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On a solid particle suspension in a slurry pipeline

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Abstract

It is widely accepted that, in principle, a physical two-layer model satisfactorily describes the flow mechanism for stratified slurries forming particle-rich and particle-lean zones in a pipeline. However, the model component dealing with the prediction of the distribution of the solids into two layers is still under investigation.

Experiments in a laboratory loop showed that there are two mechanisms for the suspension of solid particles in a carrier - turbulent mixing in a flowing carrier and dispersion due to high shear rate in a transition zone between a particle-rich and a particle-lean layer in a pipeline.

An analysis of a mechanism for the particle suspension by the carrier turbulence is submitted and a relationship is proposed for use in the two-layer model to estimate the amount of solid particles supported by turbulent eddies in a pipeline. The relationship is derived from a balance of the kinetic energy required and available to suspend an amount of solids in a pipeline section and calibrated by the experimental data. The correlation thus obtained can be implemented in the physical two-layer model to predict the partially-stratified flow in a slurry pipeline.

1 Introduction

When solids such as sand or gravel are transported in a pipeline some degree of slurry flow stratification occurs owing to the effect of the tendency of solid particles in the carrying liquid to settle. Slurry flow is stratified, forming a particle-rich and a particle-lean zone in the pipeline cross section. According to the shape of its concentration profile, slurry flow may be considered fully-stratified or partially-stratified.

The physical two-layer model (2LM) takes into account the slurry flow stratification and transforms a real concentration profile in a pipeline cross section into simplified two-layer pattern (Fig.1).

The model is based on the assumption that there are two physical mechanisms for solid particle support in a pipeline - interparticle contact and particle suspension in a carrying liquid. Thus solids are transported as a suspended load and as a contact load. The model is composed of a set of equations expressing the conservation of mass and momentum in both layers in a pipeline section. A set of equations is computed by iteration. The model was originally developed for fully-stratified flow. Recently experiments, including the observation of velocity and/or concentration distribution in a pipeline cross section, have shown that model principles can also be used to describe phenomena occurring in partially-stratified (heterogeneous) slurry flow (Gillies et al.[4], Matousek[5]). However, to use the model as a predictive tool for partially-stratified flow in a pipeline a rule for solids division into two layers must be incorporated to the model.

2 Solids division into two layers - state of the art

For fully-stratified flow, 2LM considers the upper layer as particle-free and the lower layer as occupied by particles, all of which are in continuous contact. In a partially-stratified flow the amount of suspended solids (contributing to suspended load, C_s=C1) and the amount of solids in contact (contributing to contact load, C_c) must be predicted by a suitable method. C_c gives the concentration in contact load in lower layer C2c (C_c=C2c.A2/A when A2 and A are cross section areas of the lower layer and the whole pipeline respectively). The volumetric in-situ concentration in a pipeline cross section $C_{vi}=C_c+C_s$.

Wilson[10] proposed a simple power-law function to express the fact that the contact-load fraction C_{cd} of transported solids (represented by volumetric delivered concentration C_{vd} of solids in slurry) diminishes with increasing mean slurry velocity V_m in a pipeline:

$$\frac{C_{cd}}{C_{vd}} = \left(\frac{V_t}{V_m}\right)^M = \left(\frac{w_p}{V_m}\right)^M \left(\sqrt{\frac{8}{\lambda_f}} \cdot 0.6 \cdot \exp[45 \cdot \frac{d_s}{D}]\right)^M \qquad (1).$$

The lowest velocity for the function application is $V_m = V_t$ (V_t is the threshold velocity at the beginning of particles suspension). This is related to the terminal settling velocity of solid particle w_p, mean particle diameter d_s, pipeline diameter D and the friction factor for fluid flow λ_f. Coefficient M was assumed to be equal 2.0.

Doron et al.[3] assumed an exponential concentration profile (obtained by the Schmidt-Rouse diffusion model) in an upper suspended layer and linked it to a uniform concentration profile of lower contact layer. The assumption seems to be too unrealistic and does not provide a successful prediction of the amount of suspended solids in slurries in pipelines on industrial scale.

Recently Gillies et al.[4] proposed an empirical correlation based on a large experimental data base collected in Saskatchewan Research Council (SRC), Canada. The data base contained data for fine and coarse particle slurries from horizontal pipelines of different sizes. When the results for all solids and pipeline diameters were plotted in semilogarithmic C_c/C_{vi} vs. V_m/w_p co-ordinates a correlation was found

$$\frac{C_c}{C_{vi}} = \exp\left(-0.0184 \cdot \frac{V_m}{w_p}\right) \qquad (2).$$

Equations for the solids division proposed for the two-layer model to date have been reached by an empirical approach, rather than by an analysis of the mechanisms active in solid particle suspension in a slurry flow.

3 Solid particle support in a slurry flow

3.1 Mechanisms for solid particle support

In a partially-stratified flow the ceiling of a contact layer is not a sharp interface. It is represented by a transition zone (called shear layer) between the region in which particles in continuous contact (Coulombic interparticle contact) form a sliding or stationary granular body at the bottom of a pipeline and the region in which solid particles are supposed to have no contact with each other and are supported exclusively by the diffusive effect of the carrier turbulence. Within the transition zone the top of the granular body is sheared off due to high shear stress while above this owing to the high shear rate solid particles are supported by repulsion forces. Bagnold[1] measured the repulsion effect of interparticle collisions in a region with a high shear rate and called it "dispersive pressure". Roco & Shook[9] proposed a method to calculate the dispersive stress caused by particle impingement in terms of their microscopic model for slurry flow. From the results of their experiments they concluded that dispersive stress had a strong effect on concentration distribution and energy dissipation in a pipeline.

The character of solid particle support changes gradually across a transition zone in which all support mechanisms meet. Nevertheless, the concentration profile within a shear layer is primarily a product of an active dispersive mechanism due to interparticle collisions. Solid particles are in sporadic contact in a major part of the region, interparticle contacts occur less often near the top of a shear layer.

For the purposes of 2LM a shear layer must be replaced by a sharp interface. The shapes of concentration profiles, which show a thick shear layer with large concentration gradient in many slurry flows, suggest that at each moment repulsion forces due to interparticle collisions are able to maintain some amount of solids in suspension within a shear layer. Therefore a part of a shear layer contributes to the suspended load and a virtual interface divides the shear layer. Two mechanisms are considered to suspend solid particles in a pipeline

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occupied by partially-stratified slurry flow: the diffusive effect of fluid turbulence and the dispersive effect of repulsion forces within a shear layer. The mechanisms should be distinguished when an equation estimating an amount of suspended solids in slurry flow is derived.

3.2 Experimental observation of the internal structure of slurry flow in a pipeline

Concentration distribution and integral flow parameters were measured in partially-stratified slurry flow in the laboratory loop DN150, with pipe sections at various inclinations (Matousek[5]). The solids tested were sands 0.2-0.5 mm (sand 1), 0.5-1.0 mm (sand 2) and 1.4-2.0 mm (sand 3) and quartz gravel 3.0-5.0 mm (gravel). Test conditions with different solids and different flow characteristics and pipe inclinations led to differences in observed degrees of flow stratification in the pipe sections.

From the observations it can be concluded that coarser solids tend to be suspended by dispersive forces rather than by turbulent diffusion. The following phenomena observed in the measuring pipe sections indicate that the concentration gradient in coarse particle slurries is primarily a product of dispersive forces within a shear layer:

a. flow restratification in a pipe under the condition of increasing slurry velocity (Fig. 2b) (this effect was observed for sand 2, sand 3 and gravel)

b. very different degree of flow stratification in ascending and descending pipe under the same flow conditions in both pipe sections (Fig. 2a) (this effect was observed for sand 2, sand 3 and gravel).

Ad. a. A steep velocity gradient between a granular bed and an upper layer produces high shear stress at the interface and a shear layer is developed. The shear layer becomes thicker when the relative velocity between sliding bed and flow in upper layer increases with increasing V_m. When a moving bed is sufficiently accelerated in a pipe the shear layer diminishes at high V_m. A high degree of stratification at the high V_m indicates that turbulent mechanism is not predominant in coarse particle suspension, even in flows with high Reynolds numbers. The restratification effect is observed in both horizontal and ascending pipes.

Ad. b. A gradual concentration variation along a pipe cross section in an ascending pipe and sharp flow stratification in a descending pipe suggest that for coarse slurry the concentration gradient is again a product of dispersive forces rather than of fluid turbulence. Owing to the propelling effect of its submerged weight component exerted in the flow direction the moving bed is fast enough to prevent the formation of a shear layer in the descending pipe. Fluid turbulence itself is not able to suspend the particles. In the ascending pipe the submerged weight component has a resisting effect on the bed sliding and owing to the originally large velocity gradient between layers a thick shear layer is developed. The effect described is observed at all measured velocities V_m (2.50-5.50 m/s). Finer slurry flow (sand 1) at the same pipe inclinations demonstrates a considerably smaller difference in the shapes of concentration profiles,

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suggesting that here the carrier turbulence is the prevailing suspension mechanism and a shear layer is not well developed (Fig. 2a).

Velocity V_b of a granular body measured at the bottom of the pipe sections was found slightly higher for coarse particle slurry (gravel) than for fine particle slurry (sand 1) under the similar test conditions (V_m, C_{vd}) in both horizontal and ascending pipes. V_b was not significantly lower in the ascending pipe than in the horizontal pipe for both sand 1 and gravel slurries. Coarse particle suspension is caused rather by high shear rate along a pipe cross section than by higher turbulent intensity of flow in the upper layer.

The experiments showed that a shear layer may be rather thick, particularly in coarse particle slurries. Forces tending to disperse solid particles within shear layer may play an important role in a support of solid particles in a pipeline.

4 Analysis of a turbulent suspension mechanism

The aim of the analysis is to propose a relationship determining the amount of solid particles supported by carrier turbulence in a pipeline. For this purpose the kinetic energy balance in a pipeline section is evaluated.

<u>Assumptions</u>:

- carrier turbulence is sufficient to suspend solid particles (length scale of turbulence is larger than particle diameter)
- solid particles are suspended exclusively by turbulent diffusion, there are no interparticle contacts
- only the velocity components (of both phases) perpendicular to the flow direction, i.e. vertical in a pipeline cross section, are incorporated in a balance.

<u>Balance components:</u>

Kinetic energy of liquid flow required to suspend solids

Solid particles suspended by carrier turbulence form a cloud in a pipeline. The volumetric concentration of suspended solid particles in a cloud is C_s. The kinetic energy E_s of a cloud of suspended solid particles tending to settle in carrying liquid is a product of the mass (m_s) of a cloud of settling solid particles and its mean velocity (i.e. w_{ph}, hindered settling velocity)

$$E_s = \frac{1}{2} \cdot m_s \cdot w_{ph}^2 .$$

The mass of a cloud in a control pipeline section of the length L and pipeline cross section area A is equal to W_s/g (W_s is the submerged weight of solids occupying the cloud in a control pipeline section, g is gravitational acceleration)

$m_s = C_s \cdot (\rho_s - \rho_f) \cdot A \cdot L$ and kinetic energy

$$E_s = \frac{1}{2} \cdot C_s \cdot (\rho_s - \rho_f) \cdot w_{ph}{}^2 \cdot A \cdot L .$$

The kinetic energy $E_{s\omega}$, which is the fraction of E_s for $w_{ph} \cdot \cos\omega$ (ω is the pipe inclination angle), determines the kinetic energy of carrier flow required to maintain a cloud in suspension.

Turbulent kinetic energy of liquid flow

The total energy of the turbulence E_{ft} (the average kinetic energy of pulsation motion) in a unit control volume of flowing fluid is derived from the total energy equation as

$$E_{ft} = \frac{\rho_f}{2} \cdot \left(\overline{v'^2_x} + \overline{v'^2_y} + \overline{v'^2_z} \right) \text{ (e.g. McComb[6]).}$$

$\overline{v'^2_x}$, $\overline{v'^2_y}$, $\overline{v'^2_z}$ are the time averages of the squares of the velocity fluctuation components in Cartesian co-ordinates directions x, y, z.

Only one fraction of the total turbulent kinetic energy is effective in maintaining solid particles in suspension against gravity. This fraction varies with the fluctuating velocity component vertical in a pipeline cross section. Turbulent kinetic energy E_f, associated with a vertical pulsative velocity component of fluid particles in a fluid stream, is written

$$E_f = \frac{1}{K} \cdot \rho_f \cdot \overline{v'^2_y} .$$

Oroskar & Turian[7] proposed the coefficient K = 4 for isotropic turbulence.
E_f in a control pipeline section of the length L is

$$E_f = \frac{\rho_f}{K} \cdot (1 - C_{vi}) \cdot \overline{v'^2_y} \cdot A \cdot L .$$

This is the kinetic energy of carrying liquid flow available to maintain solid particles in suspension by turbulence.

<u>Kinetic energy balance:</u>

Kinetic energy balance $E_{s\omega} = E_f$ in a pipeline section determines the amount of solids suspended by turbulence in a slurry flow.

$$\frac{C_s}{C_{vi}} = \frac{2}{K} \cdot \frac{\rho_f}{\rho_s - \rho_f} \cdot \left(\frac{\overline{v'_y}}{w_{ph} \cdot \cos\omega} \right)^2 \cdot \frac{1 - C_{vi}}{C_{vi}} .$$

The balance equation provides the dimensionless groups of parameters which determine the C_s/C_{vi} ratio. From this equation a correlation based on parameters which are the input parameters to the two-layer model can be proposed.

A characteristic value of turbulent pulsative velocity (a root mean square fluctuation velocity in the y-direction) $\sqrt{\overline{v'^2_y}}$ can be estimated as being equal to shear velocity u∗ (e.g. Laufer's experiments in Davies[2]) in a pipeline cross section for fluid flow. Then

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$$\sqrt{\overline{v'^2_y}} = u_* = \sqrt{\frac{\tau_w}{\rho_f}} = V_m \cdot \sqrt{\frac{\lambda_f}{8}} .$$

For slurry flow it can be assumed that $\sqrt{\overline{v'^2_y}}$ is a function of V_m and may be influenced by the presence of solids in fluid flow. The hindering effect of solids concentration on the particle settling velocity in a cloud of suspended particles is described by equation

$w_{ph} = w_p \cdot (1 - C_s)^m$ (Richardson & Zaki[8]).

When solids and liquid are considered to be of constant specific gravity (for example sand or gravel in isothermal water flow) a correlation may get the form of the power law equation

$$\frac{C_s \cdot (1 - C_s)^m}{C_{vi}} = X \cdot \left(\frac{V_m}{w_p . \cos\omega} \right)^Y \cdot \left(\frac{1 - C_{vi}}{C_{vi}} \right)^Z \qquad (3).$$

The correlation was tested by experimental data processed by 2LM to get the C_s values. The coefficients X, Y, Z were determined by regression of processed experimental data.

5 Determination of solids fraction suspended by turbulence for 2LM - calibration of analytical equation by experimental data

The correlation (3) provides a good agreement with data for slurries in which turbulent suspension in the pipe predominates over the dispersion effect in the shear layer (see Fig. 3 for sand 1 in a 150 mm pipeline and similar sand 4 (0.05-0.60 mm) in a 650 mm pipeline). Data for sand 2 fit the correlation for high V_m where the turbulent suspension mechanism becomes effective. Although subject to modification in the light of an increased data base, the correlation with coefficient values

$$X = 0.1574, Y = 0.0555, Z = 0.5619$$

fits very well the available data (regression coefficient is 0.99 for sand 1 data at 0, 25, 35 deg. pipeline inclinations).

The nonlinear relationship between C_s and C_{vi} expresses the fact that the ability of a carrier to suspend particles by turbulence is proportional to the amount of carrier in a pipeline section. The amount of solid particles supported by turbulence is not dependent on pipe diameter D according to the correlation (3). Comparison of experimental data from DN150 and DN650 seems to confirm this prediction. Experimental data obtained in SRC for a variety of pipe diameters (DN53, DN159, DN263, DN495) also did not show any significant influence of D on the determined C_c (Gillies et al.[4]).

The correlation (3) is not found in coarse particle slurries (sand 2 at low V_m, sand 3, gravel) where suspension mechanism occurring in the shear layer

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predominates. The Gillies type of correlation provides a reasonable fit for experimental data for the flow of coarse particle slurries.

Gillies et al.[4] observed a systematic deviation in their correlation for the fine sand data, particularly at high C_{vi}. The likely explanation is that the dimensionless groups C_c/C_{vi} vs. V_m/w_p do not sufficiently represent the process of turbulent suspension of solid particles.

6 Conclusion

The equation (3) - with coefficients X, Y, Z determined experimentally - predicts the amount of solids which is supported by turbulence in slurry flow. The correlation can be implemented in the physical two-layer model to predict the solids division into two layers of partially-stratified flow in a slurry pipeline.

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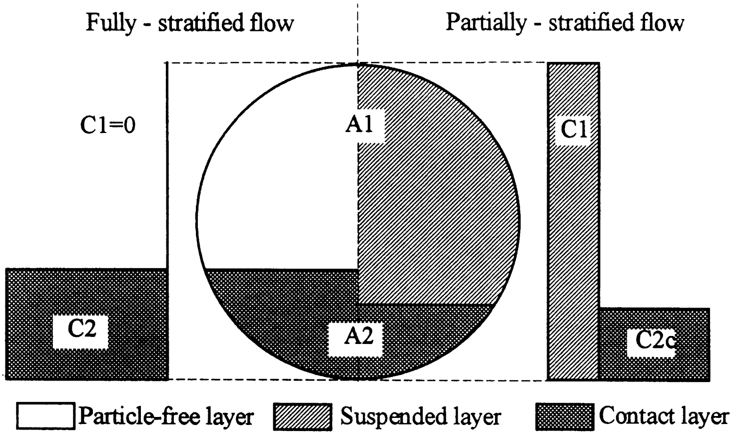

Figure 1: Schematic cross-section for two-layer model.

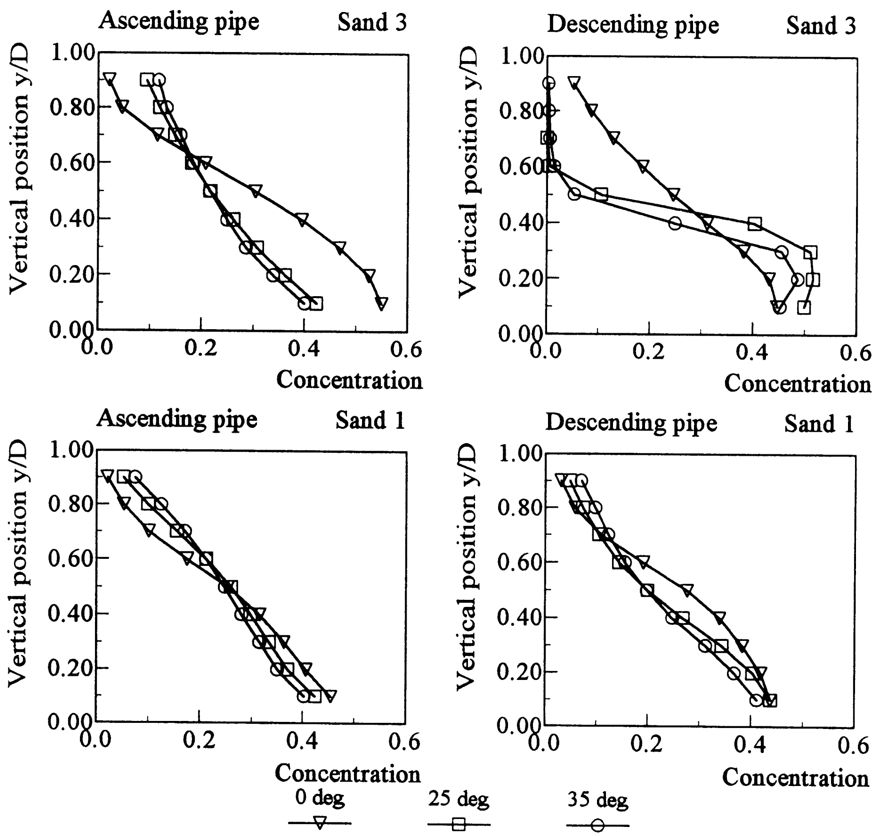

Figure 2a: Concentration distribution in inclined pipe (Vm=3.50 m/s, incl. in legend).

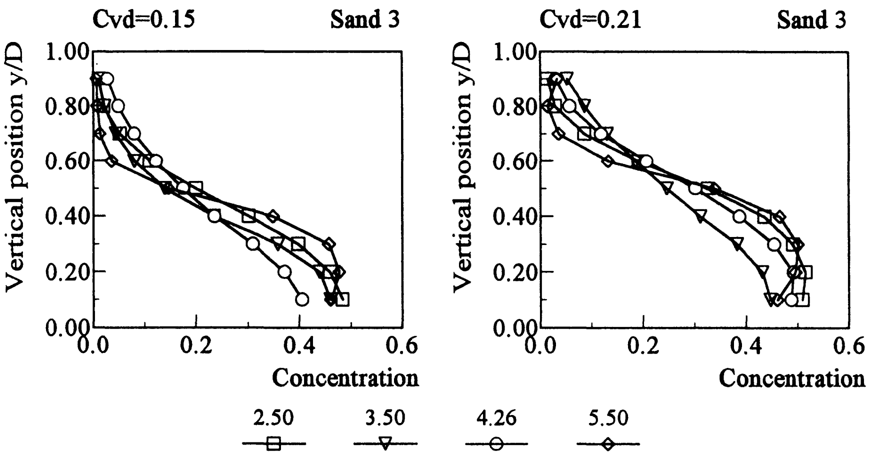

Figure 2b: Concentration distribution in horizontal pipe (Vm in legend).

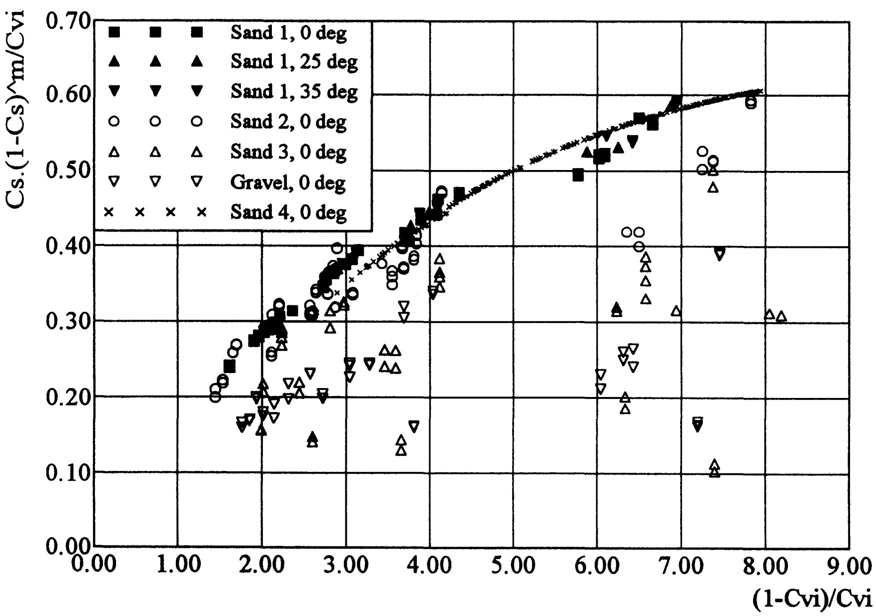

Figure 3: Correlation between dimensionless groups.