Alternatively

$$h_6 = h_1 - (h_1 - h_6)$$
$$= h_1 - \text{specific refrigerating effect}$$

from the information obtained

$$\text{Theoretical COP} = \frac{h_1 - h_6}{h_2 - h_1}$$

In a refrigerator trial

$$\text{Actual COP} = \frac{\text{Actual refrigerating effect}}{\text{Actual energy input}}$$

Example 18.1 *A vapour compression refrigerator uses the refrigerant ISCEON 69-S (Rhône-Poulenc) and operates between the pressure limits of 462.47 kN/m² and 1785.90 kN/m². At entry to the compressor the refrigerant is dry saturated and after compression it has a temperature of 59 °C. The compressor has a bore and stroke of 75 mm and runs at 8 rev/s with a volumetric efficiency of 80 per cent. The temperature of the liquid refrigerant as it leaves the condenser is 32 °C and its specific heat capacity is 1.32 kJ/kg K. The specific heat capacity of the superheated vapour may be assumed constant. Determine*

(a) the coefficient of performance of the refrigerator
(b) the mass flow of the refrigerant in kg/h
(c) the cooling water required by the condenser in kg/h if the cooling water temperature rise is limited to 12 °C

Take the specific heat capacity of water as 4.187 kJ/kg K. The relevant properties of the refrigerant 69-S are given in the table.

Pressure (kN/m²)	Sat temp. t_f (°C)	Spec. enthalpy (kJ/kg)		Spec. vol (m³/kg)		Spec. entropy (kJ/kg K)	
		h_f	h_g	v_f	v_g	s_f	s_g
462.47	−10	35.732	231.40	0.000 8079	0.045 73	0.141 8	0.861 4
1 785.90	40	99.270	246.40	0.000 9487	0.011 05	0.353 7	0.809 3

SOLUTION
First draw a diagram (Fig. 18.8).

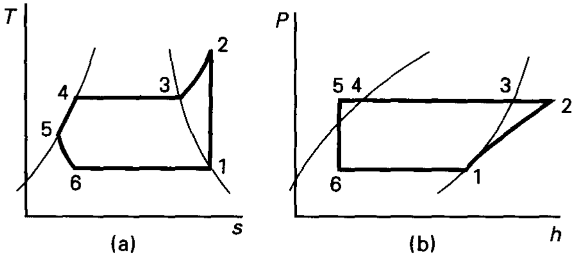

Fig. 18.8 Diagrams for Example 18.1

(a)
From the table, $h_1 = 231.4$ kJ/kg and $s_1 = 0.861\,4$ kJ/kg K

$$s_1 = s_2$$

$$s_2 = s_3 + c_{pV} \ln \frac{T_2}{T_3}$$

$$T_2 = 59 + 273 = 332 \text{ K}$$

$$T_3 = 40 + 273 = 313 \text{ K}$$

$$\therefore \quad 0.861\,4 = 0.809\,3 + c_{pV} \ln \frac{332}{313}$$
$$= 0.809\,3 + c_{pV} \ln 1.06$$
$$= 0.809\,3 + 0.058\, c_{pV}$$

$$\therefore \quad c_{pV} = \frac{0.861\,4 - 0.809\,3}{0.058} = \frac{0.052\,1}{0.05\,8} = \mathbf{0.898\ kJ/kg\ K}$$

$$h_2 = h_3 + c_{pV}(T_3 - T_2) = 246.4 + 0.898 \times (332 - 313)$$
$$= 246.4 + (0.898 \times 19)$$
$$= 246.4 + 17.06$$
$$= \mathbf{263.46\ kJ/kg}$$

$$h_5 = h_4 - c_{pL}(T_4 - T_5) = 99.27 - 1.32 \times (40 - 32)$$
$$= 99.27 - (1.32 \times 8)$$
$$= 99.27 - 10.56$$
$$= \mathbf{88.71\ kJ/kg}$$

And $h_5 = h_6$, so

$$\text{COP} = \frac{h_1 - h_6}{h_2 - h_1} = \frac{231.4 - 88.71}{263.46 - 231.4}$$
$$= \frac{142.69}{32.06}$$
$$= \mathbf{4.45}$$

(b)

Specific volume of refrigerant at entry to compressor is $v_1 = \mathbf{0.045\,73\ m^3/kg}$

$$\text{Swept volume of compressor/rev} = \left(\pi \times \frac{0.075^2}{4} \times 0.075\right) \text{m}^3$$

$$\text{Effective swept volume/rev} = 0.8 \times \left(\pi \times \frac{0.075^2}{4} \times 0.075\right) \text{m}^3$$

$$\text{Effective swept volume/h} = 0.8 \times 8 \times 3600 \times \left(\pi \times \frac{0.075^2}{4} \times 0.075\right) \text{m}^3$$

$$\therefore \quad \text{Mass flow of refrigerant/h} = \frac{0.8 \times 8 \times 3600}{0.045\,73}\left(\pi \times \frac{0.075^2}{4} \times 0.075\right)$$
$$= \mathbf{166.94\ kg}$$

(c)

$$\text{Heat transfer in condenser} = h_2 - h_5$$
$$= 263.46 - 88.71$$
$$= \mathbf{174.75\ kJ/kg}$$

$$\therefore \quad \text{Heat transfer/h} = (174.75 \times 166.94)\ \text{kJ}$$

Let $\dot{m}$ = mass flow of water required per hour

Then $\dot{m} \times 4.187 \times 12 = 174.75 \times 166.94$

$$\therefore \quad \dot{m} = \frac{174.75 \times 166.94}{4.187 \times 12} = \mathbf{580.62\ kg/h}$$

18.7 *The heat pump*

During the analysis of the refrigeration process, notice that more energy is rejected at the high temperature than is required to drive the refrigerator. If the temperature during the rejection process is sufficiently high, perhaps the heat transfer during rejection could be usefully used in a warming process. That this heat transfer is greater than the energy required to drive the plant presents an attractive idea. The concept was suggested by Lord Kelvin in 1852.

The vapour compression refrigerator, with suitably arranged pressures and temperatures, can be considered as being suitable for a **heat pump.** Many commercial machines have been manufactured using this process; the evaporator is buried under the soil or suspended in a river or lake. But the heat pump has not gained wide acceptance as a heating system. It is more complex, more difficult to run and more difficult to maintain than its conventional counterparts. However, a decrease in fossil fuel availability could encourage its further development and more widespread use.

Example 18.2 A simple heat pump circulates refrigerant R401 (SUVA MP52, Du Pont) and is required for space heating. The heat pump consists of an evaporator, compressor, condenser and throttle regulator. The pump works between the pressure limits 411.2 kN/m² and 1118.9 kN/m². The heat transfer from the condenser unit is 100 MJ/h. The R401 is assumed dry saturated at the beginning of compression and has a temperature of 60°C after compression. At the end of the condensation process the refrigerant is liquid but not undercooled. The specific heat capacity of the superheated vapour can be assumed constant. Determine

(a) *the massflow of R401 in kg/h, assuming no energy loss*
(b) *the dryness fraction of the R401 at the entry to the evaporator*
(c) *the power of the driving motor, assuming that only 70 per cent of the power of the driving motor appears in the R401*
(d) *the ratio of the heat transferred from the condenser to the power required to drive the motor in the same time*

The relevant properties of R401 are given in the table.

Pressure (kN/m²)	Sat. temp. t_f (°C)	Spec. enthalpy (kJ/kg)		Spec. entropy (kJ/kg K)	
		h_f	h_g	s_f	s_g
411.2	15	219.0	409.3	1.067 4	1.743 1
1 118.9	50	265.5	426.4	1.217 3	1.719 2

SOLUTION
First draw a diagram (Fig. 18.9).

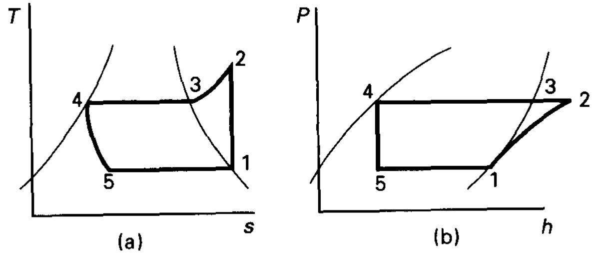

Fig. 18.9 Diagrams for Example 18.2

(a)
From the table $s_1 = 1.743\ 1$ kJ/kg

$$s_2 = s_3 + c_{pV} \ln \frac{T_2}{T_3}$$

$$s_1 = s_2$$

$$T_2 = 60 + 273 = 333\ \text{K}$$

$$T_3 = 50 + 273 = 323\ \text{K}$$

$$\therefore \quad 1.743\ 1 = 1.719\ 2 + c_{pV} \ln \frac{333}{323}$$
$$= 1.719\ 2 + c_{pV} \ln 1.039\ 2$$
$$= 1.719\ 2 + 0.030\ 4\ c_{pV}$$

$$\therefore \quad c_{pV} = \frac{1.743\ 1 - 1.719\ 2}{0.0304} = \mathbf{0.786\ kJ/kg\ K}$$

$$h_2 = h_3 + c_{pV}(T_2 - T_3) = 426.4 + 0.786 \times (333 - 323)$$
$$= 426.4 + (0.786 \times 10)$$
$$= 426.4 + 7.86$$
$$= \mathbf{434.26\ kJ/kg}$$

$$\text{Heat transfer from condenser} = 434.26 - 265.5$$
$$= \mathbf{168.76\ kJ/kg}$$

$$\therefore \quad \text{Mass flow of R401} = \frac{100\ 000}{168.76} = \mathbf{592.6\ kg/h}$$

(b)

$h_4 = h_5 = 265.5$ kJ/kg

$$\therefore \quad 265.5 = 219.0 + x_5(409.3 - 219.0)$$

$$x_5 = \frac{265.5 - 219.0}{409.3 - 219.0} = \frac{46.5}{190.3} = \mathbf{0.244}$$

(c)

$$\text{Specific work} = h_2 - h_1 = 434.26 - 409.3 = \mathbf{24.96\ kJ/kg}$$

$$\text{Mass flow of refrigerant} = \frac{592.6}{3600} = \mathbf{0.164\,6\ kg/s}$$

$$\therefore \quad \text{Power to driving motor} = \frac{24.96 \times 0.164\,6}{0.7}$$

$$= \mathbf{5.87\ kW}$$

(d)

$$\text{Heat transfer from condenser} = \frac{100\,000}{3600}\ \text{kJ/s}$$

$$\therefore \quad \text{Ratio} = \frac{100\,000}{3600 \times 5.87}$$

$$= \mathbf{4.73{:}1}$$

18.8 The vapour absorption refrigerator

Figure 18.10 shows a circuit for a type of **vapour absorption refrigerator**. The arrangement shown is sometimes called the Electrolux refrigerator or the Servel refrigerator. It was originally devised by Carl G. Munters and Baltzar von Platen in Stockholm.

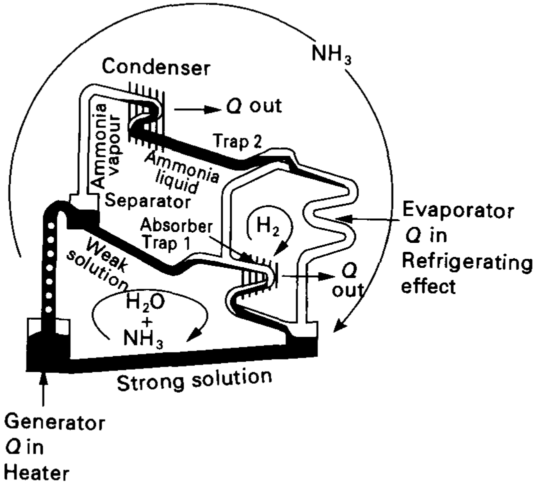

Fig. 18.10 Vapour absorption refrigerator

A solution of ammonia and water part-fills the generator. A vertical tube passes through the top of the generator and is immersed in the ammonia-water solution. A heater warms the solution; vapour formed above the surface of the solution forces the level of the solution down, so some solution rises up the vertical tube. The solution level in the generator eventually reaches the bottom of the vertical tube and some vapour passes into the tube. Fresh solution passing into the bottom of the generator again lifts the surface level above the bottom of the vertical tube; the process is then repeated. Thus, alternate small quantities of weak solution of ammonia in water and ammonia rich vapour lift in the vertical tube and pass into the separator.

In the separator, solution drains into **trap 1**. The ammonia vapour passes up out of the separator and on into a condenser; it condenses and the liquid ammonia drains into **trap** 2. Now, following trap I is the absorber and following trap 2 is the evaporator; connections are as shown in Fig. 18.10. The evaporator-absorber system contains some hydrogen at a partial pressure which is less than the ammonia pressure on the condenser side of trap 2 and the separator side of trap I. Liquid ammonia from trap 2 drains into the evaporator and evaporates; the partial pressure of this evaporated ammonia plus the partial pressure of the hydrogen balances the ammonia pressure on the other side of the traps. Thus, in the evaporator there is a lower ammonia pressure, so the saturation temperature at which it evaporates is lower. This is the refrigeration temperature and the evaporation produces the refrigerating effect.

The low-temperature ammonia vapour and the hydrogen eventually appear in the absorber. Here the ammonia is absorbed in the weak solution draining from trap I. The hydrogen remains in the evaporator-absorber system; it is unable to leave because of traps I and 2 and the solution in the bottom of the absorber. The strong ammonia-water solution drains from the absorber and passes back to the generator to complete the circuit. There are no moving parts and there is pressure balance throughout. The heater can be electric or it can be fuelled by liquid fuel or gas.

The circuit shown is common in some domestic refrigerators. It has a low coefficient of performance. Larger commercial plants are made which require a mechanical circulating pump. They are sometimes employed where waste heat is available.

Questions

1. A vapour compression refrigerator uses SUVA MP52 (BOC-Du Pont) refrigerant between the pressure limits 110.9kN/m^2 and 860.7kN/m^2. At the beginning of compression the refrigerant is dry saturated and at the end of compression it has a temperature of 52°C. In the condenser the refrigerant is condensed but not undercooled. The mass flow of refrigerant is 4 kg/min. Determine
   (a) the theoretical coefficient of performance
   (b) the temperature rise of the cooling water in the condenser if the cooling water flow rate is 960 kg/h
   (c) the ice produced by the evaporator in kg/h from water at 15°C to ice at 0 0C.

   Specific enthalpy of fusion of ice = 336 kJ/kg
   Specific heat capacity of water = 4.187 kJ/kg