# MECH 4880

# Unit 8 – Vapour Compression Refrigeration

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Never Stand Still

School of Mechanical and Manufacturing Engineering

# Week 8 - Notices

- This week we cover vapour compression
- Next week is the laboratory class
- Location Willis Annexe 116
  - Lab will form basis for Assignment 2
  - Lab will run between 3:00pm to 6:00pm depending on your group.
  - Groups will be posted on Moodle.
- Tutorial 3 will be released later this week.

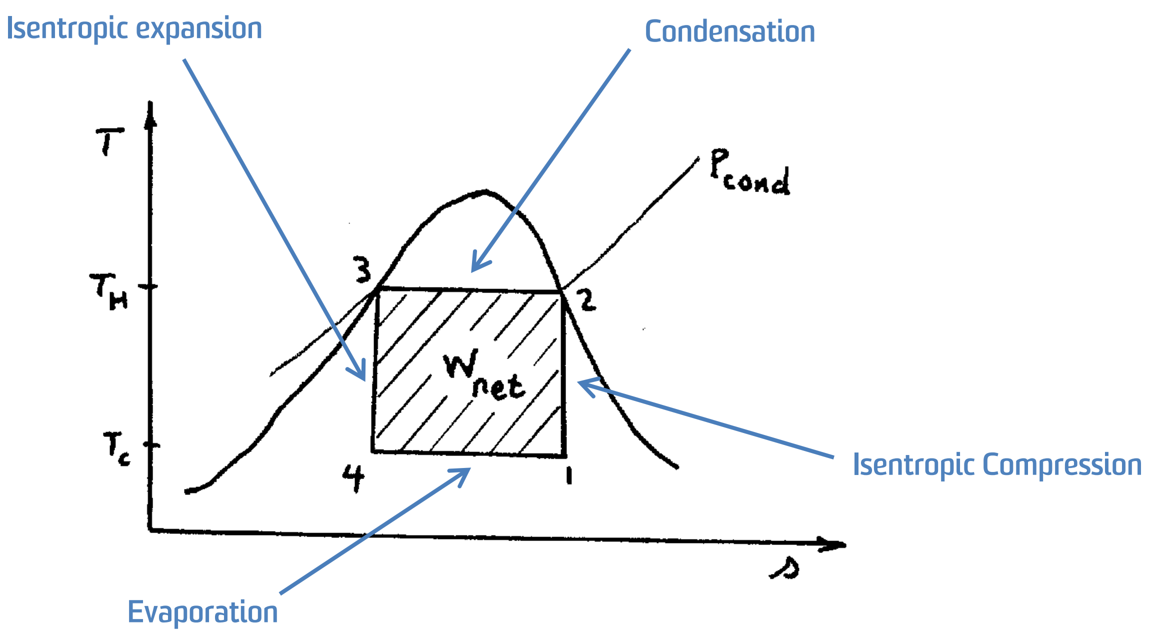
# Vapour Compression Refrigeration

- The reversed Carnot cycle is the most efficient refrigerator (or heat pump) possible.
- If the refrigerant is a gas the Carnot cycle cannot be implemented in practice and the less efficient Brayton-Joule cycle has to be used.
- When the refrigerant is a vapour, then the reversed Carnot cycle can be made almost completely practical by operating in the liquid-vapour region - although may not be feasible in practice

# The Ideal Cycle

The *ideal cycle* can be considered to be *one of two forms*.

(a) The most commonly seen form is as follows.



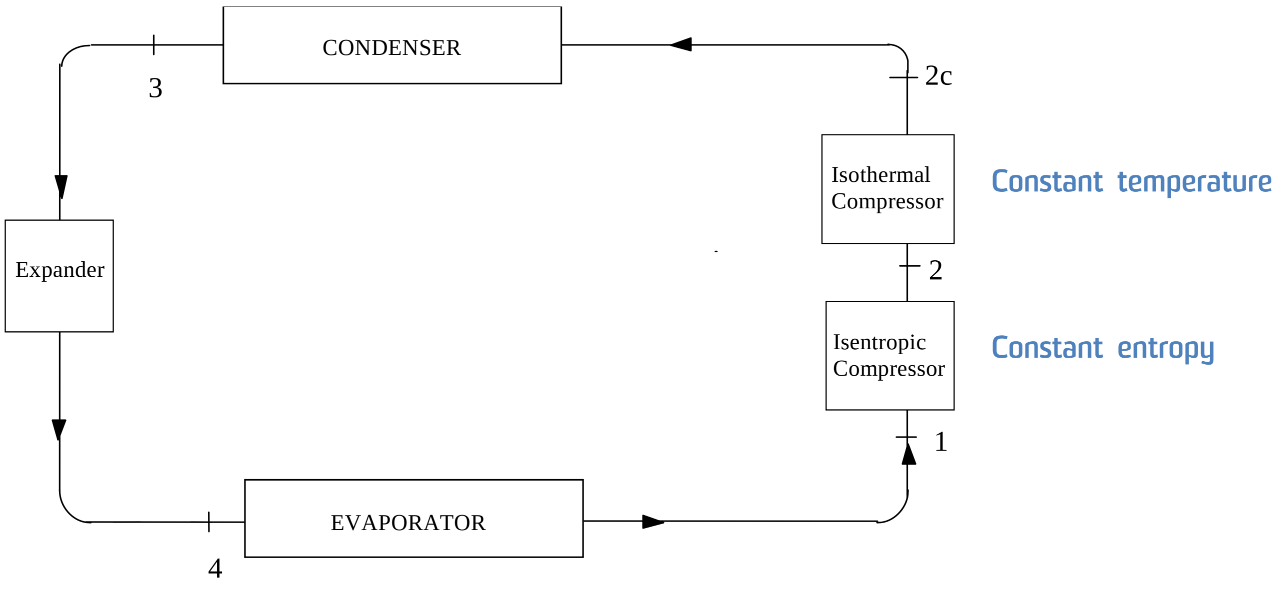

$$COP_c = \frac{q_{ref}}{w_{net}} = \frac{T_C}{T_H - T_C}$$

$$q_{ref} = T_C(s_1 - s_4)$$

$$w_{net} = q_{cond} - q_{ref}$$
$$= (T_H - T_C)(s_1 - s_4)$$

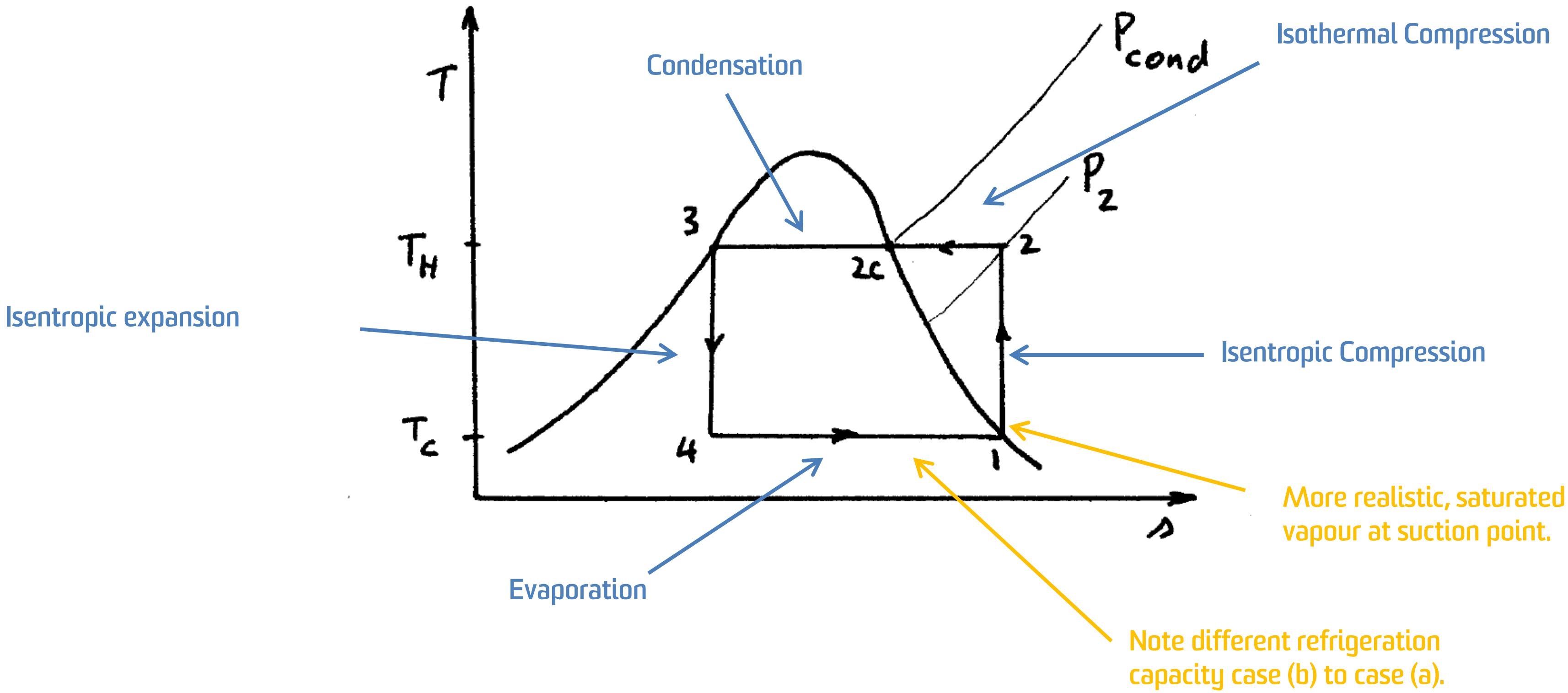
# The Ideal Cycle

(b) where we now have two compressors, an isentropic compressor and an isothermal compressor (see the figure below).

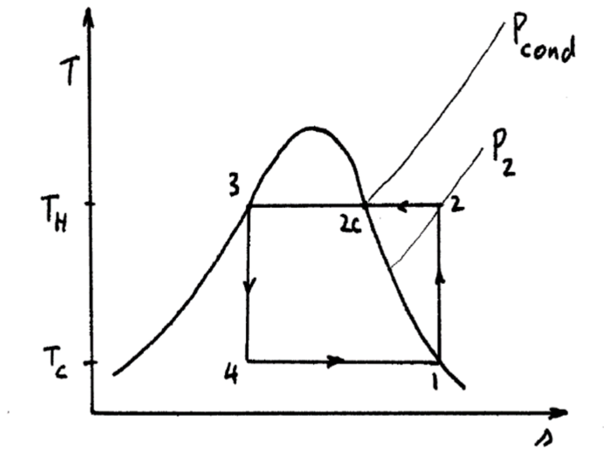


# The Ideal Cycle

The resulting T-s diagram is



# The Ideal Cycle




As before, we have that

$$COP_c = \frac{q_{ref}}{w_{net}}$$

Where

$$q_{ref} = q_{41} = h_1 - h_4 \equiv T_c(s_1 - s_4)$$

and from the First Law of Thermodynamics,

$$w_{net} = q_{23} - q_{41}$$

i.e.

$$\begin{aligned} w_{net} &= T_H(s_2 - s_3) - T_C(s_1 - s_4) \\ &= (T_H - T_C)(s_1 - s_4) \end{aligned}$$

∴

$$COP_c = \frac{T_C}{T_H - T_C}$$

Evaporating T

Condensing T

# The Ideal Cycle

Both (a) and (b) are valid Carnot cycles, with exactly the same Coefficient of Performance, COP, but with different cooling capacities, *q,* and different power inputs.

***Case (a)*** *is more realistic* in that *only one compressor* is used, whereas in case (b), there are two compressors.

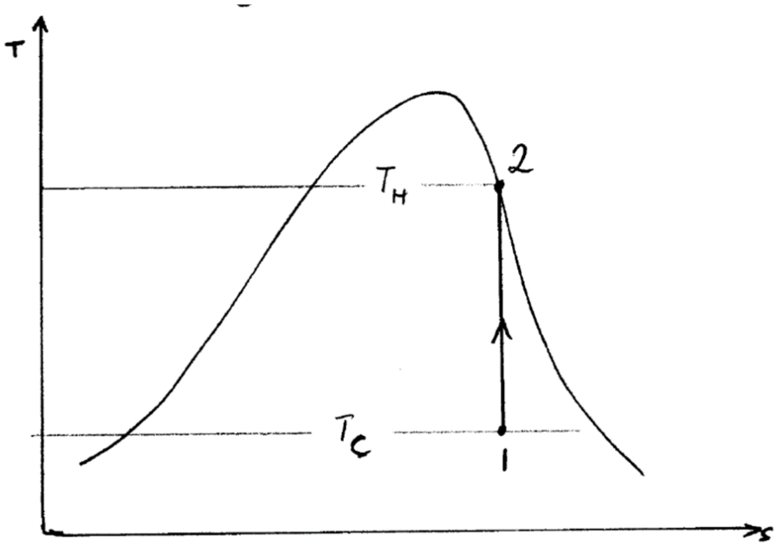
***Case (b)*** *is more realistic* in regard to the *inlet conditions* at suction, i.e. point 1.

# Theoretical (or Standard) Vapour Compression Cycle

While the cycle shown before offers a high coefficient of performance, practical considerations require certain revisions.

*(i) Work of Compression*

In *case (a)* we saw that the *compression* is *"wet"*, viz.




- In this type of process "wet vapour" is taken from the evaporator and compressed isentropically until point 2 is obtained.
- Although this is possible and some *early* compressors did operate on this principle, there are however practical problems.

# Theoretical (or Standard) Vapour Compression Cycle

These problems are:

(1) During compression the droplets of liquid are vaporised by the internal heat transfer process which requires a finite amount of time. This time is not normally available and liquid droplets may become trapped in the head of the cylinder by the rising piston, possibly damaging the valves or cylinder head.

(2) The refrigerating effect is reduced and therefore a larger compressor may be required to circulate the refrigerant.

(3) The liquid droplets may wash away the lubricating oil from the cylinder walls, accelerating wear.

It is therefore normally undesirable to have "wet" compression, i.e. as per *case (a).*

# Question

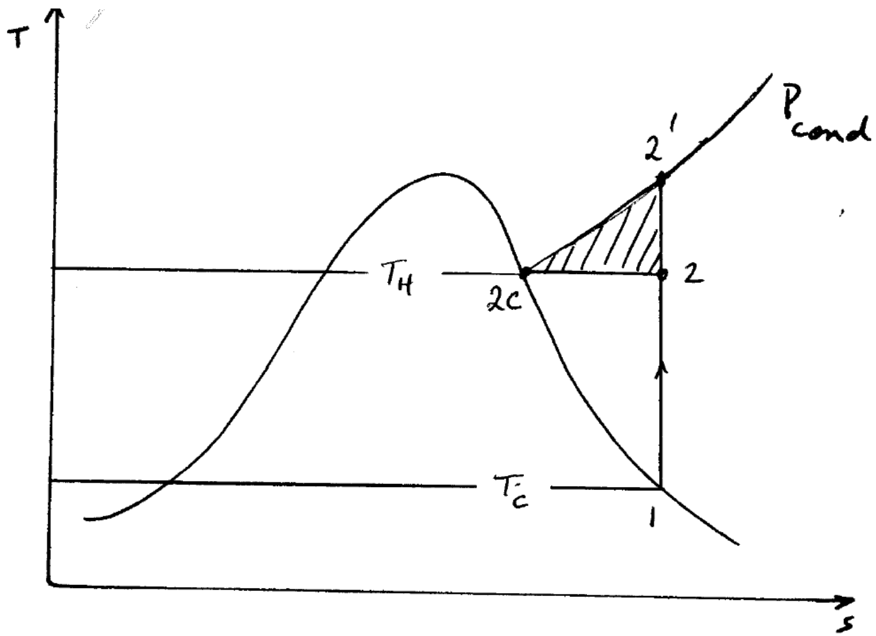
What situation may cause liquid to come back to the compressor?

- Not enough evaporation in evaporator
- Too much refrigerant – specially when using capillary tubes for throttling.
- Beyond the valve limit, wrong orifice different refrigerant used in existing system, eg R134a    -    R404a

Normally continue isentropic compression to point 2′

# Theoretical (or Standard) Vapour Compression Cycle

Consider then the alternative of *case (b).*




It is generally impractical to stop the isentropic compression in the “first” compressor at point 2 and then continue an isothermal compression in the “second” compressor to 2C.  It is normal to continue the isentropic compression to point 2' , i.e. to the condenser pressure.

The shaded area represents the additional work required as a result of this.

# Theoretical (or Standard) Vapour Compression Cycle

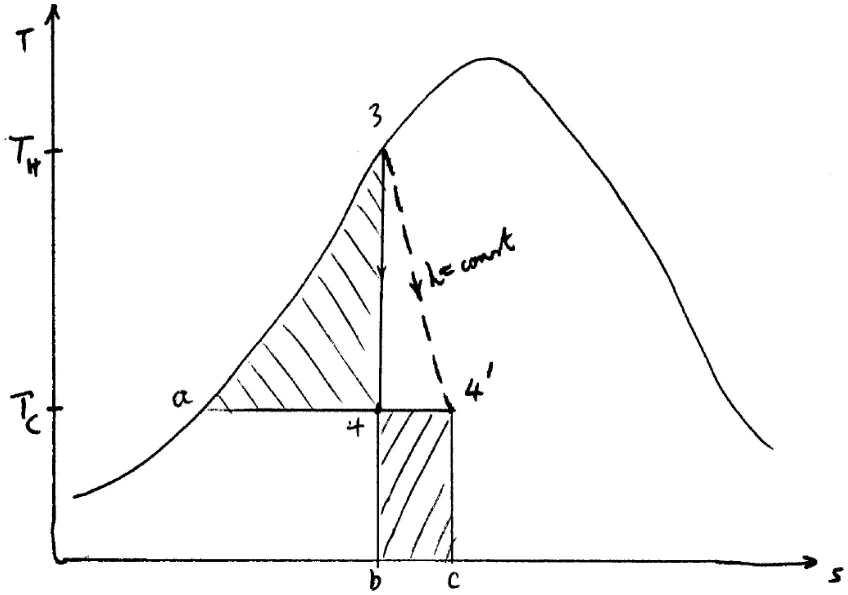
*(ii) Expansion Process*

- Despite the theoretical advantages of using reversible expansion for the process 3- 4, it is hardly ever attempted in practice for ordinary vapour compression cycles, because;
    - the extra cost of the expansion engine or turbine is not worth "even" the theoretical gain and,
    - when account is taken of inefficiencies of the expander the gain becomes very small.

The most common alternative is to replace the isentropic expansion by a simple throttling process.

# Theoretical (or Standard) Vapour Compression Cycle

*(ii) Expansion Process (con't)*




It can be easily seen that the *loss in refrigerating effect* due to the introduction of throttling is

$$q_{loss} = h_{4'} - h_4 \equiv T_c\left(s_{4'} - s_4\right)$$

# Theoretical (or Standard) Vapour Compression Cycle

We have shown that

$$q_{loss} = h_{4'} - h_4 \equiv T_c\left(s_{4'} - s_4\right)$$

However, we also lose the work that the turbine (or expander) would have developed, i.e.

$$w_{exp_{loss}} = h_3 - h_4$$

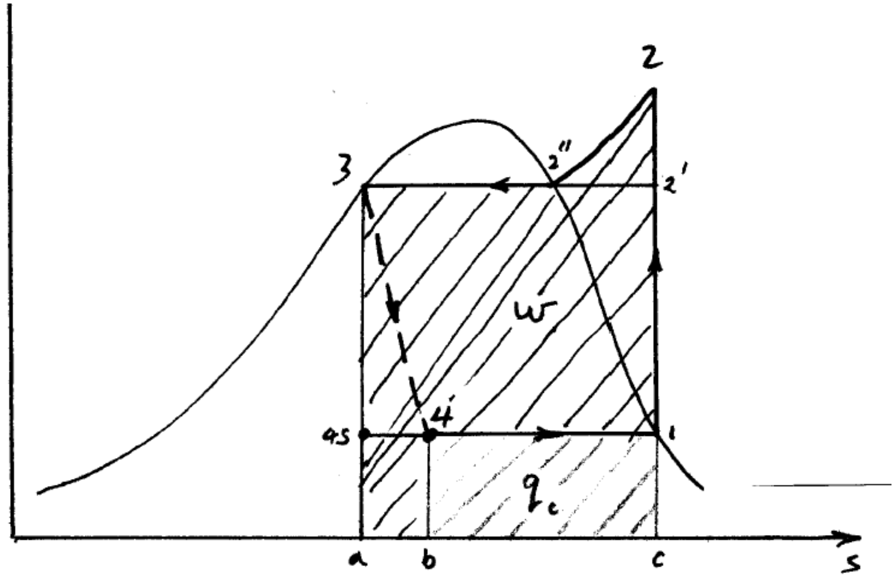
but $h_3 = h_{4'}$

$$w_{exp_{loss}} = h_{4'} - h_4$$

Hence, the lost work is equal to the lost refrigerating effect.

# The Theoretical Cycle

The cycle with the above two modifications is called the *Theoretical Cycle*.




- Note that the area 2'22'' represents the increase in work required due to the superheat horn,
- the area 4s4ba represents the loss of refrigerating effect and equally the loss of expander work.
- All of these facts result is a lower COP for the theoretical cycle in comparison with the ideal cycle.

The cycle consists of,

1 - 2 isentropic compression (reversible adiabatic)

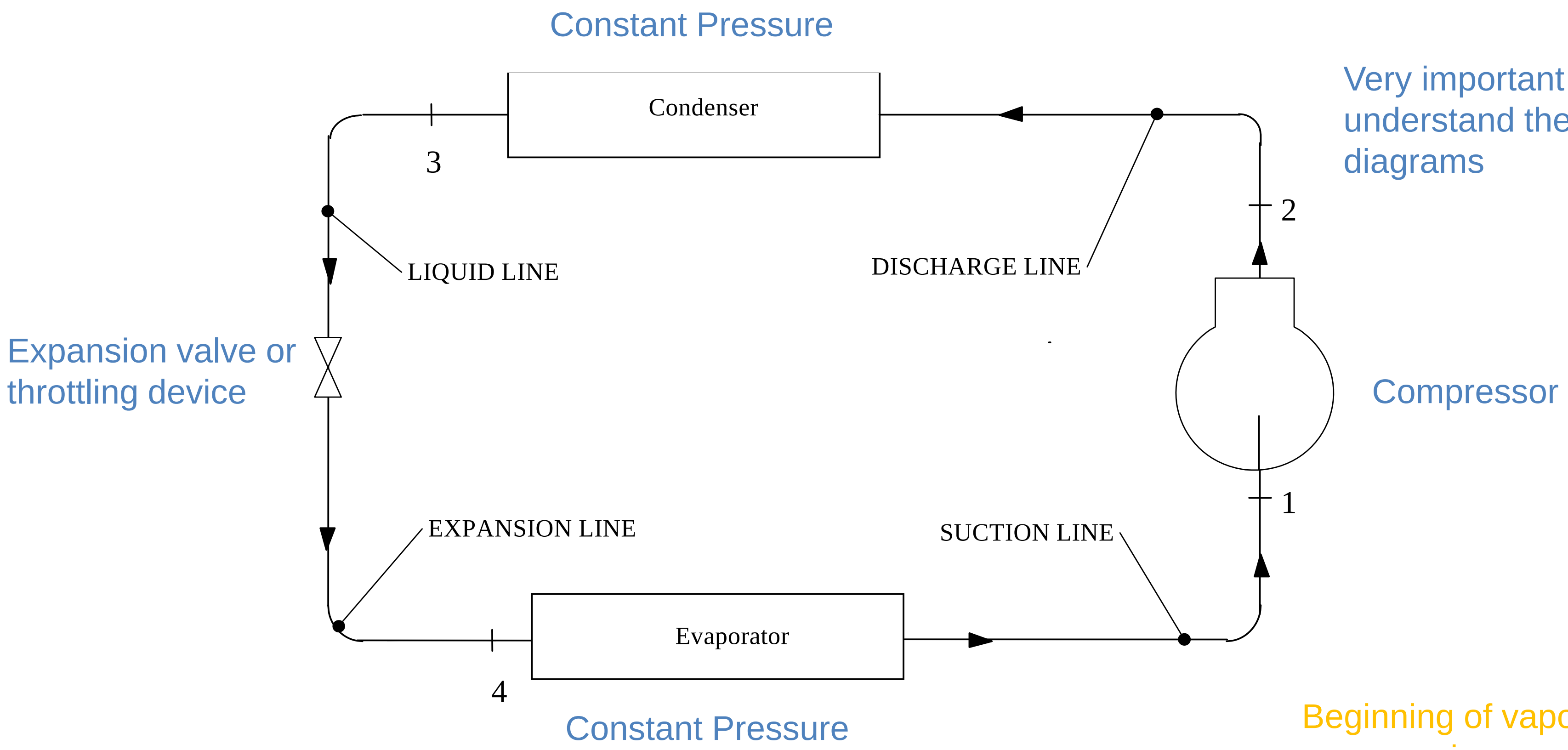
2 - 3 condensation at constant pressure

3 - 4 throttling (irreversible) constant enthalpy

4 - 1 evaporation at constant pressure

# The Theoretical Cycle

The plant is shown in the figure below. Common names for the lines interconnecting the equipment have been labelled.

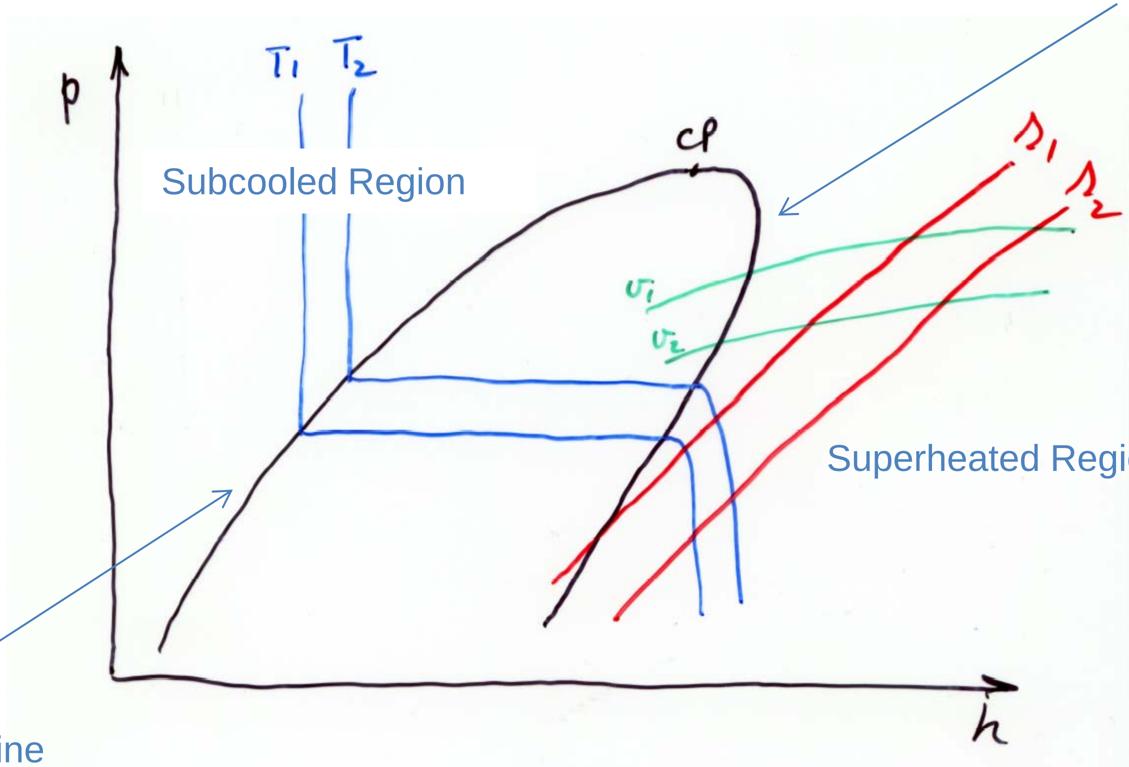



Very important you understand these diagrams

Beginning of vapour compression problem solving

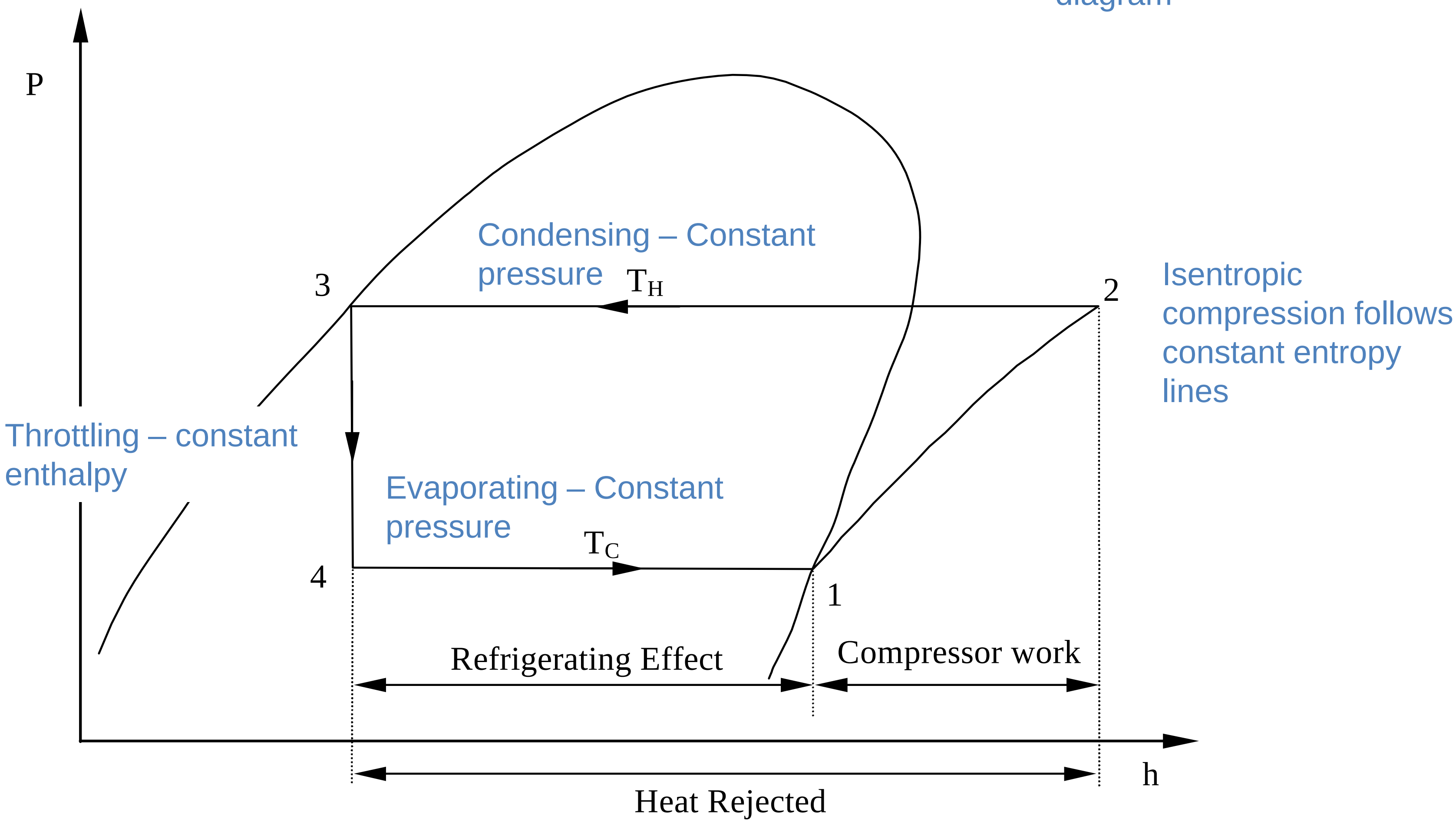
# The Pressure-Enthalpy Diagram

The refrigeration cycle consists of two constant pressure processes and one constant enthalpy process, it is convenient to represent the cycle on a pressure-enthalpy diagram.

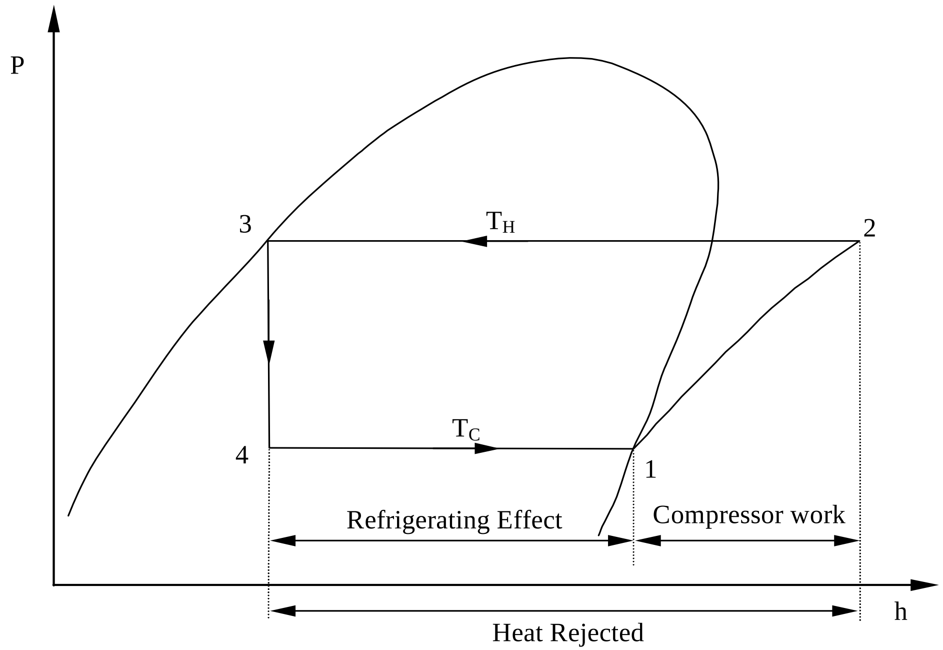


# The Pressure-Enthalpy Diagram

Very important to understand the P-h diagram



# Analysis of the Theoretical Cycle




Refrigerating effect

$$q_{ref} = h_1 - h_4$$

Heat rejected in condenser

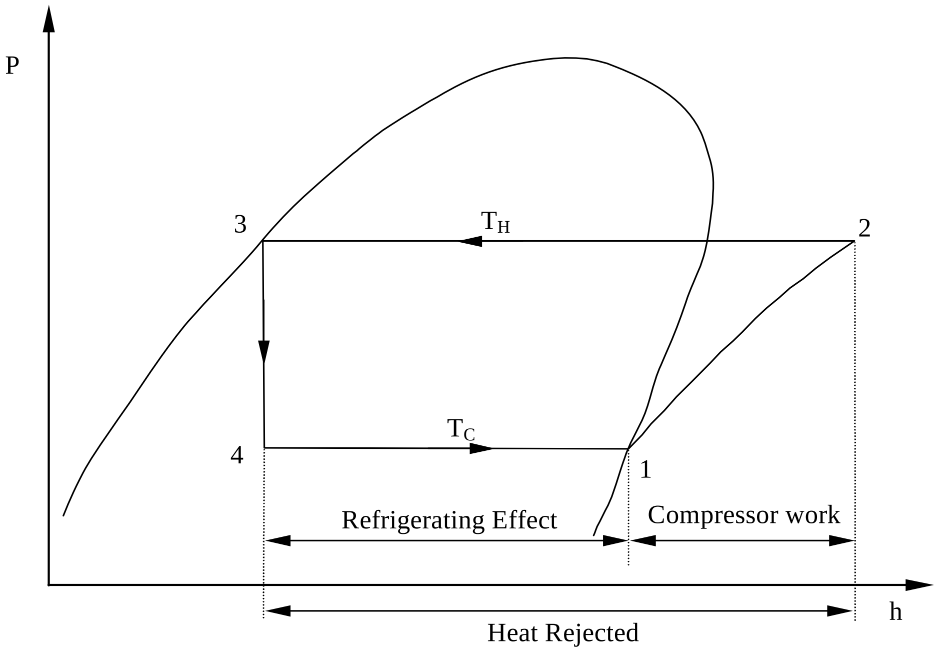
$$q_{cond} = h_2 - h_3$$

Compressor work

$$w = h_2 - h_1$$

per unit mass

# Analysis of the Theoretical Cycle

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$$q_{ref} = h_1 - h_4$$

Heat rejected in condenser

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Compressor work

$$w = h_2 - h_1$$

per unit mass

For the theoretical cycle

$$COP = \frac{h_1 - h_4}{h_2 - h_1}$$ *AS/NZS 3823 Cooling - EER*

$$PF = \frac{h_2 - h_3}{h_2 - h_1}$$ *AS/NZS 3823 Heating - COP*

# Refrigerant circulation rate

Refrigerant circulation rate given as:

$$\dot{m} = \frac{\dot{Q}_{ref}}{h_1 - h_4}$$

The *refrigerant volumetric flow rate*, often called the theoretical piston displacement is defined as:

$$\dot{V} = \dot{m} v_{suction(or\ 1)}$$

Specific volume at point 1, inlet of compressor

This should *not* be confused with the *actual piston displacement*, or as often called, the *swept volume*.

# Swept Volume

The swept volume for a reciprocating compressor is:

$$\dot{V}_{swept} = \left( \frac{\pi D^2}{4} s \right) nN$$

where

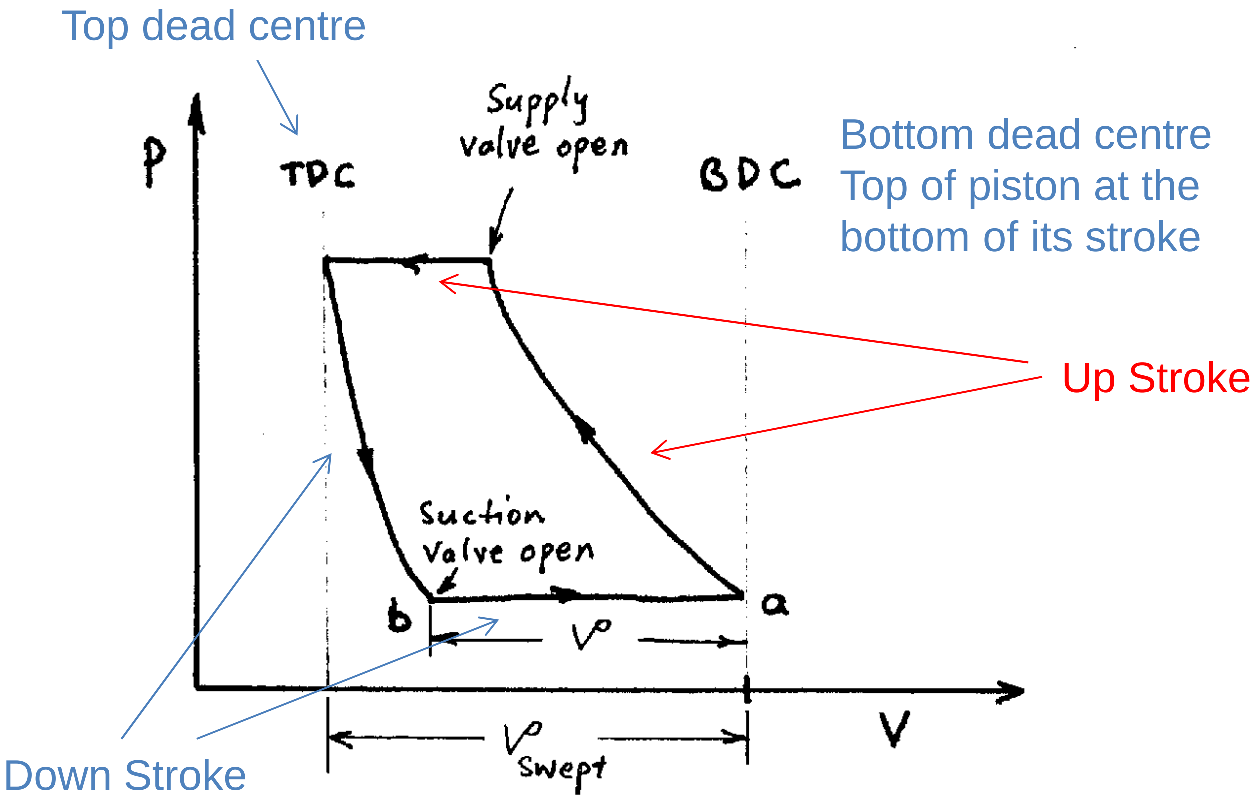
| | |
|---|---|
| D | = diameter of piston (m) |
| s | = stroke (m) |
| n | = number of cylinders |
| N | = speed (rev/sec) |

Swept volume is a function of various physical aspects of the compressor

# Volumetric Efficiency

At this stage it is useful to define the *volumetric efficiency*.

$$\eta_v = \frac{volume\ flow\,rate}{swept\,volume\ flow\,rate}$$



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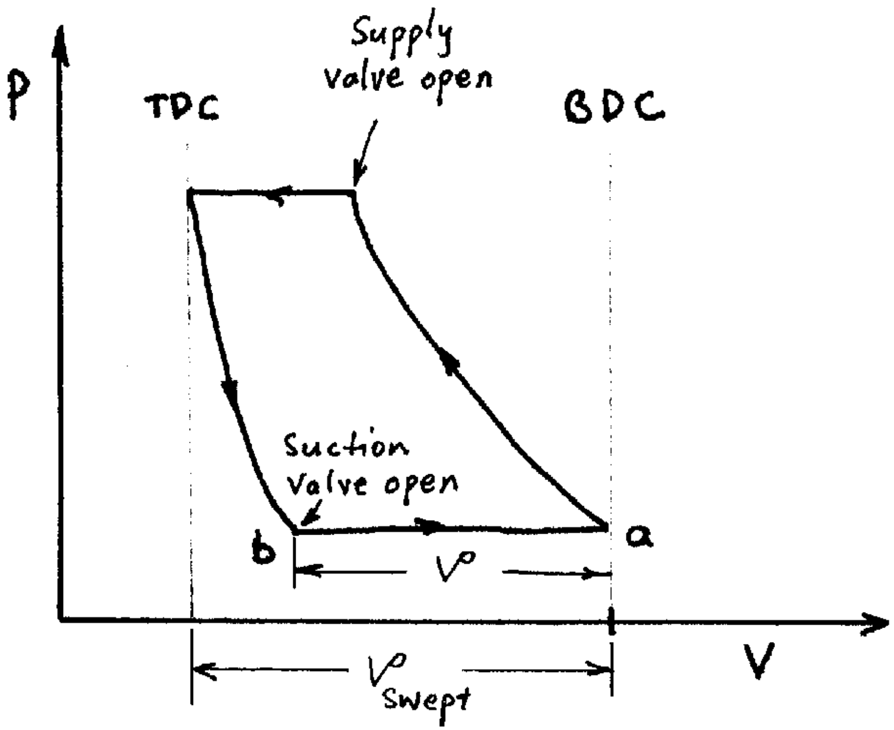


from the figure we have

$$\eta_v = \frac{V_a - V_b}{V_{swept}} = \frac{\dot{V}}{\dot{V}_{swept}}$$

we can write

$$\dot{V} = \eta_v \dot{V}_{swept}$$

Note that

$$\dot{V}_{swept} = f\left(compressor\ geometry\ only\right)$$

# Example 1

A refrigeration system using R22 operates on a standard vapour-compression cycle in which the evaporating temperature is -8ºC and the condensing temperature is 42ºC. The compressor used in this system is a six-cylinder compressor operating at 1740 rpm. The cylinder bore is 67 mm, the piston stroke is 57 mm and for the given operating conditions the volumetric efficiency of the compressor is 77%.

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Determine the:

(a) volume flow rate measured at compressor suction;

(b) mass flow rate of refrigerant;

(c) refrigerating capacity of the system;

(d) power consumption;

(e) heat rejected from the condenser

(f) COP, and compare this with COPc.

# Example 1

Solution:

(a)

$$\dot{V} = \eta_v \dot{V}_{swept}$$

we can calculate,

67mm cylinder bore

57mm stroke

Number of cylinders

$$\dot{V}_{swept} = \left(\frac{\pi D^2}{4}\right) snN = \left(\frac{\pi \times .067^2}{4}\right) 0.057 \times 6 \times \frac{1740}{60}$$

rpm

sec

$$\dot{V}_{swept} = 0.035 m^3 / s$$

# Example 1

Solution:

(a) $$\dot{V} = \eta_v \dot{V}_{swept}$$

we can calculate,

$$\dot{V}_{swept} = \left(\frac{\pi D^2}{4}\right) snN = \left(\frac{\pi \times .067^2}{4}\right) 0.057 \times 6 \times \frac{1740}{60}$$

$$\dot{V}_{swept} = 0.035 m^3 / s$$

hence

$$\begin{aligned} \dot{V} &= \eta_v \times \dot{V}_{swept} \\ &= 0.77 \times 0.035 \\ &= 0.0269 m^3 / s \quad (26.9 L / s) \end{aligned}$$

# Example 1

Solution:

(b) the mass flow rate is given by,

$$\dot{m} = \frac{\dot{V}}{v_1}$$

Where $v_{1(suction)} = v_g(-8^{o}C) = 0.0615 m^3/kg$ (from refrigerant tables)

## SATURATED PROPERTIES OF R22

| T DEG.C | P KPA | 1/V(F) KG/M3 | V(G) M3/KG | H(F) | H(FG) KJ/KG | H(G) | S(F) | S(FG) KJ/KG.K | S(G) |
|---|---|---|---|---|---|---|---|---|---|
| -40.0 | 104.9 | 1410. | .20583 | .00 | 233.20 | 233.20 | .0000 | 1.0002 | 1.0002 |
| -39.0 | 109.9 | 1407. | .19712 | 1.06 | 232.60 | 233.66 | .0045 | .9934 | .9979 |
| -38.0 | 115.0 | 1404. | .18886 | 2.12 | 232.00 | 234.12 | .0090 | .9866 | .9956 |
| -37.0 | 120.4 | 1401. | .18101 | 3.19 | 231.39 | 234.58 | .0135 | .9798 | .9934 |
| -36.0 | 125.9 | 1398. | .17356 | 4.26 | 230.77 | 235.03 | .0180 | .9731 | .9912 |
| -35.0 | 131.6 | 1395. | .16647 | 5.33 | 230.16 | 235.49 | .0225 | .9664 | .9890 |
| -34.0 | 137.5 | 1392. | .15973 | 6.40 | 229.54 | 235.94 | .0270 | .9598 | .9868 |
| -33.0 | 143.7 | 1389. | .15333 | 7.48 | 228.91 | 236.39 | .0315 | .9532 | .9847 |
| -32.0 | 150.0 | 1386. | .14723 | 8.56 | 228.28 | 236.84 | .0360 | .9466 | .9826 |
| -31.0 | 156.6 | 1383. | .14143 | 9.64 | 227.64 | 237.28 | .0404 | .9401 | .9805 |
| -30.0 | 163.4 | 1380. | .13590 | 10.72 | 227.00 | 237.73 | .0449 | .9336 | .9785 |
| -29.0 | 170.4 | 1377. | .13063 | 11.81 | 226.36 | 238.17 | .0493 | .9271 | .9764 |
| -28.0 | 177.7 | 1374. | .12561 | 12.90 | 225.71 | 238.61 | .0538 | .9207 | .9744 |
| -27.0 | 185.2 | 1371. | .12082 | 14.00 | 225.05 | 239.05 | .0582 | .9143 | .9725 |
| -26.0 | 192.9 | 1368. | .11626 | 15.09 | 224.39 | 239.49 | .0626 | .9079 | .9705 |
| -25.0 | 200.9 | 1365. | .11190 | 16.19 | 223.73 | 239.92 | .0670 | .9016 | .9686 |
| -24.0 | 209.1 | 1362. | .10774 | 17.29 | 223.06 | 240.35 | .0714 | .8953 | .9667 |
| -23.0 | 217.6 | 1359. | .10377 | 18.40 | 222.38 | 240.78 | .0758 | .8890 | .9648 |
| -22.0 | 226.4 | 1356. | .09997 | 19.50 | 221.70 | 241.21 | .0802 | .8828 | .9630 |
| -21.0 | 235.4 | 1353. | .09635 | 20.61 | 221.02 | 241.63 | .0846 | .8765 | .9611 |
| -20.0 | 244.7 | 1350. | .09288 | 21.73 | 220.33 | 242.06 | .0890 | .8704 | .9593 |
| -19.0 | 254.3 | 1347. | .08956 | 22.84 | 219.63 | 242.48 | .0934 | .8642 | .9575 |
| -18.0 | 264.2 | 1343. | .08639 | 23.96 | 218.93 | 242.89 | .0977 | .8581 | .9558 |
| -17.0 | 274.4 | 1340. | .08335 | 25.08 | 218.23 | 243.31 | .1021 | .8520 | .9540 |
| -16.0 | 284.8 | 1337. | .08044 | 26.21 | 217.51 | 243.72 | .1064 | .8459 | .9523 |
| -15.0 | 295.6 | 1334. | .07765 | 27.33 | 216.80 | 244.13 | .1108 | .8398 | .9506 |
| -14.0 | 306.7 | 1331. | .07498 | 28.46 | 216.08 | 244.54 | .1151 | .8338 | .9489 |
| -13.0 | 318.1 | 1328. | .07242 | 29.60 | 215.35 | 244.95 | .1195 | .8278 | .9472 |
| -12.0 | 329.8 | 1324. | .06997 | 30.73 | 214.62 | 245.35 | .1238 | .8218 | .9456 |
| -11.0 | 341.8 | 1321. | .06762 | 31.87 | 213.88 | 245.75 | .1281 | .8159 | .9440 |
| -10.0 | 354.2 | 1318. | .06536 | 33.01 | 213.13 | 246.15 | .1324 | .8099 | .9423 |
| -9.0 | 366.9 | 1315. | .06320 | 34.16 | 212.38 | 246.54 | .1367 | .8040 | .9407 |
| -8.0 | 379.9 | 1311. | .06112 | 35.30 | 211.63 | 246.93 | .1410 | .7981 | .9392 |
| -7.0 | 393.3 | 1308. | .05912 | 36.45 | 210.87 | 247.32 | .1453 | .7923 | .9376 |
| -6.0 | 407.1 | 1305. | .05720 | 37.61 | 210.10 | 247.70 | .1496 | .7864 | .9360 |
| -5.0 | 421.2 | 1302. | .05536 | 38.76 | 209.32 | 248.09 | .1539 | .7806 | .9345 |
| -4.0 | 435.7 | 1298. | .05359 | 39.92 | 208.55 | 248.47 | .1582 | .7748 | .9330 |
| -3.0 | 450.5 | 1295. | .05188 | 41.08 | 207.76 | 248.84 | .1624 | .7691 | .9315 |
| -2.0 | 465.8 | 1292. | .05024 | 42.25 | 206.97 | 249.22 | .1667 | .7633 | .9300 |
| -1.0 | 481.4 | 1288. | .04867 | 43.41 | 206.17 | 249.58 | .1710 | .7576 | .9285 |
| .0 | 497.4 | 1285. | .04715 | 44.59 | 205.37 | 249.95 | .1752 | .7518 | .9271 |
| 1.0 | 513.8 | 1281. | .04569 | 45.76 | 204.55 | 250.31 | .1795 | .7461 | .9256 |
| 2.0 | 530.7 | 1278. | .04428 | 46.94 | 203.74 | 250.67 | .1837 | .7405 | .9242 |
| 3.0 | 547.9 | 1275. | .04293 | 48.12 | 202.92 | 251.03 | .1879 | .7348 | .9227 |
| 4.0 | 565.5 | 1271. | .04162 | 49.30 | 202.08 | 251.38 | .1922 | .7292 | .9213 |
| 5.0 | 583.6 | 1268. | .04037 | 50.49 | 201.25 | 251.73 | .1964 | .7235 | .9199 |
| 6.0 | 602.1 | 1264. | .03916 | 51.67 | 200.40 | 252.08 | .2006 | .7179 | .9185 |
| 7.0 | 621.0 | 1261. | .03799 | 52.87 | 199.55 | 252.42 | .2048 | .7123 | .9172 |
| 8.0 | 640.4 | 1257. | .03686 | 54.06 | 198.70 | 252.76 | .2091 | .7067 | .9158 |
| 9.0 | 660.2 | 1254. | .03577 | 55.26 | 197.83 | 253.09 | .2133 | .7012 | .9144 |
| 10.0 | 680.5 | 1250. | .03472 | 56.46 | 196.96 | 253.43 | .2175 | .6956 | .9131 |
| 11.0 | 701.2 | 1246. | .03371 | 57.67 | 196.09 | 253.75 | .2217 | .6901 | .9118 |
| 12.0 | 722.4 | 1243. | .03273 | 58.88 | 195.20 | 254.08 | .2259 | .6846 | .9104 |
| 13.0 | 744.1 | 1239. | .03179 | 60.09 | 194.31 | 254.40 | .2301 | .6790 | .9091 |
| 14.0 | 766.3 | 1236. | .03088 | 61.30 | 193.41 | 254.71 | .2343 | .6735 | .9078 |

# SATURATED PROPERTIES OF R22

| T DEG.C | P KPA | 1/V(F) KG/M3 | V(G) M3/KG | H(F) | H(FG) KJ/KG | H(G) | S(F) | S(FG) KJ/KG.K | S(G) |
|---|---|---|---|---|---|---|---|---|---|
| -40.0 | 104.9 | 1410. | .20583 | .00 | 233.20 | 233.20 | .0000 | 1.0002 | 1.0002 |
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| -36.0 | 125.9 | 1398. | .17356 | 4.26 | 230.77 | 235.03 | .0180 | .9731 | .9912 |
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| -24.0 | 209.1 | 1362. | .10774 | 17.29 | 223.06 | 240.35 | .0714 | .8953 | .9667 |
| -23.0 | 217.6 | 1359. | .10377 | 18.40 | 222.38 | 240.78 | .0758 | .8890 | .9648 |
| -22.0 | 226.4 | 1356. | .09997 | 19.50 | 221.70 | 241.21 | .0802 | .8828 | .9630 |
| -21.0 | 235.4 | 1353. | .09635 | 20.61 | 221.02 | 241.63 | .0846 | .8765 | .9611 |
| -20.0 | 244.7 | 1350. | .09288 | 21.73 | 220.33 | 242.06 | .0890 | .8704 | .9593 |
| -19.0 | 254.3 | 1347. | .08956 | 22.84 | 219.63 | 242.48 | .0934 | .8642 | .9575 |
| -18.0 | 264.2 | 1343. | .08639 | 23.96 | 218.93 | 242.89 | .0977 | .8581 | .9558 |
| -17.0 | 274.4 | 1340. | .08335 | 25.08 | 218.23 | 243.31 | .1021 | .8520 | .9540 |
| -16.0 | 284.8 | 1337. | .08044 | 26.21 | 217.51 | 243.72 | .1064 | .8459 | .9523 |
| -15.0 | 295.6 | 1334. | .07765 | 27.33 | 216.80 | 244.13 | .1108 | .8398 | .9506 |
| -14.0 | 306.7 | 1331. | .07498 | 28.46 | 216.08 | 244.54 | .1151 | .8338 | .9489 |
| -13.0 | 318.1 | 1328. | .07242 | 29.60 | 215.35 | 244.95 | .1195 | .8278 | .9472 |
| -12.0 | 329.8 | 1324. | .06997 | 30.73 | 214.62 | 245.35 | .1238 | .8218 | .9456 |
| -11.0 | 341.8 | 1321. | .06762 | 31.87 | 213.88 | 245.75 | .1281 | .8159 | .9440 |
| -10.0 | 354.2 | 1318. | .06536 | 33.01 | 213.13 | 246.15 | .1324 | .8099 | .9423 |
| -9.0 | 366.9 | 1315. | .06320 | 34.16 | 212.38 | 246.54 | .1367 | .8040 | .9407 |
| -8.0 | 379.9 | 1311. | .06112 | 35.30 | 211.63 | 246.93 | .1410 | .7981 | .9392 |
| -7.0 | 393.3 | 1308. | .05912 | 36.45 | 210.87 | 247.32 | .1453 | .7923 | .9376 |

## SUPERHEATED PROPERTIES OF R22

| TEMP. (P.SAT) | | SAT. STATE | SUPERHEAT,K 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -40.0 | V | .2058 | .2108 | .2158 | .2208 | .2257 | .2306 | .2354 | .2451 | .2548 | .2643 | .3022 | .3489 | .3953 |
| ( 104.9) | H | 233.2 | 236.2 | 239.2 | 242.3 | 245.4 | 248.4 | 251.6 | 257.9 | 264.3 | 270.8 | 297.7 | 333.6 | 372.0 |
| | S | 1.0002 | 1.0130 | 1.0256 | 1.0380 | 1.0502 | 1.0623 | 1.0743 | 1.0978 | 1.1208 | 1.1433 | 1.2295 | 1.3299 | 1.4238 |
| -39.0 | V | .1971 | .2019 | .2067 | .2114 | .2161 | .2208 | .2255 | .2347 | .2439 | .2531 | .2893 | .3339 | .3783 |
| ( 109.9) | H | 233.7 | 236.7 | 239.7 | 242.8 | 245.9 | 249.0 | 252.1 | 258.4 | 264.8 | 271.3 | 298.4 | 334.4 | 372.7 |
| | S | .9979 | 1.0107 | 1.0232 | 1.0356 | 1.0479 | 1.0600 | 1.0719 | 1.0954 | 1.1184 | 1.1409 | 1.2270 | 1.3273 | 1.4212 |
| -38.0 | V | .1889 | .1935 | .1980 | .2025 | .2071 | .2115 | .2160 | .2249 | .2337 | .2424 | .2770 | .3197 | .3621 |
| ( 115.0) | H | 234.1 | 237.1 | 240.2 | 243.3 | 246.4 | 249.5 | 252.6 | 259.0 | 265.4 | 271.9 | 299.0 | 335.1 | 373.5 |
| | S | .9956 | 1.0084 | 1.0210 | 1.0334 | 1.0456 | 1.0577 | 1.0696 | 1.0931 | 1.1160 | 1.1385 | 1.2245 | 1.3248 | 1.4185 |
| -37.0 | V | .1810 | .1854 | .1898 | .1941 | .1984 | .2027 | .2070 | .2155 | .2239 | .2323 | .2654 | .3063 | .3468 |
| ( 120.4) | H | 234.6 | 237.6 | 240.7 | 243.8 | 246.9 | 250.0 | 253.1 | 259.5 | 265.9 | 272.5 | 299.6 | 335.8 | 374.3 |
| | S | .9934 | 1.0061 | 1.0187 | 1.0311 | 1.0433 | 1.0554 | 1.0673 | 1.0908 | 1.1137 | 1.1362 | 1.2221 | 1.3222 | 1.4159 |
| -36.0 | V | .1736 | .1778 | .1820 | .1861 | .1903 | .1944 | .1985 | .2066 | .2147 | .2227 | .2544 | .2935 | .3322 |
| ( 125.9) | H | 235.0 | 238.1 | 241.2 | 244.3 | 247.4 | 250.5 | 253.7 | 260.0 | 266.5 | 273.1 | 300.3 | 336.5 | 375.0 |
| | S | .9912 | 1.0039 | 1.0165 | 1.0289 | 1.0411 | 1.0532 | 1.0651 | 1.0885 | 1.1115 | 1.1339 | 1.2198 | 1.3198 | 1.4134 |
| -35.0 | V | .1665 | .1705 | .1745 | .1785 | .1825 | .1865 | .1904 | .1982 | .2059 | .2136 | .2440 | .2814 | .3184 |
| ( 131.6) | H | 235.5 | 238.6 | 241.6 | 244.7 | 247.9 | 251.0 | 254.2 | 260.6 | 267.1 | 273.6 | 300.9 | 337.2 | 375.8 |
| | S | .9890 | 1.0017 | 1.0143 | 1.0267 | 1.0389 | 1.0510 | 1.0629 | 1.0863 | 1.1092 | 1.1317 | 1.2174 | 1.3174 | 1.4109 |
| -34.0 | V | .1597 | .1636 | .1675 | .1713 | .1751 | .1789 | .1827 | .1902 | .1976 | .2049 | .2340 | .2698 | .3053 |
| ( 137.5) | H | 235.9 | 239.0 | 242.1 | 245.2 | 248.4 | 251.5 | 254.7 | 261.1 | 267.6 | 274.2 | 301.6 | 337.9 | 376.5 |
| | S | .9868 | .9996 | 1.0121 | 1.0245 | 1.0367 | 1.0488 | 1.0607 | 1.0841 | 1.1070 | 1.1294 | 1.2151 | 1.3150 | 1.4084 |
| -33.0 | V | .1533 | .1571 | .1608 | .1644 | .1681 | .1717 | .1753 | .1825 | .1896 | .1967 | .2246 | .2589 | .2929 |
| ( 143.7) | H | 236.4 | 239.5 | 242.6 | 245.7 | 248.9 | 252.0 | 255.2 | 261.7 | 268.2 | 274.8 | 302.2 | 338.6 | 377.3 |
| | S | .9847 | .9974 | 1.0100 | 1.0224 | 1.0346 | 1.0466 | 1.0585 | 1.0819 | 1.1048 | 1.1272 | 1.2129 | 1.3126 | 1.4059 |
| -32.0 | V | .1472 | .1508 | .1544 | .1579 | .1614 | .1649 | .1684 | .1753 | .1821 | .1889 | .2156 | .2485 | .2811 |
| ( 150.0) | H | 236.8 | 239.9 | 243.1 | 246.2 | 249.4 | 252.5 | 255.7 | 262.2 | 268.7 | 275.4 | 302.8 | 339.3 | 378.1 |
| | S | .9826 | .9953 | 1.0079 | 1.0203 | 1.0325 | 1.0445 | 1.0564 | 1.0798 | 1.1027 | 1.1251 | 1.2106 | 1.3103 | 1.4035 |
| -31.0 | V | .1414 | .1449 | .1483 | .1517 | .1551 | .1584 | .1617 | .1684 | .1749 | .1814 | .2071 | .2386 | .2698 |
| ( 156.6) | H | 237.3 | 240.4 | 243.5 | 246.7 | 249.9 | 253.0 | 256.3 | 262.7 | 269.3 | 275.9 | 303.5 | 340.0 | 378.8 |
| | S | .9805 | .9933 | 1.0058 | 1.0182 | 1.0304 | 1.0424 | 1.0543 | 1.0777 | 1.1006 | 1.1229 | 1.2084 | 1.3080 | 1.4012 |

# Example 1

Solution:

(b) the mass flow rate is given by,

$$\dot{m} = \frac{\dot{V}}{v_1}$$

where $v_{1(suction)} = v_g\left(-8^{\circ}C\right) = 0.0615 m^3 / kg$ (from refrigerant tables)

therefore

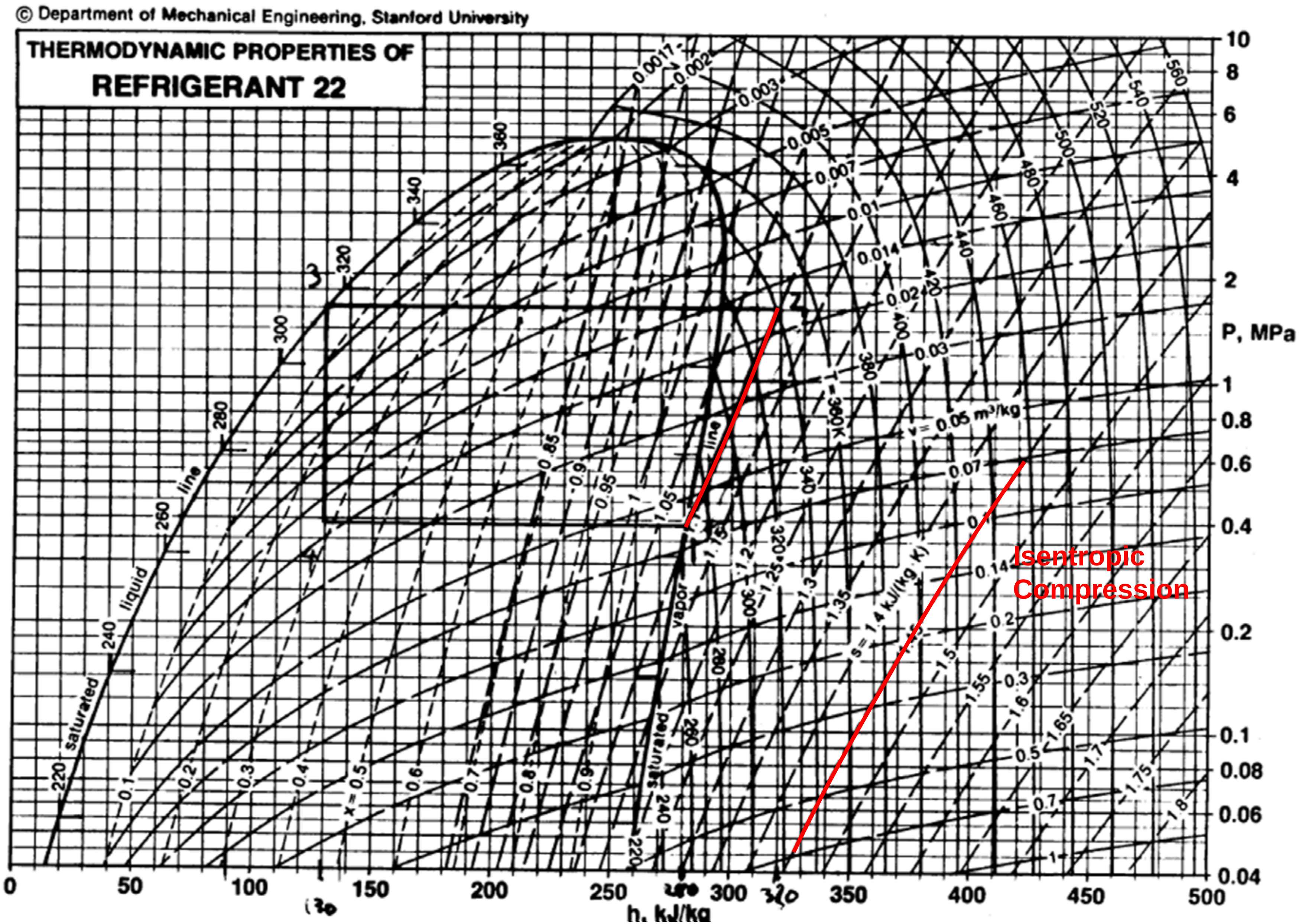
$$\dot{m} = \frac{0.0269}{0.0615}$$
$$= 0.438 kg / s$$

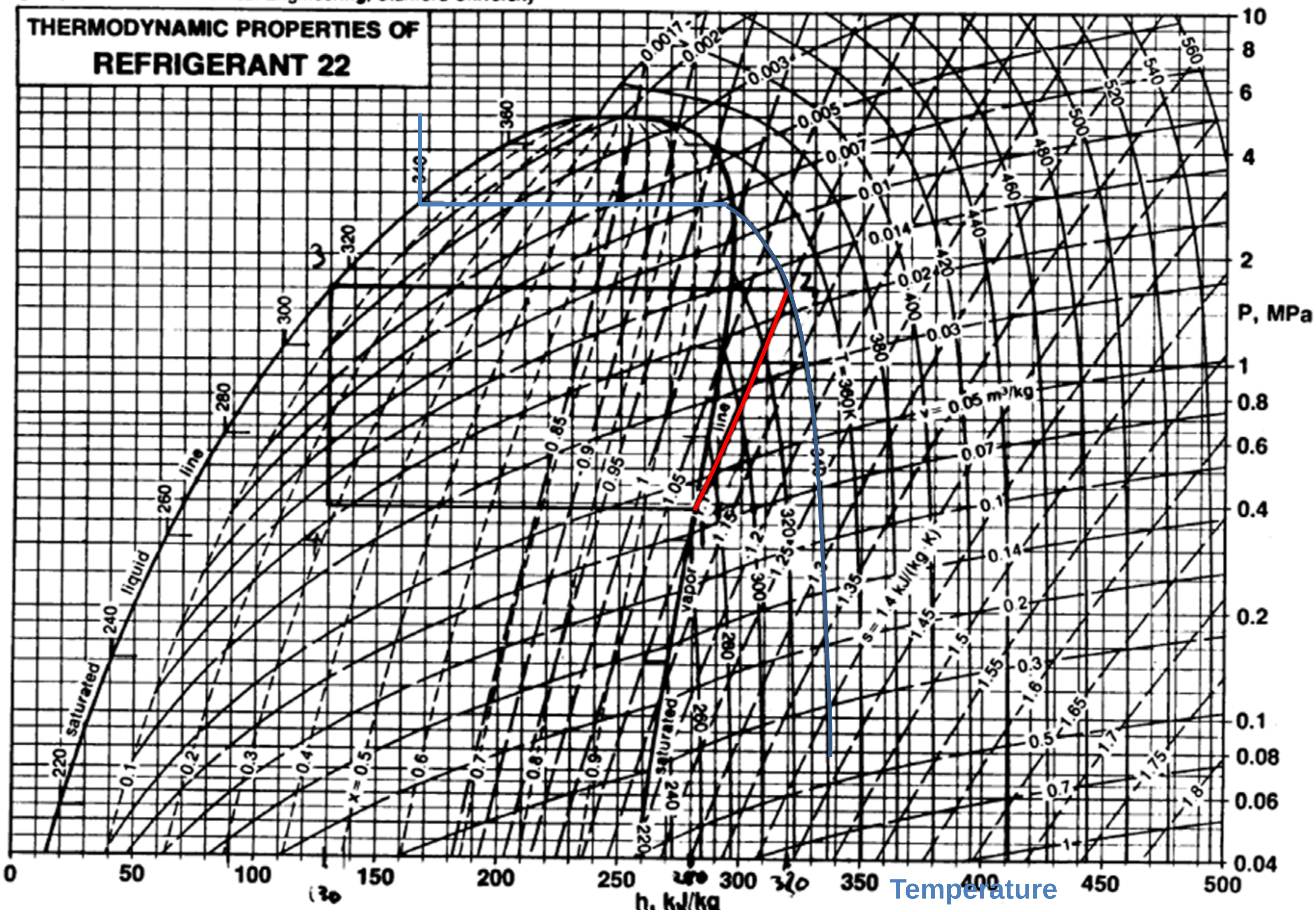
Note: there is some variance in refrigerant tables use the tables provided on Moodle

# Example 1

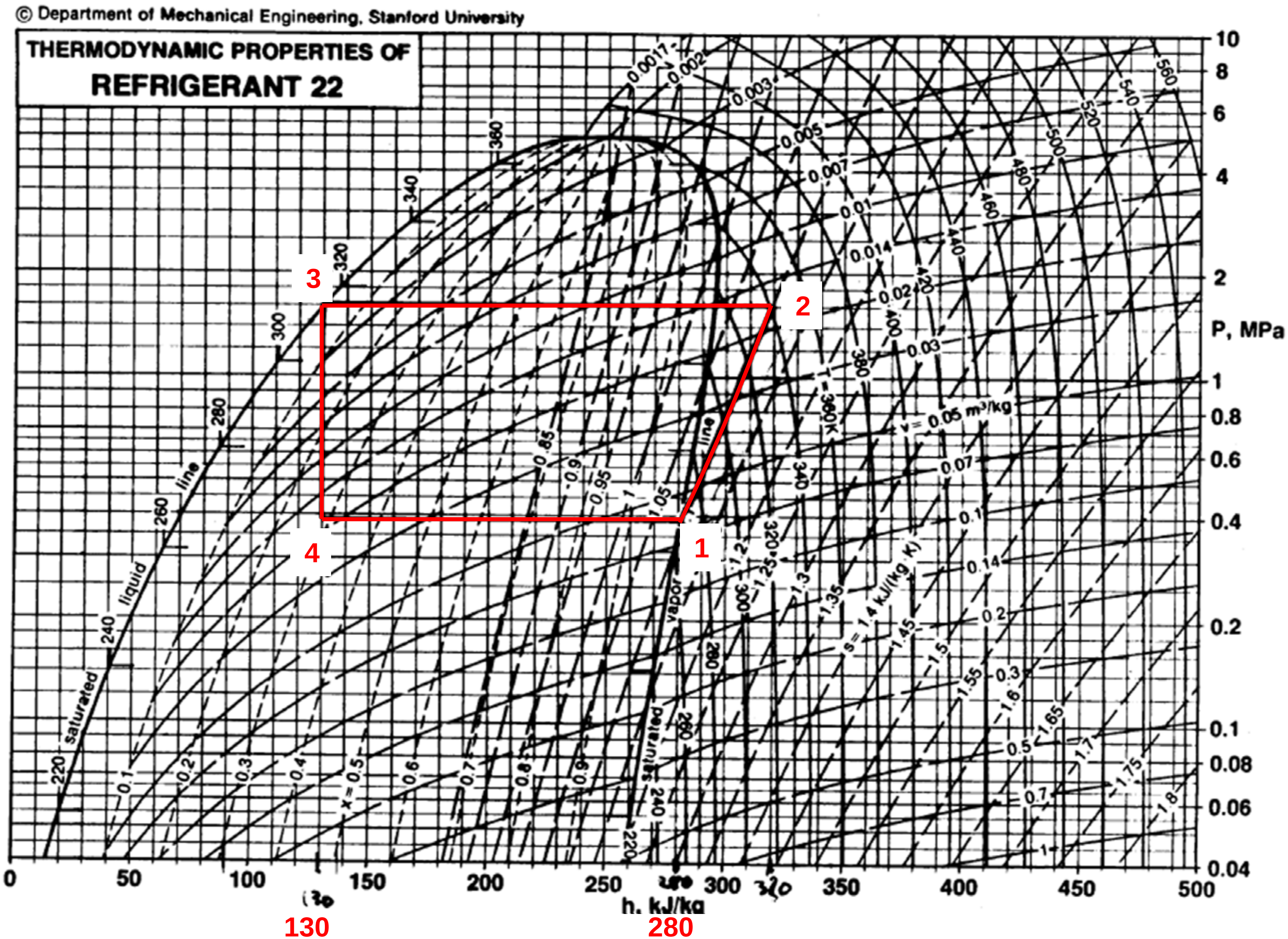
Solution:

(c) The easiest way to answer the rest of the question is to draw the cycle on a P-h diagram


© Department of Mechanical Engineering, Stanford University
THERMODYNAMIC PROPERTIES OF
REFRIGERANT 22
saturated liquid line
saturated vapor line
P, MPa
h, kJ/kg
v = 0.05 m³/kg
s = 1.4 kJ/(kg·K)
T = 360 K
x = 0.5
Isentropic
Compression




Temperature Lines


© Department of Mechanical Engineering, Stanford University
THERMODYNAMIC PROPERTIES OF
REFRIGERANT 22
P, MPa
h, kJ/kg
saturated liquid line
saturated vapor line
v = 0.05 m³/kg
s = 1.4 kJ/(kg·K)
T = 360 K
1
2
3
4
130
280

# Example 1

Solution:

(c) The easiest way to answer the rest of the question is to draw the cycle on a P-h diagram

$$\dot{Q}_{ref} = \dot{m}\left(h_1 - h_4\right)$$

Hence (from the P-h diagram or tables),

$h_1 = 280 kJ/kg$ and $h_4 = 130 kJ/kg = h_3$

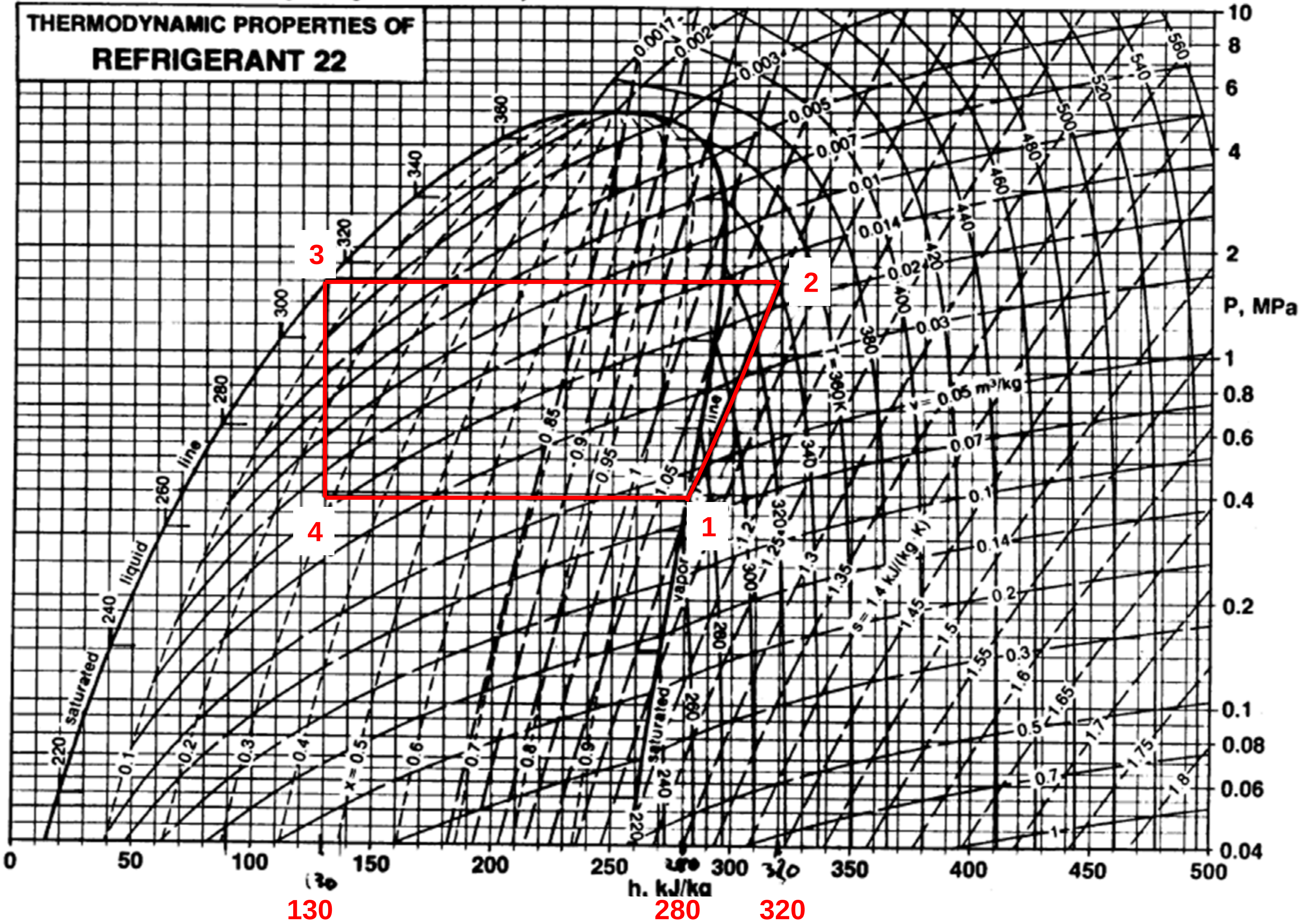
$$\dot{Q}_{ref} = 0.438\left(280 - 130\right) = 65.7 kW(R)$$

# Example 1

Solution:

(d) The power required can be calculated from,

$$\dot{W} = \dot{m}\left(h_2 - h_1\right)$$


THERMODYNAMIC PROPERTIES OF
REFRIGERANT 22
3
2
1
4
P, MPa
h, kJ/kg
saturated liquid line
saturated vapor line
130
280
320

# Example 1

Solution:

(d) The power required can be calculated from,

$$\dot{W} = \dot{m}\left(h_2 - h_1\right)$$

hence from the chart we have

$h_2 = 320\ kJ/kg$ and $h_1 = 280 kJ / kg$

therefore $\dot{W} = 17.5 kW$

# Example 1

Solution:

(e) The heat rejected from the condenser is given by,

$$\dot{Q}_{cond} = \dot{m}\left(h_2 - h_3\right) = 83.2kW$$

note that it is also $\dot{Q}_{cond} = \dot{Q}_{ref} + \dot{W}$

# Example 1

Solution:

(e) The heat rejected from the condenser is given by,

$$\dot{Q}_{cond} = \dot{m}\left(h_2 - h_3\right) = 83.2kW$$

note that it is also $\dot{Q}_{cond} = \dot{Q}_{ref} + \dot{W}$

(f) The COP is calculated from,

$$COP = \frac{\dot{Q}_{ref}}{\dot{W}} = \frac{65.7}{17.5} = 3.75$$

this compares with the Carnot COP of,

$$COP_{carnot} = \frac{T_c}{T_H - T_c} = \frac{\left(273 - 8\right)}{42 - -8} = 5.3$$

# Example 1

Solution:

(e) The heat rejected from the condenser is given by,

$$\dot{Q}_{cond} = \dot{m}\left(h_2 - h_3\right) = 83.2kW$$

note that it is also $\dot{Q}_{cond} = \dot{Q}_{ref} + \dot{W}$

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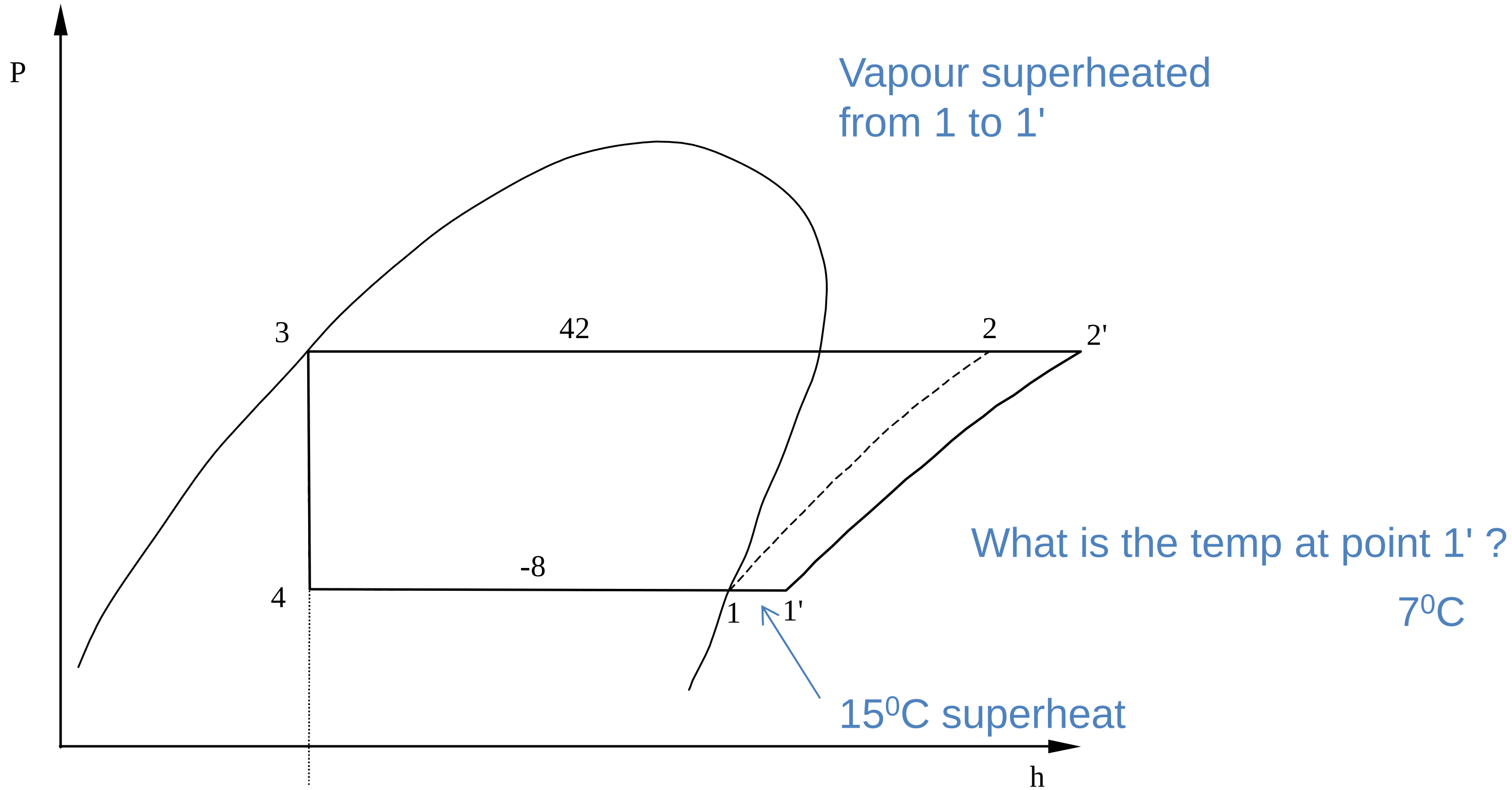
this compares with the Carnot COP of,

$$COP_{carnot} = \frac{T_c}{T_H - T_c} = \frac{\left(273 - 8\right)}{42 - -8} = 5.3$$

# Do "Specific Properties" Tell the Whole Story?

Let us consider the vapour compression system presented in Example 1.

The same hardware, except that we now adjust the controls such that the vapour is now superheated when it enters the compressor.



# Do "Specific Properties" Tell the Whole Story?

The compressor is the same as before with the same volumetric efficiency

$$\dot{V} = 26.9L/s$$

(1) has the refrigerating capacity of the system increased, decreased or remained the same compared with the original cycle?

(2) is more, less or the same power required than before?

(a) original system

$$q_{ref} = q_{41} = 150kJ/kg$$

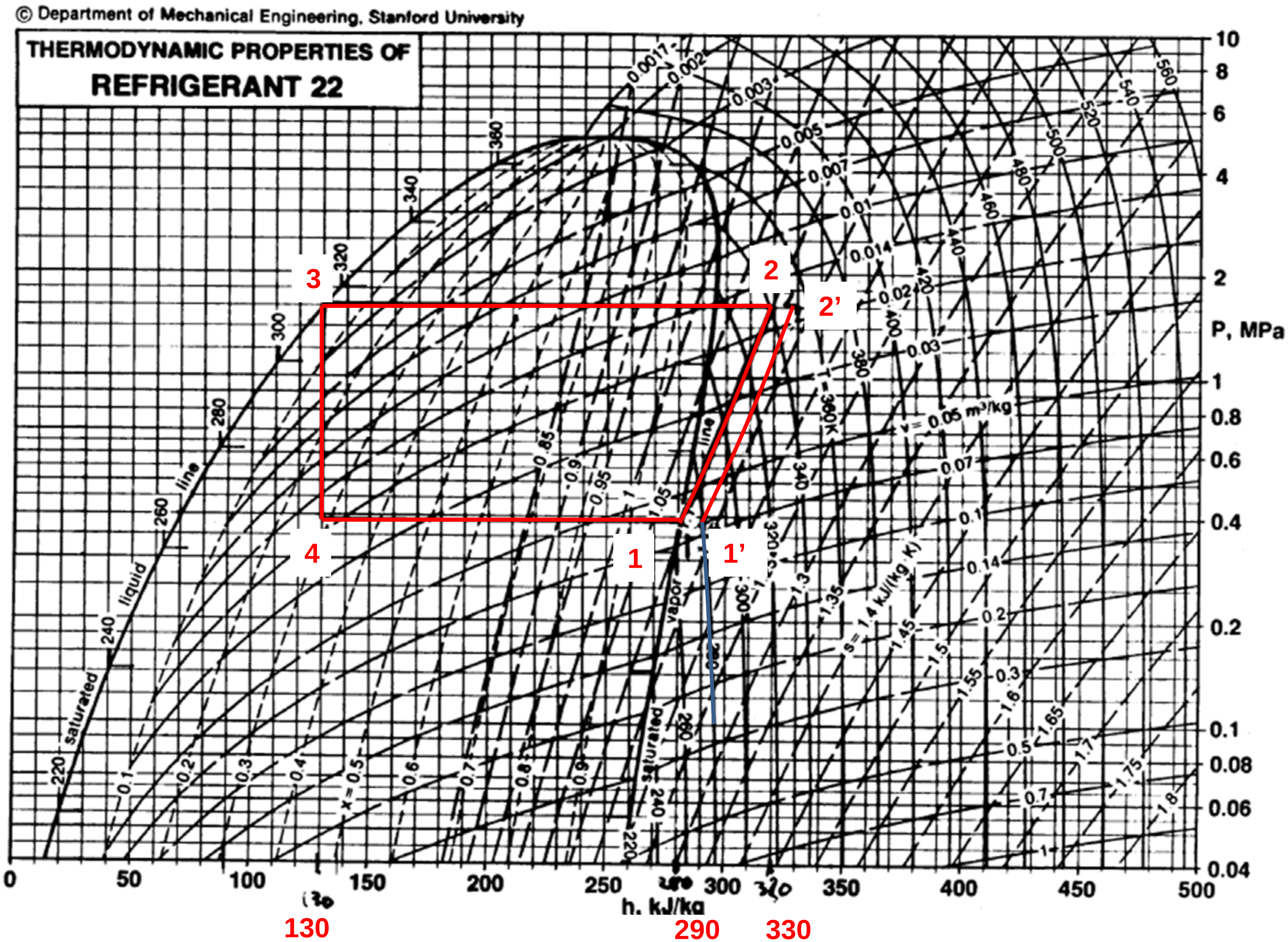
$$w = w_{12} = 40kJ/kg$$

# Do "Specific Properties" Tell the Whole Story?

(b) for the new system

from chart $h_{1'} = 290 kJ / kg$ and $h_{2'} = 330 kJ / kg$

At T (273 + 7) = 280K


© Department of Mechanical Engineering, Stanford University
THERMODYNAMIC PROPERTIES OF
REFRIGERANT 22
P, MPa
h, kJ/kg
saturated liquid line
saturated vapor line
T = 360 K
v = 0.05 m³/kg
s = 1.4 kJ/(kg. K)
x = 0.5
1
1'
2
2'
3
4
130
290
330

# Do "Specific Properties" Tell the Whole Story?

(b) for the new system

from chart $h_{1'} = 290kJ/kg$ and $h_{2'} = 330kJ/kg$

Therefore $q_{ref} = q_{41'} = 290 - 130 = 160kJ/kg$

Also $w = w_{1'2'} = 330 - 290 = 40kJ/kg$

Now to compare

(1) From the chart $v_{1'} = 0.066m^3/kg$

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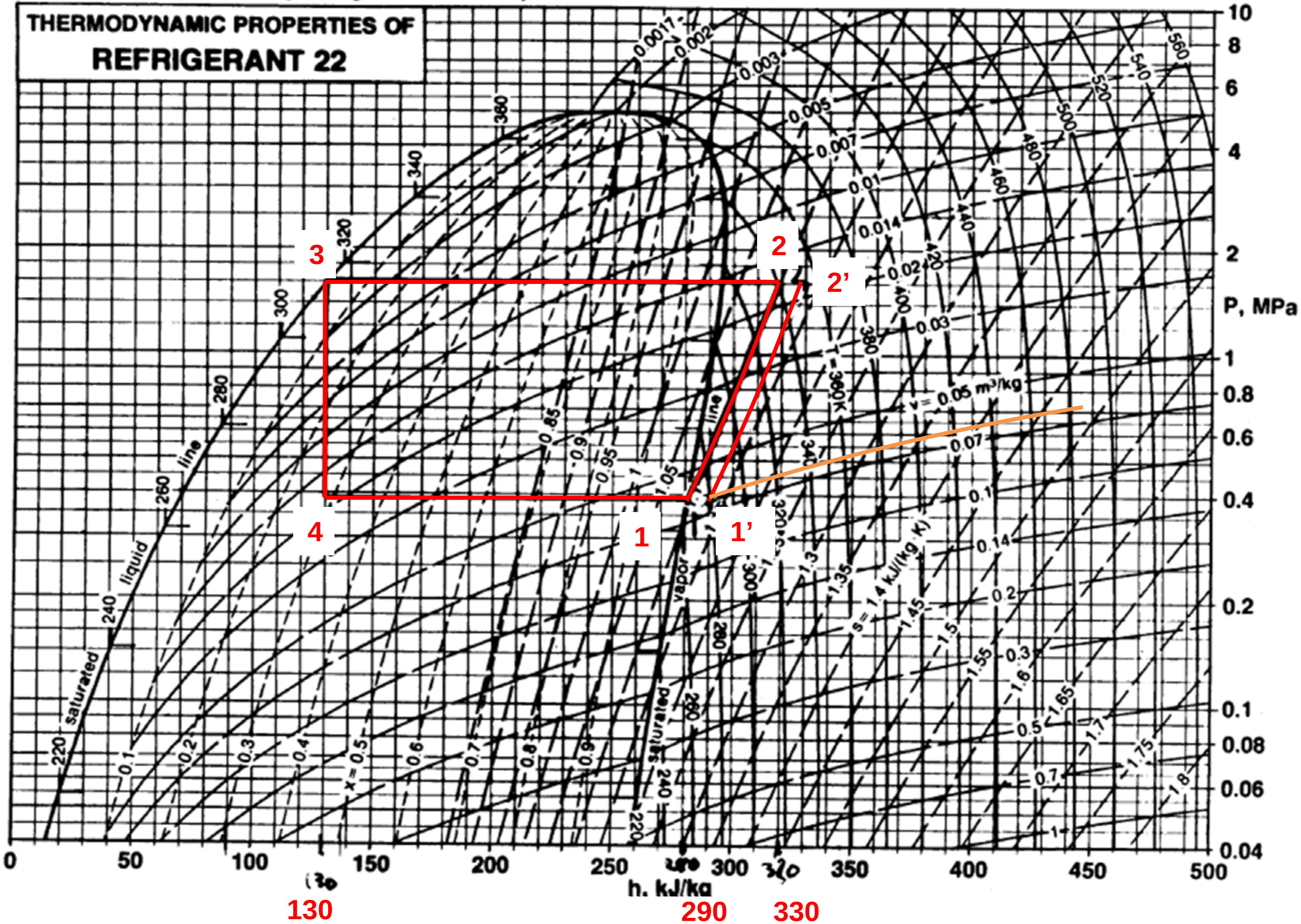


# Do "Specific Properties" Tell the Whole Story?

(b) for the new system

from chart $h_{1'} = 290kJ/kg$ and $h_{2'} = 330kJ/kg$

Therefore $q_{ref} = q_{41'} = 290 - 130 = 160kJ/kg$

Also $w = w_{1'2'} = 330 - 290 = 40kJ/kg$

Now to compare

(1) From the chart $v_{1'} = 0.066m^3/kg$

$$\dot{Q}_{ref} = \left(\frac{\dot{V}}{v_{1'}}\right) q_{41'} = \left(\frac{0.0269}{0.066}\right) \times 160 = 65.2kW$$

compared with the original value of 65.7 kW

# Do "Specific Properties" Tell the Whole Story?

(1) From the chart

$$\dot{Q}_{ref} = \left(\frac{\dot{V}}{v_{1'}}\right) q_{41'} = \left(\frac{0.0269}{0.066}\right) \times 160 = 65.2 kW$$

compared with the original value of 65.7 kW

- Therefore, the refrigerating capacity has gone down slightly (not up, as the refrigerating effect would have us believe). Why?

# Do "Specific Properties" Tell the Whole Story?

(1) From the chart

$$\dot{Q}_{ref} = \left(\frac{\dot{V}}{v_{1'}}\right) q_{41'} = \left(\frac{0.0269}{0.066}\right) \times 160 = 65.2kW$$

compared with the original value of 65.7 kW

- Therefore, the refrigerating capacity has gone down slightly (not up, as the refrigerating effect would have us believe). Why?
- The reason – the specific volume has changed (from 0.0615 to 0.066), resulting in a decrease in the mass flow rate. Therefore, although $\Delta h \uparrow \dot{m} \downarrow$ , where $\dot{m}$ goes down more than $\Delta h$ has gone up.

# Do "Specific Properties" Tell the Whole Story?

(2)

$$\dot{W} = \left(\frac{\dot{V}}{v_{1'}}\right) w_{1'2'} = \left(\frac{0.0269}{0.066}\right) \times 40 = 16.3\ kW$$

compared with the original value of  17.5 kW

Therefore, the specific properties do ***not*** tell the whole story!  In fact, they sometimes give a wrong indication, as in this case.

What can we do?

# "Volumic" Properties

Recall the equation for refrigerating capacity, i.e.

$$\begin{aligned}\dot{Q}_{ref} &= \dot{m}\left(h_1 - h_4\right)\\ &= \frac{\dot{V}}{v_1}\left(h_1 - h_4\right)\\ &= \dot{V}\left(\frac{h_1 - h_4}{v_1}\right)\end{aligned}$$

Where $$\dot{V} = \eta_v \dot{V}_{swept}$$

Since $\dot{V}$ is constant for a given machine, then we can define

Volumic refrigerating effect $= \dfrac{h_1 - h_4}{v_1}$

This property has the units of *J/m³* and gives a truer indication of trends.

# "Volumic" Properties

Similarly,

$$\dot{W} = \dot{m}\left(h_2 - h_1\right)$$
$$= \dot{V}\left(\frac{h_2 - h_1}{v_1}\right)$$

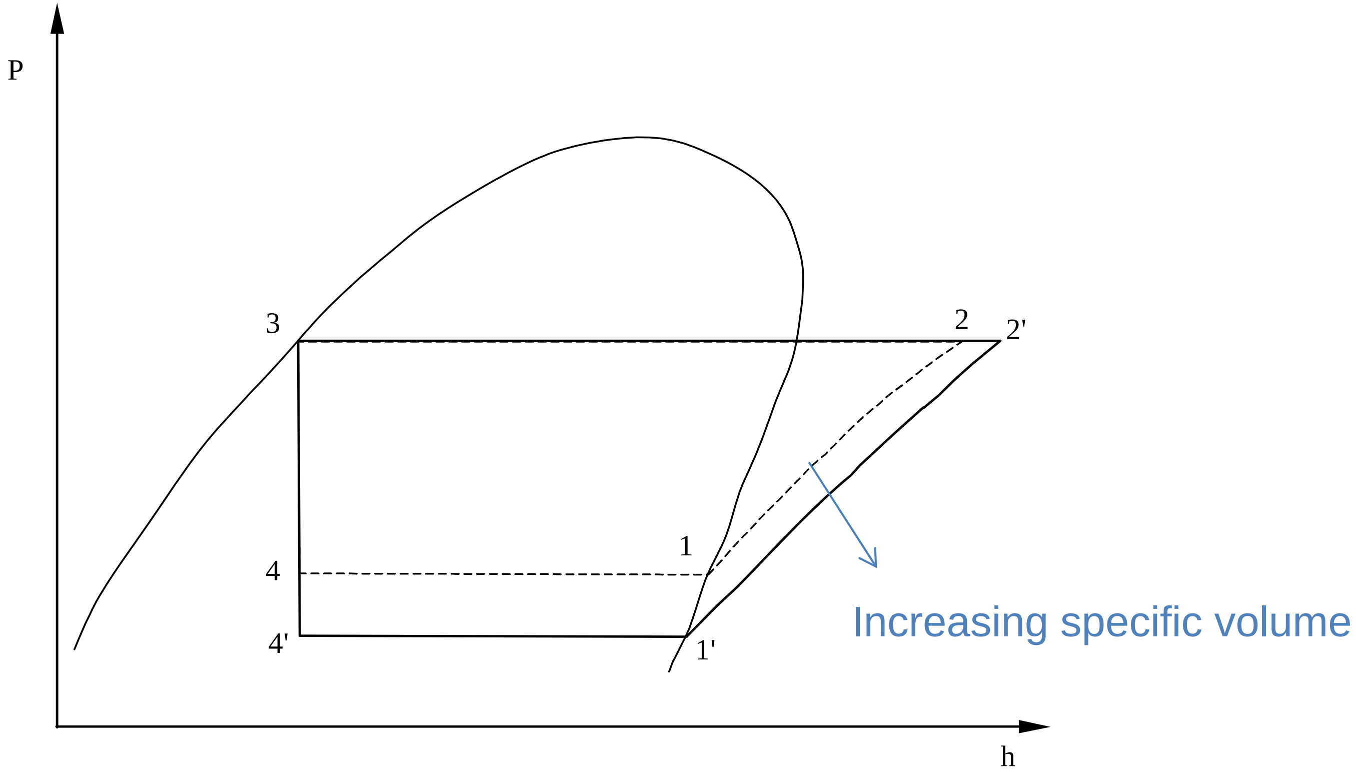
Therefore

Volumic work of adiabatic compression $= \dfrac{h_2 - h_1}{v_1}$

# Effect of Operating Conditions

Effect of Evaporator Pressure

Lower evaporator temperature what effect will this have on capacity?



# Effect of Operating Conditions

Effect of Evaporator Pressure

$$\dot{Q}_{ref} = \dot{V}_{swept}\eta_v\left(\frac{h_1 - h_4}{v_1}\right)$$

where $\dot{V}_{swept}$ is fixed for a particular machine.

Similarly

$$\dot{W}_{ad} = \dot{V}_{swept}\eta_v\left(\frac{h_2 - h_1}{v_1}\right)$$

How do these vary with evaporator temperature?

# Effect of Operating Conditions

i) a decrease in volumic refrigerating effect, since

$$\left(h_{1'} - h_{4'}\right) < \left(h_1 - h_4\right)$$

Also

$$v_{1'} > v_1$$

Therefore

$$\left(\frac{h_{1'} - h_{4'}}{v_{1'}}\right) << \left(\frac{h_1 - h_4}{v_1}\right)$$

Volumic refrigeration effect – lower

(ii) a drop in volumetric efficiency $\eta_v$ due to the higher pressure ratio.

Therefore, the refrigerating capacity drops significantly;

# Effect of Operating Conditions

(iii) although there is an increase in the specific work required, i.e.

$$\left(h_{2'} - h_{1'}\right) > \left(h_2 - h_1\right)$$

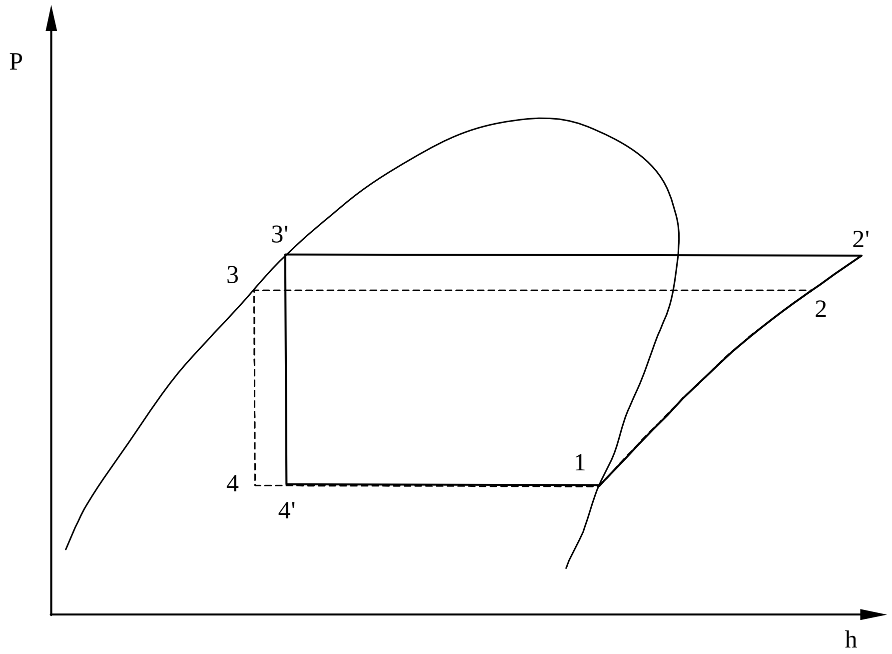
And specific volume also increases

$$\left(\frac{h_{2'} - h_{1'}}{v_{1'}}\right) \begin{matrix} > \\ \text{or} \\ < \\ \text{or} \\ = \end{matrix} \left(\frac{h_2 - h_1}{v_1}\right)$$

Therefore, the power requirements may increase, decrease or remain the same.

The decreases in volumic refrigerating effect is always larger than variations in power requirements, therefore ***COP will always drop*** when the evaporating temperature is reduced.

# Effect of Condenser Pressure




The effect of increasing the condenser temperature results in,

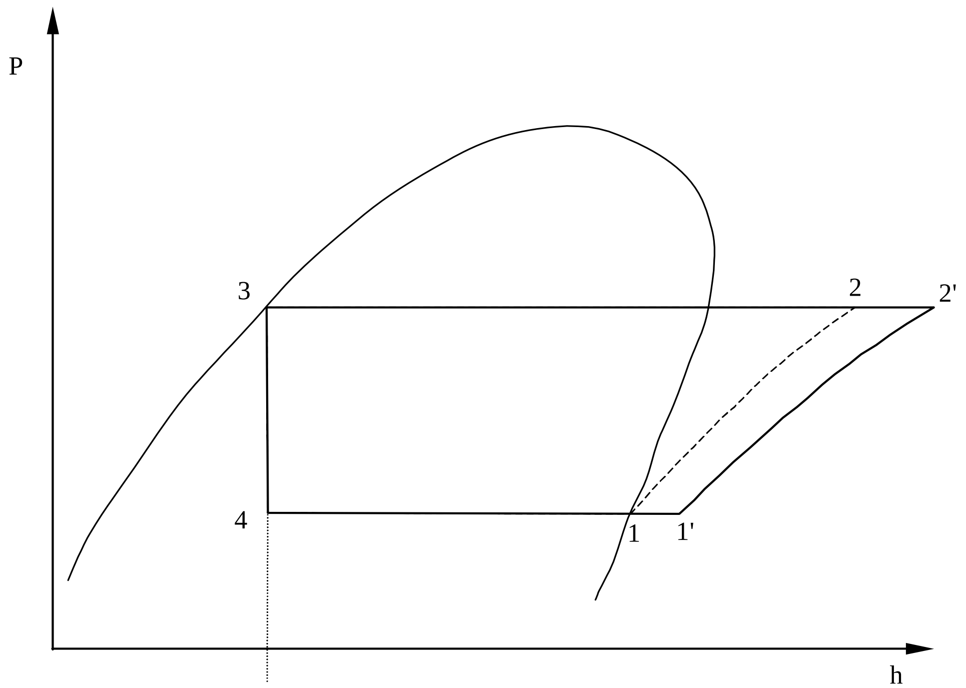
(i) decrease in refrigerating effect and hence a drop in volumic refrigerating effect;

(ii) decrease in volumetric efficiency due to the higher pressure ratios;

(iii) increase in specific work and hence in the volumic work of adiabatic compression.

All these factors contribute to a decrease in refrigerating capacity and an increase in power consumption.

# Effect of Suction Vapour Superheat




Superheating of the suction vapour is advisable in practice for reciprocating compressors because it ensures complete vaporisation of the liquid in the evaporator before it enters the compressor.

# Effect of Suction Vapour Superheat

(i) an increase in the refrigerating effect from $(h_1 - h_4)$ to $(h_{1'} - h_4)$ whilst the specific volume increases from $\nu_1$ to $\nu_{1'}$ Hence, whether

$$\left(\frac{h_{1'} - h_4}{v_{1'}}\right) \overset{>}{\underset{<}{or}} \left(\frac{h_1 - h_4}{v_1}\right)$$

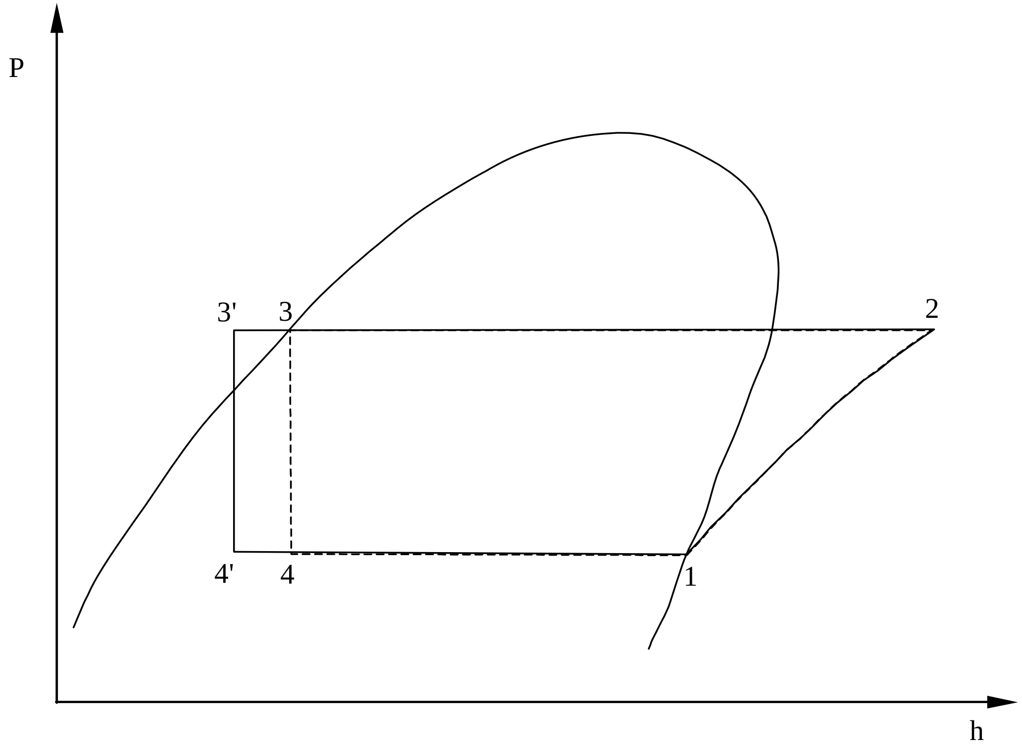
depends on the relative rates of increase of $(h_{1'1} - h_4)$ and $v_{1'}$

(ii) Similarly, the volumic work may increase or decrease.

The net effect is that the COP may increase or decrease.

*(Manufacturer's often specify a certain superheat for ideal operation)*

# Effect of Liquid Subcooling

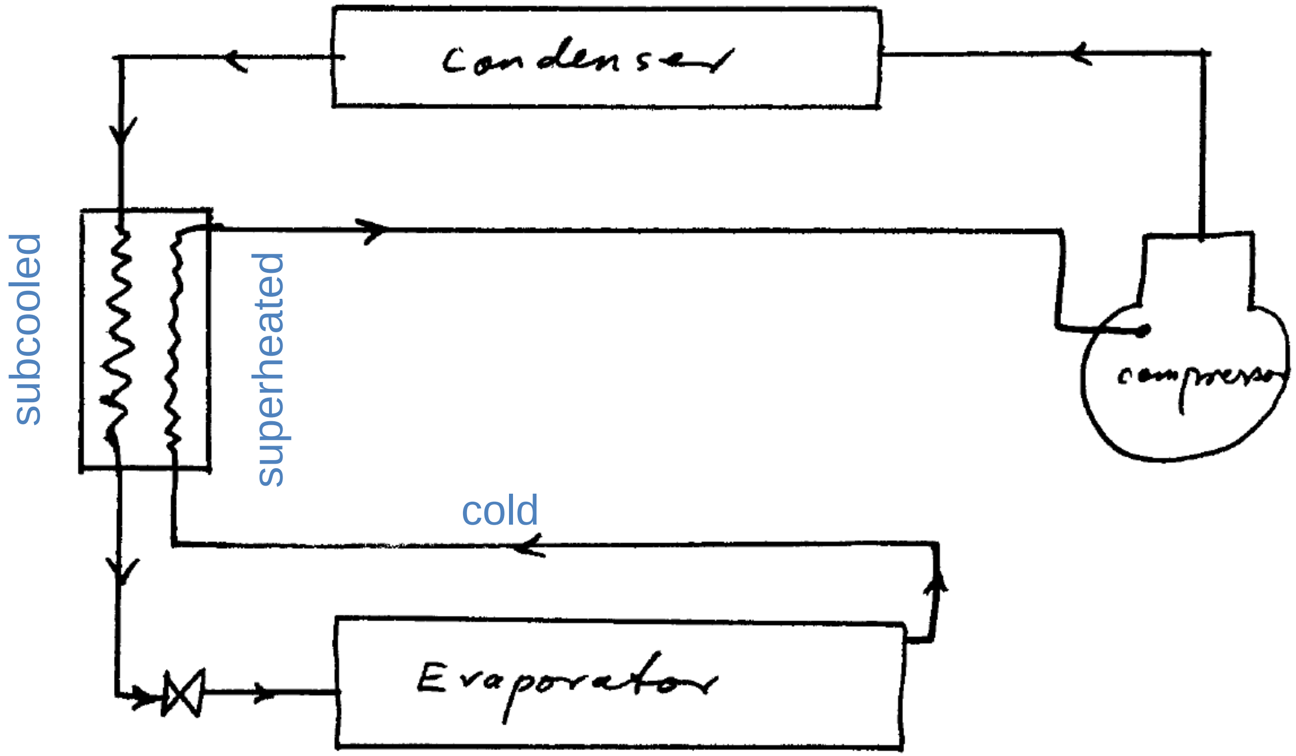



It can be seen that liquid subcooling results in a greater refrigerating effect for the same compressor work.

The only disadvantage is that either a subcooler or additional cooling is required at the condenser.

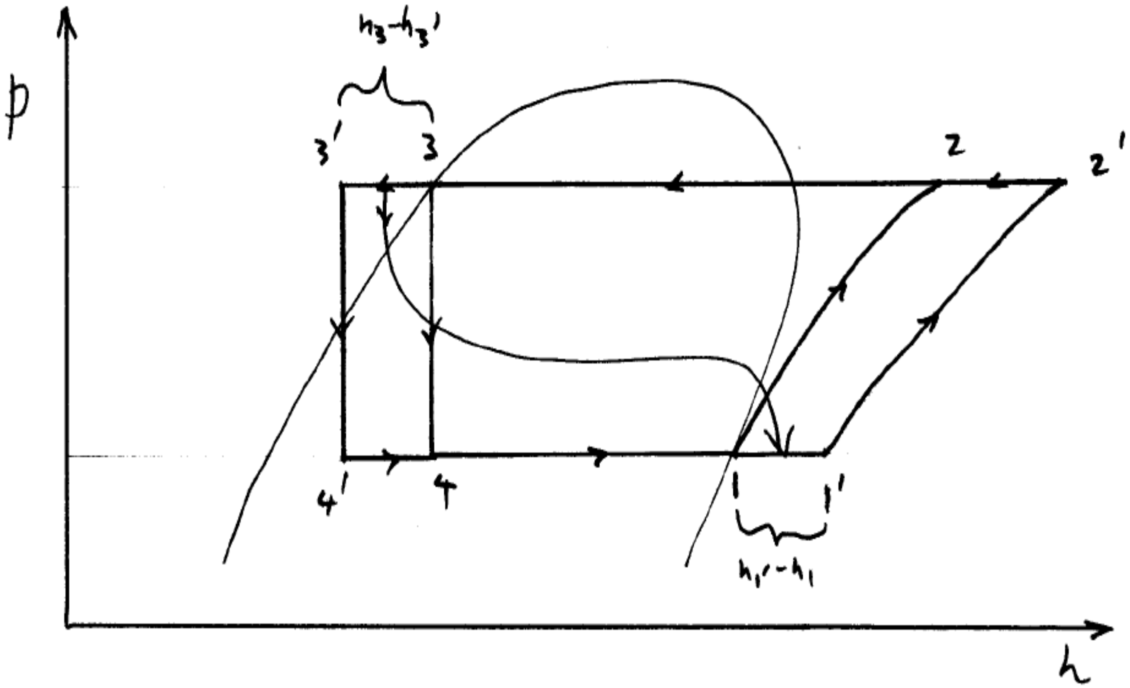
# Effect of Liquid Subcooling

(i) Using a Liquid-Vapour Regenerative Heat Exchanger



# Effect of Liquid Subcooling

The effect on the thermodynamic cycle is as shown.




An example of a typical liquid-to-suction heat exchanger.

# Example 2

A manufacturer's table for a certain compressor on R12 gives the refrigerating capacity as 9.65 kW and the shaft power as 3.82 kW at the following conditions

How much subcooling and superheating?

$t_e = -20^oC$
$t_c = 30^oC$

Subcooled 5K

Superheated 38K

temperature of liquid leaving condenser = 25ºC
temperature of vapour entering compressor = 18ºC

(a) Determine the mass flow rate at these conditions and the isentropic efficiency.

(b) Supposing that the compressor operates an evaporator with liquid feed via a TX valve giving a superheat at the outlet (of the evaporator) of 5 K and the superheating to 18ºC is done in a liquid to suction heat exchanger. Determine,

(i) the temperature of the liquid reaching the expansion valve;

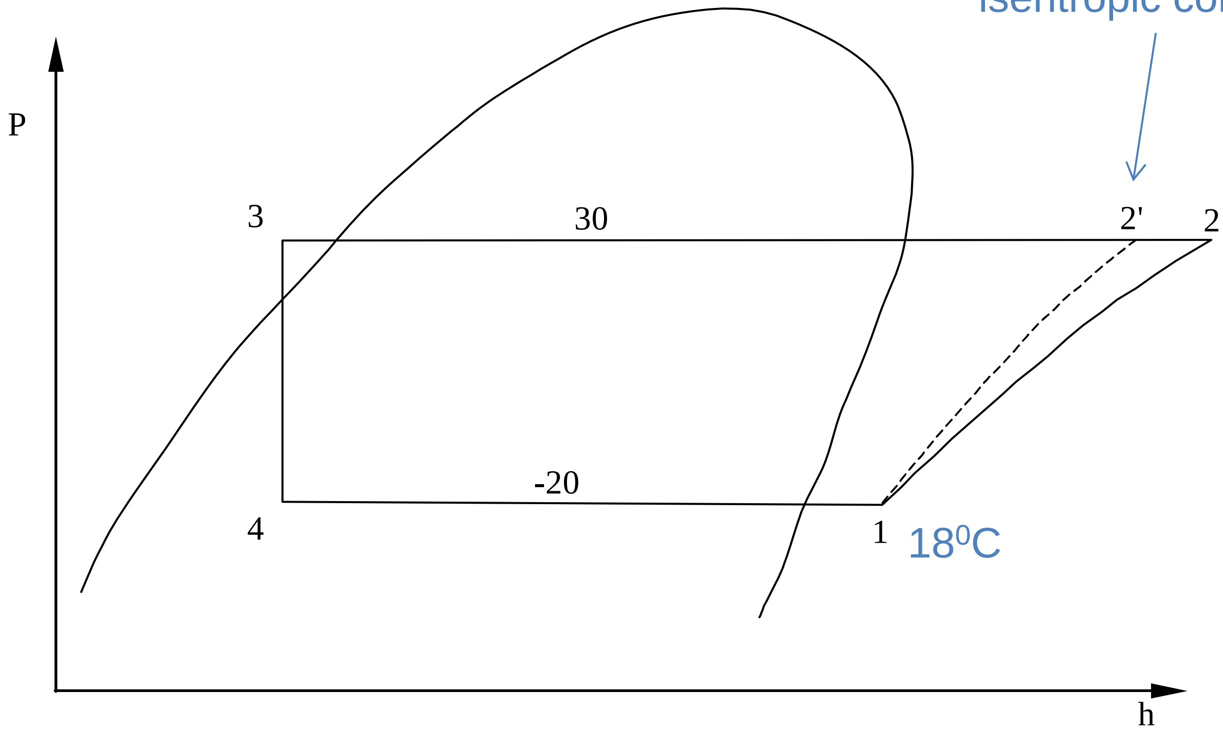
(ii) the surface area required in the het exchanger based on an overall coefficient of heat transfer of 50 $W/m^2K$.

# Example 2

*Solution*:

(a)

Sometimes we denote this as “2s” showing the line if isentropic compression



# Example 2

*Solution*:

(i) We know that $$\dot{m} = \frac{\dot{Q}_{ref}}{h_1 - h_4}$$

from the tables we have $h_4 = h_3 = h_f(25^0C) = 59.7\ kJ/kg$

# SATURATED PROPERTIES OF R12

| T DEG.C | P KPA | 1/V(F) KG/M3 | V(G) M3/KG | H(F) | H(FG) KJ/KG | H(G) | S(F) | S(FG) KJ/KG.K | S(G) |
|---|---|---|---|---|---|---|---|---|---|
| -40.0 | 64.1 | 1516. | .24208 | .00 | 169.60 | 169.60 | .0000 | .7274 | .7274 |
| -39.0 | 67.2 | 1514. | .23178 | .88 | 169.18 | 170.06 | .0038 | .7225 | .7263 |
| -38.0 | 70.4 | 1511. | .22199 | 1.77 | 168.76 | 170.52 | .0075 | .7177 | .7252 |
| -37.0 | 73.7 | 1508. | .21271 | 2.65 | 168.34 | 170.98 | .0113 | .7128 | .7241 |
| -36.0 | 77.1 | 1505. | .20390 | 3.53 | 167.91 | 171.45 | .0150 | .7080 | .7230 |
| -35.0 | 80.6 | 1502. | .19553 | 4.42 | 167.49 | 171.91 | .0187 | .7033 | .7220 |
| -34.0 | 84.3 | 1500. | .18758 | 5.31 | 167.06 | 172.37 | .0224 | .6986 | .7210 |
| -33.0 | 88.1 | 1497. | .18002 | 6.19 | 166.63 | 172.83 | .0261 | .6939 | .7200 |
| -32.0 | 92.1 | 1494. | .17283 | 7.08 | 166.20 | 173.28 | .0298 | .6892 | .7190 |
| -31.0 | 96.1 | 1491. | .16599 | 7.97 | 165.77 | 173.74 | .0335 | .6846 | .7180 |

| T DEG.C | P KPA | 1/V(F) KG/M3 | V(G) M3/KG | H(F) | H(FG) KJ/KG | H(G) | S(F) | S(FG) KJ/KG.K | S(G) |
|---|---|---|---|---|---|---|---|---|---|
| 15.0 | 491.1 | 1347. | .03543 | 50.10 | 143.69 | 193.79 | .1915 | .4987 | .6902 |
| 16.0 | 505.7 | 1343. | .03444 | 51.05 | 143.14 | 194.19 | .1948 | .4950 | .6898 |
| 17.0 | 520.5 | 1340. | .03348 | 52.00 | 142.59 | 194.59 | .1980 | .4914 | .6894 |
| 18.0 | 535.7 | 1336. | .03256 | 52.96 | 142.04 | 194.99 | .2012 | .4878 | .6891 |
| 19.0 | 551.2 | 1333. | .03166 | 53.91 | 141.48 | 195.39 | .2045 | .4843 | .6887 |
| 20.0 | 567.0 | 1329. | .03079 | 54.87 | 140.91 | 195.79 | .2077 | .4807 | .6884 |
| 21.0 | 583.2 | 1325. | .02996 | 55.83 | 140.35 | 196.18 | .2109 | .4771 | .6881 |
| 22.0 | 599.7 | 1322. | .02915 | 56.80 | 139.78 | 196.57 | .2142 | .4736 | .6877 |
| 23.0 | 616.6 | 1318. | .02836 | 57.76 | 139.20 | 196.96 | .2174 | .4700 | .6874 |
| 24.0 | 633.8 | 1315. | .02760 | 58.73 | 138.62 | 197.35 | .2206 | .4665 | .6871 |
| 25.0 | 651.3 | 1311. | .02687 | 59.70 | 138.04 | 197.73 | .2238 | .4630 | .6868 |
| 26.0 | 669.2 | 1307. | .02615 | 60.67 | 137.45 | 198.12 | .2270 | .4595 | .6865 |

# Example 2

*Solution*:

(i) We know that $$\dot{m} = \frac{\dot{Q}_{ref}}{h_1 - h_4}$$

from the tables we have $h_4 = h_3 = h_f(25^0C) = 59.7\ kJ/kg$

and

$$h_1 = h\left(-20^oC, 38K_{superheat}\right) = 201.86kJ/kg$$

# SUPERHEATED PROPERTIES OF R12

| TEMP. (P.SAT) | | SAT. STATE | SUPERHEAT,K 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -40.0 | V | .2421 | .2479 | .2537 | .2594 | .2651 | .2708 | .2765 | .2877 | .2989 | .3101 | .3541 | .4086 | .4627 |
| ( 64.1) | H | 169.6 | 172.4 | 175.2 | 178.0 | 180.8 | 183.7 | 186.6 | 192.4 | 198.4 | 204.4 | 229.4 | 262.3 | 297.1 |
| | S | .7274 | .7392 | .7508 | .7623 | .7737 | .7849 | .7960 | .8178 | .8391 | .8600 | .9398 | 1.0320 | 1.1171 |
| -39.0 | V | .2318 | .2373 | .2429 | .2484 | .2538 | .2593 | .2647 | .2754 | .2861 | .2968 | .3388 | .3909 | .4425 |
| ( 67.2) | H | 170.1 | 172.8 | 175.7 | 178.5 | 181.3 | 184.2 | 187.1 | 193.0 | 198.9 | 205.0 | 230.0 | 263.0 | 297.7 |
| | S | .7263 | .7381 | .7497 | .7612 | .7725 | .7837 | .7948 | .8166 | .8379 | .8588 | .9384 | 1.0305 | 1.1155 |
| -38.0 | V | .2220 | .2273 | .2326 | .2379 | .2431 | .2483 | .2535 | .2638 | .2740 | .2841 | .3244 | .3741 | .4234 |
| ( 70.4) | H | 170.5 | 173.3 | 176.1 | 179.0 | 181.8 | 184.7 | 187.6 | 193.5 | 199.5 | 205.5 | 230.6 | 263.7 | 298.4 |
| | S | .7252 | .7370 | .7486 | .7600 | .7714 | .7826 | .7936 | .8154 | .8367 | .8575 | .9371 | 1.0290 | 1.1139 |
| -37.0 | V | .2127 | .2178 | .2229 | .2279 | .2329 | .2379 | .2429 | .2527 | .2625 | .2722 | .3106 | .3581 | .4053 |
| ( 73.7) | H | 171.0 | 173.8 | 176.6 | 179.5 | 182.3 | 185.2 | 188.1 | 194.0 | 200.0 | 206.1 | 231.2 | 264.3 | 299.1 |
| | S | .7241 | .7359 | .7475 | .7589 | .7703 | .7814 | .7925 | .8142 | .8355 | .8563 | .9358 | 1.0276 | 1.1123 |
| -36.0 | V | .2039 | .2088 | .2136 | .2185 | .2233 | .2280 | .2328 | .2422 | .2516 | .2609 | .2976 | .3430 | .3882 |
| ( 77.1) | H | 171.4 | 174.3 | 177.1 | 180.0 | 182.8 | 185.7 | 188.7 | 194.6 | 200.6 | 206.6 | 231.8 | 265.0 | 299.8 |
| | S | .7230 | .7348 | .7464 | .7578 | .7692 | .7803 | .7914 | .8131 | .8343 | .8551 | .9345 | 1.0262 | 1.1108 |
| -35.0 | V | .1955 | .2002 | .2049 | .2095 | .2141 | .2187 | .2232 | .2322 | .2412 | .2501 | .2853 | .3287 | .3719 |
| ( 80.6) | H | 171.9 | 174.7 | 177.6 | 180.5 | 183.3 | 186.3 | 189.2 | 195.1 | 201.1 | 207.2 | 232.4 | 265.6 | 300.5 |
| | S | .7220 | .7337 | .7453 | .7568 | .7681 | .7792 | .7903 | .8120 | .8332 | .8540 | .9333 | 1.0248 | 1.1093 |

| TEMP. (P.SAT) | | SAT. STATE | SUPERHEAT,K 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -30.0 | V | .1595 | .1633 | .1671 | .1709 | .1746 | .1783 | .1820 | .1893 | .1966 | .2038 | .2322 | .2673 | .3020 |
| ( 100.3) | H | 174.2 | 177.1 | 180.0 | 182.9 | 185.8 | 188.8 | 191.8 | 197.8 | 203.8 | 210.0 | 235.5 | 268.9 | 304.0 |
| | S | .7171 | .7288 | .7404 | .7518 | .7631 | .7742 | .7852 | .8068 | .8279 | .8486 | .9273 | 1.0183 | 1.1022 |
| -29.0 | V | .1533 | .1570 | .1606 | .1642 | .1678 | .1714 | .1749 | .1819 | .1889 | .1958 | .2231 | .2567 | .2901 |
| ( 104.7) | H | 174.7 | 177.5 | 180.5 | 183.4 | 186.3 | 189.3 | 192.3 | 198.3 | 204.4 | 210.6 | 236.1 | 269.6 | 304.7 |
| | S | .7162 | .7279 | .7395 | .7509 | .7621 | .7732 | .7842 | .8058 | .8269 | .8475 | .9262 | 1.0171 | 1.1009 |
| -28.0 | V | .1474 | .1509 | .1544 | .1579 | .1613 | .1648 | .1682 | .1749 | .1816 | .1883 | .2145 | .2467 | .2787 |
| ( 109.2) | H | 175.1 | 178.0 | 180.9 | 183.9 | 186.8 | 189.8 | 192.8 | 198.8 | 204.9 | 211.1 | 236.7 | 270.2 | 305.4 |
| | S | .7153 | .7270 | .7386 | .7500 | .7612 | .7723 | .7833 | .8048 | .8259 | .8465 | .9251 | 1.0159 | 1.0996 |
| -27.0 | V | .1417 | .1451 | .1485 | .1519 | .1552 | .1585 | .1617 | .1682 | .1747 | .1811 | .2062 | .2372 | .2679 |
| ( 113.8) | H | 175.6 | 178.5 | 181.4 | 184.4 | 187.3 | 190.3 | 193.3 | 199.4 | 205.5 | 211.7 | 237.3 | 270.9 | 306.1 |
| | S | .7144 | .7261 | .7377 | .7491 | .7603 | .7714 | .7824 | .8039 | .8250 | .8456 | .9241 | 1.0147 | 1.0983 |
| -26.0 | V | .1364 | .1396 | .1429 | .1461 | .1493 | .1525 | .1556 | .1619 | .1680 | .1742 | .1984 | .2281 | .2576 |
| ( 118.6) | H | 176.0 | 178.9 | 181.9 | 184.8 | 187.8 | 190.8 | 193.8 | 199.9 | 206.0 | 212.3 | 237.9 | 271.5 | 306.8 |
| | S | .7135 | .7253 | .7368 | .7482 | .7594 | .7705 | .7815 | .8030 | .8240 | .8446 | .9230 | 1.0135 | 1.0970 |
| -25.0 | V | .1312 | .1344 | .1375 | .1406 | .1437 | .1467 | .1498 | .1558 | .1617 | .1676 | .1909 | .2194 | .2477 |
| ( 123.6) | H | 176.5 | 179.4 | 182.4 | 185.3 | 188.3 | 191.3 | 194.3 | 200.4 | 206.6 | 212.8 | 238.5 | 272.2 | 307.4 |
| | S | .7127 | .7244 | .7360 | .7473 | .7586 | .7696 | .7806 | .8021 | .8231 | .8437 | .9220 | 1.0124 | 1.0958 |
| -24.0 | V | .1264 | .1294 | .1324 | .1354 | .1384 | .1413 | .1442 | .1500 | .1557 | .1614 | .1837 | .2112 | .2384 |
| ( 128.7) | H | 176.9 | 179.9 | 182.8 | 185.8 | 188.8 | 191.8 | 194.8 | 200.9 | 207.1 | 213.4 | 239.1 | 272.8 | 308.1 |
| | S | .7119 | .7236 | .7351 | .7465 | .7577 | .7688 | .7797 | .8012 | .8222 | .8428 | .9210 | 1.0113 | 1.0945 |
| -23.0 | V | .1217 | .1246 | .1275 | .1304 | .1332 | .1361 | .1389 | .1445 | .1500 | .1554 | .1769 | .2033 | .2294 |
| ( 134.0) | H | 177.4 | 180.3 | 183.3 | 186.3 | 189.3 | 192.3 | 195.4 | 201.5 | 207.7 | 213.9 | 239.7 | 273.5 | 308.8 |
| | S | .7111 | .7228 | .7343 | .7457 | .7569 | .7680 | .7789 | .8004 | .8213 | .8419 | .9200 | 1.0102 | 1.0933 |
| -22.0 | V | .1172 | .1201 | .1229 | .1256 | .1284 | .1311 | .1338 | .1392 | .1445 | .1497 | .1704 | .1958 | .2209 |
| ( 139.4) | H | 177.8 | 180.8 | 183.8 | 186.8 | 189.8 | 192.8 | 195.9 | 202.0 | 208.2 | 214.5 | 240.3 | 274.2 | 309.5 |
| | S | .7103 | .7220 | .7335 | .7449 | .7561 | .7672 | .7781 | .7995 | .8205 | .8410 | .9191 | 1.0091 | 1.0922 |
| -21.0 | V | .1130 | .1157 | .1184 | .1211 | .1237 | .1263 | .1290 | .1341 | .1392 | .1443 | .1642 | .1886 | .2128 |
| ( 145.1) | H | 178.3 | 181.3 | 184.3 | 187.3 | 190.3 | 193.3 | 196.4 | 202.5 | 208.8 | 215.1 | 240.9 | 274.8 | 310.2 |
| | S | .7095 | .7212 | .7327 | .7441 | .7553 | .7664 | .7773 | .7987 | .8197 | .8401 | .9181 | 1.0080 | 1.0910 |
| -20.0 | V | .1089 | .1115 | .1141 | .1167 | .1193 | .1218 | .1243 | .1293 | .1342 | .1391 | .1583 | .1818 | .2050 |
| ( 150.8) | H | 178.7 | 181.7 | 184.7 | 187.8 | 190.8 | 193.8 | 196.9 | 203.1 | 209.3 | 215.6 | 241.5 | 275.5 | 310.9 |
| | S | .7087 | .7204 | .7320 | .7433 | .7545 | .7656 | .7765 | .7979 | .8188 | .8393 | .9172 | 1.0070 | 1.0899 |

# Example 2

*Solution*:

(i) We know that
$$\dot{m} = \frac{\dot{Q}_{ref}}{h_1 - h_4}$$

from the tables we have $h_4 = h_3 = h_f(25^0C) = 59.7\ kJ/kg$

and
$$h_1 = h\left(-20^{o}C, 38K_{superheat}\right) = 201.86kJ/kg$$

Hence
$$h_1 - h_4 = 142.16kJ/kg$$

therefore
$$\dot{m} = \frac{9.65}{142.16}$$
$$= 0.0679kg/s$$

# Example 2

*Solution*:

(ii) to determine he isentropic efficiency we use,

$$\eta_{1s} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

we can calculate,

$$h_2 - h_1 = w = \frac{\dot{W}}{\dot{m}} = \frac{3.82}{0.0679} = 56.27 kJ / kg$$

To find $h_{2s}$, we use $s_{2s} = s_1 = 0.7938\ kJ / KgK$ hence from tables (at $t_c = 30^oC$), $t_{2s} = 79^0C$ and $h_{2s} = 234.8$ kJ / kg

| TEMP. (P.SAT) | | SAT. STATE | SUPERHEAT,K 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25.0 | V | .0269 | .0276 | .0284 | .0291 | .0298 | .0305 | .0312 | .0325 | .0338 | .0351 | .0399 | .0457 | .0514 |
| ( 651.3) | H | 197.7 | 201.4 | 204.9 | 208.5 | 212.1 | 215.6 | 219.1 | 226.1 | 233.2 | 240.2 | 268.5 | 304.7 | 341.8 |
| | S | .6868 | .6988 | .7106 | .7220 | .7333 | .7443 | .7551 | .7762 | .7967 | .8166 | .8915 | .9771 | 1.0557 |
| 26.0 | V | .0262 | .0269 | .0276 | .0283 | .0290 | .0297 | .0304 | .0317 | .0329 | .0342 | .0389 | .0446 | .0501 |
| ( 669.2) | H | 198.1 | 201.8 | 205.4 | 208.9 | 212.5 | 216.0 | 219.6 | 226.6 | 233.7 | 240.7 | 269.1 | 305.3 | 342.5 |
| | S | .6865 | .6985 | .7103 | .7218 | .7330 | .7441 | .7549 | .7760 | .7965 | .8163 | .8912 | .9767 | 1.0552 |
| 27.0 | V | .0255 | .0262 | .0269 | .0276 | .0283 | .0289 | .0296 | .0309 | .0321 | .0333 | .0380 | .0435 | .0488 |
| ( 687.5) | H | 198.5 | 202.2 | 205.8 | 209.4 | 212.9 | 216.5 | 220.0 | 227.1 | 234.2 | 241.2 | 269.7 | 305.9 | 343.2 |
| | S | .6862 | .6982 | .7100 | .7215 | .7328 | .7438 | .7546 | .7758 | .7962 | .8161 | .8909 | .9763 | 1.0547 |
| 28.0 | V | .0248 | .0255 | .0262 | .0269 | .0276 | .0282 | .0288 | .0301 | .0313 | .0325 | .0370 | .0424 | .0476 |
| ( 706.2) | H | 198.9 | 202.5 | 206.2 | 209.8 | 213.4 | 217.0 | 220.5 | 227.6 | 234.7 | 241.8 | 270.2 | 306.6 | 343.8 |
| | S | .6859 | .6979 | .7097 | .7213 | .7325 | .7436 | .7544 | .7755 | .7960 | .8158 | .8906 | .9760 | 1.0543 |
| 29.0 | V | .0241 | .0249 | .0255 | .0262 | .0269 | .0275 | .0281 | .0293 | .0305 | .0317 | .0361 | .0413 | .0464 |
| ( 725.2) | H | 199.3 | 202.9 | 206.6 | 210.2 | 213.8 | 217.4 | 221.0 | 228.1 | 235.2 | 242.3 | 270.8 | 307.2 | 344.5 |
| | S | .6855 | .6977 | .7095 | .7210 | .7323 | .7433 | .7542 | .7753 | .7957 | .8156 | .8904 | .9756 | 1.0538 |
| 30.0 | V | .0235 | .0242 | .0249 | .0255 | .0262 | .0268 | .0274 | .0286 | .0298 | .0309 | .0352 | .0403 | .0453 |
| ( 744.6) | H | 199.6 | 203.3 | 207.0 | 210.6 | 214.3 | 217.9 | 221.4 | 228.6 | 235.7 | 242.8 | 271.4 | 307.8 | 345.2 |
| | S | .6853 | .6974 | .7092 | .7207 | .7320 | .7431 | .7539 | .7751 | .7955 | .8154 | .8901 | .9752 | 1.0534 |
| 31.0 | V | .0229 | .0236 | .0242 | .0249 | .0255 | .0261 | .0267 | .0279 | .0290 | .0301 | .0343 | .0393 | .0442 |
| ( 764.3) | H | 200.0 | 203.7 | 207.4 | 211.1 | 214.7 | 218.3 | 221.9 | 229.1 | 236.2 | 243.3 | 272.0 | 308.5 | 345.9 |
| | S | .6850 | .6971 | .7089 | .7205 | .7318 | .7429 | .7537 | .7748 | .7953 | .8151 | .8898 | .9749 | 1.0530 |
| 32.0 | V | .0223 | .0230 | .0236 | .0243 | .0249 | .0255 | .0261 | .0272 | .0283 | .0294 | .0335 | .0384 | .0431 |
| ( 784.5) | H | 200.4 | 204.1 | 207.8 | 211.5 | 215.1 | 218.8 | 222.4 | 229.5 | 236.7 | 243.9 | 272.6 | 309.1 | 346.5 |
| | S | .6847 | .6968 | .7087 | .7203 | .7316 | .7426 | .7535 | .7746 | .7951 | .8149 | .8896 | .9746 | 1.0526 |

# Example 2

*Solution*:

(ii) to determine he isentropic efficiency we use,

$$\eta_{1s} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

we can calculate,

$$h_2 - h_1 = w = \frac{\dot{W}}{\dot{m}} = \frac{3.82}{0.0679} = 56.27 kJ / kg$$

To find $h_{2s}$, we use $s_{2s} - s_1 = 0.7938\ kJ / KgK$ hence from tables (at $t_c = 30^oC$), $t_{2s} = 79^0C$ and $h_{2s} = 234.8$ kJ / kg

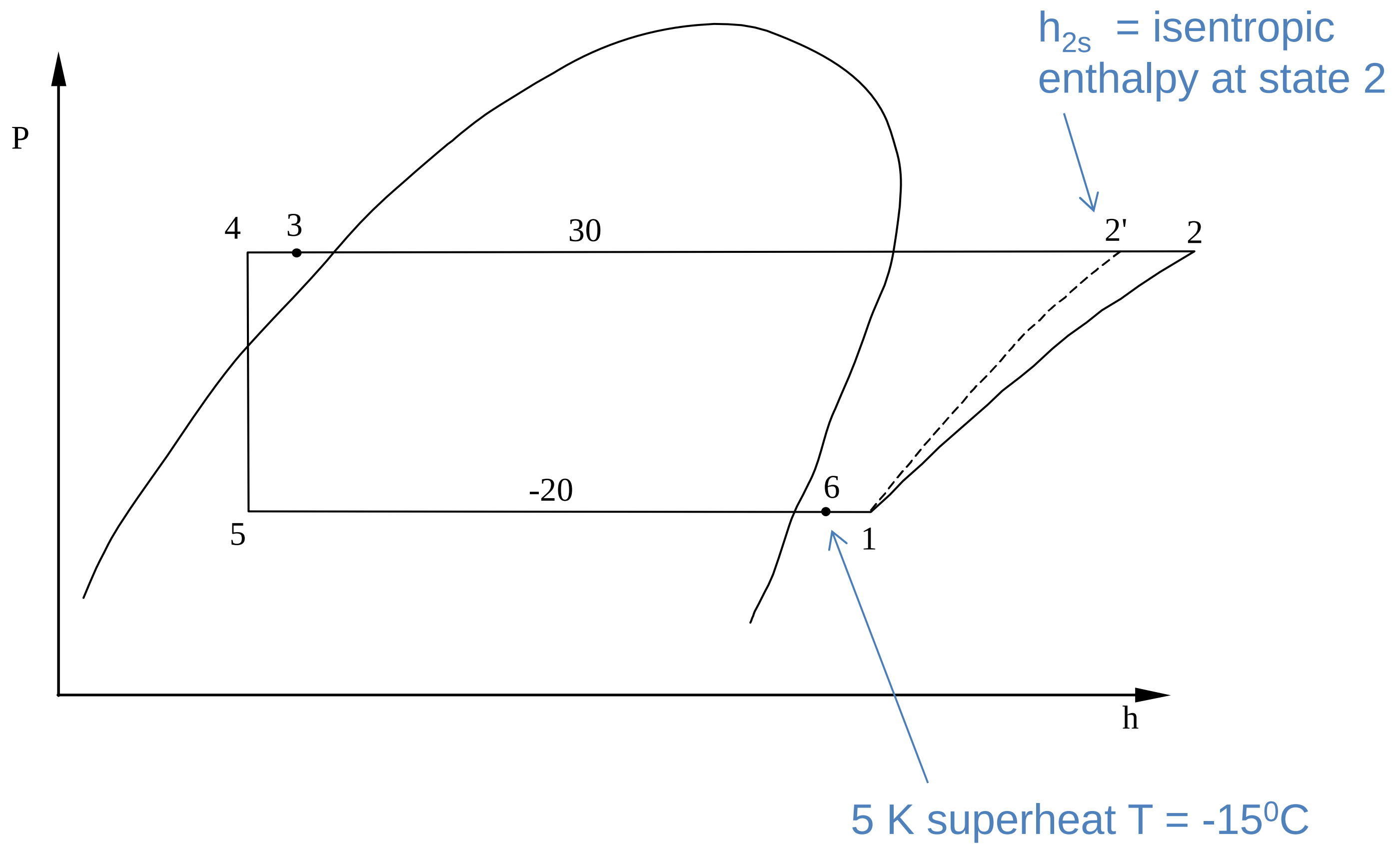
therefore

$$\eta_{1s} = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{234.8 - 201.86}{56.27} = 59\%$$

# Example 2

*Solution*:

(b)




From tables $h_6 = h\left(-20^oC\, evap, 5K\, superheat\right) = 181.7 kJ / kg$

| TEMP. (P.SAT) | | SAT. STATE | SUPERHEAT,K | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 150 | 200 |
| -30.0 | V | .1595 | .1633 | .1671 | .1709 | .1746 | .1783 | .1820 | .1893 | .1966 | .2038 | .2322 | .2673 | .3020 |
| ( 100.3) | H | 174.2 | 177.1 | 180.0 | 182.9 | 185.8 | 188.8 | 191.8 | 197.8 | 203.8 | 210.0 | 235.5 | 268.9 | 304.0 |
| | S | .7171 | .7288 | .7404 | .7518 | .7631 | .7742 | .7852 | .8068 | .8279 | .8486 | .9273 | 1.0183 | 1.1022 |
| -29.0 | V | .1533 | .1570 | .1606 | .1642 | .1678 | .1714 | .1749 | .1819 | .1889 | .1958 | .2231 | .2567 | .2901 |
| ( 104.7) | H | 174.7 | 177.5 | 180.5 | 183.4 | 186.3 | 189.3 | 192.3 | 198.3 | 204.4 | 210.6 | 236.1 | 269.6 | 304.7 |
| | S | .7162 | .7279 | .7395 | .7509 | .7621 | .7732 | .7842 | .8058 | .8269 | .8475 | .9262 | 1.0171 | 1.1009 |
| -28.0 | V | .1474 | .1509 | .1544 | .1579 | .1613 | .1648 | .1682 | .1749 | .1816 | .1883 | .2145 | .2467 | .2787 |
| ( 109.2) | H | 175.1 | 178.0 | 180.9 | 183.9 | 186.8 | 189.8 | 192.8 | 198.8 | 204.9 | 211.1 | 236.7 | 270.2 | 305.4 |
| | S | .7153 | .7270 | .7386 | .7500 | .7612 | .7723 | .7833 | .8048 | .8259 | .8465 | .9251 | 1.0159 | 1.0996 |
| -27.0 | V | .1417 | .1451 | .1485 | .1519 | .1552 | .1585 | .1617 | .1682 | .1747 | .1811 | .2062 | .2372 | .2679 |
| ( 113.8) | H | 175.6 | 178.5 | 181.4 | 184.4 | 187.3 | 190.3 | 193.3 | 199.4 | 205.5 | 211.7 | 237.3 | 270.9 | 306.1 |
| | S | .7144 | .7261 | .7377 | .7491 | .7603 | .7714 | .7824 | .8039 | .8250 | .8456 | .9241 | 1.0147 | 1.0983 |
| -26.0 | V | .1364 | .1396 | .1429 | .1461 | .1493 | .1525 | .1556 | .1619 | .1680 | .1742 | .1984 | .2281 | .2576 |
| ( 118.6) | H | 176.0 | 178.9 | 181.9 | 184.8 | 187.8 | 190.8 | 193.8 | 199.9 | 206.0 | 212.3 | 237.9 | 271.5 | 306.8 |
| | S | .7135 | .7253 | .7368 | .7482 | .7594 | .7705 | .7815 | .8030 | .8240 | .8446 | .9230 | 1.0135 | 1.0970 |
| -25.0 | V | .1312 | .1344 | .1375 | .1406 | .1437 | .1467 | .1498 | .1558 | .1617 | .1676 | .1909 | .2194 | .2477 |
| ( 123.6) | H | 176.5 | 179.4 | 182.4 | 185.3 | 188.3 | 191.3 | 194.3 | 200.4 | 206.6 | 212.8 | 238.5 | 272.2 | 307.4 |
| | S | .7127 | .7244 | .7360 | .7473 | .7586 | .7696 | .7806 | .8021 | .8231 | .8437 | .9220 | 1.0124 | 1.0958 |
| -24.0 | V | .1264 | .1294 | .1324 | .1354 | .1384 | .1413 | .1442 | .1500 | .1557 | .1614 | .1837 | .2112 | .2384 |
| ( 128.7) | H | 176.9 | 179.9 | 182.8 | 185.8 | 188.8 | 191.8 | 194.8 | 200.9 | 207.1 | 213.4 | 239.1 | 272.8 | 308.1 |
| | S | .7119 | .7236 | .7351 | .7465 | .7577 | .7688 | .7797 | .8012 | .8222 | .8428 | .9210 | 1.0113 | 1.0945 |
| -23.0 | V | .1217 | .1246 | .1275 | .1304 | .1332 | .1361 | .1389 | .1445 | .1500 | .1554 | .1769 | .2033 | .2294 |
| ( 134.0) | H | 177.4 | 180.3 | 183.3 | 186.3 | 189.3 | 192.3 | 195.4 | 201.5 | 207.7 | 213.9 | 239.7 | 273.5 | 308.8 |
| | S | .7111 | .7228 | .7343 | .7457 | .7569 | .7680 | .7789 | .8004 | .8213 | .8419 | .9200 | 1.0102 | 1.0933 |
| -22.0 | V | .1172 | .1201 | .1229 | .1256 | .1284 | .1311 | .1338 | .1392 | .1445 | .1497 | .1704 | .1958 | .2209 |
| ( 139.4) | H | 177.8 | 180.8 | 183.8 | 186.8 | 189.8 | 192.8 | 195.9 | 202.0 | 208.2 | 214.5 | 240.3 | 274.2 | 309.5 |
| | S | .7103 | .7220 | .7335 | .7449 | .7561 | .7672 | .7781 | .7995 | .8205 | .8410 | .9191 | 1.0091 | 1.0922 |
| -21.0 | V | .1130 | .1157 | .1184 | .1211 | .1237 | .1263 | .1290 | .1341 | .1392 | .1443 | .1642 | .1886 | .2128 |
| ( 145.1) | H | 178.3 | 181.3 | 184.3 | 187.3 | 190.3 | 193.3 | 196.4 | 202.5 | 208.8 | 215.1 | 240.9 | 274.8 | 310.2 |
| | S | .7095 | .7212 | .7327 | .7441 | .7553 | .7664 | .7773 | .7987 | .8197 | .8401 | .9181 | 1.0080 | 1.0910 |
| -20.0 | V | .1089 | .1115 | .1141 | .1167 | .1193 | .1218 | .1243 | .1293 | .1342 | .1391 | .1583 | .1818 | .2050 |
| ( 150.8) | H | 178.7 | 181.7 | 184.7 | 187.8 | 190.8 | 193.8 | 196.9 | 203.1 | 209.3 | 215.6 | 241.5 | 275.5 | 310.9 |
| | S | .7087 | .7204 | .7320 | .7433 | .7545 | .7656 | .7765 | .7979 | .8188 | .8393 | .9172 | 1.0070 | 1.0899 |

# Example 2

But now for the heat exchanger

$$h_1 - h_6 = h_3 - h_4$$

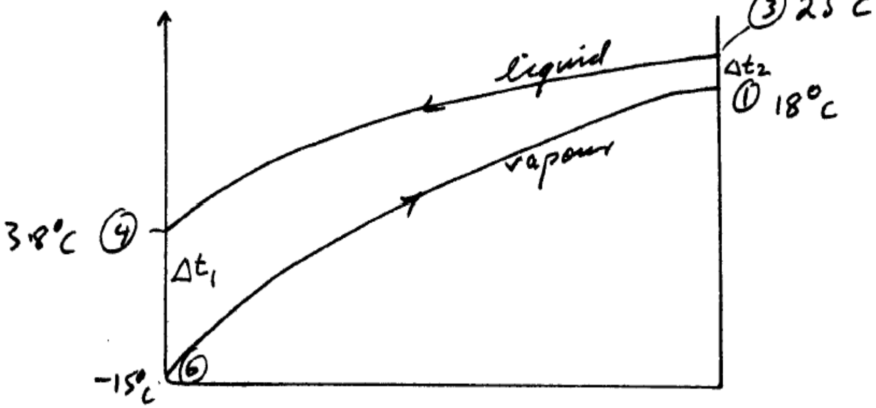
But $h_3 = 59.7\,Jk/kg$ and $h_1 = 201.86\,kJ/kg$

Therefore $h_4 = 59.7 - 201.86 + 181.7 = 39.54\,kJ/kg$

From tables at (30ºC condensing)

$h_4 = h_f(t_4)$ therefore $t_4 = 3.8\ ^0C$

For the heat exchanger



# Example 2

Since

$$\dot{Q}_{HE} = UA\Delta T_{LMTD}$$

Where

$$\Delta T_{LMTD} = \frac{\Delta t_1 - \Delta t_2}{ln\left(\frac{\Delta t_1}{\Delta t_2}\right)}$$

$$= \frac{18.8 - 7}{ln\left(\frac{18.8}{7}\right)}$$

$$= 11.94$$

But we also know that

$$\dot{Q}_{HE} = \dot{m}(h_1 - h_6)$$

$$= (0.0679)(201.86 - 181.7)$$

$$= 1.369 kW$$

# Example 2

Therefore we can calculate the require heat transfer area,

$$A = \frac{\dot{Q}_{HE}}{U \Delta T_{LMTD}}$$

Given $U = 50 W / m^2 K$

$$A = \frac{1.369 \times 10^3}{50 \times 11.94}$$

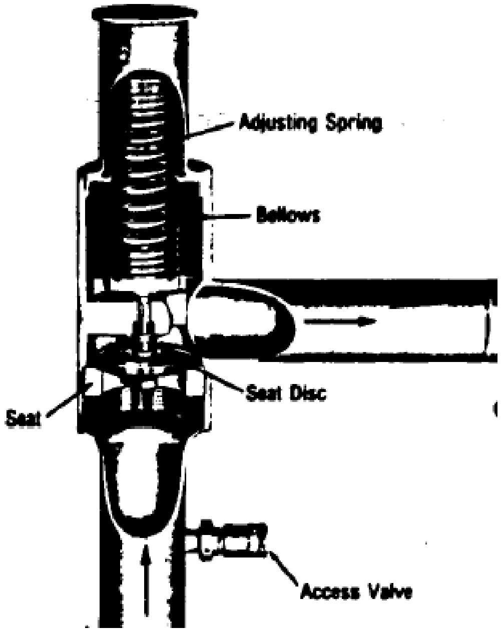
$$= 2.29 m^2$$

# Effects of Heat Transfers and Pressure Drops

*(a) Suction Pipe*

- The most important changes are those in the suction pipe because they modify the state of the vapour at the entry to the compressor and cause significant changes in performance.

- Values used for suction throttling are called Evaporator pressure regulators (EPR)).




Where do you think such a valve is useful?

Remote refrigeration cabinets

# Effects of Heat Transfers and Pressure Drops

*(b) Delivery line*

Pressure drop between the compressor and condenser is harmful because it increases the work required

*(c) Liquid line*

Pressure drop in the liquid line has a harmful effect since it may also result in the partial vaporisation of the liquid refrigerant.

The degree of sub-cooling required to prevent vaporisation within a given lift can be determined by applying the steady state energy equation,

$$0 = \left(h_2 - h_1\right) + g\left(z_2 - z_1\right)$$

# Effects of Heat Transfers and Pressure Drops

$$p_1 - p_2 = \frac{g\left(z_2 - z_1\right)}{v_f}$$

Where

- $p_1$ is the pressure at the bottom of the riser;
- $p_2$ is the saturation pressure of the liquid at temperature (*t1*) and
- $v_f$ is the specific volume determined at $t_1$.

# Example 3

Ammonia liquid leaves a receiver at a pressure of 1.35 MPa and a temperature of 34ºC and flows adiabatically up a vertical pipe.
At what height above the inlet will it become saturated liquid?

*Solution:*

From the ammonia tables, at 1.35 MPa, t = 35ºC. Therefore, the liquid is sub-cooled 1K.

The saturation pressure at 34ºC is 1312 kPa.

| T DEG.C | P KPA | 1/V(F) KG/M3 | V(G) M3/KG | H(F) | H(FG) KJ/KG | H(G) | S(F) | S(FG) KJ/KG.K | S(G) |
|---|---|---|---|---|---|---|---|---|---|
| 15.0 | 728.7 | 618. | .17461 | 250.52 | 1205.65 | 1456.17 | .9449 | 4.1841 | 5.1291 |
| 16.0 | 753.2 | 616. | .16914 | 255.27 | 1201.70 | 1456.98 | .9604 | 4.1560 | 5.1164 |
| 17.0 | 778.3 | 615. | .16387 | 260.04 | 1197.73 | 1457.76 | .9758 | 4.1280 | 5.1037 |
| 18.0 | 804.1 | 613. | .15880 | 264.81 | 1193.72 | 1458.53 | .9911 | 4.1000 | 5.0912 |
| 19.0 | 830.5 | 612. | .15392 | 269.58 | 1189.70 | 1459.28 | 1.0064 | 4.0722 | 5.0786 |
| 20.0 | 857.5 | 610. | .14921 | 274.36 | 1185.64 | 1460.01 | 1.0216 | 4.0445 | 5.0661 |
| 21.0 | 885.3 | 609. | .14468 | 279.15 | 1181.57 | 1460.72 | 1.0368 | 4.0169 | 5.0537 |
| 22.0 | 913.7 | 607. | .14031 | 283.95 | 1177.46 | 1461.41 | 1.0519 | 3.9894 | 5.0413 |
| 23.0 | 942.8 | 606. | .13610 | 288.75 | 1173.33 | 1462.08 | 1.0670 | 3.9619 | 5.0289 |
| 24.0 | 972.7 | 604. | .13204 | 293.56 | 1169.17 | 1462.73 | 1.0820 | 3.9346 | 5.0166 |
| 25.0 | 1003.2 | 603. | .12812 | 298.38 | 1164.98 | 1463.36 | 1.0970 | 3.9074 | 5.0043 |
| 26.0 | 1034.5 | 601. | .12434 | 303.20 | 1160.77 | 1463.96 | 1.1119 | 3.8802 | 4.9921 |
| 27.0 | 1066.5 | 600. | .12070 | 308.03 | 1156.52 | 1464.55 | 1.1267 | 3.8532 | 4.9799 |
| 28.0 | 1099.2 | 598. | .11718 | 312.86 | 1152.25 | 1465.12 | 1.1415 | 3.8262 | 4.9677 |
| 29.0 | 1132.7 | 597. | .11378 | 317.71 | 1147.95 | 1465.66 | 1.1562 | 3.7993 | 4.9555 |
| 30.0 | 1167.0 | 595. | .11050 | 322.56 | 1143.62 | 1466.18 | 1.1709 | 3.7725 | 4.9434 |
| 31.0 | 1202.0 | 594. | .10732 | 327.41 | 1139.27 | 1466.68 | 1.1856 | 3.7457 | 4.9313 |
| 32.0 | 1237.9 | 592. | .10426 | 332.28 | 1134.88 | 1467.15 | 1.2001 | 3.7191 | 4.9192 |
| 33.0 | 1274.6 | 591. | .10130 | 337.15 | 1130.46 | 1467.61 | 1.2147 | 3.6925 | 4.9072 |
| 34.0 | 1312.0 | 589. | .09844 | 342.03 | 1126.01 | 1468.04 | 1.2291 | 3.6660 | 4.8951 |
| 35.0 | 1350.4 | 587. | .09567 | 346.91 | 1121.53 | 1468.44 | 1.2436 | 3.6395 | 4.8831 |
| 36.0 | 1389.5 | 586. | .09300 | 351.81 | 1117.01 | 1468.82 | 1.2579 | 3.6132 | 4.8711 |

| T<br>DEG.C | P<br>KPA | 1/V(F)<br>KG/M3 | V(G)<br>M3/KG | H(F) | H(FG)<br>KJ/KG | H(G) | S(F) | S(FG)<br>KJ/KG.K | S(G) |
|---|---|---|---|---|---|---|---|---|---|
| 15.0 | 728.7 | 618. | .17461 | 250.52 | 1205.65 | 1456.17 | .9449 | 4.1841 | 5.1291 |
| 16.0 | 753.2 | 616. | .16914 | 255.27 | 1201.70 | 1456.98 | .9604 | 4.1560 | 5.1164 |
| 17.0 | 778.3 | 615. | .16387 | 260.04 | 1197.73 | 1457.76 | .9758 | 4.1280 | 5.1037 |
| 18.0 | 804.1 | 613. | .15880 | 264.81 | 1193.72 | 1458.53 | .9911 | 4.1000 | 5.0912 |
| 19.0 | 830.5 | 612. | .15392 | 269.58 | 1189.70 | 1459.28 | 1.0064 | 4.0722 | 5.0786 |
| 20.0 | 857.5 | 610. | .14921 | 274.36 | 1185.64 | 1460.01 | 1.0216 | 4.0445 | 5.0661 |
| 21.0 | 885.3 | 609. | .14468 | 279.15 | 1181.57 | 1460.72 | 1.0368 | 4.0169 | 5.0537 |
| 22.0 | 913.7 | 607. | .14031 | 283.95 | 1177.46 | 1461.41 | 1.0519 | 3.9894 | 5.0413 |
| 23.0 | 942.8 | 606. | .13610 | 288.75 | 1173.33 | 1462.08 | 1.0670 | 3.9619 | 5.0289 |
| 24.0 | 972.7 | 604. | .13204 | 293.56 | 1169.17 | 1462.73 | 1.0820 | 3.9346 | 5.0166 |
| 25.0 | 1003.2 | 603. | .12812 | 298.38 | 1164.98 | 1463.36 | 1.0970 | 3.9074 | 5.0043 |
| 26.0 | 1034.5 | 601. | .12434 | 303.20 | 1160.77 | 1463.96 | 1.1119 | 3.8802 | 4.9921 |
| 27.0 | 1066.5 | 600. | .12070 | 308.03 | 1156.52 | 1464.55 | 1.1267 | 3.8532 | 4.9799 |
| 28.0 | 1099.2 | 598. | .11718 | 312.86 | 1152.25 | 1465.12 | 1.1415 | 3.8262 | 4.9677 |
| 29.0 | 1132.7 | 597. | .11378 | 317.71 | 1147.95 | 1465.66 | 1.1562 | 3.7993 | 4.9555 |
| 30.0 | 1167.0 | 595. | .11050 | 322.56 | 1143.62 | 1466.18 | 1.1709 | 3.7725 | 4.9434 |
| 31.0 | 1202.0 | 594. | .10732 | 327.41 | 1139.27 | 1466.68 | 1.1856 | 3.7457 | 4.9313 |
| 32.0 | 1237.9 | 592. | .10426 | 332.28 | 1134.88 | 1467.15 | 1.2001 | 3.7191 | 4.9192 |
| 33.0 | 1274.6 | 591. | .10130 | 337.15 | 1130.46 | 1467.61 | 1.2147 | 3.6925 | 4.9072 |
| 34.0 | 1312.0 | 589. | .09844 | 342.03 | 1126.01 | 1468.04 | 1.2291 | 3.6660 | 4.8951 |
| 35.0 | 1350.4 | 587. | .09567 | 346.91 | 1121.53 | 1468.44 | 1.2436 | 3.6395 | 4.8831 |
| 36.0 | 1389.5 | 586. | .09300 | 351.81 | 1117.01 | 1468.82 | 1.2579 | 3.6132 | 4.8711 |

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*Solution:*

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|---|---|---|---|---|---|---|---|---|---|
| 15.0 | 728.7 | 618. | .17461 | 250.52 | 1205.65 | 1456.17 | .9449 | 4.1841 | 5.1291 |
| 16.0 | 753.2 | 616. | .16914 | 255.27 | 1201.70 | 1456.98 | .9604 | 4.1560 | 5.1164 |
| 17.0 | 778.3 | 615. | .16387 | 260.04 | 1197.73 | 1457.76 | .9758 | 4.1280 | 5.1037 |
| 18.0 | 804.1 | 613. | .15880 | 264.81 | 1193.72 | 1458.53 | .9911 | 4.1000 | 5.0912 |
| 19.0 | 830.5 | 612. | .15392 | 269.58 | 1189.70 | 1459.28 | 1.0064 | 4.0722 | 5.0786 |
| 20.0 | 857.5 | 610. | .14921 | 274.36 | 1185.64 | 1460.01 | 1.0216 | 4.0445 | 5.0661 |
| 21.0 | 885.3 | 609. | .14468 | 279.15 | 1181.57 | 1460.72 | 1.0368 | 4.0169 | 5.0537 |
| 22.0 | 913.7 | 607. | .14031 | 283.95 | 1177.46 | 1461.41 | 1.0519 | 3.9894 | 5.0413 |
| 23.0 | 942.8 | 606. | .13610 | 288.75 | 1173.33 | 1462.08 | 1.0670 | 3.9619 | 5.0289 |
| 24.0 | 972.7 | 604. | .13204 | 293.56 | 1169.17 | 1462.73 | 1.0820 | 3.9346 | 5.0166 |
| 25.0 | 1003.2 | 603. | .12812 | 298.38 | 1164.98 | 1463.36 | 1.0970 | 3.9074 | 5.0043 |
| 26.0 | 1034.5 | 601. | .12434 | 303.20 | 1160.77 | 1463.96 | 1.1119 | 3.8802 | 4.9921 |
| 27.0 | 1066.5 | 600. | .12070 | 308.03 | 1156.52 | 1464.55 | 1.1267 | 3.8532 | 4.9799 |
| 28.0 | 1099.2 | 598. | .11718 | 312.86 | 1152.25 | 1465.12 | 1.1415 | 3.8262 | 4.9677 |
| 29.0 | 1132.7 | 597. | .11378 | 317.71 | 1147.95 | 1465.66 | 1.1562 | 3.7993 | 4.9555 |
| 30.0 | 1167.0 | 595. | .11050 | 322.56 | 1143.62 | 1466.18 | 1.1709 | 3.7725 | 4.9434 |
| 31.0 | 1202.0 | 594. | .10732 | 327.41 | 1139.27 | 1466.68 | 1.1856 | 3.7457 | 4.9313 |
| 32.0 | 1237.9 | 592. | .10426 | 332.28 | 1134.88 | 1467.15 | 1.2001 | 3.7191 | 4.9192 |
| 33.0 | 1274.6 | 591. | .10130 | 337.15 | 1130.46 | 1467.61 | 1.2147 | 3.6925 | 4.9072 |
| 34.0 | 1312.0 | 589. | .09844 | 342.03 | 1126.01 | 1468.04 | 1.2291 | 3.6660 | 4.8951 |
| 35.0 | 1350.4 | 587. | .09567 | 346.91 | 1121.53 | 1468.44 | 1.2436 | 3.6395 | 4.8831 |
| 36.0 | 1389.5 | 586. | .09300 | 351.81 | 1117.01 | 1468.82 | 1.2579 | 3.6132 | 4.8711 |

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At what height above the inlet will it become saturated liquid?

*Solution:*

From the ammonia tables, at 1.35 MPa, t = 35ºC. Therefore, the liquid is sub-cooled 1K.

The saturation pressure at 34ºC is 1312 kPa.

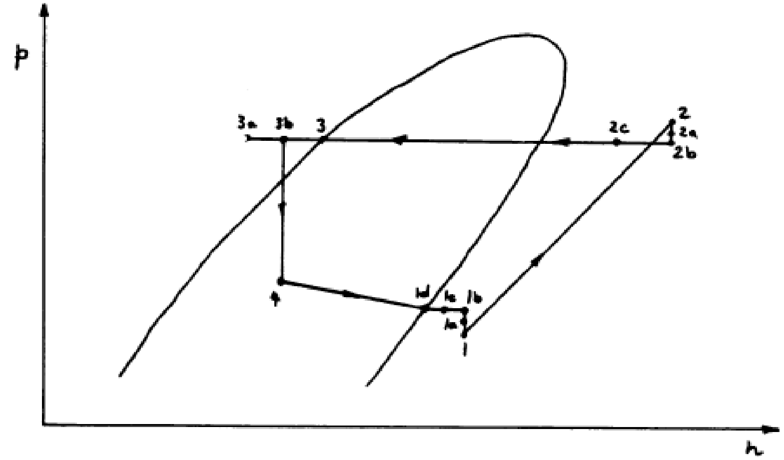
$$p_1 - p_2 = \frac{g\left(z_2 - z_1\right)}{v_f}$$

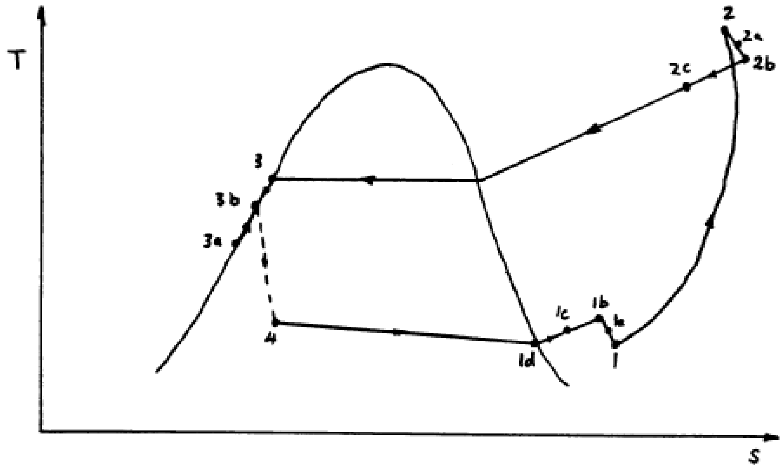
$$\mathrm{v_f}\left(\mathrm{t_1}\right) = 0.0017$$

$$p_1 - p_2 = 1350 - 1312 = \frac{9.81\left(\Delta z\right)}{0.0017}$$

$$\Delta z = 6.6m$$

# Actual Vapour Compression Cycle



# Actual Vapour Compression Cycle

The cycle consists of

(i) Superheating of the vapour in the evaporator, 1d-ic.
(ii) Heat gain and superheating of the vapour in suction line, 1c-1b.
(iii) Pressure drop in the suction line, 1b-1a.
(iv) Pressure drop at the compressor-suction valve, 1a-1.
(v) Polytropic compression with friction and heat transfer to the surroundings instead of isentropic compression, 1-2.
(vi) Pressure drop at the compressor discharge valve, 2-2a.
(vii) Pressure drop in the delivery line, 2a-2b.
(viii) Heat loss and desuperheating of the vapour in the delivery line, 2b-2c.
(ix) Pressure drop in the condenser, 2c-3.
(x) Subcooling of the liquid in the condenser or subcooler, 3-3a.
(xi) Heat gain in the liquid line, 3a-3b.
(xii) Pressure drop in the evaporator, 4-1d.