8 In a refrigeration system, a fluid known as a refrigerant undergoes alternating changes in its phase, pressure and volume to produce cooling. In this question, you will be guided to design a simple refrigeration system using the data provided.

Fig. 8.1 shows the variation of pressure against volume of the refrigerant as it cycles through four states P, Q, R and S. The four stages of the cyclic process are evaporation, condensation, compression and throttling (pressure releasing).

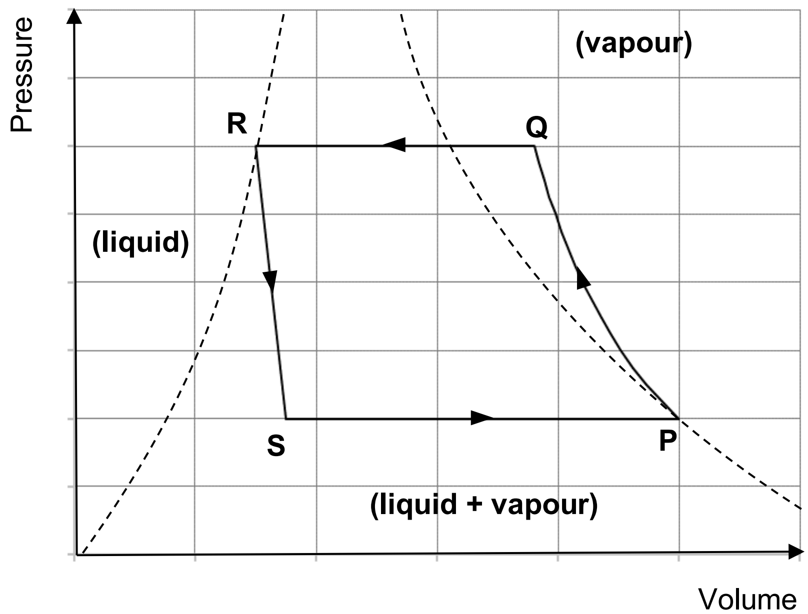

Fig. 8.1

The evaporation phase is considered the cooling phase of the cycle where heat is absorbed from the interior of the refrigerator. The compression phase requires an input of external work on the refrigerant. The performance rating of a refrigerator can therefore be thought as the ratio of the output of heat absorbed from the interior of the refrigerator against the input of work done during the compression phase.

The dotted lines on Fig. 8.1 separate the pressure-volume regions into the respective phase of matter in which the refrigerant exists at that pressure-volume state. For example, in the region labelled **(liquid + vapour)**, the refrigerant exists as a liquid-vapour mixture.

(a) Using the information provided in Fig. 8.1, match each stage in the cycle with its description in the chart below. P→Q has been matched.

Stage		*Description*
P→Q	• —— •	Evaporation
Q→R	• •	Condensation
R→S	• •	Compression

S→P	•	•	Throttling (Pressure release)

[2]

The enthalpy of a system can be understood as the measure of a system's total thermal energy content per unit mass while the entropy of a system can be understood as the measure of a system's enthalpy per unit temperature that is unavailable for doing useful work.

Fig. 8.2 is a table showing the enthalpy and entropy of the refrigerant as a saturated vapour and as a saturated liquid at various pressures and temperatures.

Pressure P / kPa	Temperature T / K	Enthalpy h / kJ kg^{-1}		Entropy s / kJ kg^{-1} K^{-1}	
		Saturated Liquid	Saturated Vapour	Saturated Liquid	Saturated Vapour
100	246.8	17.3	234.5	0.072	0.952
200	263.1	38.5	244.5	0.155	0.938
300	273.9	52.8	250.9	0.208	0.931
400	282.1	64.0	255.6	0.248	0.927
500	288.9	73.4	259.3	0.280	0.924
600	294.8	81.5	262.4	0.308	0.922
700	299.9	88.8	265.1	0.332	0.920
800	304.5	95.5	267.3	0.354	0.918
900	308.7	101.6	269.3	0.374	0.917
1000	312.6	107.4	271.0	0.392	0.916
1200	319.5	117.8	273.9	0.425	0.913
1400	325.6	127.3	276.2	0.453	0.911
1600	331.1	136.0	277.9	0.479	0.908
1800	336.1	144.1	279.2	0.503	0.905
2000	340.7	151.8	280.1	0.525	0.902

Fig. 8.2

(b) When the refrigerant is at the boundary between a pure liquid and a liquid-vapour mixture, it is considered a saturated liquid and a small expansion will cause it to start evaporating.

(i) Deduce what a saturated vapour is.

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.... [1]

(ii) By referring to Fig. 8.1, identify the state (P, Q, R or S) at which the refrigerant is a saturated vapour, and another at which it is a saturated liquid.

saturated vapour: ………………… , saturated liquid: …………………. [1]

(c) Fig. 8.3 is an incomplete table showing the thermal properties of the refrigerant at states P, Q, R and S in the cyclic process.

State	Pressure P / kPa	Temperature T / K	Enthalpy h / kJ kg^{-1}	Entropy s / kJ kg^{-1} K^{-1}
P	300			
Q	1200	322.0		
R				
S				0.443

Fig. 8.3

(i) Using Fig. 8.2 and your answer to **(b)(ii)**, fill in the missing values in Fig. 8.3 for state P. [2]

(ii) At state Q, the enthalpy and entropy of the refrigerant at various pressures are shown in the graphs in Fig. 8.4 and Fig. 8.5.

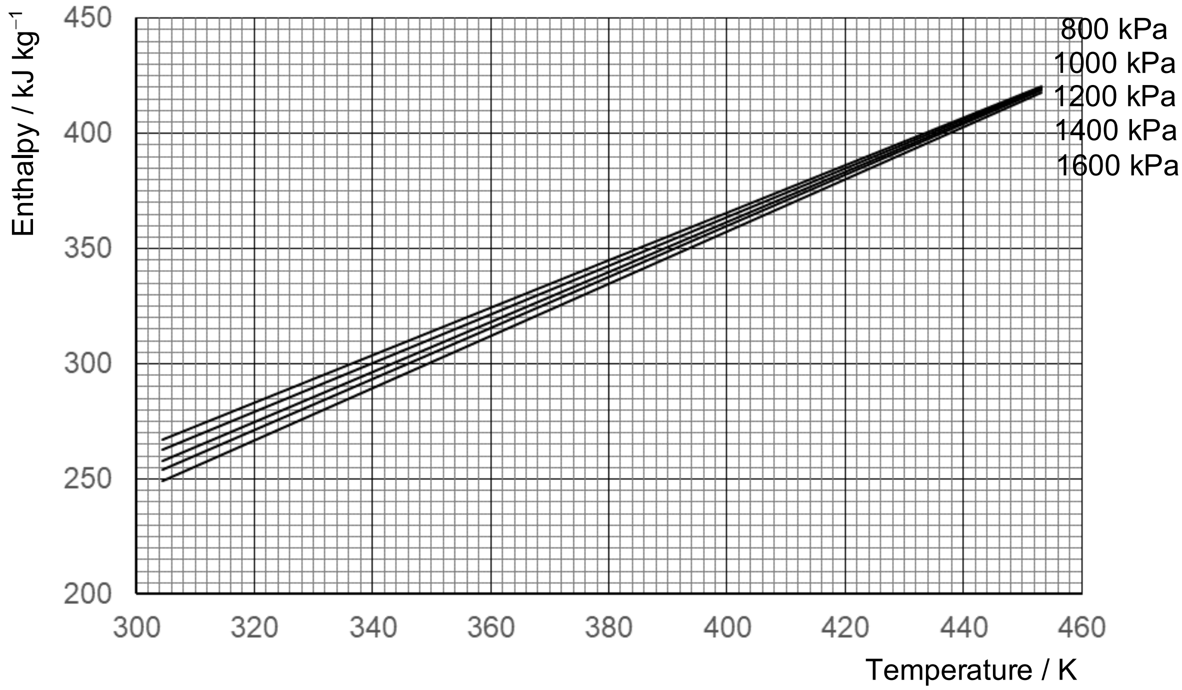

Fig. 8.4

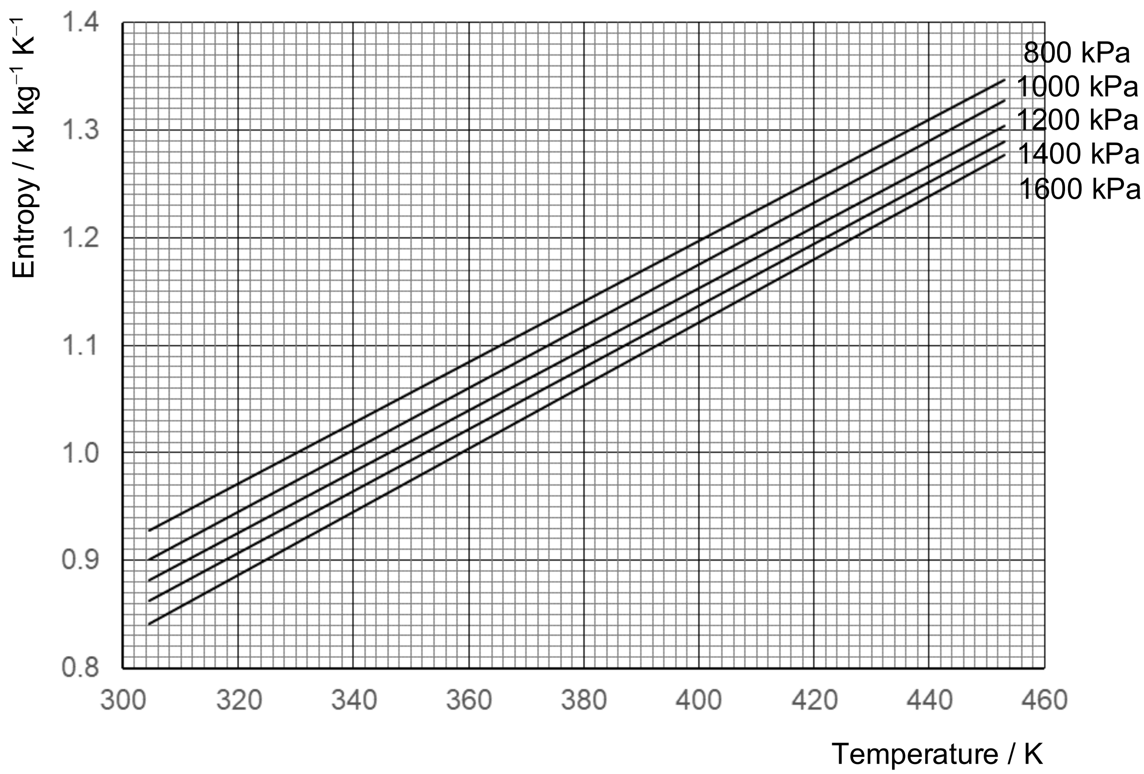

Fig. 8.5

The process P→Q takes place at constant entropy as the pressure of the refrigerant increases to 1200 kPa.

1. Use Fig. 8.5 to verify that the temperature of the refrigerant at state Q is 322.0 K.

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………………………………………………………………………………………… [1]

2. Fill in the missing values in Fig. 8.3 for <u>state Q</u>. [1]

(iii) The process Q→R takes place at constant pressure.
Using Fig. 8.2 and your answer to **(b)(ii)**, fill in the missing values in Fig. 8.3 for <u>state R</u>. [2]

(iv) The process R→S takes place at constant enthalpy while the process S→P takes place at constant temperature and pressure.
Fill in the missing values in Fig. 8.3 for <u>state S</u>. [1]

(d) **(i)** There is energy input during the compression stage of the refrigeration process. The work done by the compressor during this stage can be calculated using

$$W = m\Delta h_c$$

where m is the mass of the system, and Δh_c is the change in enthalpy during the compression stage.

If the compressor compresses 3.20 kg of refrigerant in 1.0 second, calculate the rate of work done by the compressor.

rate of work done = ………………………………. kW [2]

(ii) The enthalpy h of a system is given by

$$h = \frac{U + pV}{m}$$

where U is the internal energy of the system,
p is the pressure of the system,
V is the volume of the system, and
m is the mass of the system.

The product pV can be understood as the amount of work needed to be done for the system to displace its volume at a particular environmental pressure.

1. State the First Law of Thermodynamics.

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……………………………………………………………………………………… [1]

2. Show, using the First Law of Thermodynamics, that for a process taking place at constant pressure, the heat Q absorbed by a system is given by

$$Q = m\Delta h$$

where m is the mass of the system, and Δh is the change in enthalpy during this stage.

[2]

3. Cooling is achieved during the evaporation stage of the cycle as heat is transferred from the surroundings to the refrigerant.

For the same system in **(d)(i)**, calculate the rate of heat removal by the refrigeration process.

rate of heat removal = ……………………………… kW [2]

(e) The typical operating temperature of a freezer is −18 °C.

Explain, with reference to the direction of heat transfer, why the refrigeration system cannot be used to cool a freezer.

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…… [2]

[Total: 20]

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