EMS717U/EMS717P

Renewable Energy Sources

Thermodynamics of Energy Conversion

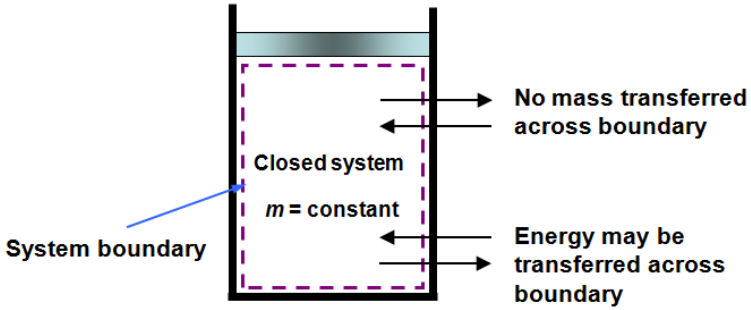
Prof. Huasheng Wang

Laws of thermodynamics

- **The first law of thermodynamics**

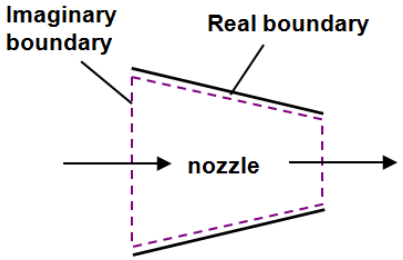
For any process of a stationary system

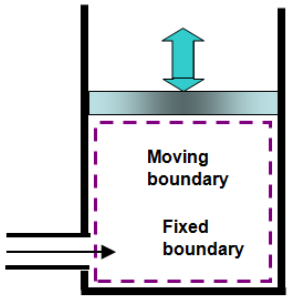
$$W + Q = E_2 - E_1$$

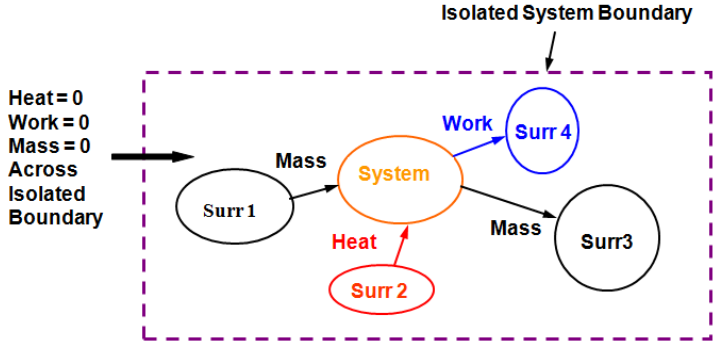


Steady flow energy equation (SFEE)

$$W + Q = \Sigma[m(h + v^2/2 + gz)]_2 - \Sigma[m(h + v^2/2 + gz)]_1$$







Laws of thermodynamics

- **Entropy and the 2nd Law of thermodynamics**

Spontaneous (no outside influence) processes lead to increase in entropy. This is the essence of the Second Law of Thermodynamics.

- $dE = 0$
- $dS \geq 0$

For an isolated system the internal energy is constant and the entropy can only increase. Entropy is constant for ideal reversible process

Fundamentals

- **Thermodynamic cycle**

Gas power cycles

- Carnot cycle
- Otto cycle (ideal cycle for spark-ignition engines)
- Diesel cycle (ideal cycle for compression-ignition engines)
- Stirling cycle
- Ericsson cycle
- Brayton cycle

Steam power cycles

- Rankine cycle

Refrigeration cycles

- Vapour-compression refrigeration cycle

Fundamentals

- **Energy conversion devices**

SFEEs (steady-flow energy equation) for components of cycles

Components	w	q	Δh
Nozzles	0	0	0
Valves	0	0	0
Throttles	0	0	0
Ducts, pipes,diffusers	0	0	0
Boilers	0	$h_{out} - h_{in}$	q_{in}
Heat exchangers	0	$\lvert h_{out} - h_{in} \rvert$	q
Condensers	0	$h_{in} - h_{out}$	q_{out}
Evaporators	0	$h_{out} - h_{in}$	q_{in}
Combustion chambers	0	$h_{out} - h_{in}$	q_{in}
Compressors, pumps, etc.	$h_{out} - h_{in}$	0 (?)	w_{in}
Turbines	$h_{in} - h_{out}$	0 (?)	w_{out}

Fundamentals

- **Thermal efficiency**

Thermal efficiency = Desired output/Required input

$$\eta_{\text{Carnot}} \equiv \frac{W_{\text{net}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{T_{\text{L}}}{T_{\text{H}}}$$

***COP* (Coefficient Of Performance)**

The performance of refrigerators and heat pumps is evaluated in terms of *coefficient of performance* (*COP*).

$$COP_{\text{R}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_{\text{L}}}{W_{\text{net,in}}}$$

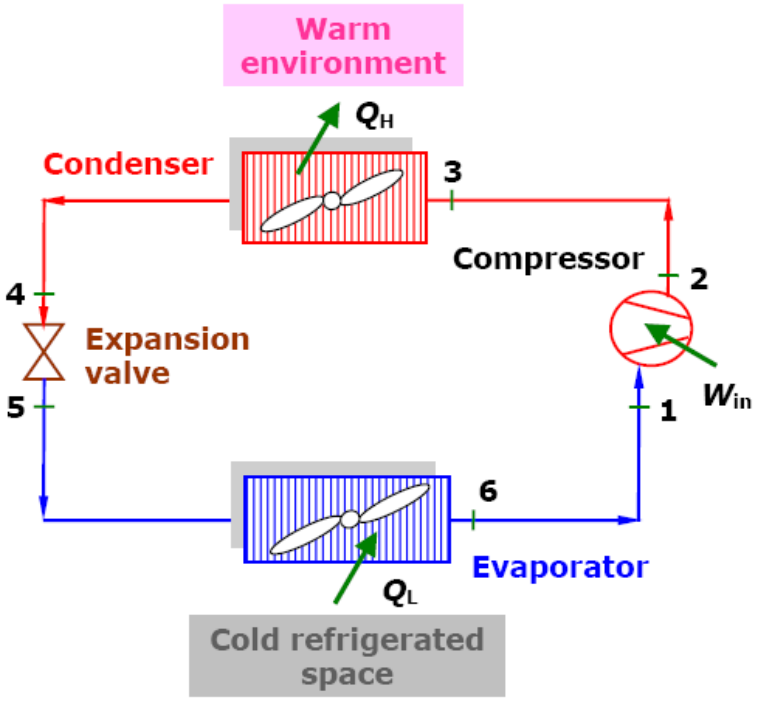
$$COP_{\text{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_{\text{H}}}{W_{\text{net,in}}}$$

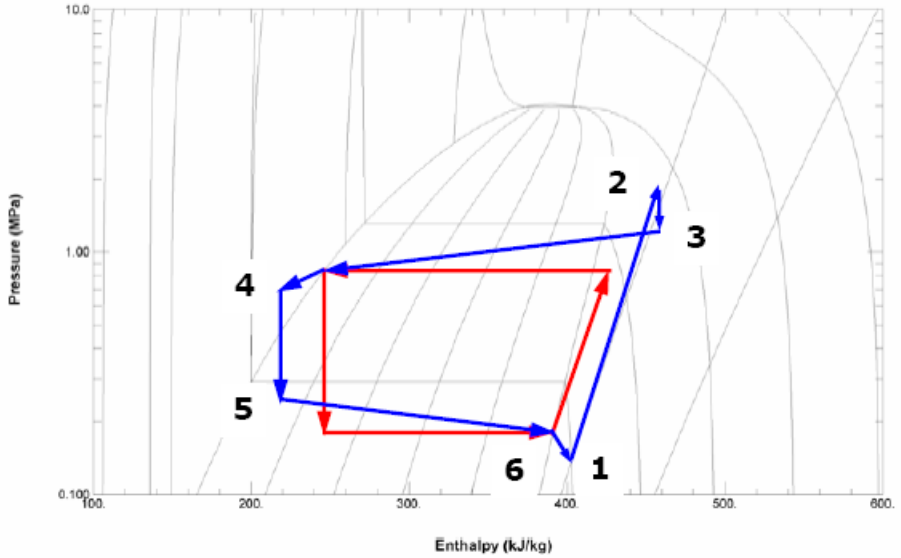
Both COP_{R} and COP_{HP} can be larger than 1. Under the same operating conditions, the *COP*s are related by

$$COP_{\text{HP}} = COP_{\text{R}} + 1$$

Fundamentals

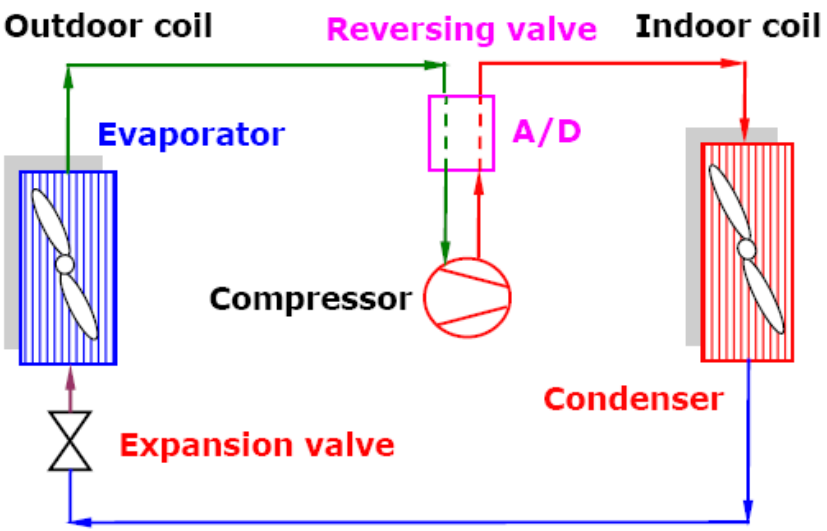
- **Vapour-compression refrigeration cycle**

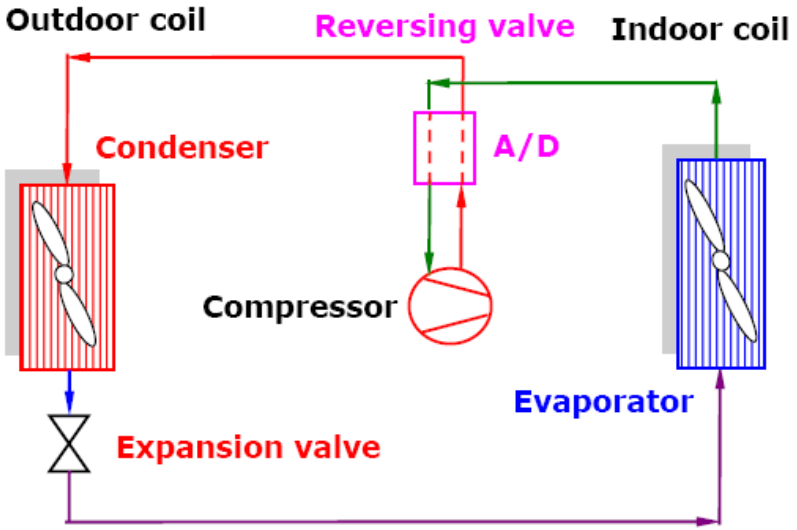




Fundamentals

- **Heat pump systems**





- High pressure/temperature vapour
- High pressure/temperature liquid
- Low pressure/temperature mixture
- Low pressure/temperature vapour

Examples - 1

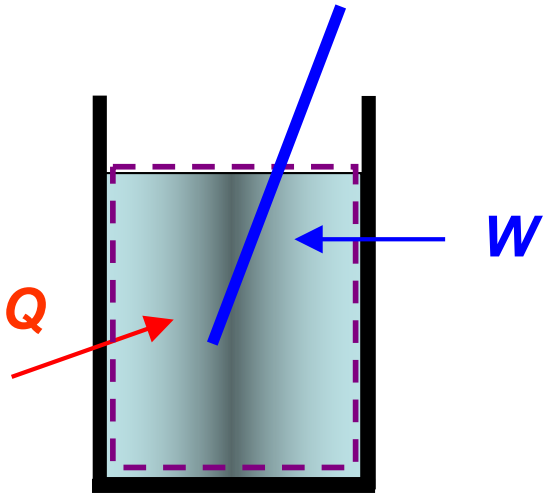
A vessel containing water is stirred so that an amount of work of 20 J is done on it. The initial and final internal energies of water are 100 J and 105 J respectively. Find the heating during this process.

$W = +20$ J

$Q = E_2 - E_1 - W$

$= (105 - 100 - 20)$ J

$= -15$ J



Note: negative Q means the water loses energy by heat in this case.

Examples - 2

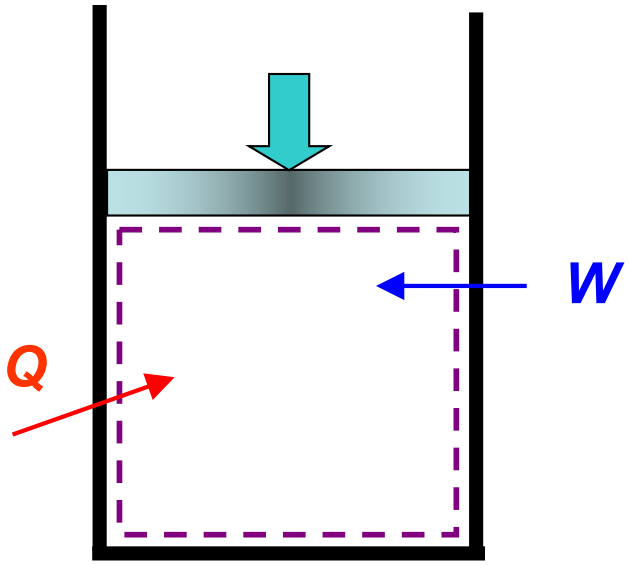
A cylinder containing air is compressed. The work done on the air is 100 J. The initial and final internal energies are equal. Determine the heating during the process.

$W = 100$ J

$Q = E_2 - E_1 - W$

$= -W$

$= -100$ J



Note: Minus sign indicates that energy is transferred *from* the system by the heat process or heating is done *by* the air *on* the surroundings.

Examples - 3

An amount of gas expands in a cylinder fitted with a piston. During the expansion process the gas does an amount of work equal to 50 J on its environment. The environment is cooler than the gas which also loses 25 J of energy by the heat mode. Find the decrease in internal energy of the gas for this process.

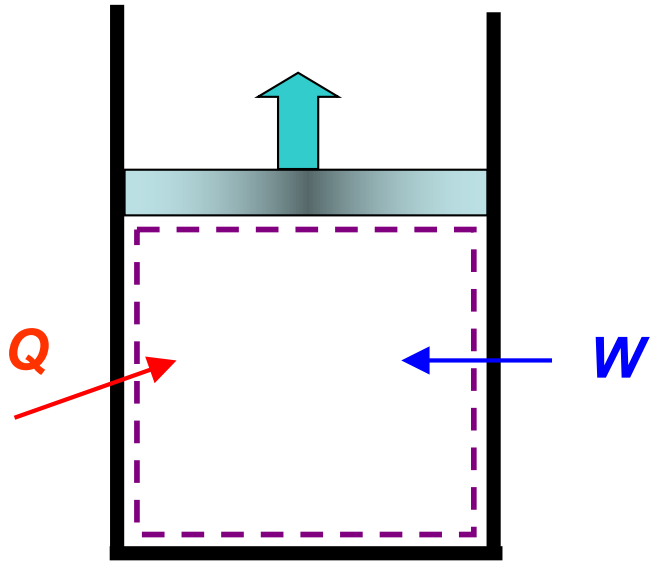
$W = -50$ J

$Q = -25$ J

$E_2 - E_1 = Q + W$

$= (-25 - 50)$ J

$= -75$ J



Question asks for *decrease* of internal energy

$E_1 - E_2 = +75$ J

Problem 2

a) Draw a diagram of a ground source heat pump for space cooling and heating.

b) Assume that the working fluid, refrigerant R134a, undergoes in the heat pump an ideal thermodynamics cycle consisting of four processes:

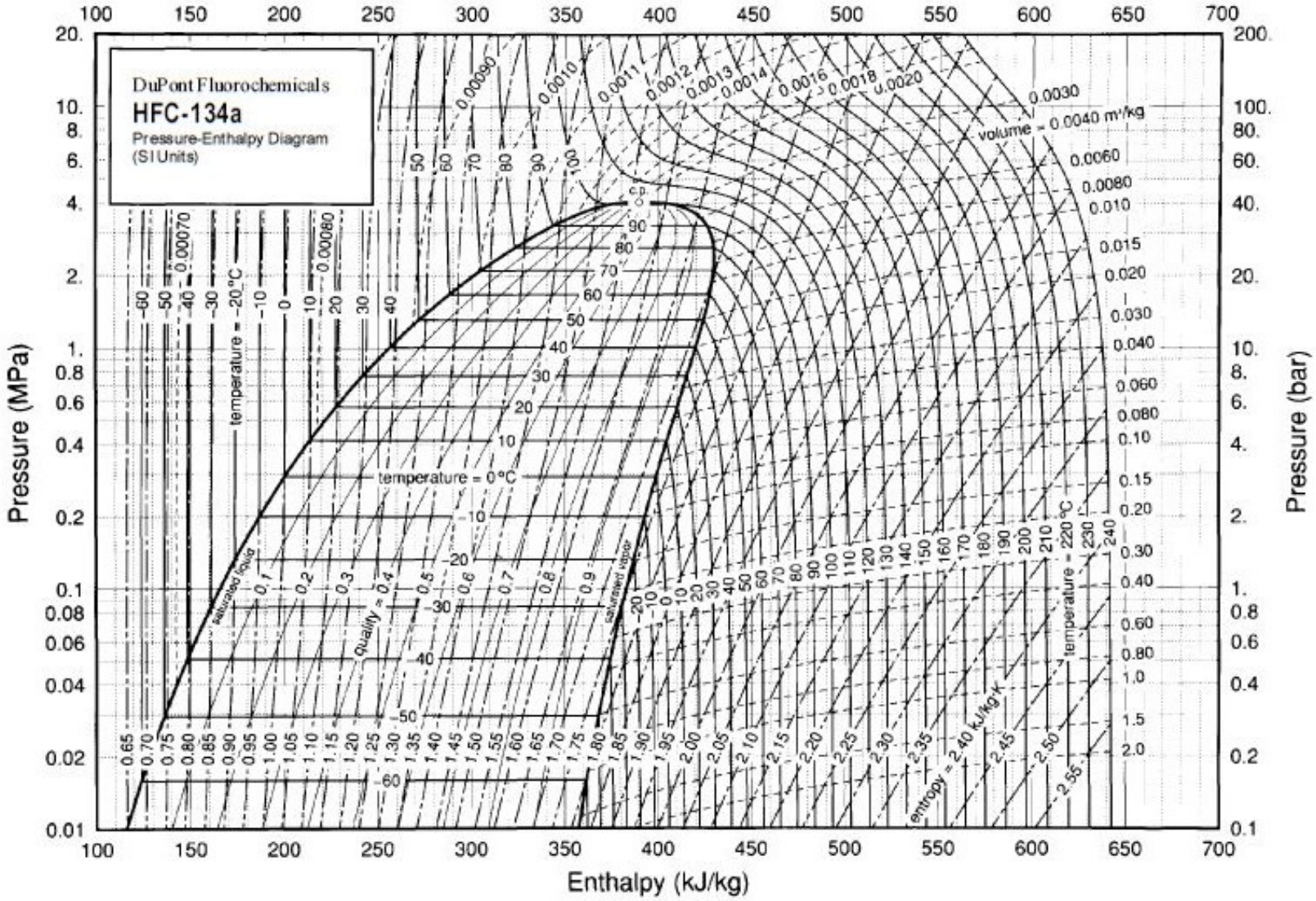
i) R134a evaporates at constant temperature of 10 ^{o}C in the evaporator to the saturation vapour state;

ii) It is adiabatically compressed by the compressor to a high temperature and high pressure vapour state;

iii) It is cooled and condensed in the condenser at constant pressure (the condensation temperature is 50 ^{o}C) to the saturation liquid state;

iv) it expands in the expansion valve through a constant enthalpy process to the evaporation temperature.

The mass flow rate of R134a is 10 g/s. Show the vapour compression cycle on the pressure P – enthalpy h diagram below



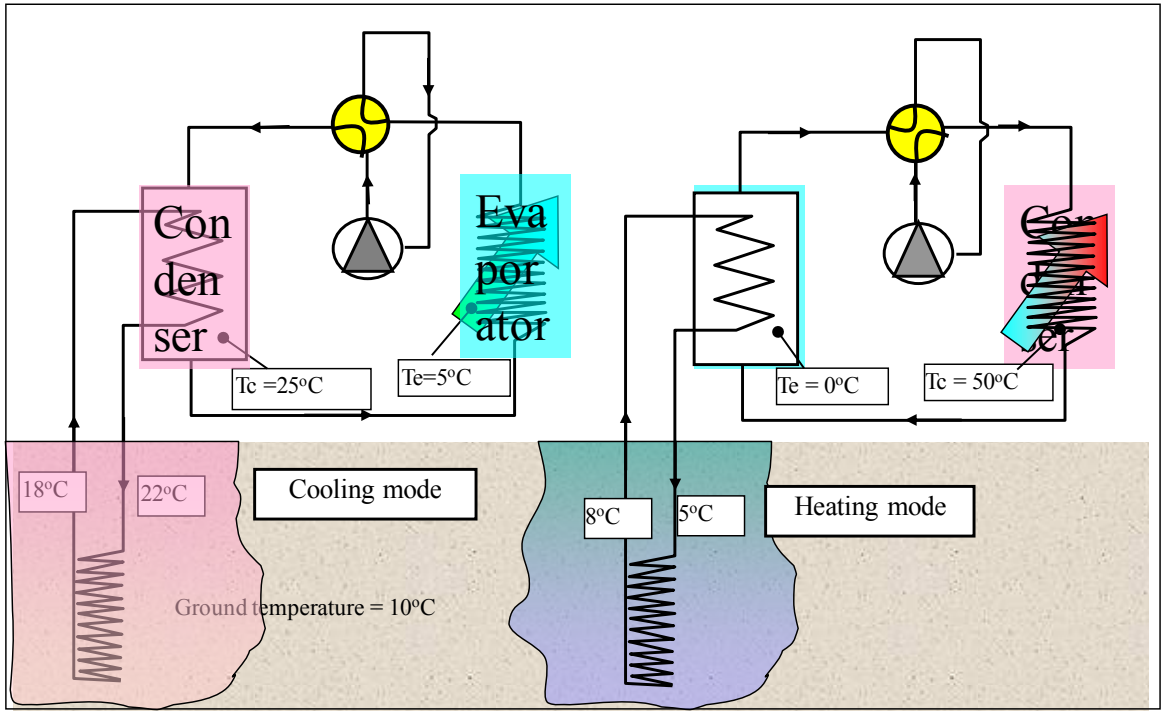
c) Calculate the heating rate by the condenser, the cooling rate by the evaporator and the work by the compressor.

d) Define the Coefficient of Performance (*COP*) for the cooling and heating modes.

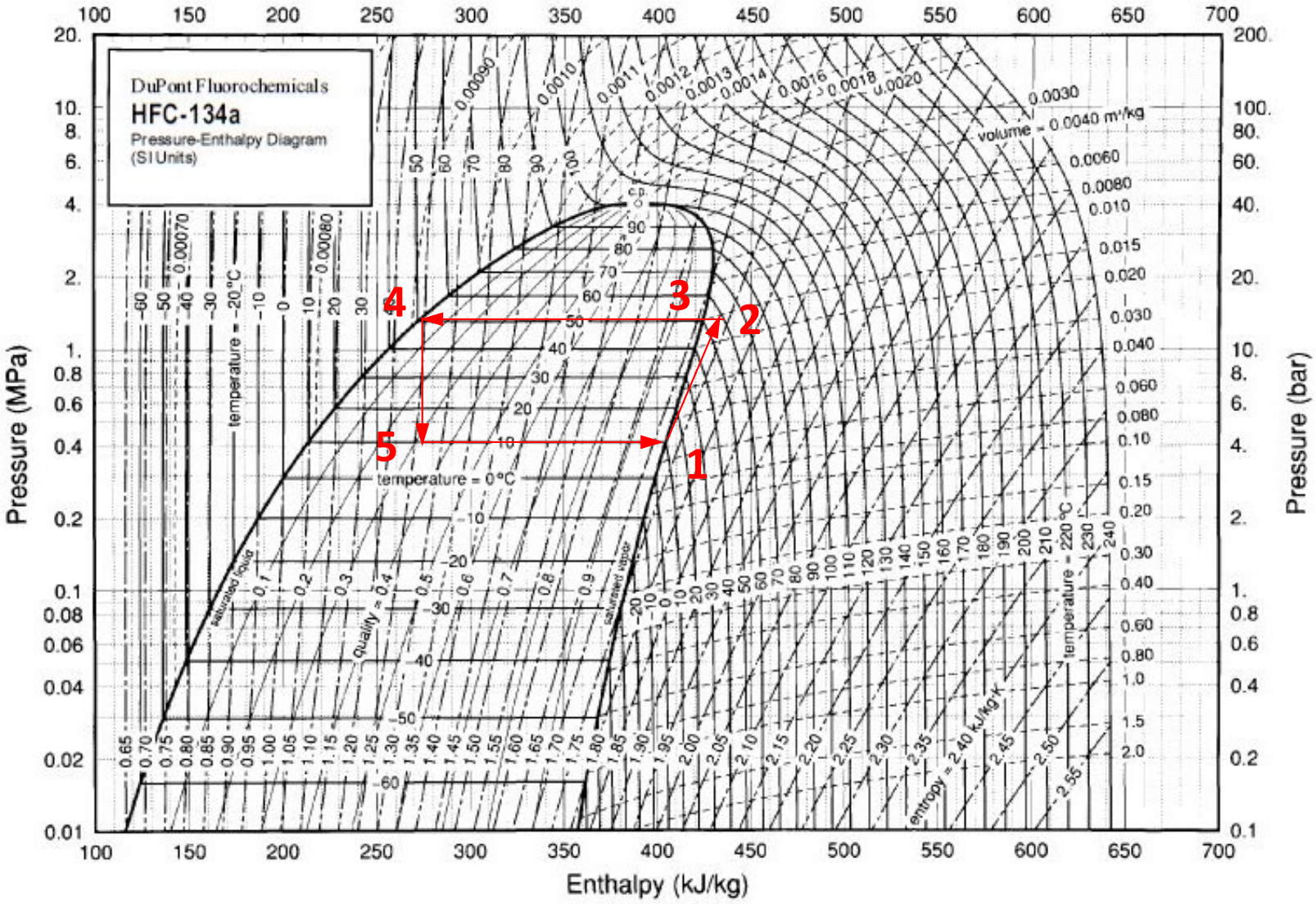
Solution

a) The figure below shows a schematic of a ground source heat pump. It is a vapour–compression refrigeration cycle using ground heat exchanger as the condenser or evaporator. Since the ground temperature reminds constant at about 12 °C through a year, the heat pump provides higher COP.

Ground source heat pumps GSHP



b) The ideal cycle is shown in *P*-*h* diagram below. State 1 is a saturated vapour state at temperature 10 °C. State 2 is a superteated vapour state with pressure $P_2 = P_3 = P_4$. State 3 is a saturated vapour state at temperature 50 °C. State 4 is the saturated liquid state at temperature 50 °C. State 5 is a two-phase state with temperature 10 °C and $h_5 = h_4$.



c) From the diagram,

$T_1 = T_5 = 10\ ^{o}C$, $h_1 = 404.3$ kJ/kg, $P_1 = 0.415$ MPa, $s_1 = 1.72$ kJ/kg K;

$s_1 = s_2 = 1.72$, $T_2 = 54.0\ ^{o}C$, $h_2 = 428.3$ kJ/kg

$P_3 = P_4 = 1.32$ MPa, $h_3 = 423.4$ kJ/kg, $h_4 = 271.6$ kJ/kg

$h_5 = h_4 = 271.6$ kJ/kg

The heating rate = $m\ (h_2 - h_4) = 0.01\ (428.3 - 271.6) = 1567$ W

The cooling rate = m $(h_1 - h_5) = 0.01\ (404.3 - 271.6) = 1327$ W

The work = m $(h_2 - h_1) = 0.01\ (428.3 - 404.3) = 240$ W

d) The Coefficient of Performance (*COP*) for the cooling and heating modes are:

COP for heating = the heating rate/the work = 1567/240 = 6.53

COP for cooling = the cooling rate/the work = 1327/240 = 5.53

Problem Solving Techniques - 1

- **General step-by-step approach**

1. **Problem statement:** list given info and objectives
2. **Schematic:** draw one to indicate relevant info on
3. **Assumptions and approximations:** simplify and justify
4. **Physical laws:** apply relevant laws and principles
5. **Properties:** refer to property relations, tables, property source
6. **Calculations;** verify units, significant figures ("do not copy")
7. **Conclusion:** reasoning, verification, and discussion; validity, significance, implications, recommendations, limitations
8. **Presentation:** neatness, organization, completeness

Problem Solving Techniques - 2

- **General step-by-step approach**

1. **Identify the problem**
2. **Make appropriate assumptions and approximations**
3. **Set up a physical model**
4. **Produce a mathematical model**
5. **Implement the model into a procedure**
6. **Verify the model and procedure using a simple case with results available**
7. **Calculate**
8. **Analyse results**
9. **Conclusion**

Problem Solving Techniques - 3

- **Conservation of mass, momentum, energy & electrical charge (the first law of thermodynamics)**

$$\left\{\begin{array}{l}\text{The net gain in} \\ X \text{ by the system}\end{array}\right\} = \left\{\begin{array}{l}\text{The net amount of } X \\ \text{transported into the system}\end{array}\right\}$$

Problem 1

Water and molten blast furnace slag enter a granulator in which the slag is cooled and vitrified to form a sand-like material. When the inlet flow rate and temperature of the slag are 1400 ^{o}C and 6 tonne/min respectively and the water inlet flow rate and temperature are 2400 m^3/h and 50 ^{o}C respectively, saturated steam at 100 ^{o}C is generated and leaves the granulator via a stack. Granulated slag and water leave as slurry from the base of the tank at a temperature of 100 ^{o}C. Determine the mass flow rate of the steam (kg/s) leaving the granulator. Take the specific enthalpy of the slag at 1400 ^{o}C and 100 ^{o}C to be 1670 J/g and 85 J/g respectively. Neglect any heat transfer from the granulator.

Solution - 1

1. Problem statement: list given info and objectives

At the inlet

T_{sl1} = 1400 °C, m_{sl1} = 6 tonne/min, h_{sl1} = 1670 J/g,

m_{w1} = 2400 m^3/h, T_{w1} = 50 °C,

At the outlet

T_{v2} = 100 °C, m_{v2} = ?

T_{w2} = T_{sl2} = 100 °C (slurry), m_{w2} = ?

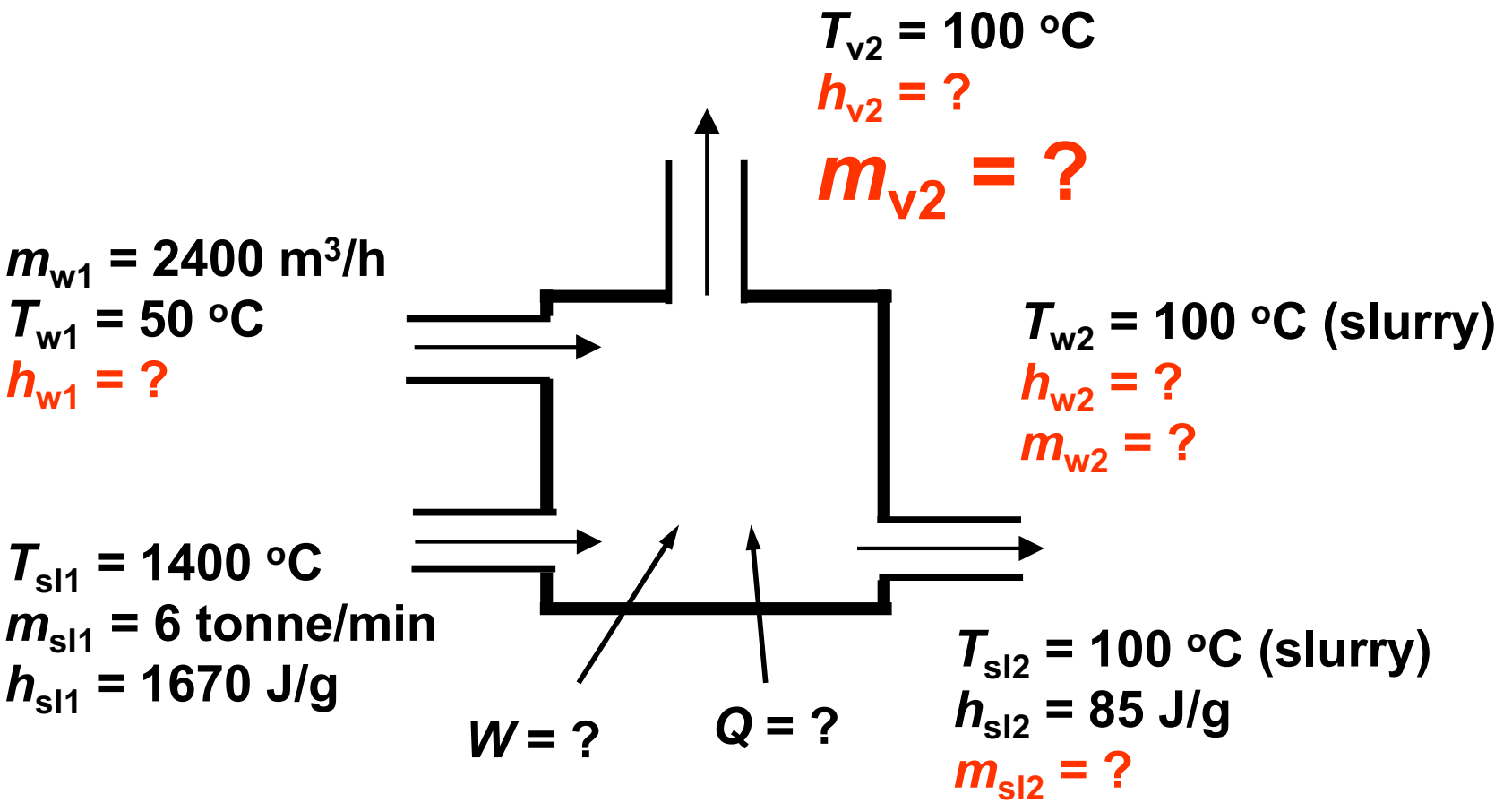
T_{sl2} = 100 °C (slurry), h_{sl2} = 85 J/g, m_{sl2} = ?

Determine

m_{v2} = ?

Solution - 2

2. Schematic: draw one to indicate relevant info on



Solution - 3

3. Assumptions and approximations: simplify and justify

a. Steady state flow?
b. Atmospheric pressure?
c. Neglect any heat transfer from the granulator?
d. Neglect potential energy change?
e. Neglect kinetic energy change?
f. Work done?
g. Slag: molten to sand-like material
h. Ideal gas?
i. Perfect gas?
j. Equilibrium state?
k. Assume equilibrium state at inlet and outlet.

Solution - 4

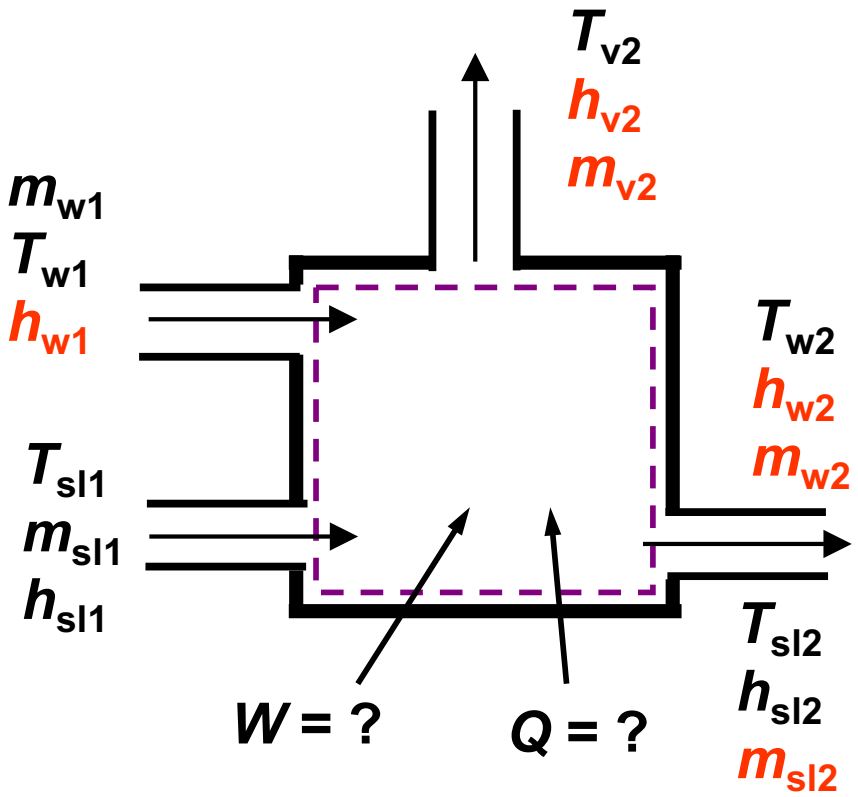
4. Physical laws: apply relevant laws and principles

Open system

Conservation of mass

$$m_{sl1} = m_{sl2}$$

$$m_{w1} = m_{w2} + m_{v2}$$



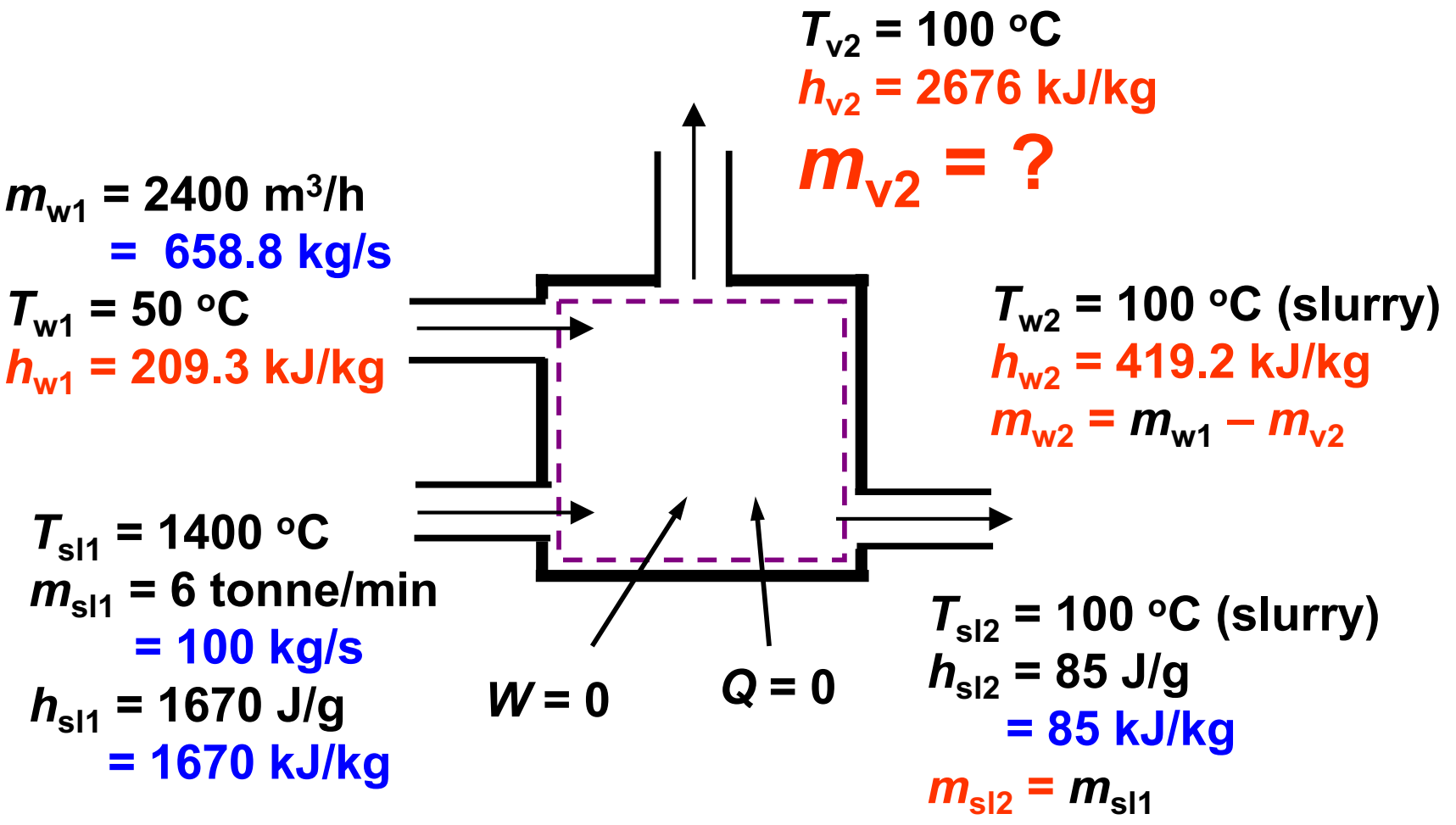
1st law of thermodynamics

$$W + Q = \Sigma[m(h + v^2/2 + gz)]_2 - \Sigma[m(h + v^2/2 + gz)]_1$$

$$m_{w1}h_{w1} + m_{sl1}h_{sl1} = m_{v2}h_{v2} + m_{w2}h_{w2} + m_{sl2}h_{sl2}$$

Solution - 5

5. Properties: refer to property relations, tables, property source



Solution - 6

6. Calculations: verify units, significant figures ("do not copy")

$$m_{sl1} = m_{sl2}$$

$$m_{w1} = m_{w2} + m_{v2}$$

$$m_{w1}h_{w1} + m_{sl1}h_{sl1} = m_{v2}h_{v2} + m_{w2}h_{w2} + m_{sl2}h_{sl2}$$

$$m_{w1}h_{w1} + m_{sl1}h_{sl1} = m_{v2}h_{v2} + (m_{w1} - m_{v2})h_{w2} + m_{sl1}h_{sl2}$$

$$m_{v2} = [m_{w1}(h_{w1} - h_{w2}) + m_{sl1}(h_{sl1} - h_{sl2})]/(h_{v2} - h_{w2})$$

$$m_{v2} = [658.8 \times (209.3 - 419.2) + 100 \times (1670 - 85)] /(2676 - 419.2)$$

$$= 8.96 \text{ kg/s}$$

Solution - 7

2. Schematic: draw one to indicate relevant info on