Unit Operations II Final Exam

Closed Notes, Show All Work

<u>Exercise 1</u>: (Graded out of 12 points)

In an industrial refrigeration plant, as shown in **Figure 1**, a forced-draft cooling tower (**Figure 2**) is used to cool condenser water. Atmospheric air enters the base of the tower and is forced upward through the falling water spray by a centrifugal fan. The cooled water collects in a basin at the bottom.

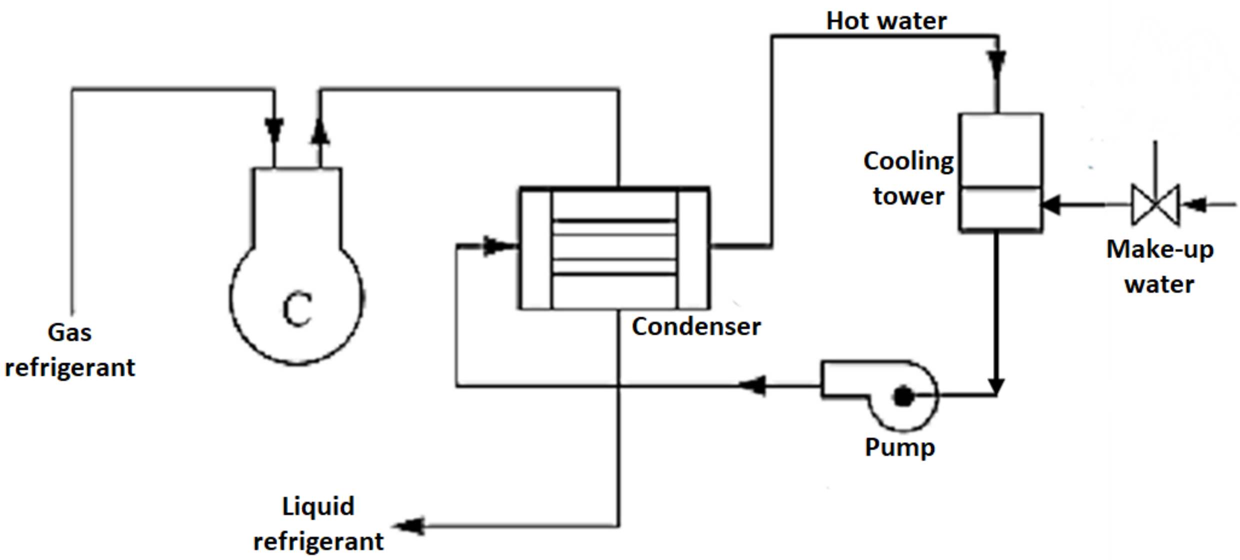

Figure 1 – an industrial refrigeration plant.

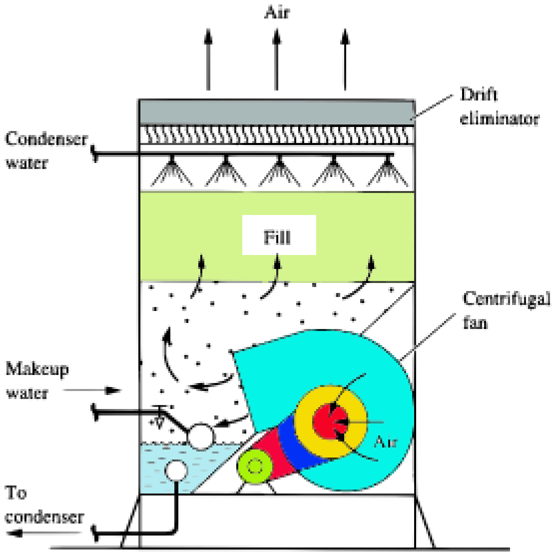

Figure 2 – a forced–draft cooling tower.

The following operating conditions have been recorded during a performance test.

Given data:

Water circuit		**Air circuit**	
Hot water inlet temperature	$T_{w,in}$ **= 40 °C**	Inlet dry-bulb temperature	$T_{DB,1}$ **= 35 °C**
Approach temperature	ΔT_{app} **= 3 °C**	Inlet wet-bulb temperature	$T_{WB,1}$ **= 28 °C**
Mass flow rate of water	$\dot{m}_w$ **= 5 000 kg/min**	Outlet dry-bulb temperature	$T_{DB,2}$ **= 38 °C**
Specific heat of water	$c_{p,w}$ **= 4.187 kJ/(kg·K)**	Outlet relative humidity	φ_2 **= 60%**

QUESTIONS —

PART A — PSYCHROMETRIC CHART READING (COMPLETE BEFORE ANY CALCULATION)

Using a standard psychrometric chart at **P = 101.325 kPa**, locate both air states and read off the following properties. Record your readings in the table — these values will feed directly into Parts B and C.

Property	**Symbol**	**State 1 — air inlet** **35 °C DB · 28 °C WB**	**State 2 — air outlet** **38 °C DB · 60% RH**
Specific enthalpy	h (kJ/kg d.a.)	…..	…..
Humidity ratio	ω (kg/kg d.a.)	…..	…..
Wet-bulb temperature (outlet only)	$T_{WB,2}$ (°C)	/	…..
Dew-point temperature	T_{DP} (°C)	…..	…..

PART B — WATER-SIDE ANALYSIS

1) Determine the cold water outlet temperature, $\mathbf{T_{w,out}}$.

2) Calculate the total heat rejected by water stream, $\mathbf{Q_w}$.

PART C — ENERGY BALANCE AND AIR FLOW

1) Give the steady-state energy balance for the tower.

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

3) Determine the amount of make-up water, $\dot{m}_{make\text{-}up}$, required to compensate for evaporative losses,
Express your answer as a percentage of the inlet water flow.

PART D — DISCUSSION

1) On your psychrometric chart, sketch and label the process path of the air (State 1 → State 2). Describe the simultaneous heat and mass transfer processes occurring as air rises through the tower.

2) If the inlet air relative humidity increased from its current value to **80%** (at the same dry-bulb temperature of **35°C**), predict — without recalculating — the direction of change for:

- **a)** the approach temperature achievable;
- **b)** the make-up water requirement;
- **c)** the required air mass flow rate.

Justify each answer qualitatively.

Exercise 2: (Graded out of 08 points)

Tomato juice at a feed flow rate of **5.5 kg/s** and inlet temperature of **60°C** is concentrated in a double-effect forward-feed evaporator. Live steam is supplied to the first effect at a pressure of **198.5 kPa** (abs).

The operating conditions and design parameters of each effect are given in the table below:

	First effect	**Second effect**
Heat transfer area, **m²**	100	100
Overall heat transfer coefficient, **W/m².°C**	2 000	1 000
Saturation pressure, **kPa**	90	17.9
Heat capacity at the exit, **J/kg.°C**	3 800	3 450

Additional data:

- Feed solids content = **11%** (mass basis),
- Feed heat capacity = **3900 J/kg·**°C,
- Assume no boiling point elevation,
- Condensate leaves each effect at the saturation temperature,
- Steady-state operation.

Required:

1) Determine the saturation temperature of live steam, and the boiling liquid in each effect,

2) Draw a clear schematic diagram of the multiple-effect evaporator used,

3) Determine the total solids flow rate in the system,

4) Determine the final mass flow rate of concentrated product,

5) Calculate the heat duty in the first effect,

6) Determine the amount of steam required,

7) Determine amount of vapour produced in the first effect,

8) Determine solids fraction of the liquid leaving the first effect,

9) Calculate the heat duty in the second effect,

10) Determine vapour produced in the second effect,

11) Determine final mass flow rate of product,

12) Determine final solids fraction,

13) Calculate steam economy.