National Exams May 2013

04-Chem-A3 Mass Transfer Operations

Three Hour Duration

NOTES:

1) If doubt exists as to the interpretation of any question, you are urged to submit a clear statement of any assumptions made along with the answer paper.

2) Property data required to solve a given problem are provided in the problem statement or are available in the recommended texts. If you are unable to locate the required data, do not let this prevent you from solving the rest of the problem. Even in the absence of property data, you still have the opportunity to provide a solution methodology.

3) This is an open-book exam.

4) Any non-communicating calculator is permitted.

5) The examination is in three parts – Part A (Questions 1 and 2), Part B (Questions 3 and 4), and Part C (Questions 5, 6, and 7). Answer **ONE** question from Part A, **ONE** question from Part B, and **TWO** questions from Part C. **FOUR** questions constitute a complete paper.

6) Either question in Part A will count for 20%. Either question in Part B will count for 20%. Each question in Part C will count for 30%.

PART A: ANSWER ONE OF QUESTIONS 1-2

Note: Four questions constitute a complete paper
(with one from Part A, one from Part B, and two from Part C)

1) Ammonia gas is diffusing through nitrogen gas, which doesn't diffuse because it is insoluble at one boundary. The total pressure is 1.013×10^5 Pa and the temperature is 298 K. The partial pressure of ammonia at one point is 1.333×10^4 Pa, and at another point 20 mm away it is 6.666×10^3 Pa. The diffusivity for the mixture at this temperature and pressure is 2.30×10^{-5} m^2/s. Calculate the flux of ammonia in mole/$m^2 \cdot s$.

2) SO_2 (A) is diffusing at steady-state through non-diffusing O_2 (B) in a metal conduit that is 2.0 m long, at a constant pressure of 10 bar and a constant temperature of 598 K. The cross-section of the conduit is rectangular and tapers uniformly from an area of 300 mm by 400 mm to an area of 300 mm by 200 mm. The partial pressure of SO_2 is 0.22 bar at the larger and 0.055 bar at the smaller end. $D_{AB} = 7.61 \times 10^{-6}$ m^2/s. Calculate the molar flux of SO_2 at the midpoint of the conduit.

PART B: ANSWER ONE OF QUESTIONS 3-4

Note: Four questions constitute a complete paper
(with one from Part A, one from Part B, and two from Part C)

3) Air at 32°C and 1.0 atm is humidified by flowing over a 1.2 m-long container filled with water. The interfacial temperature is 20°C. If the initial relative humidity of the air is 25% and its velocity is 0.15 m/s, calculate

a) the convective mass transfer coefficient, and
b) the amount of water evaporated per unit width of the container.

For air: $\upsilon = 1.51 \times 10^{-5}$ m^2/s, $D_{AB} = 2.77 \times 10^{-5}$ m^2/s.

Water vapour pressure: $p_A^{sat}(20°C) = 0.02308$ atm, $p_A^{sat}(32°C) = 0.04696$ atm.

4) The winter-kill of fish in mountain lakes has been attributed in part to the depletion of oxygen in the water because the frozen surface separates the air from the surface of the lake. However, in the spring the water is again oxygenated due to its contact with the air.

The elevation of one mountain lake is 2133 m, and the atmospheric pressure is 0.769 atm. This lake is very deep, and just as the layer of ice on the lake thaws in early spring, the oxygen concentration in the water is measured at 3.0 x 10^{-5} kmol/m^3.

Find the concentration of oxygen, due to diffusion from the atmosphere, at a depth of 0.06 m after

a) one day,
b) three days, and
c) thirty days.

The temperature of the lake is uniform at 5°C. Assume that the concentration of oxygen in the water at the surface is in equilibrium with the air. Use Henry's law to find the interfacial composition:

$$p_A = k_H x_A \qquad \text{where } k_H = 2.91 \times 10^4 \text{ atm/(kmol } O_2\text{/kmol solution)}$$

Data: D_{AB} (5°C) = 1.58 × 10^{-9} m^2/s $\qquad$ C_{A0} = 3.0 x 10^{-5} kmol/m^3

PART C: ANSWER TWO OF QUESTIONS 5-7

Note: Four questions constitute a complete paper
(with one from Part A, one from Part B, and two from Part C)

5) A gas stream contains 4.0 mol% NH_3, and its ammonia content must be reduced to 0.5 mol% in a packed absorption tower that operates at 293 K and 1.013×10^5 Pa. The inlet pure water flow is 68.0 kmol/h and the total inlet gas flow is 57.8 kmol/h. The tower diameter is 747 cm. The film mass-transfer coefficients are

$$k'_y a = 0.0739 \text{ kmol/m}^3\cdot\text{s}\cdot\text{mol frac} \qquad k'_x a = 0.169 \text{ kmol/m}^3\cdot\text{s}\cdot\text{mol frac}$$

The vapour-liquid equilibrium data are listed in the chart below. Using the design methods for dilute gas mixtures, calculate the tower height.

Mole Fraction NH_3 in Liquid, x_A	Partial Pressure of NH_3 in Vapour, p_A (mm-Hg)		Mole Fraction NH_3 in Vapour, y_A (P = 1 atm)	
	20 °C	30 °C	20 °C	30 °C
0.0000	0.0	0.0	0.0000	0.0000
0.0208	12.0	19.3	0.0158	0.0254
0.0258	15.0	24.4	0.0197	0.0321
0.0309	18.2	29.6	0.0239	0.0390
0.0405	24.9	40.1	0.0328	0.0527
0.0503	31.7	51.0	0.0416	0.0671
0.0737	50.0	79.7	0.0657	0.1050
0.0960	69.9	110.	0.0915	0.1450
0.1370	114.0	179.	0.1500	0.2350

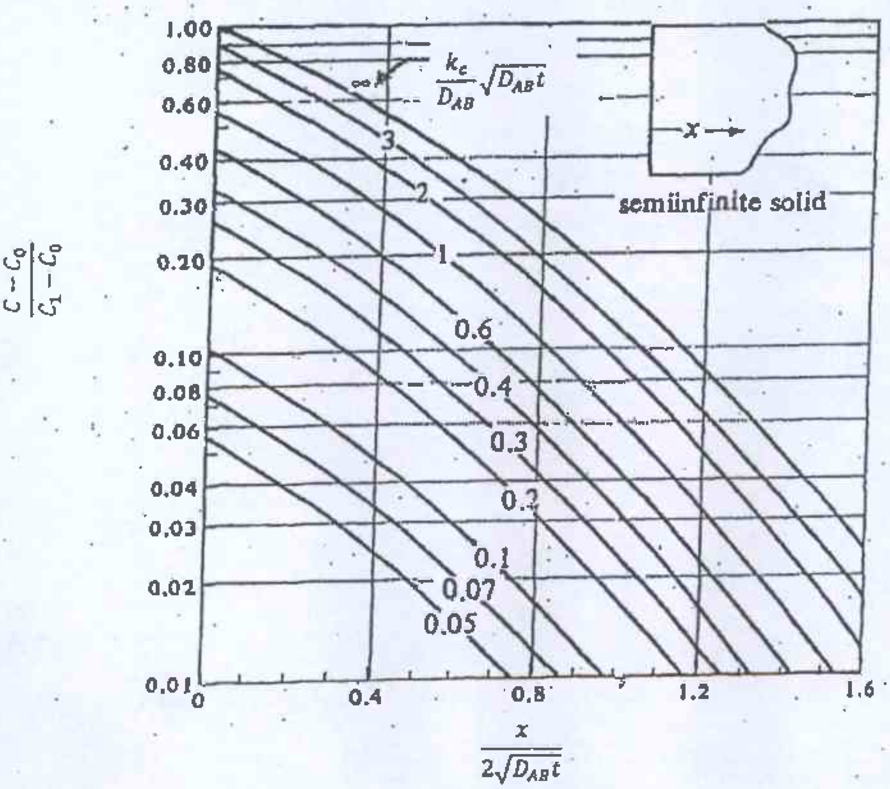
6) a) Estimate the height and base diameter of a natural-draft hyperbolic cooling tower that will handle a flow of 5000 kg/s of water entering at 310 K and leaving at 296 K. The ambient dry-bulb air temperature is 288 K and the ambient wet-bulb temperature is 283 K. Let the performance coefficient $C_t = 5.2$. State any assumptions you make.

b) A thermal power plant uses a cooling tower to provide water at 30°C to the condensers. Warm water at 40°C leaves the condensers at a rate of 1000 kg/s and is sent to the cooling tower. On a particularly hot summer day, the atmospheric air is at 40°C and 1.0 bar with 30% relative humidity. The air leaves the cooling tower at 35°C with 70% relative humidity. Calculate

i) the air flow rate required, and
ii) the make-up water flow rate.

Show your work on your chart. **Do not forget to hand in your chart with the exam booklet, and write your name on the chart.**

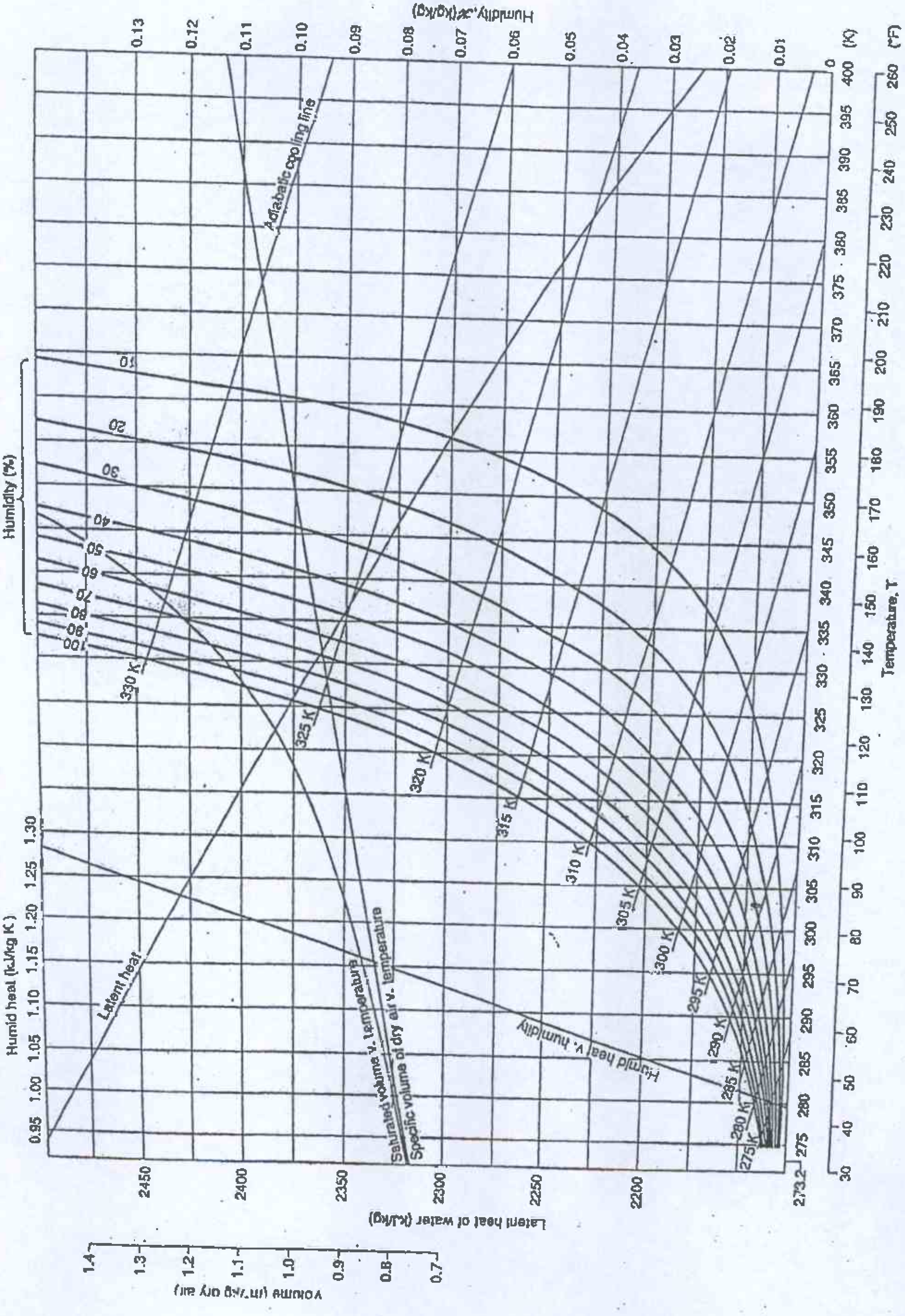
7) Case hardening is a simple method of hardening mild steel by introducing carbon into it through its surface. A large-diameter mild steel rod with an initial carbon content of 0.2 wt% is to be case hardened. It is packed in carbonaceous material and maintained at a high temperature. Thermodynamic data indicate that the equilibrium concentration of carbon in iron at the phase interface is 1.5 wt%. Treating the rod as a semi-finite solid, calculate the time required for the rod to have a carbon concentration of 0.8 wt% at a depth of 1.0 mm below the surface. The diffusivity of carbon in steel at the process temperature is 5.6×10^{-10} m^2/s. You should make use of the attached chart, which is a dimensionless representation of unsteady-state molecular diffusion in a semi-infinite solid.



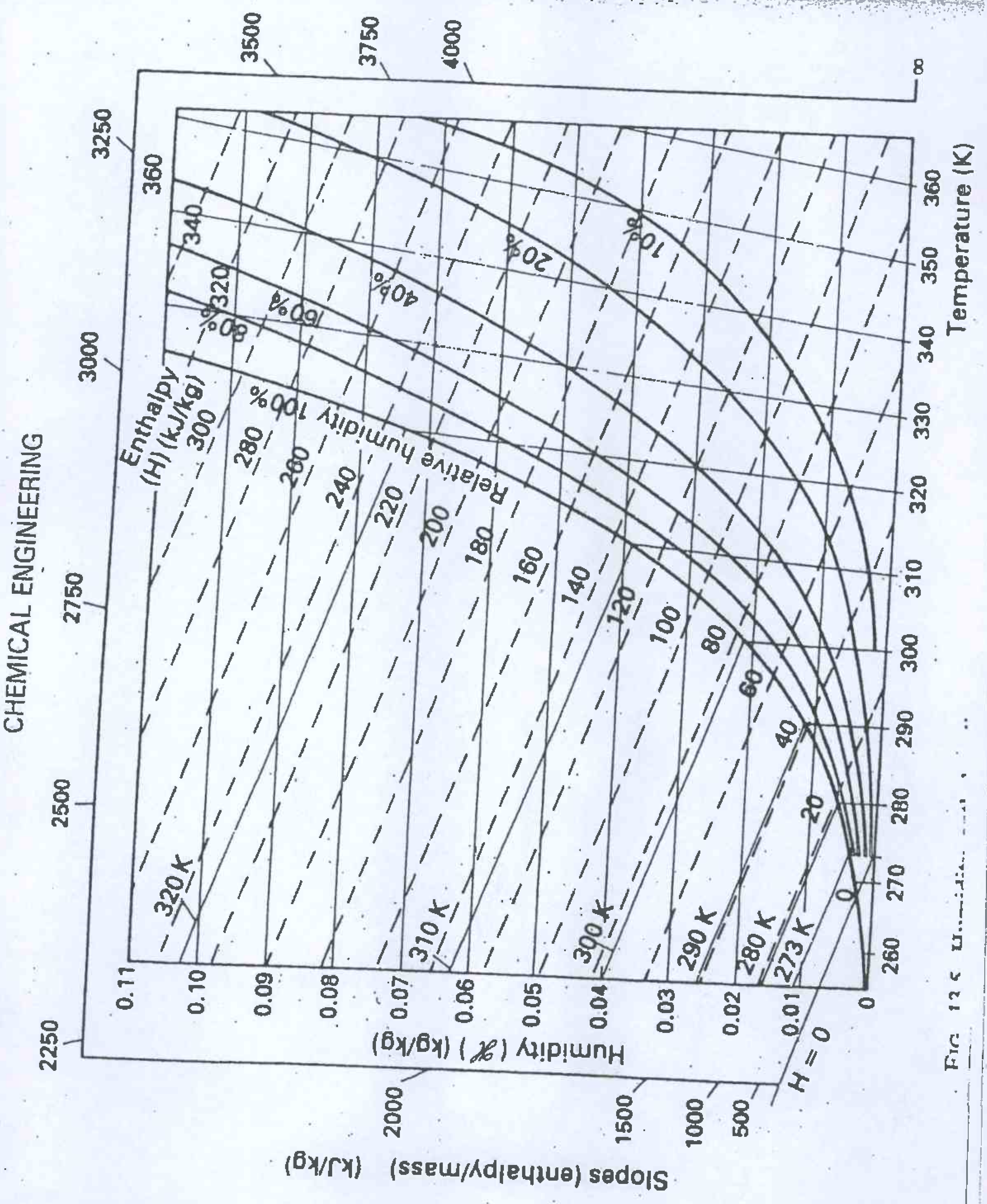
C = concentration of carbon at a depth of $x > 0$ at a time $t > 0$

C_0 = concentration of carbon at a depth of $x > 0$ at a time $t = 0$

C_i = concentration of carbon at a depth of $x = 0$ at a time $t > 0$



Humidity, ℋ (kg/kg)
Humidity (%)
Adiabatic cooling line
Latent heat
Humid heat (kJ/kg K)
Saturated volume v. temperature
Specific volume of dry air v. temperature
Humid heat v. humidity
Temperature, T
(K)
(°F)
Latent heat of water (kJ/kg)
Volume (m³/kg dry air)



CHEMICAL ENGINEERING
588
Enthalpy (H) (kJ/kg)
Relative humidity 100%
80%
60%
40%
20%
10%
Temperature (K)
Humidity ($\mathscr{H}$) (kg/kg)
Slopes (enthalpy/mass) (kJ/kg)
H = 0
320 K
310 K
300 K
290 K
280 K
273 K