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Analysis of slurry flow regimes downstream of a pipe bend

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ABSTRACT

The influence of the pipe bend between downward and horizontal flows on transition velocities between slurry flow regimes in a horizontal pipe has been characterized using electrical resistance tomography. The experiments have been carried out using a pipe loop of diameter 0.076 and 10 m long. The slurry mixture consisted of water and 100 μm diameter glass beads. The influence of solids concentration and the distance from the bend outlet on transition velocities have been studied. Two transition velocities have been determined: the transition between a pseudo-homogenous flow and a heterogeneous flow and the limit deposit velocities at the onset of solid particle bed. Results have shown that the bend significantly contributes to the suspension of the solids particles and to the decrease in the transition velocities between the slurry flow regimes occurring in a horizontal pipe. The distance from the bend outlet where these transitions take place increases with the velocity. Furthermore, the solids concentration influences these transitions at low concentration while there is little influence at high concentration. These observations have been compared with correlations for the transition velocities in a horizontal pipe.

Keywords: Tomography; ERT; Bend; Flow transitions; Flow regimes

1. Introduction

Many processes in the mineral and chemical industries involve slurry flows. The design and optimization of these processes are particularly challenging due to the complex nature of solid–liquid multiphase flows. Several parameters are required to describe the process hydrodynamics conditions: the physical properties of the liquid and the solid phase, the size distribution of the solid particles, the diameter of the pipe or the vessel, the bulk slurry transport velocity and the solids concentration.

In pipeline transport, the slurry concentration profile in the pipe is of paramount importance to predict the pressure drop and the friction losses, which are needed to size pumps and pipes and determine the operating conditions. For chemical reactors, the slurry concentration profile is also required to understand the hydrodynamics and predict the reactor performance, such as chemical conversion and heat transfer.

An important challenge brought by slurry flows concerns the availability of reliable non-intrusive measurement methods, like tomography, to obtain concentration and velocity profiles required to design and scale-up slurry flow processes. The lack of suitable experimental data makes difficult the development, tuning and validation of the models whether they are theoretical, empirical or numerical.

Some applications of electrical resistance tomography (ERT) to slurry flow in a pipe at laboratory scale have been reported (e.g., (Fangary et al., 1998; Lucas et al., 1999; Pachowko et al., 2004; Wood et al., 2004; Norman and Bonnecaze, 2005; Pullum et al., 2006; Stevenson et al., 2006)). According to these studies, ERT is a promising technique to visualize slurry flow in a pipe. However, hardware and software limitations make it difficult to quantitatively exploit ERT images. For that purpose, a strategy for the characterization of slurry flows in pipe using ERT has been developed by the authors, which combines quantitative image reconstruction techniques (Giguère et al., 2008b) and a procedure for the direct interpretation of resistance measurements (Giguère et al., 2008a). This strategy has successfully been applied to identify slurry flow regimes and transitions in a pipe for various operating conditions, such as slurry velocity and bulk solids concentration (Giguère et al., 2008a).

Slurry flow regimes in pipes are usually classified according to the solid phase concentration profile, this latter being

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Nomenclature

Symbol

C	solids concentration (% v/v)
C_B	bulk solids concentration (% v/v)
C_{B0}	bulk slurry concentration at reference condition (% v/v)
C_D	drag coefficient
d	particle diameter (m)
D	pipe diameter (m)
E_D	total energy required to suspend solid particles (J)
E_T	total energy available to suspend solid particles (J)
F_{LD}	dimensionless limit deposition velocity
$F_{LD,HP}$	dimensionless limit deposition velocity in horizontal pipe
δF_{LD}	change in dimensionless limit deposition velocity
g	gravitational acceleration (9.81) (m/s^2)
L	distance from bend outlet (m)
n	hindered settling velocity exponent
V_{LH}	limit homogeneous velocity (m/s)
V_{LD}	limit deposition velocity (m/s)
V_t	solid particle terminal velocity (m/s)

Greek symbols

α	correction factor
β_1	regression coefficient
β_0	regression coefficient
Ψ	symmetry indicator
Ψ_0	symmetry indicator at reference condition
ρ_L	liquid density (kg/m^3)
ρ_S	solid density (kg/m^3)

a function of the velocity in the pipe (Govier and Aziz, 1972; Shook and Roco, 1991; Doron and Barnea, 1996; Abulnaga, 2002). With settling slurries, for which the density of the solid phase is higher than the density of the carrier phase, there are typically four main regimes in a horizontal pipe. Namely: flow with a stationary bed, flow with a moving bed, heterogeneous flow (asymmetric) and pseudo-homogenous flow (symmetric). Following the terminology of Doron and Barnea (1996), the velocity at the transition between pseudo-homogenous and heterogeneous slurry flow regime has been defined in the following as the limit homogenous velocity (V_{LH}), while the velocity separating the heterogeneous flow conditions and the onset of stationary particle bed at the bottom of the pipe has been defined as the limit deposit velocity (V_{LD}).

The transition between these flow regimes are generally represented by means of the pressure gradient versus the velocity of the slurry. They form the base on which most models relating the pressure drop and the friction losses are developed. Correlations available for the transition velocities between the slurry regimes can be found in slurry handbooks (Govier and Aziz, 1972; Shook and Roco, 1991; Abulnaga, 2002; Wilson et al., 2006). The limit deposit velocity is by far the most investigated in the literature because of its importance in the design of slurry pipeline.

One of the first correlations for V_{LD} was established by Durand and Condolios (1952) as

$$V_{LD} = F_{LD}\sqrt{2gD\left(\frac{\rho_S - \rho_L}{\rho_L}\right)}, \tag{1}$$

where D is the pipe diameter, ρ_S and ρ_L are the density of the solid and the liquid phase, and F_{LD} is a dimensionless deposition velocity coefficient that depends on the particle diameter and solids concentration. The value of F_{LD} was represented in graphical form for uniform particle size up to 3 mm and concentration in ranging from 2% to 15% (v/v). A similar correlation was proposed by Wilson and Judge (1976) to generalize the effect of particle diameter on F_{LD} as

$$F_{LD} = 2 + 0.3\log_{10}\left(\frac{d}{DC_D}\right), \tag{2}$$

where d is the particle diameter and C_D is drag coefficient. Another useful correlation has been introduced and presented in a nomographic chart (Thomas, 1979). Nevertheless, these correlations can only provide an estimate of the maximum value of the limit deposit velocity that can be encountered at any solids concentration (Gillies et al., 2000).

Some correlations accounting for the influence of solids concentration are available to predict the limit deposit velocity (e.g., (Oroskar and Turian, 1980; Parzonka et al., 1981; Wilson, 1986; Gillies and Shook, 1991; Gillies et al., 2000)). In particular, Oroskar and Turian (1980) used a semi-theoretical mechanistic approach to develop a correlation valid for a wide range of parameters, including the solids concentration. To establish their correlation, they considered an energy balance between the total energy provided by the fluid turbulence and the amount of energy necessary to maintain solid particles in suspension. For homogeneous flow regime, the energy provided by the fluid turbulence exceeds the energy necessary to maintain all the solid particles in suspensions. The V_{LH} and V_{LD} correspond to the limiting cases where the energy from fluid turbulence becomes insufficient to maintain the particles in suspension.

Using power-law type regression, the authors found a relationship for V_{LD} in term of concentration C,

$$V_{LD} \propto C^{0.1536}(1 - C)^{0.3564}. \tag{3}$$

To account for the influence of solid particles on turbulence, a modification of this approach has been suggested (Davies, 1987). Namely,

$$V_{LD} \propto (1 + \alpha C)^{1.09}(1 - C)^{0.55n}, \tag{4}$$

where α is a correction factor and n is the hindered settling velocity exponent (Maude and Whitmore, 1958). It is interesting to underline that the correction factor describes reasonably well the influence of solids concentration in experimental observations reported in the literature. In particular, it allows for predicting the presence of a maximum in V_{LD} for slurries having a broad distribution of particle diameters or high fines content.

Correlations for the transition velocity between the pseudo-homogeneous and the heterogeneous slurry regimes have been discussed in some handbooks (Govier and Aziz, 1972; Abulnaga, 2002). Following the work of Spells (1955), a correlation was reported by Govier and Aziz (1972) for the