# UNIVERSITY COLLEGE LONDON

*University of London*

# EXAMINATION FOR INTERNAL STUDENTS

*For The Following Qualification:-*

*M.Sc.*

**M11: Fluid Particle Systems**

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| COURSE CODE | : | **CENG0M11** |
| DATE | : | **06-MAY-03** |
| TIME | : | **10.00** |
| TIME ALLOWED | : | **3 Hours** |

*Answer* ***FOUR QUESTIONS. Answer at least ONE question from each section.***
**Only the first FOUR answers will be marked.**
*ALL questions carry a total of* ***20 MARKS*** *each, distributed as shown* [ ]

**Section A**

**1.**

(i) Derive an overall, steady-state force balance for a control volume of a fluidised bed and use it to obtain an expression for the fluid pressure drop $\Delta p$ and the *unrecoverable pressure loss* $\Delta P$ across the control volume [4]

Use this to show that the unrecoverable pressure loss *across the whole bed*, $\Delta P_B$, remains independent of the fluid velocity and hence sketch the theoretical relationship between $\Delta P_B$ and volumetric flux of the fluid, $u$, starting at $u = 0$. Describe how this compares with experimental observations giving reasons for any differences. [3]

(ii) Show that the effect of the fluid pressure gradient gives rise to the following expression for the effective weight $w_e$ (weight minus buoyancy force) of a particle immersed in a fluidised bed:

$$w_e = V(\rho_p - \rho_f) g \varepsilon ,$$

where $V$ is the particle volume, $\rho_p$ and $\rho_f$ are the particle and fluid densities, and $\varepsilon$ is the void fraction. [4]

(iii) Derive an expression for the expansion characteristics $\varepsilon(u)$, of a homogeneously fluidised bed on the basis of the following constitutive relation for the pressure drop through a bed of particles:

$$\Delta P = K u^a \varepsilon^b ,$$

where $K$ is a constant, $u$ is the fluid flux, $\varepsilon$ is the void fraction, and the parameters $a$ and $b$ depend on the particle Reynolds number. [7]

What do experimental measurements reveal about the values of $a$ and $b$. [2]

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**2.**

(i) Describe carefully, with the aid of sketches, how a homogeneously fluidised bed responds to both a sudden increase and a sudden decrease in the fluid velocity. Hence confirm that the bed surface velocity, following such a change, may be assumed to travel at velocity $U_2 - U_1$, the difference in fluid fluxes after and before the flow rate change. State any simplifying assumptions that are made, and discuss practical limitations to the simple theory. [10]

(ii) Use the analysis of part (i) to evaluate the kinematic wave speed for a fluidised suspension in terms of the Richardson-Zaki parameter $n$. [4]

(iii) Discuss briefly the significance of the kinematic wave speed for the stability of the state of homogeneous fluidisation. [6]

## Section B

**3.**

(i) Experiments have to be carried out to study elutriation (or carryover) of small spherical mono-size particles from a gas-fluidized bed. In order to identify the operative conditions in the fluid-bed, the particle terminal fall velocity, $u_t$, has to be determined.

The force balance on a particle, written as a function of the Reynolds and Archimedes dimensionless numbers, may be applied to give $u_t$.

$$C_D Re_t^2 = \frac{4}{3} Ar$$

where:

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

Assuming creeping flow regime, calculate the particle terminal fall velocity with:

$d_p$ = particle diameter = 40 $\mu m$
$\rho_p$ = particle density = 1400 kg m$^{-3}$
$\rho_f$ = gas density = 1.22 kg m$^{-3}$
$\mu$ = gas viscosity = 1.8x10$^{-5}$ kg m$^{-1}$ s$^{-1}$
$g$ = acceleration gravity = 9.81 m s$^{-2}$

[10]

(ii) Discuss the effect of increasing gas temperature and pressure on the calculation of the particle terminal fall velocity. [6]

**CONTINUED**

(iii) To avoid or reduce elutriation of particles from the fluidized bed, the operative gas velocity has to be kept between the minimum fluidization velocity, $u_{mf}$, and the particle terminal fall velocity, $u_t$. If the system of particles under investigation was not mono-size but contained a distribution of different sizes, which particle diameter should you use to calculate $u_{mf}$ for the polydisperse system and which particle diameter should you use to calculate $u_t$ so that elutriation is reduced.

[4]

**4.**

(i) Consider a fluidized bed of solids operated at constant temperature $T_s$. Hot fluidizing gas at temperature $T_{gi}$ enters the bed, with $T_{gi}>T_s$. The expression for the distance "$L_n$" at which the gas-to-particle temperature difference falls by a factor "n" from its initial value is shown in Eq. (1):

$$L_n = -5.5\left[\frac{\ln n\,\mu^{1.3}\,d_p^{0.7}\,C_g}{u_{rel}^{0.3}\,\rho_g^{0.3}\,(1-\varepsilon)k_g}\right] \quad (1)$$

Write the heat balance equation across an element of fluid-bed of height dL and show the derivation of Eq.(1). [14]

To this end, use the following information:

Assume the following boundary conditions: $T_g=T_{gi}$ at $L=0$ ; and denote with $T_{ge}$ the temperature of the gas leaving the fluid-bed element, where $T_{ge}<T_{gi}$.

The surface area of solids per unit volume of bed S ($m^{-1}$) is expressed as:

$$S = \frac{6(1-\varepsilon)}{d_p}$$

The gas-to-particle heat transfer coefficient $h_{gp}$ ($W\ m^{-2}\ K^{-1}$) is expressed as:

$$h_{gp} = \frac{0.03\,d_p^{0.3}\,\rho_g^{1.3}\,u_{rel}^{1.3}\,k_g}{\mu^{1.3}}$$

$d_p$ = particle diameter ($\mu m$)
$\rho_g$ = gas density ($kg\ m^{-3}$)
$\mu$ = gas viscosity ($N\ s\ m^{-2}$)
$k_g$ = gas conductivity ($W\ m^{-1}\ K^{-1}$)
$C_g$ = specific heat capacity of the gas ($J\ kg^{-1}\ K^{-1}$)
$u_{rel}$ = gas-particle relative velocity ($m\ s^{-1}$)
$\varepsilon$ = fluid-bed voidage
$\Delta T_g$ = change in temperature of the gas flowing through the element of bed (K)
dL = element of bed dL deep and of unit cross section area (m)

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(ii) Using the equation derived for "$L_n$" (Eq.1) and the data given below, calculate the distance penetrated by the gas into a bed of constant temperature before the difference between its temperature and that of the bed solids is reduced by half. [6]

$d_p$ = 300 μm
$\rho_g$ = 1.2 kg $m^{-3}$
μ = $1.8 \times 10^{-5}$ N s $m^{-2}$
$k_g$ = 0.0262 W $m^{-1}$ $K^{-1}$
$C_g$ = 1005 J $kg^{-1}$ $K^{-1}$
ε = 0.45
$u_{mf}$ = minimum fluidization velocity = 0.10 m $s^{-1}$

**Section C**

**5.**

(i) Sketch the product CSD (crystal size distribution) from a continuous MSMPR (mixed-suspension, mixed-product-removal) crystallizer in terms of *population density* and *mass fraction*. [2]

(ii) State the *population balance* concept and show that the CSD from a continuous MSMPR crystallizer at steady-state may be expressed by:

$$n(L) = n^{\circ} \exp(-L / G\tau)$$

where $L$ is the crystal size, $G$ is the overall linear crystal growth rate and $\tau$ is the mean residence time in the vessel. State clearly any assumptions that you may make. [6]

(iii) The suspension density $M_T$ in a continuous MSMPR crystallizer operated at steady-state is given by the equation:

$$M_T = 6 f_v \rho_c n^{\circ} (G\tau)^4$$

where $f_v$ and $\rho_c$ are the crystal volume shape factor and density respectively, $n^O$ is the nuclei population density, $G$ is the linear crystal growth rate and $\tau$ is the mean residence time within the crystallizer.

The CSD from an MSMPR crystallizer with a working volume of 1 $m^3$ operated with a magma density of 100kg crystals/$m^3$ slurry and a production rate of 1000kg crystals/hr has a Sauter mean size of 100 μm. Calculate:

**CONTINUED**

a) the linear crystal growth rate (m/s)
b) the population density of nuclei (#/m$^4$) and,
c) the nucleation rate (#/sm$^3$).

[Take the crystal volume shape factor to be 1.0 and the crystal density to be 2000 kg/m$^3$] [12]

**6.**

(i) Define the moments about the origin of the CSD (crystal size distribution) from a continuous MSMPR (mixed-suspension, mixed-product-removal) crystallizer and explain their physical significance. [8]

(ii) An MSMPR crystallizer is operated continuously at steady state. The suspension density $M_T$ is given by:

$$M_T = 6 f_v \rho_c n^o (G\tau)^4$$

where $f_v$ and $\rho_c$ are the volume shape factor and crystal density respectively, $n^o$ is the nuclei population density, $B^o$ is the nucleation rate, $G$ is the linear crystal growth rate and $\tau$ is the mean residence time within the crystallizer.

The crystal growth rate and nucleation rate $B^o$ are found to be related by:

$$B^o \propto M_T G^2$$

Estimate the effect of decreasing the throughput of the crystallizer by 50% on:

a) the crystal growth rate (m/s)
b) the nucleation rate (#/sm$^3$), and
c) the dominant crystal size (μm)

You may assume that the suspension density is controlled to a constant value. [12]

**END OF PAPER**