Dear CN3124E/TCN 3124 Students:

Attached please find the five questions for the CN3124E/TCN3124 assignment #1. The numbers cited refer to the following main textbook listed in the module website.


**CN3124E Particle Technology Assignment #1**

**Due 7:00pm, Feb. 21, 2018**

1. MR 1.3.
2. MR 2.2.
3. MR 3.4.
4. MR 5.4.
5. MR 6.4.

Kindly submit your assignment through your class representative. The graded assignments will be returned to you through your class representative on 7 March at 7:00pm.

Sincerely yours,

Chi-Hwa Wang
CN3124E/TCN3124
1.1 For a regular cuboid particle of dimensions $1.00 \times 2.00 \times 6.00 \text{mm}$, calculate the following diameters:

(a) the equivalent volume sphere diameter;

(b) the equivalent surface sphere diameter;

(c) the surface-volume diameter (the diameter of a sphere having the same external surface to volume ratio as the particle);

(d) the sieve diameter (the width of the minimum aperture through which the particle will pass);

(e) the projected area diameters (the diameter of a circle having the same area as the projected area of the particle resting in a stable position).

[Answer: (a) 2.84 mm; (b) 3.57 mm; (c) 1.80 mm; (d) 2.00 mm; (e) 2.76 mm, 1.60 mm and 3.91 mm.]

1.3 Repeat Exercise 1.1 for a disc-shaped particle of diameter 2.00 mm and length 0.500 mm.

[Answer: (a) 1.44 mm; (b) 1.73 mm; (c) 1.00 mm; (d) 2.00 mm; (e) 2.00 mm and 1.13 mm (unlikely to be stable in this position).]
EXERCISE 1.3:
Repeat Exercise 1.1 for a disc-shaped particle of diameter 2.00 mm and length 0.500 mm.

SOLUTION TO EXERCISE 1.3:
(a) volume of disc \( \frac{\pi x^2 h}{4} = \frac{\pi (2)^2 \times 0.5}{4} = 1.5708 \text{ mm}^3 \)

If \( x_v \) is the equivalent volume sphere diameter, then \( \frac{\pi}{6} x_v^3 = 1.5708 \)
Hence, \( x_v = 1.442 \text{ mm} \).

(b) surface area of disc \( = \left( \frac{\pi x^2}{4} \times 2 \right) + \pi x h = \left( \frac{\pi (2)^2}{4} \times 2 \right) + \pi \times 2 \times 0.5 = 9.4248 \text{ mm}^2 \)
If \( x_s \) is the equivalent surface sphere diameter, then \( \pi x_s^2 = 9.4248 \)
Hence, \( x_s = 1.732 \text{ mm} \).

(c) Surface to volume ratio of the disc \( = \frac{9.4248}{1.5708} = 6.0 \text{ mm}^2 / \text{ mm}^3 \)
If \( x_{sv} \) is the surface-volume sphere diameter, then \( \frac{6}{x_{sv}} = 6.0 \)
Hence, \( x_{sv} = 1.0 \text{ mm} \).

(d) Sieve diameter is the second smallest dimension, i.e. 2 mm.

(e) The disc has two resting positions:
projected area 1 = \( 0.5 \times 2.0 = 1.0 \text{ mm}^2 \)
projected area 2 = \( \frac{\pi x^2}{4} = \pi \text{ mm}^2 \)

If \( x_p \) is the projected area diameter, then
\( \frac{\pi}{4} x_p^2 = 1.0; \quad \frac{\pi}{4} x_{p2}^2 = \pi \)

Giving two projected area diameters:
\( x_{p1} = 1.13 \text{ mm}; x_{p2} = 2 \text{ mm.} \) (The disc is unlikely to be stable in position 1)
EXERCISE 2.2:
A particle of equivalent sphere volume diameter 0.2 mm, density 2500 kg/m³ and sphericity 0.6 falls freely under gravity in a fluid of density 1.0 kg/m³ and viscosity 2 x 10⁻⁵ Pas. Estimate the terminal velocity reached by the particle. (Answer: 0.6 m/s)

SOLUTION TO EXERCISE 2.2:
In this case we know the particle size and are required to determine its terminal velocity without knowing which regime is appropriate. The first step is, therefore, to calculate the dimensionless group $C_D \text{Re}_p^2$:

$$C_D \text{Re}_p^2 = \frac{4 \times \rho_f \rho_p - \rho_f)}{\mu^2} \left[ \frac{0.2 \times 10^{-3}}{2 \times 10^{-5}} \right] \times (2500 - 1.0) 	imes 9.81 \left( \frac{1}{2 \times 10^{-5}} \right)^3$$

$$= 653.7$$

This is the relationship between drag coefficient $C_D$ and single particle Reynolds number $\text{Re}_p$ for particles of size 0.2 mm and density 2500 kg/m³ falling in a fluid of density 1.0 kg/m³ and viscosity 2 x 10⁻⁵ Pas. Since $C_D \text{Re}_p^2$ is a constant, this relationship will give a straight line of slope -2 when plotted on the log-log coordinates of the standard drag curve.

For plotting the relationship:

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These values are plotted on the standard drag curves for particles of different sphericity (Text- Figure 2.3). The result is shown in Figure 2.2.1.

Where the plotted line intersects the standard drag curve for a sphericity of 0.6 ($\psi = 0.6$), $\text{Re}_p = 6.0$.

The terminal velocity $U_T$ may be calculated from:

$$\text{Re}_p = 6 = \frac{\rho_f \chi \rho_p \chi U_T}{\mu}$$

Hence, terminal velocity, $U_T = 0.6$ m/s
Figure 2.2.1: Single particle drag curves: Solution to Exercise 2.2.
EXERCISE 3.4
A height-time curve for the sedimentation of a suspension in a vertical cylindrical vessel is shown in Text-Figure 3.E2.1. The initial solids concentration of the suspension is 200 kg/m³. Determine:

Figure 3.E2.1: Batch settling test results. Height versus time curve for use in Exercises 3.2 and 3.4
a) The velocity of the interface between clear liquid and suspension of concentration 200 kg/m$^3$.

b) The time from the start of the test at which the suspension of concentration 400 kg/m$^3$ is in contact with the clear liquid.

c) The velocity of the interface between the clear liquid and suspension of concentration 400 kg/m$^3$.

d) The velocity at which a layer of concentration 400 kg/m$^3$ propagates upwards from the base of the vessel.

e) The concentration of the final sediment.

SOLUTION TO EXERCISE 3.4

(a) Since the initial suspension concentration is 200 kg/m$^3$, the velocity required in this question is the velocity of the AB interface. This is given by the slope of the straight portion of the height-time curve (Solution Manual-Figure 3.4.1).

\[
\text{Slope} = \frac{0 - 80}{27.5 - 0} = -2.91 \text{ cm/s (value given in book is incorrect)}
\]

Therefore, velocity of the interface between clear liquid and suspension of concentration 200 kg/m$^3$ is 2.91 cm/s downwards.

(b) We must first find the point on the curve corresponding to the point at which a suspension of concentration 400 kg/m$^3$ interfaces with the clear suspension. From Equation 3.38, with $C = 400$, $C_B = 200$ and $h_0 = 80$ cm, we find:

\[
h_1 = \frac{200 \times 80}{400} = 40 \text{ cm}
\]

A line drawn through the point $t = 0, h = h_1$ tangent to the curve locates the point on the curve corresponding to the time at which a suspension of concentration 240 kg/m$^3$ interfaces with the clear suspension (Solution Manual-Figure 3.4.1). The coordinates of this point are

$t = 32.5 \text{ sec}, h = 27.5 \text{ cm}$.

(c) The velocity of this interface is the slope of the curve at this point:

slope of curve at 32.5 sec, 27.5 cm = $-0.40 \text{ cm/s}$
downward velocity of interface = 0.4 cm/s

(d) From the consideration above, after 32.5 seconds the layer of concentration 400 kg/m³ has just reached the clear liquid interface and has travelled a distance of 27.5 cm from the base of the vessel in this time.

Therefore, upward propagation velocity of this layer = $\frac{h}{t} = \frac{27.5}{32.5} = 0.846$ cm/s

(e) To find the concentration of the final sediment we again use Text-Equation 3.38.

The value of $h_1$ corresponding to the final sediment ($h_{1S}$) is found by drawing a tangent to the part of the curve corresponding to the final sediment and projecting it to the h axis.

In this case $h_{1S} = 20$ cm and so from Text-Equation 3.38,

final sediment concentration, $C = \frac{C_0h_0}{h_{1S}} = \frac{200 \times 80}{20} = 800$ kg/m³

[Answers: (a) 2.9 cm/s downwards; (b) 32.5 s; (c) 0.40 cm/s downwards; (d) 0.846 cm/s upwards; (e) 800 kg/m³.]
Figure 3.4.1: Batch settling test results; solution to Exercise 3.4.
EXERCISE 5.4:
(a) Explain why the permeability of the sediment from a flocculated mineral suspension (less than 5 microns) is greater than the permeability of the sediment of the same mineral suspension that settles while dispersed.
(b) Fine clay particles (approximately 0.15 microns diameter) wash from a farmer’s soil into a river due to rain. i) Explain why the particles will remain suspended and be carried down stream in the fast flowing fresh water. ii) Explain what happens to the clay when the river empties into the ocean.

SOLUTION TO EXERCISE 5.4:
(a) The flocculated suspension has particles which have attractive forces between them. They form low density sediments relative to the dispersed particles which pack to high densities due to the repulsive forces between particles. The higher void fraction in the flocculated sediments results in greater permeability. The relation ship between packed bed permeability and voidage is described in Chapter 6.

(b) i) The clay particles develop a negative surface charge in the fresh (low salt) water producing repulsion between them so they tend not to aggregate. Brownian motion and the hydrodynamic forces and turbulence of the fast flowing water keep the particles suspended in the flow and wash the particles down stream.
ii) When the river empties into the ocean, the high salt concentration of the ocean reduces the charge on the particles and van der Waals attraction dominates. The attraction causes the particles to aggregate. Relative to the fast flowing river, the ocean (away form the breaking waves) is calm. The mass of the aggregates is large enough to cause them to settle out onto the ocean floor. This is how river deltas are created.
EXERCISE 6.4: A solution of density 1100 kg/m³ and viscosity $2 \times 10^{-3}$ Pas is flowing under gravity at a rate of 0.24 kg/s through a bed of catalyst particles. The bed diameter is 0.2 m and the depth is 0.5 m. The particles are cylindrical, with a diameter of 1 mm and length of 2 mm. They are packed to give a voidage of 0.3. Calculate the depth of liquid above the top of the bed. [Hint: apply the mechanical energy equation between the bottom of the bed and the surface of the liquid]

SOLUTION TO EXERCISE 6.4: Calculate the frictional pressure loss through the bed.

Superficial liquid velocity, $U = \frac{0.24}{1100 \times \frac{\pi}{4} (0.2)^2} = 6.94 \times 10^{-3}$ m/s

Surface-volume diameter of particles, $x_{sv}$:

Volume of one cylindrical particle = $\frac{\pi}{2}$ mm³

Surface area of one cylindrical particle = $2.5\pi$ mm²

Surface-volume ratio of particles = $\frac{2.5\pi}{\pi/2} = 5$ mm²/mm³

For a sphere of diameter $x_{sv}$, surface-volume ratio = $\frac{6}{x_{sv}}$

Hence, diameter of sphere which has the same surface-volume ratio as the particles, $x_{sv} = 1.2$ mm
Checking the Reynolds number (Text-Equation 6.12),

\[ \text{Re}' = \frac{U \rho_f x_{sv}}{\mu (1 - \varepsilon) \rho_v} = \frac{6.94 \times 10^{-3} \times 1100 \times 1.2 \times 10^{-3}}{2 \times 10^{-3} \times (1 - 0.3)} = 6.5 \]

The Reynolds number is less than 10 and so we can assume that laminar flow dominates. The Ergun equation (Text-Equation 6.15) reduces to:

\[
\left( -\Delta p \right) \frac{\varepsilon^3}{H} = \frac{150 \mu U \varepsilon^2 (1 - \varepsilon)^2}{x_{sv}^2}
\]

With \( \mu = 0.002 \, \text{Pa.s} \), \( \rho_f = 1100 \, \text{kg/m}^3 \), \( x_{sv} = 1.2 \, \text{mm} \), \( \varepsilon = 0.3 \) and \( H = 0.5 \, \text{m} \),

\[
\frac{\left( -\Delta p \right)}{0.5} = 150 \frac{2 \times 10^{-3} \times 6.94 \times 10^{-3}}{(1.2 \times 10^{-3})^2} \times \frac{(1 - 0.3)^2}{0.3^3} = 26240 \, \text{Pa/m}
\]

which gives \( -\Delta p = 13120 \, \text{Pa} \).

Expressed in terms of head of liquid, friction head loss through the bed, \( h_{\text{loss}} = \frac{13120}{1100 \times 9.81} = 1.216 \, \text{m} \).

Applying the mechanical energy balance between the liquid surface (position 1) and the bottom of the packed bed (position 2): (Solution Manual-Figure 6.4.1)

\[
z_1 + \frac{U_1^2}{2g} + \frac{p_1}{\rho_f} = z_2 + \frac{U_2^2}{2g} + \frac{p_2}{\rho_f} + h_{\text{loss}}
\]

Assuming that \( p_1 = p_2 = \text{atmospheric} \) and that \( U_1 = U_2 \),

\( z_1 - z_2 = h_{\text{loss}} = 1.216 \, \text{m} \)

The height of the packed bed is 0.5 m and so the depth of liquid above the bed is 0.716 m (1.216 - 0.5 m).
Q1. (MR 1.3)
Some students missed out the units associated with the numerical answers.

Q2. (MR 2.2)
Some students gave the wrong Reynold number from the figure, hence, wrong terminal velocity was provided in their assignments.

Q3. (MR 3.4)
Some students did not read precisely the h vs. t diagram and gave values off the standard values for h/t for part (d).

Q4. (MR 5.4)
a) In part a, some students did not mention the effect of attractive and repulsive force between the particles and the void fraction.
b) In part b, some students did not mention the effect of surface charge of the particles and the forces among the particles. Some students did not mention the effect of water flow behaviors.

Q5. (MR 6.4)
a) Some of the students did not answer all the questions.
b) The main common mistake in this question is that some students did not indicate the way to calculate the difference between $Z_1$ and $Z_2$. Some students simply took the head loss as $Z_2-Z_1$ without reasons.
1. Answers Parts (a), (b), and (c).

(a) Calculate the effective volume fraction for a suspension of 150nm silica particles at 30 volume % solid in a solution of 0.004 M KCl.

Give your brief answer here:

\[ \phi_{\text{eff}} = \frac{\text{volume of solid + excluded volume}}{\text{total volume}} \]

For particles stabilized by electrical double layer repulsion, the excluded volume can be estimated using the range of the repulsion as estimated by the Debye length (\(k^{-1}\)). The inverse Debye length (\(k\)) is a function of the salt concentration ([C]) for monovalent salts.

\[ k = 3.29 \sqrt{[C]} \text{ nm}^{-1} \]

for 0.004 M KCl

\[ k = 3.29 \times (0.004)^{0.5} = 0.208 \text{nm}^{-1} \]

so the Debye length is 4.8nm

The volume of one particle corresponds to \( \phi = 0.3 \) then the volume of one particle plus its excluded volume is equal to the effective volume fraction of the suspension.

For the particle alone,

\[ \text{Vol} = \frac{\pi}{6} x^3 = \frac{\pi}{6} (150 \text{nm})^3 = 1.77 \times 10^6 \text{nm}^3 \]

For the particle and excluded volume,

\[ \text{Vol} = \pi/6 (150+4.8+4.8 \text{nm})^3 = 2.129 \times 10^6 \text{nm}^3 \]

Then \( \frac{\phi}{\phi_{\text{eff}}} = \frac{1.77}{2.129} \) so that \( \phi_{\text{eff}} = 0.36 \)

(Continued on the next page)
(b) What is meant by the DLVO theory?

**Give your brief answer here:**

DLVO Theory: Total particle interaction could be determined by simply summing the contributions from the van der Waals interaction and the EDL interactions.

(c) What is bridging flocculation? What types of polymers are most suitable to induce bridging attraction? What relative surface coverage of the polymer on the particle surface is typically optimum for flocculation?

**Give your brief answer here:** Bridging flocculation is a method in which polymer that adsorb on another particle’ surface ad hold them together. The optimum amount of polymer to add is usually just enough to cover half of the total particle surface area.
2. A suspension in water of uniformly sized spheres of diameter 100 μm and density 1100 kg/m³ has a solids volume fraction of 0.25. The suspension settles to a bed of solids volume fraction 0.5. (For water: density, 1000 kg/m³ and viscosity, 0.001 Pa.s). The single particle terminal velocity of the spheres in water may be taken as 0.44mm/s. Calculate:
   a) The velocity at which the clear water/suspension interface settles;
   b) The velocity at which the sediment/suspension interface rises.

**Give your brief answer here:**
Question 2
A suspension in water of uniformly sized spheres of diameter 100 μm and density 1100 kg/m³ has a solids volume fraction of 0.25. The suspension settles to a bed of solids volume fraction 0.5. (For water: density, 1000 kg/m³ and viscosity, 0.001 Pas)

The single particle terminal velocity of the spheres in water may be taken as 0.44 mm/s.
Calculate:

a) The velocity at which the clear water/suspension interface settles;
b) The velocity at which the sediment/suspension interface rises.

SOLUTION
(a) Solids concentration of initial suspension, C_B = 0.25.

Text-Equation 3.28 allows us to calculate the velocity of interfaces between suspensions of different concentrations:

The velocity of the interface between initial suspension (B) and clear liquid (A) is therefore:

$$U_{\text{int,}AB} = \frac{U_p A C_A - U_p B C_B}{C_A - C_B}$$

Since \( C_A = 0 \), the equation reduces to

$$U_{\text{int,}AB} = U_p B$$

\( U_p B \) is the hindered settling velocity of particles relative to the vessel wall in batch settling and is given by Text-Equation 3.24:

$$U_p = U_{Te}$$

To check whether Stokes Law is valid, we calculate the single particle Reynolds number at the terminal velocity:
\[ \text{Re}_p = \frac{(100 \times 10^{-6}) \times 0.44 \times 10^{-3} \times 1000}{0.001} = 0.044 \]

This value is less than the limiting value for Stokes Law (0.3) and so Stokes Law applies and therefore in Text-Equation 3.24 exponent \( n = 4.65 \).

The voidage of the initial suspension, \( \varepsilon_B = 1 \cdot C_B = 0.75 \)

hence, \( U_pB = 0.44 \times 10^{-3} \times 0.75 \times 4.65 \)

\[ = 1.15 \times 10^{-4} \text{ m/s} \]

Hence, the velocity of the interface between the initial suspension and the clear liquid is \( 0.115 \text{ mm/s} \). The fact that the velocity is positive indicates that the interface is moving downwards.

(b) Here again we apply Text-Equation 3.28 to calculate the velocity of interfaces between suspensions of different concentrations:

The velocity of the interface between initial suspension (B) and sediment (S) is therefore:

\[ U_{\text{int, BS}} = \frac{U_pB C_B - U_pS C_S}{C_B - C_S} \]

With \( C_B = 0.25 \) and \( C_S = 0.50 \) and since the velocity of the sediment, \( U_pS \) is zero, we have:

\[ U_{\text{int, BS}} = \frac{U_pB \cdot 0.25 - 0}{0.25 - 0.50} = -U_pB \]

And from part (a), we know that \( U_pB = 0.115 \text{ mm/s} \), and so \( U_{\text{int, BS}} = -0.115 \text{ mm/s} \)

The negative sign signifies that the interface is moving upwards. So, the interface between initial suspension and sediment is moving upwards at a velocity of \( 0.115 \text{ mm/s} \).
(Continued on the back of this page) sphere diameter $x_v$, equivalent surface sphere diameter $x_s$ surface-volume equivalent sphere $x_{sv}$, sieve diameter, and projected area diameter, of a rectangular cuboid of dimension $A$ mm $\times$ $B$ mm $\times$ $C$ mm.


Your parameter value for $(A, B, C)$ will be based on the last digit of your metric card number. E.g. If your metric card number is A0175446E, please take the $(A, B, C)$ values from parameter set (6) above. A similar rule is applied to other cases.

Give your brief answer here:

Answer part (0):

- **Volume of rectangular**: $ABC=(3)(7)(4)=84 \text{ mm}^3$

  $$\frac{\pi}{6} x_v^3 = 84 \quad \rightarrow \quad x_v = 5.43$$

- **Surface area of rectangular**: $2(4\times3) + 2(4\times7) + 2(7\times3) = 122 \text{ mm}^2$

  $$\pi x_s^2 = 122 \quad \rightarrow \quad x_s = 6.23$$

- **Surface to volume ratio**: $\frac{122}{84} = 1.45 \text{ mm}^2/\text{mm}^3$

  $$\frac{6}{x_{sv}} = 1.45 \quad \rightarrow \quad x_{sv} = 4.13 \text{ mm}$$

- **The second smallest dimension is the sieve diameter**: 4 mm

- **Project area diameter**

  Area1 = 3(7) = 21 mm$^2$ \quad Area2 = 7(4) = 28 mm$^2$ \quad Area2 = 4(3) = 12 mm$^2$

  $$\frac{\pi}{4} x_{pl}^2 = 21 \quad \rightarrow \quad x_{pl} = 5.17 \text{ mm}$$
\[ \frac{\pi}{4} x^2 \text{p}_2 = 28 \quad \rightarrow \quad x_{p2} = 5.97 \text{ mm} \]

\[ \frac{\pi}{4} x^2 \text{p}_3 = 12 \quad \rightarrow \quad x_{p3} = 3.91 \text{ mm} \]

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<th>Xs</th>
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<td>135</td>
<td>174</td>
<td>1.29</td>
<td>45.00</td>
<td>27.00</td>
</tr>
</tbody>
</table>

**CN3124E/TCN3124 Quiz 1**

**Average** 26.29  
**Median** 27

Remarks:

**Question 1:** Some students calculated the Dedye length \((k^{-1})\) incorrectly. This resulted in mistake in the evaluation of particle volume and ultimately the effective volume fraction.

**Question 2:** Some students did not use the information provided by the problem statement for single particle terminal velocity and calculated this value by their own laminar solution.

**Question 3:** Some students calculated the projection diameters incorrectly because of the wrong formula used for the area of the projection circle.