553	4.55	210.25	4.29	229.03	0.0267	0.9619				-35
-30	84.43	0.7201	0.2257	12.58	213.12	12.64	232.19	0.0530	0.9559					-30
-25	106.5	0.7280	0.18152	18.95	215.99	19.85	235.32	0.0789	0.9505					-25
-20	132.8	0.7361	0.14735	25.37	218.86	25.47	238.45	0.1046	0.9457					-20
-15	164.0	0.7445	0.12066	31.85	221.72	31.97	241.51	0.1299	0.9415					-15
-10	200.7	0.7533	0.09960	38.38	224.56	38.53	244.55	0.1550	0.9378					-10
-5	243.5	0.7625	0.08282	44.96	227.38	45.15	247.54	0.1798	0.9345					-5
0	293.0	0.7722	0.06934	51.61	230.18	51.83	250.50	0.2043	0.9316					0
5	349.9	0.7823	0.05840	58.31	232.96	58.59	253.39	0.2285	0.9290					5
10	414.9	0.7929	0.04947	65.09	235.69	65.42	256.22	0.2528	0.9266					10
15	488.7	0.8041	0.04213	71.93	238.39	72.32	258.97	0.2768	0.9245					15
20	572.1	0.8160	0.03601	78.85	241.04	79.32	261.64	0.3006	0.9225					20
25	665.8	0.8286	0.03092	85.85	243.64	86.40	264.23	0.3243	0.9207					25
30	770.6	0.8421	0.02665	92.93	246.17	93.58	266.71	0.3479	0.9190					30
35	887.5	0.8565	0.02304	100.11	248.63	100.87	269.08	0.3714	0.9173					35
40	1017	0.8720	0.01997	107.39	251.00	108.28	271.31	0.3949	0.9155					40
45	1161	0.8889	0.01734	114.79	253.27	115.82	273.40	0.4184	0.9137					45
50	1319	0.9073	0.01509	122.30	255.42	123.50	275.32	0.4419	0.9117					50
55	1492	0.9274	0.01314	129.96	257.43	131.35	277.03	0.4655	0.9095					55
60	1681	0.9498	0.01144	137.79	259.25	139.38	278.51	0.4893	0.9069					60
65	1891	0.9751	0.00996	145.80	260.86	147.64	279.69	0.5133	0.9038					65
70	2118	1.0038	0.00865	154.04	262.20	156.16	280.52	0.5377	0.9000					70
75	2366	1.0372	0.00749	162.54	263.17	165.00	280.88	0.5625	0.8953					75
80	2635	1.0774	0.00644	171.43	263.66	174.27	280.65	0.5881	0.8895					80
85	2929	1.1273	0.00548	180.81	263.45	184.11	279.51	0.6149	0.8812					85
90	3247	1.1938	0.00459	190.96	262.13	194.82	277.04	0.6435	0.8699					90
95	3594	1.2905	0.00373	202.49	258.75	207.14	272.08	0.6760	0.8524					95
100	3975	1.5269	0.00266	218.73	248.46	224.00	259.02	0.7222	0.8139					100
101.03	4059	1.9665	0.0019685	232.95	233.90	241.88	241.88	0.7678	0.7678					101.03

(Refer Slide Time 10:50)



In a vapour compression refrigeration cycle working with refrigerant R-134a, the evaporator and condenser temperatures are -5 °C and 30 °C respectively.

Determine

a) compression work
b) refrigerating effect
c) heat rejected in the condenser
d) COP
e) cycle efficiency

$w_c = h_1 - h_2$

$q_L = h_1 - h_4$

$q_H = h_3 - h_2$

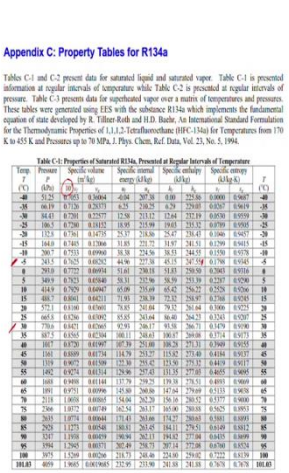
$COP = \frac{q_L}{|w_c|}$

$\eta = \frac{COP_{VCRS}}{COP_{Carnot}}$

$h_1 = 247.53 \frac{kJ}{kg}$

$s_1 = 0.9345 \frac{kJ}{kg\,K}$

$h_2 = h_3 = 770.6\ kJ/kg$



Appendix C: Property Tables for R134a

Tables C-1 and C-2 present data for saturated liquid and saturated vapor. Table C-1 is presented information at regular intervals of temperature while Table C-2 is presented at regular intervals of pressure. Table C-3 presents data for superheated vapor over a matrix of temperatures and pressures. These tables were generated using EES with the substance R134a which implements the fundamental equation of state developed by R. Tillner-Roth and H.D. Baehr, An International Standard Formulation for the Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (HFC-134a) for Temperatures from 170 K to 455 K and Pressures up to 70 MPa, J. Phys. Chem, Ref. Data, Vol. 23, No. 5, 1994.

Table C-1: Properties of Saturated R134a, Presented at Regular Intervals of Temperature

Temp	Pressure	Specific volume (m³/kg)		Specific internal energy (kJ/kg)		Specific enthalpy (kJ/kg)		Specific entropy (kJ/kg-K)		Temp
T (°C)	P (kPa)	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g	T (°C)
-40	51.25	0.7055	0.36064	-0.04	207.38	0.00	225.86	0.0000	0.9687	-40
-35	66.19	0.7120	0.28373	6.25	210.25	6.29	229.05	0.0262	0.9619	-35
-30	84.43	0.7201	0.22877	12.58	213.12	12.64	232.19	0.0520	0.9559	-30
-25	106.5	0.7280	0.18522	18.95	215.99	19.03	235.32	0.0779	0.9505	-25
-20	132.8	0.7361	0.14755	25.37	218.86	25.47	238.43	0.1040	0.9457	-20
-15	164.0	0.7445	0.12006	31.85	221.72	31.97	241.51	0.1299	0.9415	-15
-10	200.7	0.7533	0.09960	38.38	224.56	38.53	244.55	0.1558	0.9378	-10
-5	243.5	0.7625	0.08282	44.96	227.38	45.15	247.54	0.1708	0.9345	-5
0	293.0	0.7722	0.06934	51.61	230.18	51.83	250.50	0.2063	0.9316	0
5	349.9	0.7825	0.05840	58.31	232.96	58.59	253.39	0.2325	0.9290	5
10	414.9	0.7929	0.04947	65.09	235.69	65.42	256.22	0.2528	0.9266	10
15	488.7	0.8041	0.04213	71.93	238.39	72.32	258.97	0.2788	0.9245	15
20	572.1	0.8160	0.03601	78.85	241.04	79.32	261.64	0.3049	0.9225	20
25	665.8	0.8286	0.03092	85.85	243.64	86.40	264.23	0.3243	0.9207	25
30	770.6	0.8421	0.02665	92.93	246.17	93.58	266.71	0.3479	0.9190	30
35	887.5	0.8565	0.02304	100.11	248.63	100.87	269.08	0.3714	0.9173	35
40	1017	0.8720	0.01997	107.39	251.00	108.28	271.33	0.3949	0.9155	40
45	1161	0.8889	0.01734	114.79	253.27	115.82	273.48	0.4184	0.9137	45
50	1319	0.9073	0.01509	122.30	255.42	123.50	275.52	0.4419	0.9117	50
55	1492	0.9274	0.01314	129.96	257.43	131.35	277.43	0.4655	0.9095	55
60	1681	0.9498	0.01144	137.78	259.25	139.38	279.21	0.4893	0.9069	60
65	1891	0.9751	0.00996	145.80	260.86	147.64	279.69	0.5133	0.9038	65
70	2118	1.0038	0.00865	154.04	262.20	156.16	280.52	0.5377	0.9000	70
75	2366	1.0372	0.00749	162.54	263.17	165.00	280.88	0.5625	0.8953	75
80	2635	1.0774	0.00644	171.43	263.66	174.27	280.65	0.5881	0.8895	80
85	2928	1.1273	0.00548	180.81	263.45	184.11	279.51	0.6149	0.8812	85
90	3247	1.1938	0.00459	190.90	262.13	194.82	277.04	0.6435	0.8699	90
95	3594	1.2905	0.00371	202.49	258.73	207.14	272.08	0.6760	0.8524	95
100	3975	1.5269	0.00266	218.73	248.46	224.60	259.02	0.7225	0.8139	100
101.03	4059	1.9045	0.0019685	232.95	233.90	241.88	241.88	0.7678	0.7678	101.03

(Refer Slide Time 12:39)

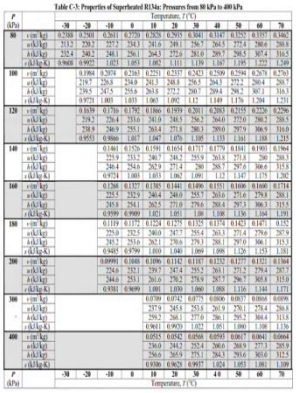


Table C-3: Properties of Superheated R134a: Pressures from 80 kPa to 400 kPa

P (kPa)		Temperature, T (°C)										
		-30	-20	-10	0	10	20	30	40	50	60	70
80	v (m³/kg)	0.2388	0.2501	0.2611	0.2720	0.2828	0.2935	0.3041	0.3147	0.3252	0.3357	0.3462
	u (kJ/kg)	213.2	220.5	227.7	234.7	241.6	248.3	254.7	264.5	272.4	280.6	288.8
	h (kJ/kg)	232.4	240.2	248.1	256.1	264.3	272.6	281.0	289.7	298.5	307.4	316.5
	s (kJ/kg-K)	0.9608	0.9922	1.023	1.053	1.082	1.111	1.139	1.167	1.195	1.222	1.249
100	v (m³/kg)		0.1984	0.2074	0.2163	0.2251	0.2337	0.2423	0.2509	0.2594	0.2678	0.2763
	u (kJ/kg)		219.7	226.8	234.0	241.1	248.1	254.7	264.3	272.2	280.4	288.7
	h (kJ/kg)		239.5	247.5	255.6	263.8	272.2	280.7	289.4	298.2	307.1	316.3
	s (kJ/kg-K)		0.9728	1.003	1.033	1.063	1.092	1.12	1.149	1.176	1.204	1.231
120	v (m³/kg)		0.1639	0.1720	0.1792	0.1860	0.1919	0.2011	0.2083	0.2155	0.2226	0.2296
	u (kJ/kg)		219.2	226.4	233.6	241.0	248.5	256.2	264.0	272.0	280.2	288.5
	h (kJ/kg)		238.9	246.9	255.1	263.4	271.8	280.3	289.0	297.9	306.9	316.0
	s (kJ/kg-K)		0.9553	0.9860	1.017	1.047	1.076	1.105	1.133	1.161	1.188	1.215
140	v (m³/kg)			0.1461	0.1526	0.1591	0.1654	0.1717	0.1779	0.1841	0.1903	0.1964
	u (kJ/kg)			225.9	233.2	240.7	248.2	255.9	263.8	271.8	280	288.3
	h (kJ/kg)			246.4	254.6	262.9	271.4	280	288.7	297.6	306.6	315.8
	s (kJ/kg-K)			0.9724	1.003	1.033	1.062	1.091	1.12	1.147	1.175	1.202
160	v (m³/kg)			0.1268	0.1327	0.1385	0.1441	0.1496	0.1551	0.1606	0.1660	0.1714
	u (kJ/kg)			225.5	232.9	240.4	248.0	255.7	263.6	271.6	279.8	288.1
	h (kJ/kg)			245.8	254.1	262.5	271.0	279.6	288.4	297.3	306.3	315.5
	s (kJ/kg-K)			0.9599	0.9909	1.021	1.051	1.08	1.108	1.136	1.164	1.191
180	v (m³/kg)			0.1119	0.1172	0.1224	0.1275	0.1325	0.1374	0.1423	0.1471	0.152
	u (kJ/kg)			225.0	232.5	240.0	247.7	255.4	263.3	271.4	279.6	287.9
	h (kJ/kg)			245.2	253.6	262.1	270.6	279.3	288.1	297.0	306.1	315.3
	s (kJ/kg-K)			0.9485	0.9799	1.010	1.040	1.069	1.098	1.126	1.153	1.181
200	v (m³/kg)			0.09991	0.1048	0.1096	0.1142	0.1187	0.1232	0.1277	0.1321	0.1364
	u (kJ/kg)			224.6	232.1	239.7	247.4	255.2	263.1	271.2	279.4	287.7
	h (kJ/kg)			244.6	253.1	261.6	270.2	278.9	287.7	296.7	305.8	315.0
	s (kJ/kg-K)			0.9381	0.9699	1.001	1.030	1.060	1.088	1.116	1.144	1.171
300	v (m³/kg)					0.0709	0.0742	0.0775	0.0806	0.0837	0.0868	0.0898
	u (kJ/kg)					237.9	245.8	253.8	261.9	270.1	278.4	286.8
	h (kJ/kg)					259.2	268.1	277.0	286.1	295.2	304.4	313.8
	s (kJ/kg-K)					0.9611	0.9920	1.022	1.051	1.080	1.108	1.136
400	v (m³/kg)					0.0515	0.0542	0.0568	0.0593	0.0617	0.0641	0.0664
	u (kJ/kg)					230.0	244.2	252.4	260.6	268.9	277.3	285.9
	h (kJ/kg)					250.6	265.9	275.1	284.3	293.6	303.0	312.5
	s (kJ/kg-K)					0.9306	0.9826	0.9927	1.024	1.053	1.081	1.109
P (kPa)		-30	-20	-10	0	10	20	30	40	50	60	70
		Temperature, T (°C)										

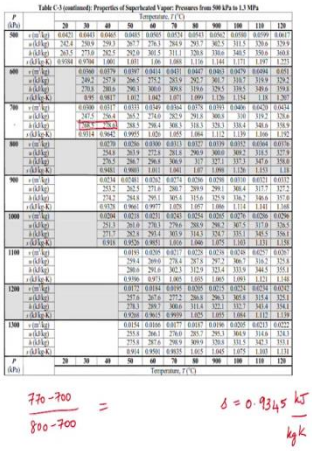


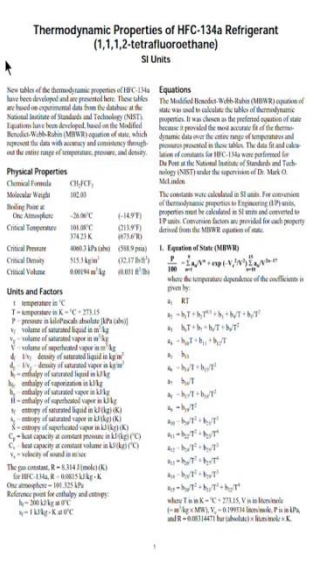
Table C-3 (continued): Properties of Superheated Vapor: Pressures from 500 kPa to 1.3 MPa

P (kPa)		Temperature, T (°C) 20	30	40	50	60	70	80	90	100	110	120
500	v (m³/kg)	0.4421	0.4641	0.4865	0.5085	0.5305	0.5524	0.5743	0.5962	0.6180	0.6399	0.6617
	u (kJ/kg)	242.4	250.9	259.3	267.7	276.3	284.9	293.7	302.5	311.5	320.6	329.9
	h (kJ/kg)	265.5	275.0	285.5	292.0	301.5	311.1	320.8	330.6	340.5	350.6	360.8
	s (kJ/kg·K)	0.9384	0.9704	1.001	1.031	1.06	1.088	1.116	1.144	1.171	1.197	1.223
600	v (m³/kg)		0.3560	0.3579	0.3597	0.3431	0.3451	0.3467	0.3483	0.3479	0.4094	0.451
	u (kJ/kg)		249.2	257.8	266.5	275.2	283.9	292.7	301.7	310.7	319.9	329.2
	h (kJ/kg)		270.8	280.6	290.1	300.0	309.8	319.6	329.5	339.5	349.6	359.8
	s (kJ/kg·K)		0.95	0.9817	1.012	1.042	1.071	1.099	1.126	1.154	1.18	1.205
700	v (m³/kg)		0.3100	0.3117	0.3133	0.3149	0.3164	0.3178	0.3193	0.3406	0.3620	0.3834
	u (kJ/kg)		247.7	256.4	265.2	274.0	282.9	291.8	300.8	310	319.3	328.6
	h (kJ/kg)		268.9	278.8	288.5	298.4	308.3	318.3	328.3	338.4	348.6	358.9
	s (kJ/kg·K)		0.9514	0.9842	0.9955	1.026	1.055	1.084	1.112	1.139	1.166	1.192
800	v (m³/kg)			0.0270	0.0286	0.3300	0.3313	0.3327	0.3339	0.3357	0.3504	0.0376
	u (kJ/kg)			244.0	263.9	272.8	281.8	290.9	300.0	309.2	318.5	327.9
	h (kJ/kg)			276.5	286.7	296.8	306.9	317	327.1	337.3	347.6	358.0
	s (kJ/kg·K)			0.9683	0.9993	1.031	1.061	1.07	1.098	1.126	1.153	1.18
900	v (m³/kg)			0.0234	0.0248	0.0262	0.0274	0.0286	0.0298	0.0310	0.0323	0.0335
	u (kJ/kg)			253.2	262.5	271.6	280.7	289.9	299.1	308.4	317.7	327.2
	h (kJ/kg)			274.2	284.8	295.1	305.4	315.6	325.9	336.2	346.6	357.0
	s (kJ/kg·K)			0.9526	0.9861	0.9977	1.028	1.057	1.086	1.114	1.141	1.168
1000	v (m³/kg)			0.0204	0.0218	0.0231	0.0243	0.0254	0.0265	0.0276	0.0286	0.0296
	u (kJ/kg)			251.3	261.0	270.3	279.6	288.9	298.2	307.5	317.0	326.5
	h (kJ/kg)			271.7	282.8	293.4	303.9	314.3	324.7	335.1	345.5	356.1
	s (kJ/kg·K)			0.918	0.9520	0.9051	1.016	1.046	1.075	1.103	1.131	1.158
1100	v (m³/kg)				0.0193	0.0205	0.0217	0.0228	0.0238	0.0248	0.0257	0.0267
	u (kJ/kg)				249.4	259.0	278.4	287.8	297.3	306.7	316.2	325.8
	h (kJ/kg)				280.0	291.0	302.3	312.9	323.4	333.9	344.5	355.1
	s (kJ/kg·K)				0.9196	0.9713	1.005	1.035	1.065	1.093	1.121	1.148
1200	v (m³/kg)				0.0172	0.0184	0.0195	0.0205	0.0215	0.0224	0.0234	0.0242
	u (kJ/kg)				257.0	267.6	277.2	286.8	296.3	305.8	315.4	325.1
	h (kJ/kg)				278.3	289.7	300.6	311.4	322.1	332.7	343.4	354.1
	s (kJ/kg·K)				0.9268	0.9615	0.9959	1.025	1.055	1.084	1.112	1.139
1300	v (m³/kg)				0.0154	0.0166	0.0177	0.0187	0.0196	0.0205	0.0213	0.0222
	u (kJ/kg)				255.8	266.1	276.0	285.7	295.3	304.9	314.6	324.3
	h (kJ/kg)				275.8	287.6	298.9	309.9	320.8	331.5	342.3	353.1
	s (kJ/kg·K)				0.914	0.9501	0.9835	1.015	1.045	1.075	1.103	1.131

P (kPa)		20	30	40	50	60	70	80	90	100	110	120
		Temperature, T (°C)										

$\frac{770-700}{800-700} = \frac{\delta - 0.9345}{}$ $\delta = 0.9345$ kJ/kgK

(Refer Slide Time: 15:47)



Thermodynamic Properties of HFC-134a Refrigerant (1,1,1,2-tetrafluoroethane)

SI Units

New tables of the thermodynamic properties of HFC-134a have been developed and are presented here. These tables are based on experimental data from the database at the National Institute of Standards and Technology (NIST). Equations have been developed, based on the Modified Benedict-Webb-Rubin (MBWR) equation of state, which represent the data with accuracy and consistency throughout the entire range of temperature, pressure, and density.

Physical Properties

Chemical Formula	CH_2FCF_3	
Molecular Weight	102.03	
Boiling Point at One Atmosphere	-26.06°C	(-14.9°F)
Critical Temperature	101.08°C 374.23 K	(213.9°F) (673.6°R)
Critical Pressure	4060.3 kPa (abs)	(588.9 psia)
Critical Density	515.3 kg/m³	(32.17 lb/ft³)
Critical Volume	0.00194 m³/kg	(0.031 ft³/lb)

Units and Factors

t = temperature in °C
T = temperature in K = °C + 273.15
P = pressure in kiloPascals absolute [kPa (abs)]
v_f = volume of saturated liquid in m^3/kg
v_g = volume of saturated vapor in m^3/kg
V = volume of superheated vapor in m^3/kg
d_f = $1/v_f$ = density of saturated liquid in kg/m^3
d_g = $1/v_g$ = density of saturated vapor in kg/m^3
h_f = enthalpy of saturated liquid in kJ/kg
h_{fg} = enthalpy of vaporization in kJ/kg
h_g = enthalpy of saturated vapor in kJ/kg
H = enthalpy of superheated vapor in kJ/kg
s_f = entropy of saturated liquid in kJ/(kg)·(K)
s_g = entropy of saturated vapor in kJ/(kg)·(K)
S = entropy of superheated vapor in kJ/(kg)·(K)
C_p = heat capacity at constant pressure in kJ/(kg)·(°C)
C_v = heat capacity at constant volume in kJ/(kg)·(°C)
v_s = velocity of sound in m/sec

The gas constant, R = 8.314 J/(mole)·(K)
for HFC-134a, R = 0.08151 kJ/kg·K
One atmosphere = 101.325 kPa
Reference point for enthalpy and entropy:
h_f = 200 kJ/kg at 0°C
s_f = 1 kJ/kg·K at 0°C

Equations

The Modified Benedict-Webb-Rubin (MBWR) equation of state was used to calculate the tables of thermodynamic properties. It was chosen as the preferred equation of state because it provided the most accurate fit of the thermodynamic data over the entire range of temperatures and pressures presented in these tables. The data fit and calculation of constants for HFC-134a were performed for Da Pore at the National Institute of Standards and Technology (NIST) under the supervision of Dr. Mark O. McLinden.

The constants were calculated in SI units. For conversion of thermodynamic properties to Engineering (I-P) units, properties must be calculated in SI units and converted to I-P units. Conversion factors are provided for each property derived from the MBWR equation of state.

1. Equation of State (MBWR)

$$\frac{P}{100} = \frac{1}{2.A_0}\rho N^2 + \exp(-N_1/N^2)\sum_{n=01}^{02} A_n \rho^{2n-01}$$

where the temperature dependence of the coefficients is given by:

a_1 RT

$a_2 = b_1T + b_2T^{1/2} + b_3 + b_4/T + b_5/T^2$

$a_3 = b_6T + b_7 + b_8/T + b_9/T^2$

$a_4 = b_{10}T + b_{11} + b_{12}/T$

$a_5 = b_{13}$

$a_6 = b_{14}/T + b_{15}/T^2$

$a_7 = b_{16}/T$

$a_8 = b_{17}/T + b_{18}/T^2$

$a_9 = b_{19}/T^2$

$a_{10} = b_{20}/T^2 + b_{21}/T^3$

$a_{11} = b_{22}/T^2 + b_{23}/T^4$

$a_{12} = b_{24}/T^2 + b_{25}/T^3$

$a_{13} = b_{26}/T^2 + b_{27}/T^4$

$a_{14} = b_{28}/T^2 + b_{29}/T^3$

$a_{15} = b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4$

where T is in K = °C + 273.15, V is in liters/mole (= m^3/kg × MW), V_c = 0.199334 liters/mole, P is in kPa, and R = 0.08314471 bar (absolute) × liters/mole × K.

(Refer Slide Time: 15:52)

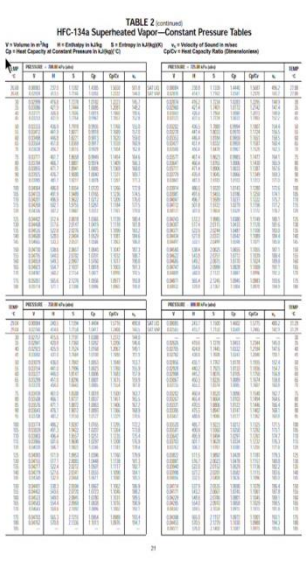
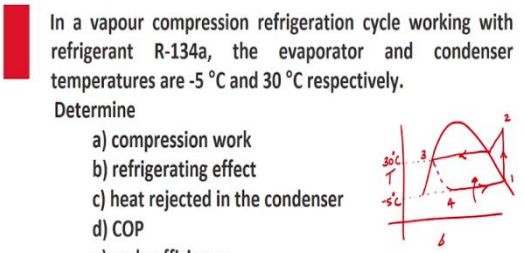


TABLE 2 (continued)
HFC-134a Superheated Vapor—Constant Pressure Tables


In a vapour compression refrigeration cycle working with refrigerant R-134a, the evaporator and condenser temperatures are -5 °C and 30 °C respectively.

Determine

a) compression work
b) refrigerating effect
c) heat rejected in the condenser
d) COP
e) cycle efficiency

$w_c = h_1 - h_2$

$q_L = h_1 - h_4$

$q_H = h_3 - h_2$

$COP = \frac{q_L}{|w_c|}$

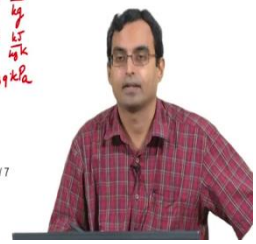
$\eta = \frac{COP_{VCRS}}{COP_{Carnot}}$

$h_1 = 395.9 \ \frac{kJ}{kg}$

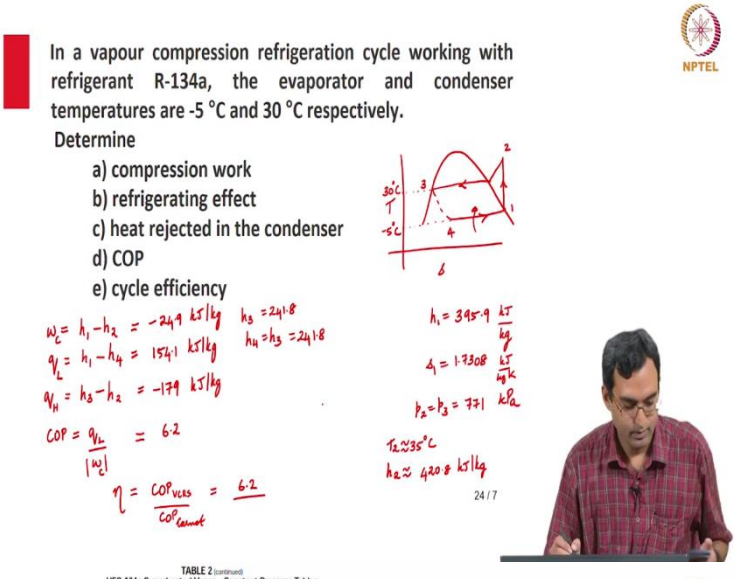
$s_1 = 1.7308 \ \frac{kJ}{kg\,K}$

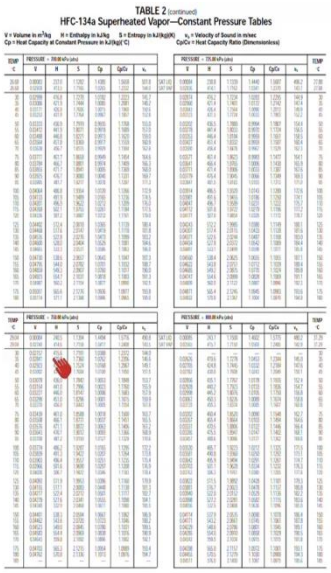
$h_2 = h_3 = 243.39 \ kJ/kg$

24 / 7

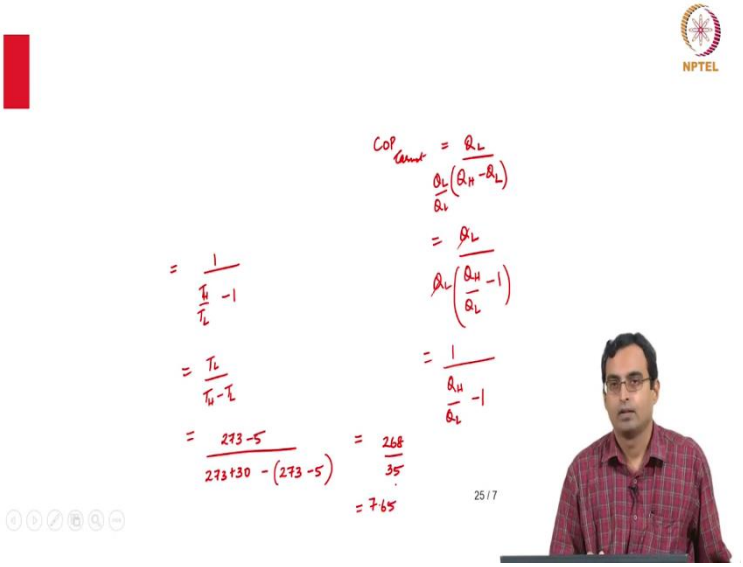


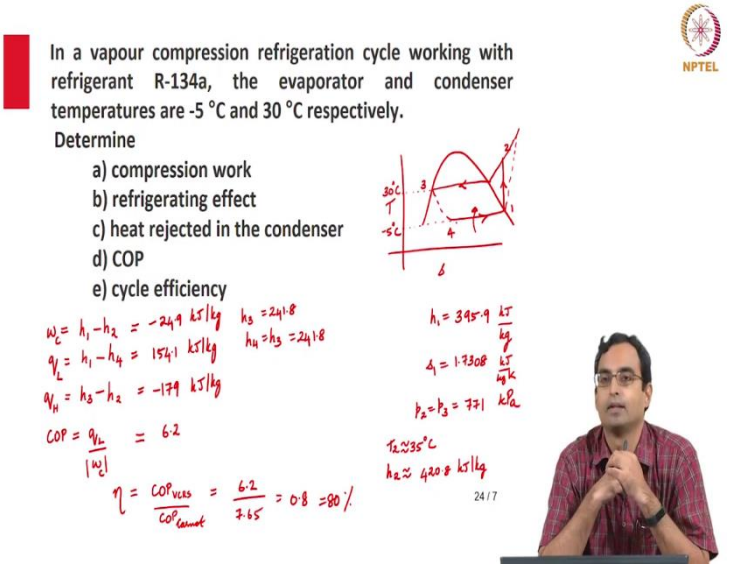
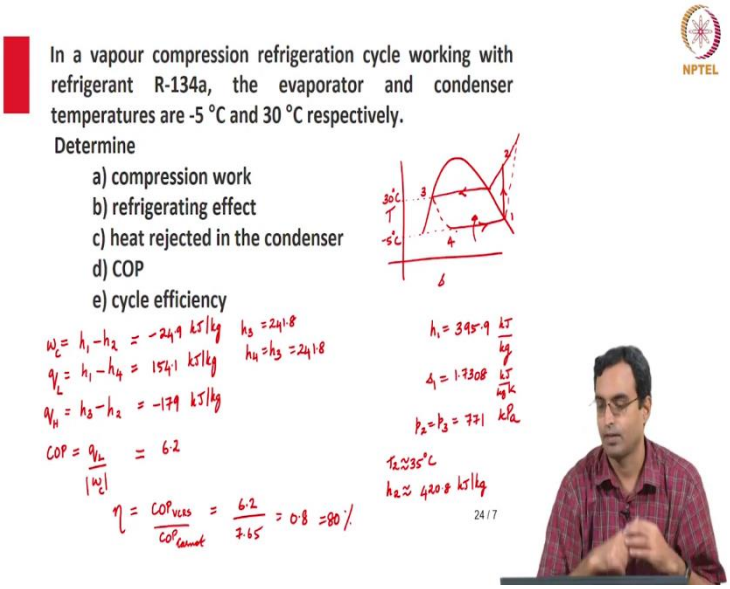
(Refer Slide Time: 17:43)





(Refer Slide Time: 21:17)





(Refer Slide Time: 23:20)