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# Unit Operations II Final Exam – Model Answer

## Exercise 1: (Graded out of 12 points)

Given data:

| Water side | Air side |
|---|---|
| $T_{w,in}$ = 40 °C; $\Delta T_{app}$ = 3 °C | Inlet : $T_{DB,1}$ = 35 °C; $T_{wB,1}$ = 28 °C |
| $\dot{m}_w$ = 5000 kg/min; $c_{p,w}$ = 4.187 kJ/(kg.K) | Outlet: $T_{DB,2}$ = 38 °C; $\phi_2$ = 60% |

Atmospheric pressure: **P = 101.325 kPa**

### PART A — PSYCHROMETRIC CHART READING

Using the psychrometric chart:

| Property | Symbol | State 1 — air inlet<br>35 °C DB · 28 °C WB | State 2 — air outlet<br>38 °C DB · 60% RH |
|---|---|---|---|
| Specific enthalpy, *h* | h (kJ/kg d.a.) | 90 | 104 |
| Humidity ratio, ω | ω (kg/kg d.a.) | 0,0212 | 0,0255 |
| Wet-bulb temperature | $T_{WB,2}$ (°C) | 28 °C | 30,7 |
| Dew-point temperature, $T_{DP}$ | $T_{DP}$ (°C) | 26 | 29 |

0.5 pts × 7

### PART B — WATER-SIDE ANALYSIS

**1) Cold water outlet temperature, $T_{w,out}$:**

$\Delta T_{app} = \mathbf{T_{w,out}} - T_{wB,1} \Rightarrow \mathbf{T_{w,out}} = \Delta T_{app} + T_{wB,1} = 3\text{ °C} + 28\text{ °C} \Rightarrow \mathbf{T_{w,out} = 31\text{ °C}}$

1 pts

**2) Total heat rejected by water stream, $Q_w$:**

$Q_w = \dot{m}_w .\, c_{p,w} .( T_{w,in} - T_{w,out}) \Rightarrow Q_w = 5000\text{ kg/min} \times 4.187\text{ kJ/(kg.K)} \times (40\text{ °C} - 31\text{ °C})$

$\Rightarrow$ $\mathbf{Q_w = 1.884\times10^5\ kJ/min = 3\,140\ kW}$

1 pts

### PART C — ENERGY BALANCE AND AIR FLOW

**1) Steady-state energy balance for the tower:** For the cooling tower:

$$\mathbf{Q_w = \dot{m}_{da}.(h_2 - h_1)}$$

1 pts

**2) Required dry-air flow rate, $\dot{m}_a$, through the cooling tower in: kg dry air.min$^{-1}$:**

$\dot{m}_{da} = Q_w/(h_2 - h_1) \Rightarrow \dot{m}_{da} = 1.884\times10^5\text{ kJ/min }/(104\text{ °C} - 90\text{ °C}) \Rightarrow \mathbf{\dot{m}_{da} = 1.35\times10^4\ kg\ dry\ air.min^{-1}}$

1 pts

**3) Amount of make-up water, $\dot{m}_{make\text{-}up}$, required to compensate for evaporative losses:**

Evaporated water: $\dot{m}_{make\text{-}up} = \dot{m}_{evap} = \dot{m}_{da}.(\omega_2 - \omega_1) \Rightarrow \dot{m}_{make\text{-}up} = 1.35\times10^4 \times (0{,}0255 - 0{,}0212)$

$\Rightarrow \mathbf{\dot{m}_{make\text{-}up} = 58.05\ kg.min^{-1}}$

1 pts

As a percentage of the inlet water flow:

% make−up = (58.05/5000)×100 $\Rightarrow$ **% make−up = 1.16%**

1 pts

**PART D — DISCUSSION**

**1) Simultaneous heat and mass transfer processes occurring as air rises through the tower:**

On the psychrometric chart, the air process follows: **State 1 → State 2**

Observed changes:

- **$T_{DB}$ increases**: 35 °C → 38 °C ⇒ Heating (Water transfers heat to air, increasing air temperature)
- **ω increases**: 0.0212 → 0.0255 ⇒ Humidification (Part of the water evaporates into the air)

Thus, simultaneous:

- **Cooling of water;**
- **Heating and humidification of air.**

1 pts

**2) Effect of increasing inlet RH to 80%:**

Since the entering air is already more humid ($RH_{in}$ = 80%**)**, it has **less capacity to absorb additional water vapor**. This reduces evaporation, which lowers cooling efficiency.

- Approach temperature increases:

0.5 pts

→ less evaporation means weaker cooling, so outlet water temperature, $T_{w,out}$, becomes higher.

- Make-up water requirement decreases:

0.5 pts

→ less water evaporates, so less replacement water is needed.

- Required air mass flow rate increases:

0.5 pts

→ each kg of humid air removes less heat, so more air is required to reject the same heat load.

## Exercise 2: (Graded out of 08 points)

**1) Saturation temperatures:** from steam tables:

- Live steam, at: **198.5 kPa** ⇒ **$T_s$ = 120 °C**
- First effect boiling temperature, at: **90 kPa** ⇒ **$T_1$ = 96 °C**
- First effect boiling temperature, at: **17.9 kPa** ⇒ **$T_1$ = 58 °C**

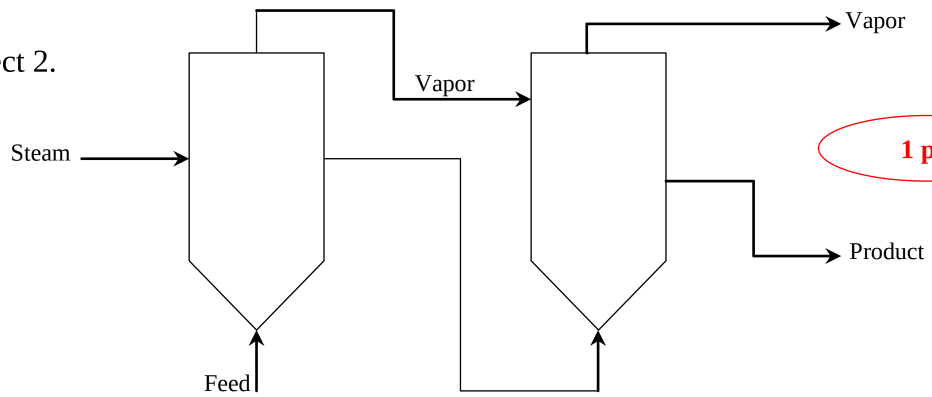
0.5 pts × 3

**2) Schematic forward-feed arrangement:**

Forward-feed arrangement: **Feed → Effect 1→Effect 2→Product**

Steam: **Steam → Effect 1**

Vapor from effect 1 heats effect 2.




1 pts

**3) Total solids flow rate in the system, $\dot{m}_s$ :**

$\dot{m}_s = x_F.F \Rightarrow \dot{m}_s = 0.11 \times 5.5 \Rightarrow$ **$\dot{m}_s = 0.605$ kg/s** 0.5 pts

**4) Final mass flow rate of concentrated product, P:** $P = F - V_1 - V_2$

- **Determine vapor produced in effect 1, $V_1$ (already question 7) :**

Feed sensible heating: $Q_{sens} = F.c_{p,f}(T_1 - T_f) \Rightarrow Q_{sens} = 5.5 \times 3.9 \times (96 - 58) \Rightarrow$ **$Q_{sens} = 815$ *k*W**

Latent heat available: $Q_{evap,1} = 4800 - 815 \Rightarrow$ **$Q_{evap,1} = 3\,985$ kW**

$\Rightarrow V_1 = Q_{evap,1} / \lambda_1 \Rightarrow V_1 = 3\,985$ *k*W / 2270 *k*J/kg $\Rightarrow$ **$V_1 = 1.76$ kg/s** 0.5 pts

*Latent heat at 96°C: $\lambda_1 = 2270$ kJ/kg, from tables.*

- **Determine vapor produced in effect 2, $V_2$ (already question 10) :**

*Latent heat at 58°C: $\lambda_2 = 2350$ kJ/kg, from tables.*

$V_2 = Q_2/ \lambda_2 \Rightarrow V_2 = 3\,800/ 2350 \Rightarrow$ **$V_2 = 1.62$ kg/s** 0.5 pts

- **Final product flow rate, P:** $P = F - V_1 - V_2 \Rightarrow P = 5.5 - 1.76 - 1.62 \Rightarrow$ **$P = 2.12$ kg/s** 0.5 pts

**5) Heat duty in the first effect:**

$Q_1 = U_1A_1\Delta T_1 \Rightarrow Q_1 = 2\,000 \times 100 \times (120 - 96) \Rightarrow$ **$Q_1 = 4\,800$ *k*W** 0.5 pts

Where: $\Delta T_1 = T_s - T_1 \Rightarrow \Delta T_1 = 120 - 96 \Rightarrow$ **$\Delta T_1 = 24$ °C**

**6) Amount of steam required, $\dot{m}_{steam}$:**

Latent heat of steam at 198.5 kPa: $\lambda_s = 2\,200$ kJ/kg

$\dot{m}_{steam} = Q_1 / \lambda_s \Rightarrow \dot{m}_{steam} = 4\,800$ *k*W / 2 200 kJ/kg $\Rightarrow$ **$\dot{m}_{steam} = 2.18$ kg/s** 0.5 pts

**8) Solids fraction of the liquid leaving the first effect:**

Liquid leaving effect 1: $L_1 = F - V_1 \Rightarrow L_1 = 5.5 - 1.76 \Rightarrow$ **$L_1 = 3.74$ kg/s**

Solids fraction: $x_1 = \dot{m}_s / L_1 \Rightarrow x_1 = 0.605$ kg/s / 3.74 kg/s $\Rightarrow$ **$x_1 = 0.162 = 16.2\%$** 0.5 pts

**9) Heat duty in the second effect:**

$Q_2 = U_2A_2\Delta T_2 \Rightarrow Q_2 = 1\,000 \times 100 \times (96 - 58) \Rightarrow$ **$Q_2 = 3\,800$ *k*W** 0.5 pts

Where: $\Delta T_2 = T_1 - T_2 \Rightarrow \Delta T_1 = 96 - 58 \Rightarrow$ **$\Delta T_2 = 38$ °C**

**11) Final mass flow rate of product:**

$P = L_1 - V_2 \Rightarrow P = 3.74$ kg/s – 1.62 kg/s $\Rightarrow$ **$P = 2.12$ kg/s** 0.5 pts

**12) Final solids fraction:**

$x_p = \dot{m}_s / P \Rightarrow x_p = 0.605$ kg/s / 2.12 kg/s $\Rightarrow$ **$x_p = 0.285 = 28.5\%$** 0.5 pts

**13) Steam economy:** $S_{Economy} = (V_1 + V_2)/ \dot{m}_{steam} \Rightarrow S_{Economy} = (1.74 + 1.62)/2.18 \Rightarrow$ **$S_{Economy} = 1.54$** 0.5 pts