National Exams May 2014

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) Each question is of equal value.

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) In a packed column operating at atmospheric pressure and 295 K, a 10% ammonia-air mixture is scrubbed with water so that the concentration of ammonia in the air is reduced to 0.1%. The entire resistance to mass transfer may be regarded as being in a thin laminar film on the gas side of the gas/liquid interface. At some intermediate point in the column, where the ammonia concentration in the bulk gas has been reduced to 5%, the partial pressure of ammonia in equilibrium with the liquid solution is 66 kPa and the molar flux of ammonia through the film (N_A) is 1.0 x 10^{-3} kmol/m^2·s. Compute the thickness of the gas film in mm. The diffusivity of ammonia in air at this temperature is 0.24 cm^2/s.

2) A spherical particle of solid iodine with a diameter of 1.5 mm. is falling in air at 75°C and 1.0 atm. The mass transfer coefficient describing the sublimation of I_2 into air under these conditions can be calculated using the following equation:

$$Sh = \frac{k_c' d_p}{D_{AB}} = 0.768[Re(Sc)^{0.5}]^{0.62}$$

The D_{AB} for I_2 in air is 0.108 cm^2/s. The vapour pressure for I_2 at 75°C is 11.2 mm of Hg. The molecular weight of I_2 is 253.8. Use 28.8 as the molecular weight of air. The viscosity of air is 2.07 x 10^{-5} Pa·s. Use 1.47 m/s as the terminal velocity of the particle.

Calculate the rate at which the particle loses mass at this diameter [mg/s]. (Note the units.)

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)

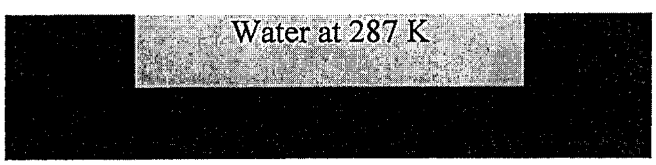
3) A pipe that transports the effluent from a reactor has begun to build up a deposit of a by-product on its inside surface, reducing its effective diameter. During a maintenance shutdown, a one-metre-long section of the pipe is cut out so that different methods of removing the coating can be tested. One simple method involves simply measuring the amount of time it takes to dissolve the material by flushing the pipe with water. Estimate how long it would take (report the time using units that make sense, i.e. not something like 4.235 x 10^6 seconds) to remove the deposit, given the following data:

Internal diameter of the pipe = D = 20 mm
Thickness of the deposit = δ = 3 mm
Velocity of the water through the pipe = u_∞ = 1.75 m/s
Molecular weight of the solid = M_A = 230
Solubility of the solid in water = 1.2 g/L
Density of the solid = ρ_A = 1400 kg/m^3
Diffusivity = $D_{A\text{-}H2O}$ = 1.35 x 10^{-5} cm^2/s
Density of water = ρ_{H2O} = 1000 kg/m^3
Viscosity of water = μ_{H2O} = 1.0 x 10^{-3} Pa·s

4) Dry air at a temperature of 300 K and 1.0 atm. is moving at a velocity of 0.5 m/s over the length of a pool of liquid water that is maintained at 287 K. The pool is 10 m. long and 4 m. wide. At 287 K, the vapour pressure of water is 1620 Pa. What is the rate of evaporation of the water?

Data: ρ_{air} = 1.1769 kg/m^3 μ_{air} = 1.8464 x 10^{-5} Pa·s $D_{H2O\text{-}air}$ = 2.45 x 10^{-5} m^2/s

Air at 300 K and 1.0 atm →
u = 0.5 m/s



← 10 m. →

The width of the pool is 4 m. into the paper.

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) An absorption column is set up for the purpose of removing cyanogen (CN) from an air stream by contacting it with water. Calculate the height of the column packing required to carry this out. The following data are available:

$k'_y a$	312 kmol/m^3·h
$k'_x a$	1800 kmol/m^3·h
Pressure	1.0 atm
Equilibrium relationship	$y_A^* = 5.3(x_A^*)^{1.07}$
CN in inlet air	1.25 mol%
CN in outlet air	75 ppm (75 x 10^{-6} mole fraction)
CN in inlet water	0.0
Inlet water flow rate	350 kmol/m^2·h
Inlet gas flow rate	85 kmol/m^2·h

6) a) Air at 298 K and 70% relative humidity is cooled to 288 K and then reheated to 293 K. Find the following (show your work on a psychrometric chart):

i) the amount of water removed per kg of dry air
ii) the wet-bulb temperature of the air initially
iii) the wet-bulb temperature of the air at the end of the process
iv) the relative humidity at the end of the process
v) the partial pressure of the water vapour in the air at the end of the process

b) Determine the height of the packing required for a natural-draft cooling tower that will be used to cool water from 35°C to 20°C. The water flux through the tower will be $L' = 2000$ kg/m^2·h (0.556 kg/m^2·s). The dry air flux through the tower will be $G' = 3000$ kg/m^2·h (0.833 kg/m^2·s). The air is available at a dry-bulb temperature of 20°C and a wet-bulb temperature of 15°C. Use the enthalpy-temperature graph and the psychrometric charts provided. Additional data are included below (L' and G' should be in kg/m^2·s):

ΔH_{vap} at 273 K = 2495 kJ/kg	$h_G a = 3.0(L')^{0.26}(G')^{0.72}$	$h_G a$ [W/m^3·K]
$(C_p)_{dry\ air}$ = 1.003 kJ/kg·K	$h_L a = 10{,}400(L')^{0.51}(G')^{1.00}$	$h_L a$ [W/m^3·K]
$(C_p)_{water\ vapour}$ = 2.006 kJ/kg·K	$k_c a = 2.95(L')^{0.26}(G')^{0.72}$	$k_c a$ [s^{-1}]
$(C_p)_{liquid\ water}$ = 4.18 kJ/kg·K		

7) Trichloroethylene (TCE), a common industrial solvent, is often found at low concentrations in industrial wastewater. Stripping is a common process for removing sparingly soluble, volatile organic solutes such as TCE from aqueous solution. Consider a cylindrical wetted-wall column that is used to study the stripping of TCE from water to air at a constant temperature of 293 K and a total system pressure of 1.0 atm. The inner diameter of the column is 4.0 cm and its height is 2 m. The volumetric flow rate of air through the column is 2000 cm^3/s, and the volumetric flow rate of water is 50 cm^3/s. Assume that the amount of water lost through evaporation is negligible.

Physical property data are given below. The system is very dilute, so that the bulk gas has the properties of air, and the bulk liquid has the properties of water.

$\rho_L = 998.2$ kg/m^3	$\rho_G = 1.19$ kg/m^3
$\mu_L = 9.93 \times 10^{-4}$ Pa·s	$\mu_G = 1.84 \times 10^{-5}$ Pa·s
$D_{TCE\text{-}H2O} = 8.90 \times 10^{-10}$ m^2/s.	$D_{TCE\text{-}Air} = 8.08 \times 10^{-6}$ m^2/s.

a) Determine the mass transfer coefficient across the liquid film, k_L.
Note: When calculating k_L, use the following Reynolds number:

$$Re_L = \frac{4w}{\pi D \mu_L}$$

where w is the mass flow rate of water, D is the inner diameter of the column, and μ_L is the viscosity of the water,.
b) Estimate the mass transfer coefficient across the gas film, k_G.
c) Define K_L as the overall liquid phase mass transfer coefficient, as given by the following equation

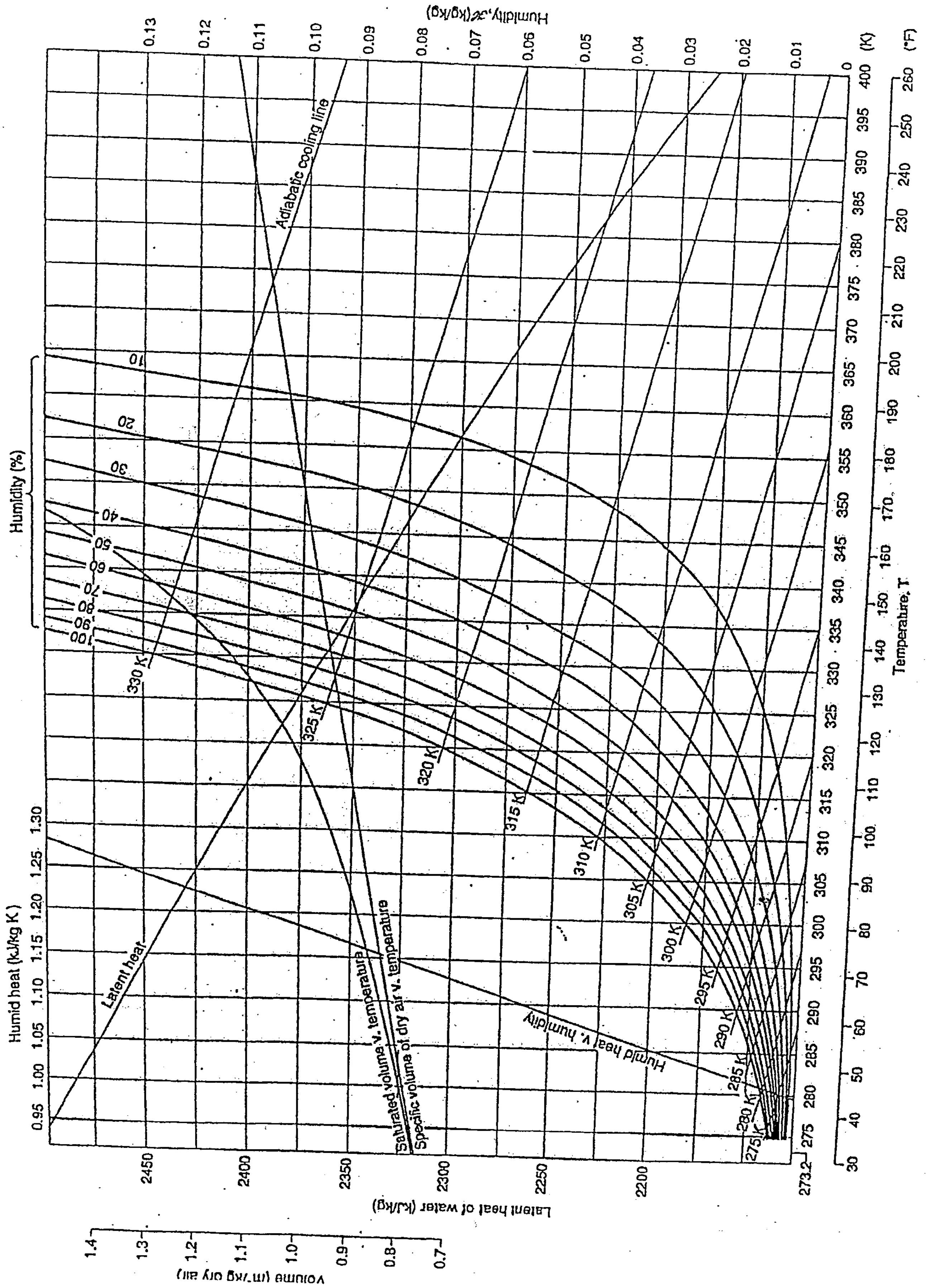
$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{Hk_G}$$

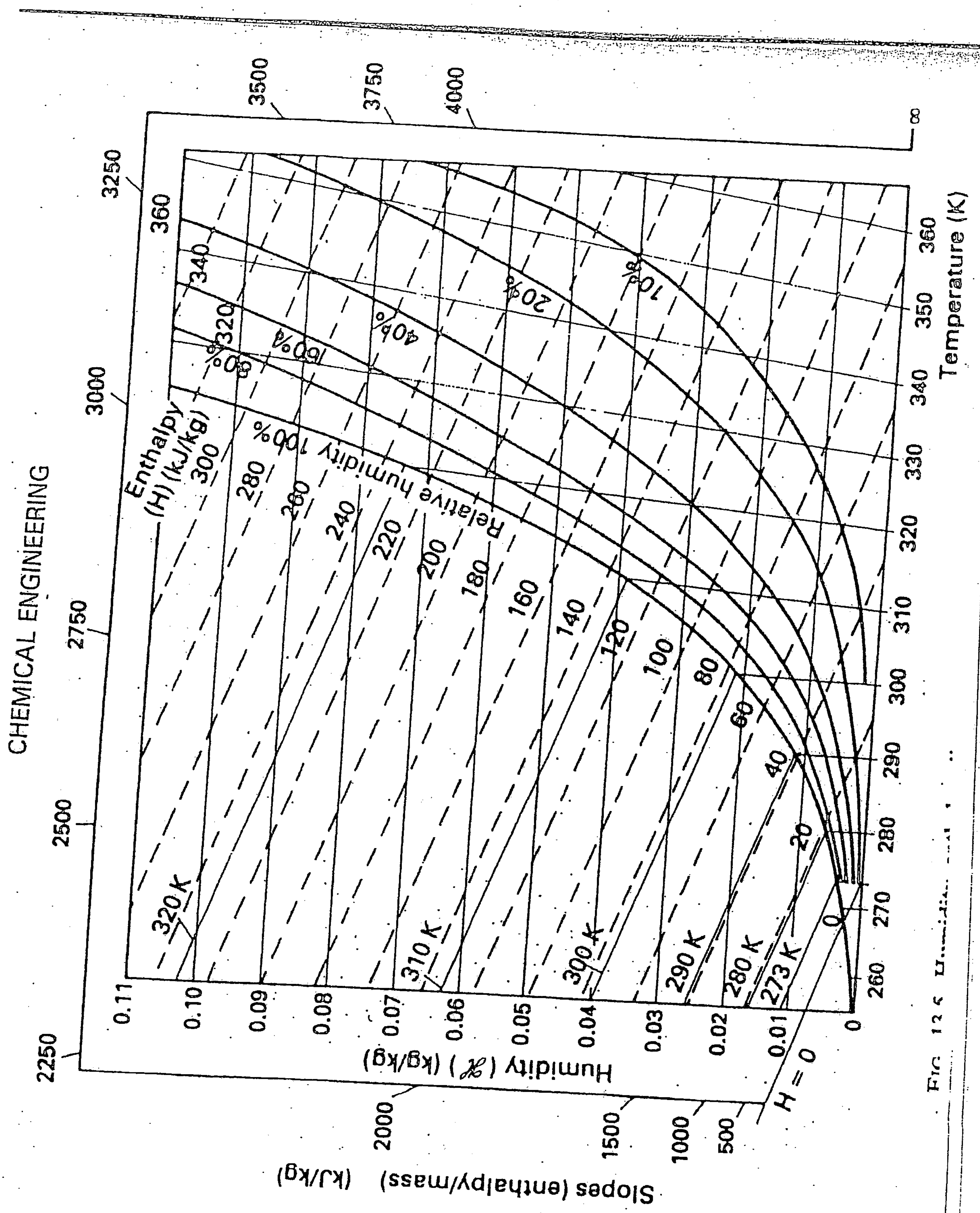
where the equilibrium solubility of the dilute TCE is well described by Henry's Law

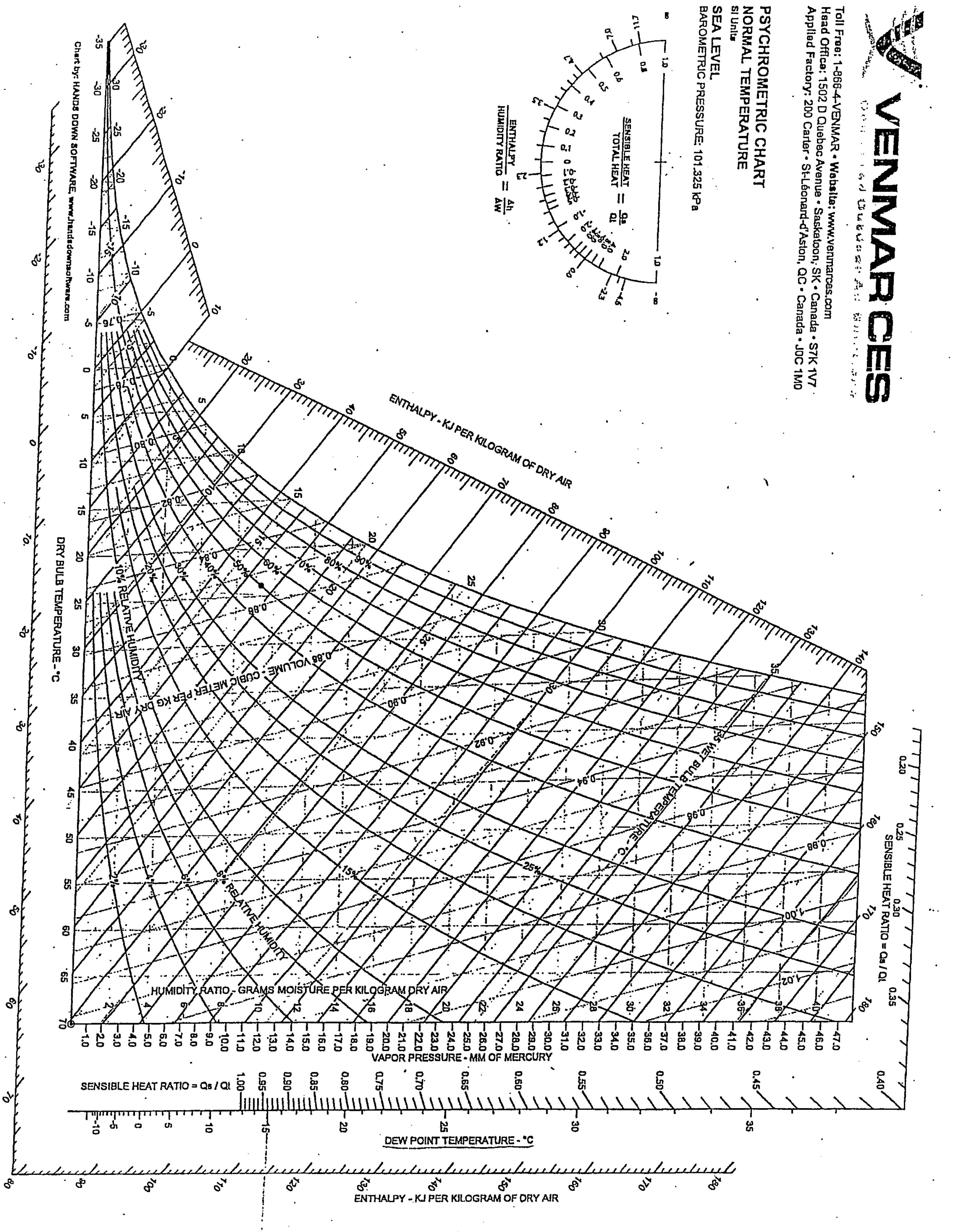
$$p_{TCE} = Hx_{TCE}$$

and p_{TCE} is the partial pressure of TCE in the gas stream, x_{TCE} is the mole fraction of TCE in the liquid phase, and H is the Henry's Law constant ($H = 3.05 \times 10^4$ atm·m^3/kmol).

What is the value of K_L? Is mass transfer in this wetted-wall tower controlled in the liquid phase, in the gas phase, or is neither one dominant, i.e. both play substantial roles?


Humidity, $\mathscr{H}$ (kg/kg)
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Adiabatic cooling line
Humidity (%)
10
20
30
40
50
60
70
80
90
100
330 K
325 K
320 K
315 K
310 K
305 K
300 K
295 K
290 K
285 K
280 K
275 K
Latent heat
Saturated volume v. temperature
Specific volume of dry air v. temperature
Humid heat v. humidity
Humid heat (kJ/kg K)
0.95
1.00
1.05
1.10
1.15
1.20
1.25
1.30
Latent heat of water (kJ/kg)
2450
2400
2350
2300
2250
2200
273.2
Volume (m³/kg dry air)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
Temperature, T
(K)
275
280
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
(°F)
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260


CHEMICAL ENGINEERING
Enthalpy (H) (kJ/kg)
Relative humidity 100%
80%
60%
40%
20%
10%
Temperature (K)
Humidity (ℋ) (kg/kg)
Slopes (enthalpy/mass) (kJ/kg)
H = 0
320 K
310 K
300 K
290 K
280 K
273 K
2250
2500
2750
3000
3250
3500
3750
4000
∞
2000
1500
1000
500
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
260
270
280
290
300
310
320
330
340
350
360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PSYCHROMETRIC CHART
NORMAL TEMPERATURE
SI Units
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
SENSIBLE HEAT / TOTAL HEAT = Qs / Qt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY - KJ PER KILOGRAM OF DRY AIR
DRY BULB TEMPERATURE - °C
RELATIVE HUMIDITY
VOLUME - CUBIC METER PER KG DRY AIR
WET BULB TEMPERATURE - °C
HUMIDITY RATIO - GRAMS MOISTURE PER KILOGRAM DRY AIR
VAPOR PRESSURE - MM OF MERCURY
SENSIBLE HEAT RATIO = Qs / Qt
DEW POINT TEMPERATURE - °C
ENTHALPY - KJ PER KILOGRAM OF DRY AIR
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