On The Error in Mass Transfer in A Stirred Vessel Predicted by Frössling-Type Correlations Based on Particle Settling Velocity

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Abstract

Mass transfer coefficients in agitated solid-liquid systems are often estimated from a Frössling-type correlation which depends on the particle slip velocity. In a stirred suspension, the slip velocity will be a function of the hydrodynamic conditions prevailing in the vessel as well as particle size, and will vary from point to point. Attempts to measure it or estimate it on the basis of Kolmogorov's theory have not been successful. In consequence, for such calculations, it has been customary to take the free terminal settling velocity of a solid particle, as a representative of its mean slip velocity but the likely error involved has never been quantified, however. Using experimentally based estimates of local slip velocity obtained in a model solid-liquid system of mechanically suspended glass beads in water, we hereby assess the order of magnitude of the error likely to be incurred when using the particle settling velocity for mass transfer calculations.

The local 3D velocity components of both the solid phase and the liquid phase were measured as a function of spatial position in a stirred vessel, using a technique of **P**ositron **E**mission **P**article **T**racking (**PEPT**). The Lagrangian data were analysed using a MATLAB code to obtain a complete Eulerian description of the solid-liquid flow including time-averaged estimates of slip velocities of the solid particles.

Three different suspensions were studied under the just-suspended regime: **mono-disperse** of **3** mm diameter particles, **binary-disperse** of **1** and **3** mm particles, and **poly-disperse** consisting of five different sizes of particles ranging from **1** to **3** mm. Experiments were conducted at four different total solid mass concentrations: **5.2 wt%, 10.6 wt%, 20 wt% and 40 wt%.** In the binary and poly-disperse suspensions the different size fractions were mixed in equal proportions. Agitation was effected by a 6-Blade 45^0 pitched-turbine operating in either up-pumping or down-pumping mode.

The azimuthally-averaged error between the local mass transfer coefficient based on the true slip velocity and that based on particle settling velocity were plotted as radial and axial profiles. Results showed that the local mass transfer rate varied considerably throughout the vessel and the use of the settling velocity can lead to extremely large errors in the estimation of the local mass transfer coefficient. The error of using true slip velocity can reach approximately three times in comparison with considering terminal settling velocity and was highest in the impeller region and near the wall. The largest particles were the most affected by the degree of poly-dispersity of the suspension, and exhibited their largest mass transfer errors in the suspension with five particle size fractions.

Theory

The Froessling type equation, established by Nienow and Miles (1978), has verified good satisfaction for determining k. it is assigning the influences of particle-fluid system properties in addition to agitation parameters. It gives Sherwood number from othe dimensionless group: $\boldsymbol{Sh = 2 + 0.44 Re\, p^{1/2}\, Sc^{1/3}}$ -----------(1)

Sherwood number: $Sh = \frac{k_{sl}}{D_A}$ --------(1-a) , Reynolds number:$Re = \frac{\rho_l\, V\, d_p}{\mu_l}$ --------- (1-b) , Schmidt number: $\frac{\mu_l}{\rho_l\, D_A}$ ----(1-c) The slip velocity term in Re number is the dominant variable to calculate (k).

One of the well known methods to estimate it is by the approach of terminal velocity. $u_t = \left(\frac{4}{3}\, g d_p \Delta\rho / \rho_l\right)^{1/2}$ ------------(2) (u_t = particle terminal velocity)

PEPT Experiments

In this study the model data of the velocity vectors in 3D reported by Guida was used to calculate the slip velocity. Then, estimate the mass transfer coefficient by Froessling equation.

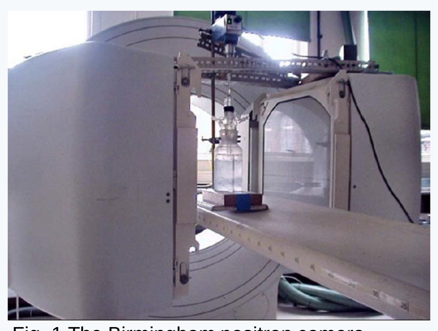


Fig. 1 The Birmingham positron camera.

1. Positron Emission Particle Tracking PEPT

Positron Emission Particle Tracking (PEPT) is a modern and unique method supplying full map of the flow patterns in transparent and opaque systems, which is impossible for other optical techniques.

the mixing vessel is centred between the 2 Gamma-ray detectors. Each detector having area of 51 X 38 cm^2, these detectors record the coordinates of both of the two γ-rays emitted from the radio activated tracer. They collect up to 105 events per **second**.

PEPT tracking time (resident time) for each experiment taken as 30 minutes for this system of mixing (glass beads- water suspension)

2. Configarations of the mixing vessel for Guida (2010):

Flat-based Perspex, cylindrical vessel, **H=T=288** mm, **4** fixed wall baffles of **width = 0.1T**, 6-blade 45^o pitched-turbine(**PBT**) which is placed at a Clearance of $\boldsymbol{C = T/4}$ from the bottom of the tank.

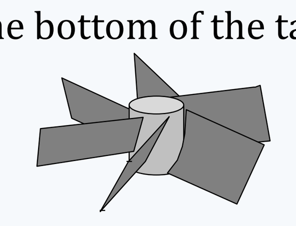


Fig. 3 6 - Pitch Blade Turbine

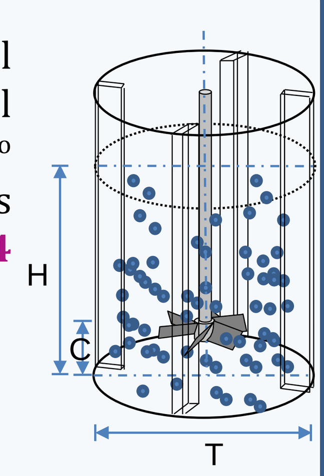
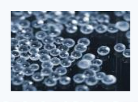


Fig 4 Mixing Tank

3. Systems of suspensions used

a) Mono-disperse suspension

2.85-3.3  + H_2O=

b) Binary-disperse suspension

1-1.25
2.85-3.3  + H_2O=

c) Poly-disperse suspension

1.00-1.25
1.50-1.85
2.00-2.3
2.55-2.85
2.85-3.3  + H_2O=

Suspensions Of 4-different concentrations:

5.2 wt%, 10.6 wt%, 20 wt% and 40 wt%.

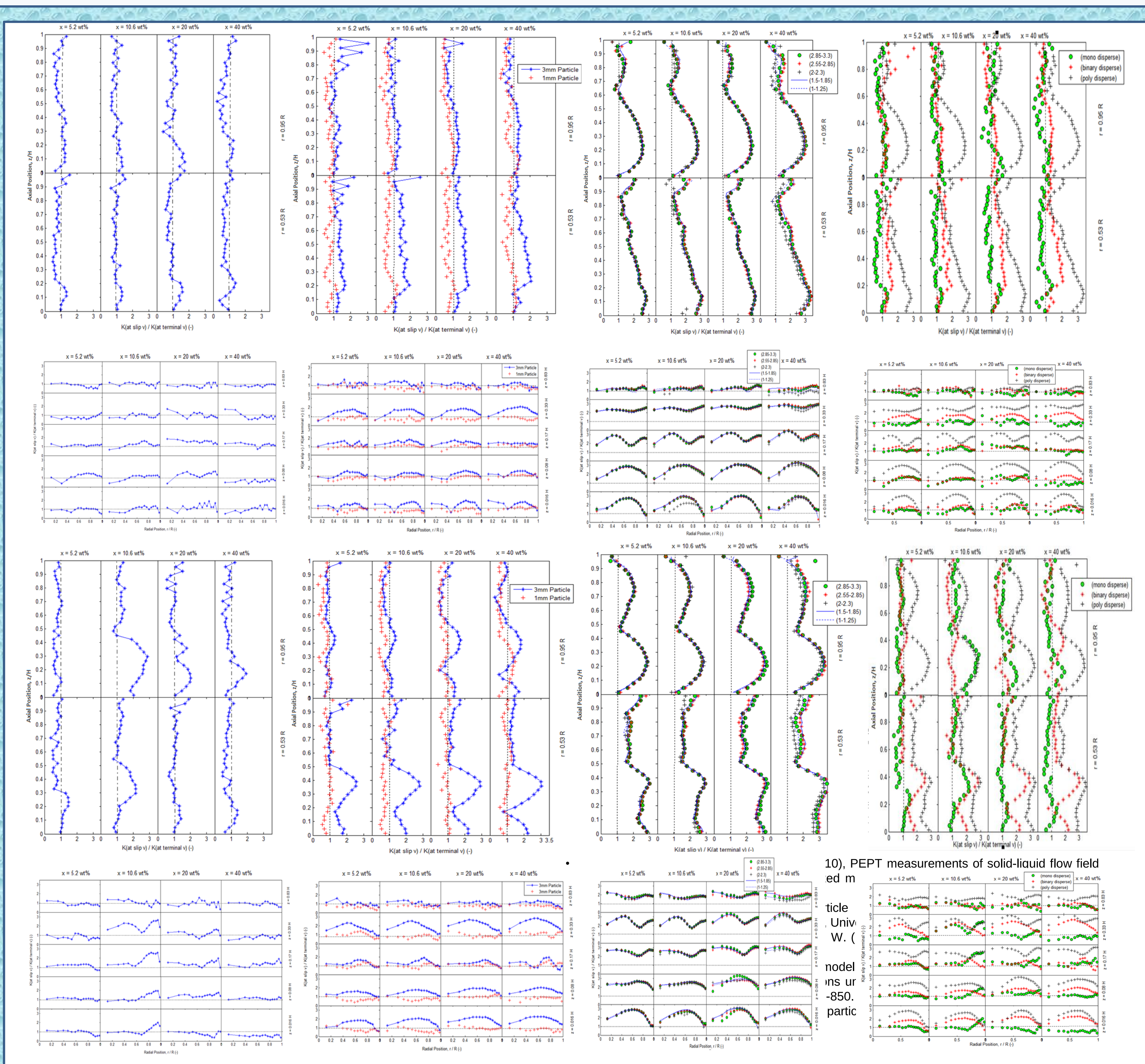
Results

The original PEPT data gives the **Cartesian coordinate (x, y, z)** of the moving tracer as a function of time. These Lagrangian flow data then converted to Eulerian description by Codes written in MATLAB language. Hence, Eulerian information obtained as an excel csv file which contains the mean velocity components (V_ϑ,V_z,V_r) for each tracer visit, the number of visits of the tracer, and a lot of important variables have been calculated as well. Therefore the slip velocity can be calculated from (Guida, 2010):

$$\mathbf{V} = \sqrt{\left(V_\vartheta^l - V_\vartheta^s\right)^2 + \left(V_r^l - V_r^s\right)^2 + \left(V_z^l - V_z^s\right)^2} \text{ -------- } (3)$$

PEPT Experiments were managed for mono, binary, and poly disperse suspensions for four different weight fractions of solids corresponding to the minimum speed (N_{js}) of particles suspension as shown in table (2). To compare the results of the estimations of mass transfer coefficient first time by depending on the slip velocity and second time by using the settling velocity, the ratio between them was plotted in vertical profiles and radial profiles for all the suspensions used in Up Pumping (**UP**) and Down Pumping (**DP**) modes of agitation. **Mass transfer coefficient ratio** = $\frac{k_{slip\ velocity}}{k_{terminal\ velocity}}$ ------------(4)

For **Radial Profiles** five special vertical sections (z/H)that expected to be important zones to study of dispersion: **z = 0.016*H***, near to the bottom of the tank; **z = 0.08*H***, approximately halfway between the lower edge of the agitator and the bottom; **z = 0.17H**, approximately under the lower edge of the impeller, **z = 0.33H**, above the upper edge of the impeller, and **z = 0.83**, in the upper zone of the mixing tank. While For **Vertical Profiles** two special radial positions were plotted: ***r* = 0.53*R***, close to the tip of the impeller; and ***r* = 0.95*R***, close to the vessel wall.



a)and **b)**representing Radial and Axial profiles of mass transfer coefficient for mono, binary, poly disperse and combination of them for (3 mm) respectively, in Down Pumping Mode.
c)and **d)**representing Radial and Axial profiles of mass transfer coefficient for mono, binary, poly disperse and combination of them for (3 mm) respectively, in Up Pumping Mode.

conclusions

- The calculated slip velocity from the three velocity components of PEPT-data gives the best prediction (more accurate one than other methods to estimate the particle relative velocity with fluid during mixing process.
- It is clearly seen that the values of mass transfer coefficient ratios ($K_{(at\ slip\ V)}/K_{(at\ terminal\ V)}$) would be good guide to the amount of error obtained when depending on the terminal settling velocity rather than using the true slip velocity from PEPT. So, the unity for each plot was highlighted by drawing dotted line to realize the deviation of mass transfer coefficient ratios around unity.
- The operation by Up Pumping mode of mixing has shown a little bit more appreciable errors in ratios.
- In binary and poly dispersion systems the largest particles (3 mm) have been displayed the greater amount of error in comparison with the smallest particles (1 mm). Even it is not clear in poly disperse like in binary due to the variant sizes of particles,
- Can be concluded from the last point that the size of the particles has a dynamic role through dispersion process may be more considered than the concentration of particles.
- The fourth column of plots on the right side demonstrates the behaviour of the same size particles (3 mm) when used in mono, binary and poly dispersion systems. Can be clearly noticed that in poly dispersion the calculated ratio of mass transfer coefficient has exhibited the significant values of error while for the mono and binary disperse the values were fluctuated to be more and less between both of them.

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