Loughborough University

22CGP060

Mixing of Fluids and Particles

Semester 1 2022/23 | In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **3 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Relevant expressions and data can be found at the end of the examination paper.

Attempt THREE Questions in Total. Each question carries 25 marks.

Candidates should show full working for all calculations and derivations.

1. (a)

(i) Explain the different hydrodynamic states in a gas-liquid reactor observed under different operating conditions. Use schematic diagrams if appropriate. [5 marks]

(ii) Explain what a cavity is and why it forms. Describe the different types of cavities formed under different operating conditions. Use schematic diagrams if appropriate. [4 marks]

(iii) Explain the implications of the different hydrodynamic states in a gas-liquid reactor and different types of cavities on power input under gassed conditions. Use schematic diagrams if appropriate. [4 marks]

(iv) Provide two recommendations for the design of a mixing process which requires dispersing an inexpensive, non-hazardous gas into a low viscosity liquid providing a brief explanation of how these recommendations will be beneficial. [2 marks]

(v) What design advice would you provide for a process that requires the dispersion of an expensive and hazardous gas into a liquid, including the reasoning behind this advice? [3 marks]

(b) You are involved in the optimisation and design of processes which require solid-liquid mixing for mass transfer. A product currently available on the market has solids in its formulation with a diameter of d_p = 210 μm and density of ρ_s = 1900 kg m^{-3}. They are used at a mass fraction of X = 10%. The liquid phase viscosity is μ = 0.035 Pa s and density is ρ_L = 1050 kg m^{-3}.

The cylindrical tank is of standard geometry, i.e. the liquid height is equal to the tank diameter (H = T), and it has a dish base. The tank diameter is T = 1.8 m. It is equipped with a down pumping pitched blade turbine of a diameter of D = T/2, which has an s value of 5.5, and is rotated at a speed of N = 70 rpm.

Continued/…

Q1 Continued/…

(i) Having made relevant calculations, would you conclude that the operation can be run successfully? [4 marks]

(ii) If you concluded in (i) that the operation cannot be run successfully, state what changes need to be made, also including your calculations on what this would correspond to in terms of power input per batch.

If you concluded in (i) that the process target can be met as it is operated, explain whether any improvements can be made to save operating costs, also including your calculations on how much power input can be reduced per batch.

[3 marks]

2. (a) A mixing operation will be carried out in a standard geometry tank to obtain an intermediate product through the addition of several miscible liquids into a bulk. The formulation requires a total of 10 small quantity additions. Each addition is made after 95% homogeneity of the previous addition was achieved. The physical properties of the added and bulk liquids can be considered to be similar. The density is 1075 kg m^{-3} and results from rheology measurements are presented in Table Q2.

As a process engineer, you are tasked to design a standard geometry mixing tank, i.e. liquid height (*H*) being the same as the tank diameter (*T*). The tank has a dish base and should be for a liquid volume of 750 litres. You are informed that an existing tank on site can be made available for the purpose. It has a drive which can be operated at a fixed speed of 60 rpm. The impellers that are available for this tank are a sawtooth impeller of a diameter of $D = T/2$, a low solidity ratio hydrofoil of $D = T/3$ or a helical ribbon of $D = 0.90T$.

Having obtained a constitutive equation that best describes the rheological behaviour of the mixture, and made subsequent relevant calculations, propose design recommendations that would best suit the requirements of this process. The proposed design recommendations should include specification of impeller choice from the selection and vessel internals where appropriate.

Calculate the energy requirement for this process.

Table Q2 Results from rheology measurements

Shear stress (Pa)	Shear rate (1/s)
0.5	50
1.0	100.0
2.5	250.0
5.0	500.0
10.0	1000.0

[11 marks]

Continued/….

Q2 Continued/…

(b)

(i) If there are physical property differences in the added and bulk liquids to blend, how would you take these into account in estimating the mixing time? [3 marks]

(ii) Provide two recommendations for a blending process for which it has been established that physical property differences will have an effect on the mixing time. [2 marks]

(c) Explain briefly what phase inversion is. Why is it important to have a knowledge of what can trigger phase inversion? State two factors that may affect phase inversion. [3 marks]

(d) An immiscible liquid-liquid dispersion process is carried out in a fully baffled, flat based stirred tank of T = 0.45 m diameter. This is of standard geometry, i.e. the dispersion height is equal to the tank diameter. The impeller used is a narrow blade hydrofoil which is of a diameter of half the tank diameter (D = T/2). The operating speed is N = 350 rpm. The viscosity of the continuous phase is much higher than that of the dispersed phase, and hence the dispersed phase can be considered inviscid. The dispersion viscosity is 0.015 Pa s and density 1100 kg m^{-3}.

The breakup process was found to be due to inertial subrange eddies for which the mechanistic model relating the maximum stable drop size to the physical properties of the continuous and dispersed phases and power per unit mass, ε (W kg^{-1}) is as follows:

$$d_{max} = A'\left(\frac{\sigma}{\rho_c}\right)^{3/5} \varepsilon^{-2/5} \left[1 + \mathrm{B}'\frac{\mu_d}{\sigma}\sqrt{\frac{\rho_c}{\rho_d}}\,\varepsilon^{1/3} d_{max}^{1/3}\right]^{3/5}$$

(i) Considering the breakup mechanism identified and the information provided, propose a scale up criterion to be used for this process. [2 marks]

(ii) Determine the impeller speed and power input in order to get the same mean droplet diameters at a larger scale, using a geometrically similar tank of T= 0.60 m diameter. [4 marks]

3. (a) 20 g of an API (labelled A) is randomly mixed together with a diluent (labelled B) to form a 400 g powder blend with the cumulative undersize distribution given in Table Q3.

Table Q3. Cumulative undersize distribution of powders A and B

Diameter (mm)	(A)	(B)
120	1	1
110	1	0.8
100	1	0.5
90	0	0.2
80	0	0

(i) 0.4 g tablets are then produced from this powder batch with a powder A concentration that follows a normal distribution. Calculate the random variance σ_R^2 in kg^2. [8 marks]

(ii) If the dosage exceeds the average by 2.5% or more this is deemed an overdose and the batch is rejected. If the 99.9% confidence interval is 3.291σ, determine whether the batch should be rejected. [5 marks]

(b) Sketch a fully-labelled schematic phase diagram for a spouted bed and show how the minimum spouting velocity and maximum spoutable bed depth are represented in this diagram. [6 marks]

(c) A high-shear, wet granulation system shows steady growth behaviour. Define this behaviour and the main mechanisms that cause it. [6 marks]

4. A computational fluid dynamics (CFD) simulation is to be carried out to design a fully-baffled, 5.0 m diameter, **continuous-flow,** stirred tank chemical reactor, which is agitated by a 2.0 m diameter pitched blade turbine rotating at 90 rpm. Two liquid reactants, with similar densities and viscosities of 1020 kg m^{-3} and a viscosity 25 mPa s, respectively are fed into the vessel through dip pipes. An exothermic homogeneous second-order chemical reaction between the two reagents occurs within the reactor to produce a single product. Cooling water is circulated through a jacket to maintain the reactor at a constant temperature.

(a) Choose the fundamental transport equations which must be solved for this problem and explain the reasons for your selection. State any reasonable assumptions that may be made to simplify a computational simulation of this mixing vessel. [7 marks]

(b) Show that the flow is turbulent. Using estimates of the range of eddy length scales in the turbulent flow, explain why a direct numerical solution (DNS) of the transport equations is infeasible for this case. Discuss alternative methods of modelling the turbulent flow, commenting on the prediction accuracy for each case. [7 marks]

(c) Discuss how you would set appropriate wall, free surface and other boundary conditions for this simulation. [5 marks]

(d) Propose a suitable method to model the moving impeller, bearing in mind accuracy of prediction and minimisation of computational effort. [3 marks]

(e) Describe briefly experimental methods that could be applied to collect data for validation of this CFD simulation. [3 marks]

END OF PAPER

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Relevant Expressions and Data

Zwietering correlation for just suspension speed

$$N_{JS} = s\nu^{0.1}\left[\frac{g\Delta\rho}{\rho_L}\right]^{0.45} {d_p}^{0.2} X^{0.13} D^{-0.85}$$

Volume of a dish base tank:

$$V = \frac{\pi}{4}T^2H - 0.0525T^3$$

Power number $$Po = \frac{P}{\rho N^3 D^5}$$

Fourier number $$\frac{1}{Fo} = \frac{\rho T^2}{\mu\vartheta}$$

Reynolds number $$Re = \frac{\rho N D^2}{\mu}$$

Mixing time correlation for 95% homogeneity in the turbulent blending regime:

$$Po^{1/3}\ Re\ Fo = 5.2\ \pm 10\%$$

$$\theta_{95} = \frac{5.2\ T^{1.5}H^{0.5}}{Po^{1/3}ND^2}$$

Mixing time correlation for 95% homogeneity in the transitional blending regime:

$$Po^{1/3}ReFo^{1/2} = 183 \pm 31.1\%$$

$$\theta_{95} = \frac{183^2T^2}{Po^{2/3}N^2D^4}\frac{\mu}{\rho} \pm 31.1\%$$

Relevant Data:

Po numbers:

Po = 1.4 for a pitched blade turbine

Po = 0.3 for a narrow blade hydrofoil

Poole Taylor and Wall Equation for powder mixing random variance:

$\sigma_R^2 = \frac{PQ}{M}\left[P\overline{W}_Q + Q\overline{W}_P\right]$

Where $W_i = \frac{\pi}{6}\rho_i \int_{x-min}^{x-max} x_i^3 n_3(x)$