

UNIVERSITY COLLEGE LONDON

University of London

EXAMINATION FOR INTERNAL STUDENTS

For The Following Qualification:--

M.Sc.

M11: Fluid Particle Systems

COURSE CODE : CENG0M11

DATE : 04-MAY-05

TIME : 14.30

TIME ALLOWED : 3 Hours

Answer **FOUR QUESTIONS** in total with **TWO** from each section.
ALL questions carry a total of **20 MARKS** each, distributed as shown []

PART A

1.

- (i) Explain what is the “unrecoverable pressure drop” in a packed bed. [4]
- (ii) Explain what is meant by “tube flow analogy” and where it originates from. In the laminar flow regime, explain what the application of the analogy involves in order to obtain the expression of the unrecoverable pressure drop in a packed bed, i.e. the Ergun equation, starting from the Hagen-Poiseuille Equation:

$$\Delta P = \frac{32 \mu LU}{D^2} \quad [6]$$

- (iii) Consider a control volume consisting of a uniform bed of particles of vertical length L and unit cross section area. The superficial velocity of the fluid is U and the velocity of the fluid within the control volume is U/ϵ . Derive the expression below which relates the drag force acting on a fluidized particle, F_d , to the pressure loss in a bed of particles that is due to energy dissipation, ΔP .

$$F_d = \frac{\pi d_p^3 \epsilon}{6(1 - \epsilon)L} \Delta P \quad [10]$$

2.

- (i) Sketch the theoretical relationship between pressure drop, ΔP , and the fluidizing gas velocity, u , starting at $u=0$. Show both the curves obtained from a hypothetical experiment when increasing and then decreasing the fluidizing gas velocity. Explain the differences between the two curves and indicate on the diagram the point of minimum fluidization velocity. [3]

By applying a force balance, write the expression of the pressure drop for a bed of particles of density ρ_p , fluidized by a fluid of density ρ_f which form a bed of depth L and voidage ϵ in a vessel of cross-section area A . Explain why the pressure drop remains constant when the minimum fluidization velocity is exceeded. [5]

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- (ii) A spherical solid material with the physical characteristics reported below is being investigated for the development of a new gas-fluidized bed process. The Ergun equation for pressure drop through packed beds of spherical particles may be applied to determine u_{mf} :

$$Ar = 1650 Re_{mf} + 24 Re_{mf}^2$$

where:

$$Ar = \frac{d_p^3 \rho_f (\rho_p - \rho_f) g}{\mu^2}$$

Calculate the minimum fluidization velocity with: [8]

d_p = particle diameter = 100 μm

ρ_p = particle density = 2000 kg m^{-3}

ρ_g = gas density = 1.22 kg m^{-3}

μ = gas viscosity = 1.8×10^{-5} $\text{kg m}^{-1} \text{s}^{-1}$

acceleration due to gravity = 9.81 m s^{-2}

- (iii) Using the Ergun equation, discuss the effect of increasing gas pressure on the minimum fluidization velocity of both small and large particles. [4]

3.

- (i) Applying the Mickley Fairbanks heat transfer model, the heat transfer coefficient h at a point on a vertical tube immersed in a fluidized bed is given by:

$$h = (h_{\text{bubble at surface}}) \varepsilon_{bw} + (h_{\text{emulsion at surface}}) (1 - \varepsilon_{bw}) \quad (1)$$

which is equal to:

$$h = [(h_r + h_g) \varepsilon_{bw}] + \frac{(1 - \varepsilon_{bw})}{\frac{1}{h_r + \frac{2k_{ew}^o}{d_p} + \alpha_w (C_{pg} \rho_g U_o)} + \frac{1}{h_{\text{packet}}}} \quad (2)$$

where

h_r is the radiant heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)

h_g is the gas convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)

ε_{bw} is the volume fraction occupied by the bubbles in the vicinity of the surface

k_{ew}^o is the effective thermal conductivity at the wall ($\text{W m}^{-1} \text{K}^{-1}$)

d_p is the particle diameter (m)

α_w is an empirical parameter

C_{pg} is the specific heat capacity of the gas ($\text{J kg}^{-1} \text{K}^{-1}$)

ρ_g is the gas density (kg m^{-3})

U_o is the fluid velocity (m s^{-1})

h_{packet} is the heat transfer coefficient of the emulsion packet ($\text{W m}^{-2} \text{K}^{-1}$)

CONTINUED

Simplify the above equation (2) for the case in which the heat transfer coefficient at the surface is to be determined for a hot fluidized bed ($>600^{\circ}\text{C}$) of small particles for long contact times. Identify which terms can be neglected and explain why. [10]

- (ii) Using the simplified equation, calculate the heat transfer coefficient h on a point on a tube with wall temperature $T_w=80^{\circ}\text{C}$ immersed in a 600°C bed of small sand particles fluidized with air at 0.2 m s^{-1} . [10]

Data:

Solids: ρ_s = particle density = 2500 kg m^{-3}
 k_s = solid thermal conductivity = $1.2\text{ W m}^{-1}\text{ K}^{-1}$
 C_{ps} = solid specific heat capacity = $756\text{ J kg}^{-1}\text{ K}^{-1}$
Gas: k_g = gas thermal conductivity = $0.063\text{ W m}^{-1}\text{ K}^{-1}$
Bed: u_{mf} = minimum fluidization velocity = 0.0075 m s^{-1}
 ϵ_{mf} = minimum fluidization voidage = 0.46
 d_{bubble} = equivalent diameter of bubbles in the fluid bed = 0.13 m
 ϵ_{bw} can be approximated to ϵ_b , bubble volume fraction in the fluid bed
 n_w = bubble frequency = 1.4 s^{-1}
 ϕ_b = thickness of the equivalent gas layer at the particle-particle contact = 0.13
Emissivities: $e_s=0.9$ and $e_w=0.8$

Use the following equations for the calculations:

$$h_r = \frac{(5.67 \times 10^{-8})(T_s^4 - T_w^4)}{(1/e_s + 1/e_w - 1)(T_s - T_w)}$$

$$h_{\text{packet}} = 1.13 \left(\frac{k_e^{\circ} \rho_s (1 - \epsilon_{mf}) C_{ps} n_w}{1 - \epsilon_{bw}} \right)^{1/2}$$

$$k_e^{\circ} = \epsilon_{mf} k_g + (1 - \epsilon_{mf}) k_s \left[\frac{1}{\phi_b (k_s/k_g) + 2/3} \right]$$

PLEASE TURN OVER

PART B

4.

- (i) Considering crystal growth as a transport process, draw a sketch to identify the key stages in the transfer of a solute growth unit from a bulk supersaturated solution to full incorporation in a solid crystal lattice. [4]
- (ii) Crystal growth is often described by 'Birth and Spread' models. Describe briefly the physical principles on which this type of model is based. Explain why these models do not accurately predict growth rates under conditions of low supersaturation. Outline briefly an alternative growth mechanism likely to represent the growth process more accurately under these conditions. [10]
- (iii) The 'Birth and Spread' principle predicts that the velocity at which a crystal face will grow will be given by:

$$v_f = A(S - 1)^{5/6} \exp\left(-\frac{B}{S - 1}\right)$$

where: v_f is the face growth velocity [m s^{-1}],
 S is the supersaturation ratio [Actual solution concentration / concentration at saturation],
 A [m s^{-1}] and B are constants for a given solute / solvent composition and temperature.

By taking logarithms or otherwise, calculate the values of the constants A and B for the crystallization of potassium dihydrogen phosphate (KH_2PO_4) from water at 30°C using the following growth data for moderate supersaturation levels:

[6]

Supersaturation ratio	Face growth velocity (m s^{-1})
1.07	3.0×10^{-8}
1.21	2.9×10^{-7}

5.

Discuss the main factors that determine the crystal size distribution (CSD) from a continuous mixed-suspension, mixed-product-removal (MSMPR) crystallizer and show, with the aid of a simple information flow diagram, how they are interrelated. [5]

CONTINUED

Given that that the CSD from a continuous MSMPR crystallizer at steady-state may be expressed by:

$$n(L) = n^0 \exp(-L/G\tau)$$

where $n(L)$ is the population density of crystals of size L , G is the linear crystal growth rate and τ is the mean residence time. Show that the dominant crystal size L_D varies with crystallizer mean residence time τ according to the expression:

$$L_D = 3G\tau$$

[Hint: the Gamma Function $\int_0^\infty e^{-p} p^j dp = j! = \Gamma(j+1)$]. [10]

An MSMPR crystallizer is required to produce 5000 kg hr^{-1} of crystals having a dominant size of $300 \mu\text{m}$ in a slurry of density $400 \text{ kg solids (m}^3 \text{ slurry)}^{-1}$.

Given that the crystal growth and nucleation kinetics are given by:

$$B^0 = 1.16 \times 10^{15} M_T G^{1.5}$$

where B^0 is the nucleation rate [$\text{s}^{-1} \text{m}^3 (\text{slurry})^{-1}$], M_T is the slurry density [$\text{kg solids (m}^3 \text{ slurry)}^{-1}$], and G is the crystal growth rate (ms^{-1}). Calculate:

- i. The crystal growth rate
- ii. The mean residence time required in the crystallizer
- iii. The crystallizer volume
- iv. The effect on the dominant crystal size if the production rate were to be doubled.

Assume that the crystal density is $2.6 \times 10^3 \text{ kg m}^{-3}$ and the volume shape factor is 3.5.

[5]

(Note: the crystal growth rate in an MSMPR crystallizer at steady-state is

given by: $G = \left[\frac{27}{2f_v \rho_c k_R L_D^4} \right]^{\frac{1}{i-1}}$ where f_v is the volume shape factor, ρ_c is the crystal density and k_R is the relative nucleation to growth rate coefficient).

PLEASE TURN OVER

6.

With the aid of a simple temperature-solubility diagram, explain the terms:

- i) undersaturated
- ii) supersaturated
- iii) metastable
- iv) labile.

[5]

Batch crystallizers are widely used in the chemical industry but uncontrolled operation can lead to unsatisfactory performance. Stating carefully any assumptions that you may make, show that a controlled cooling curve for a seeded well-mixed batch cooling crystallizer may be given by the expression:

$$\theta(t) = \theta_o - \phi YZ \left(1 + YZ + \frac{1}{3} Y^2 Z^2 \right)$$
$$\phi = \frac{3M_{so}}{dc^*/d\theta}$$

[10]

where θ is the solution temperature, θ_o is the initial solution temperature, M_{so} is the initial seed mass, c^* is the solubility, Y is the dimensionless crystal size and Z is dimensionless time.

Compare the controlled cooling curve and consequent transient supersaturation with those for natural cooling and explain their effect on the product crystal size distribution.

[5]

END OF PAPER