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Coarse particle support in turbulent flow of visco-plastic carrier

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Abstract. The paper deals with a flow behaviour of mixture composed of coarse glass-bead particles and non-Newtonian carrying liquid of Herschel-Bulkley type in a pressurized pipe. Essentially, there are two mechanisms governing support of particles in the flowing carrier: mutual inter-particle collisions and interaction of particles with carrier turbulent eddies. The turbulent support is quantified by a turbulent-diffusion model, which predicts a distribution of concentration of particles in the flow. In the model, the particle turbulent diffusivity is an important parameter dependent on a number of flow quantities, e.g. the carrier rheological parameters. In case of Newtonian carrier, the viscosity is the only rheological parameter and it is constant throughout the flow. In the non-Newtonian carrier, however, local values of the viscosity vary with the shear strain and so affect the particle diffusivity. The paper discusses experimental and analytical results for non-Newtonian mixture flows of measured rheological parameters and flow characteristics. Based on measured concentration profiles, a suitable method is used to determine the local particle diffusivity experimentally.

1 Introduction

Conveying and pumping of non-Newtonian slurries are processes which occur in many branches of industry as mining, dredging, chemistry, or food industry. Depending on slurry properties and conveying conditions, non-Newtonian slurries can flow in the laminar regime or in the turbulent regime in pressurized pipes [1,2]. While laminar flow is relatively simple and its behaviour is well understood, turbulent flow is much more complex and much less understood. A degree of complexity further increases if coarse particles are involved [3-5].

For stratified and heterogeneous flows of coarse-grain slurries with a Newtonian carrier (as water), relatively successful models are available for predicting the distribution of particles in pipe flow [6-9]. Such models are not readily available for turbulent flows of complex slurries based on a non-Newtonian carrier. As a first approximation, it can be assumed that the Newtonian models may be used for non-Newtonian conditions provided that rheology of the non-Newtonian carrier is taken into account. The aim of this paper to evaluate a capability of the Newtonian-based turbulent diffusion model appropriately modified for non-Newtonian liquid to predict a distribution of volumetric concentration of coarse particles in a vertical of a pipe cross section. The attention focusses on the key parameter of the turbulent-diffusion model - the particle diffusivity.

2 Survey of modelling of concentration distribution

A distribution of solid particles in slurry flowing through a pressurized pipe is an important property of the flow. Together with a distribution of particle velocity across the flow cross sectional area, it determines the flow internal structure resulting from mechanisms that govern particle support in flowing carrying liquid and hence affect flow friction.

Basically, there are two very different mechanisms that can support particles in flowing slurry: the interaction of a particle with turbulent eddies of the flowing carrier and the interaction of a particle with other particle through contacts. The contacts between particles are either permanent or sporadic. Sporadic contacts have a form of inter-particle collisions. Hence, particles can be dispersed and distributed throughout a slurry flow either by a diffusive action of turbulent eddies (e.g. [10]) or by collisions between particles travelling at different velocities (e.g. [11]).

A turbulent-diffusion model of the Schmidt-Rouse type have proven to be successful in predicting concentration profiles of fine particles (supported by turbulent eddies) in dilute suspensions based on Newtonian carrying liquids [12],

$$\frac{dc}{dy} = \frac{-v_t}{\varepsilon_s} \cdot c \qquad (1)$$

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in which dc/dy is the concentration gradient, v_t is the terminal settling velocity of particle, ε_s is the local turbulent diffusivity of particle at vertical position y, and c is the local volumetric concentration of particles at the position y.

A typical modification of the model in order to make it useable for concentrated slurries is an implementation of the hindered settling effect to the model equation [6,10,13],

$$\frac{dc}{dy} = \frac{-v_t}{\varepsilon_s} \cdot (1-c)^m \cdot c \qquad (2)$$

in which and m is the exponent in Richardson-Zaki equation for hindered settling velocity [14].

3 Experimental work

3.1 Experimental rig

A pipe loop (Figure 1) is located in the Water Engineering Laboratory of the Czech Technical University in Prague. It is composed of pieces of a PE pipe (I.D. 51.4mm, blank pipe in Figure 1) and piece of transparent acrylic pipe (I.D. 50.0mm, grey pipe in Figure 1). The total length of the loop is 22.96m and its volume is 45.08l. The length of the horizontal section is 6.20m. The pump EBARA 3M 40-200/7,5kW is driven by an electric motor with a variable frequency converter TECO GD100-011G-4 11kW. Pump parameters are: power 7,5kW, impeller diameter 200mm, maximum flow 11.67l/s, total head from 58m to 44m (valid for water for maximum flow).

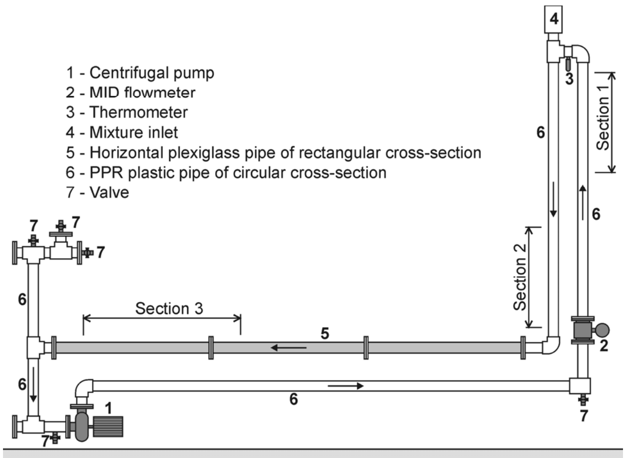

Figure 1. Test pipe loop in Water Engineering Laboratory.

Differential pressures are measured over vertical Sections 1, 2 (1.3m long) and the horizontal Section 3 (1m long) using the differential pressure transducers Fischer Rosemount DP1151 (Sections 1 and 2) and the transducer Siemens Sitrans P DSIII (Section 3). An electromagnetic flow meter Krohne Optiflux 5000 measures the flow rate in the vertical pipe mounted to the discharge outlet of the centrifugal pump. The temperature of the flowing medium is measured in the vertical invert pipe. The rheology of fluids are tested on viscometer HAAKE VT 550.

An ERT (Electrical Resistance Tomography) equipment was used to measure a distribution of particle concentration in the pipe. The equipment contained 3 rings located at 3 different locations along the transparent acrylic horizontal pipe. Each ring had 16 electrodes and was able to sense a tomographic image of conductivity distribution in one pipe cross section. The rings were connected with the UCT processing unit controlled by UCT Tomography software. The processed ERT data were further post-processed by EIDORS procedures.

A sedimentation column was exploited to test the terminal settling velocity of particles in quiescent non-Newtonian liquid of different rheologies.

3.2 Tested materials

Tested mixtures are composed of Carbopol solutions as carrying liquids and glass beads as conveyed solids. Carbopol is an acidic powder. After mixing with water and neutralizing, it forms a non-Newtonian solution of Herschel-Bulkley type described using the rheological model $\tau = \tau_y + K\dot{\gamma}^n$, in which $\dot{\gamma}$ (s^{-1}) is the shear rate. Values of the rheological parameters (τ_y, K, n) depend on a concentration of the powder in the solution. A big advantage of Carbopol is its transparency and a quite simple preparation of a solution of various concentrations. Transparency is very useful for visual observations of solids in non-Newtonian mixtures flow.

The fraction of glass beads TK1.5 is virtually monodisperse with d_{50} = 1.5 mm, the sieving test showed that all grains were finer than 1.61 mm and all grains were coarser than 1.49 mm. Its density is ρ_s = 2488 kg/m^3. The B7 fraction is narrow graded (grain sizes from 400 to 600 micron) with the median size d_{50} = 0.57 mm, and density of particles 2450 kg/m^3.

3.3 Measured quantities and flow conditions

A set of quantities was measured and stored at each installed flow condition forming a test run. The output of the magnetic flow meter was interpreted as the average velocity of the mixture in the pipe, V_m. The differential pressure measured in the horizontal pipe (Section 3) was recalculated to the hydraulic gradient, i. Furthermore, ERT images and temperature were measured at each test run. Test runs collected for slurry of one value of the mean volumetric concentration of particles, C_v, in the loop formed one test series. C_v was determined as the ratio of the known volume of particles introduced to the loop and the total volume of the loop. Samples of flowing liquid were taken from the loop before and after the test series for viscometry tests in the rotational viscometer. For some series, rheological parameters were determined also for several runs within the series.

A typical test series collected a set of test runs for a broad range of velocities with the same slurry. Results of one series produced one flow curve as in Figure 2. Table 1 gives a list of collected test series used in the evaluation of turbulent diffusivities. Table 2 specifies flow conditions for the runs incorporated to the evaluation.

Table 1. Survey of test series

Test no.	Code of test series
1	CBP0,175b_TK1,5_20140803_a
2	CBP0,175b_TK1,5_20140803_b
3	CBP0,150e_B7_20150520_a
4	CBP0,250b_TK1,5_B7_20150812_b

Table 2. Flow conditions for test series

Test No.	C_v [-]	d_m [mm]	V_m range [m s^{-1}]	No. of profiles	τ_y [Pa]	K [Pa s^n]	n [-]
1	0.1	1.5	3.41-4.51	5	0.811	1.414	0.504
2	0.2	1.5	3.51-4.45	5	1.872	2.365	0.476
3	0.2	0.57	3.39-3.79	3	1.435	1.296	0.534
4	0.167	1.04	3.38-4.52	6	0.462	0.452	0.623

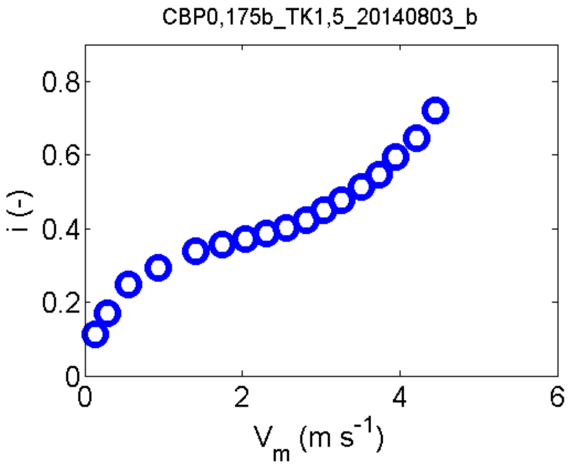

Figure 2. Flow curve (hydraulic gradient versus average velocity of mixture flow) for Test series No. 2.

4 Determination of particle diffusivity from experiments

Turbulent-regime test runs (e.g. the 5 points at the highest velocities in Figure 2) were processed to evaluate the particle turbulent diffusivity for the Rouse-Schmidt turbulent-diffusion model (Eq. 2). The evaluation process required measured concentration profiles as inputs.

4.1 Concentration profile and gradient

Measured profiles of local chord-averaged volumetric concentration (left panels of Figure 3) exhibited a non-uniform distribution (and hence non-zero concentration gradient) of conveyed particles in in the pipe cross section. In order to determine local gradients, the concentration profiles were approximated by a high order polynomic function. This smoothened a profile curve and enabled to obtain values of the local gradient *dc/dy* by differentiating the polynomic function.

4.2 Local settling velocity

An additional input to the evaluation procedure was the vertical distribution of local settling velocities of particles. In flowing non-Newtonian liquids, the local viscosity varies across the pipe cross section because it is sensitive to the local strain rate (i.e. to a velocity profile of the flow). This feature cannot be captured by the static settling velocity test and hence our velocities measured in the sedimentation column could not be directly used in the evaluation procedure.

Instead, it was assumed that the local terminal settling velocity could be calculated using a method for a Newtonian carrier [15] provided that suitable local turbulent viscosities replaced the Newtonian dynamic viscosity.

A distribution function based on results of DNS-simulations of turbulent flows of Herschel-Bulkley was employed to get the vertical distribution of chord-averaged values of the turbulent viscosity of particles. The local values of this viscosity were used to calculate the local settling velocity using the Haider-Levenspiel method [15].

4.3 Distribution of diffusivity and average diffusivity

The local settling velocity and the local concentration gradient were fed to turbulent diffusion formula (Eq. 2) to get local values of the particle diffusivity ε_s (right panels of Figure 3). The local particle diffusivity seems to be almost uniformly distributed throughout the core of the flow. Hence, the average cross-sectional value of the particle diffusivity, $\varepsilon_{s,mean}$, is a useful parameter to model particle suspension using a turbulent-diffusion model. For our purposes, values of $\varepsilon_{s,mean}$ were determined as average values from the core of flow within the range <-0.5R;0.5R>.

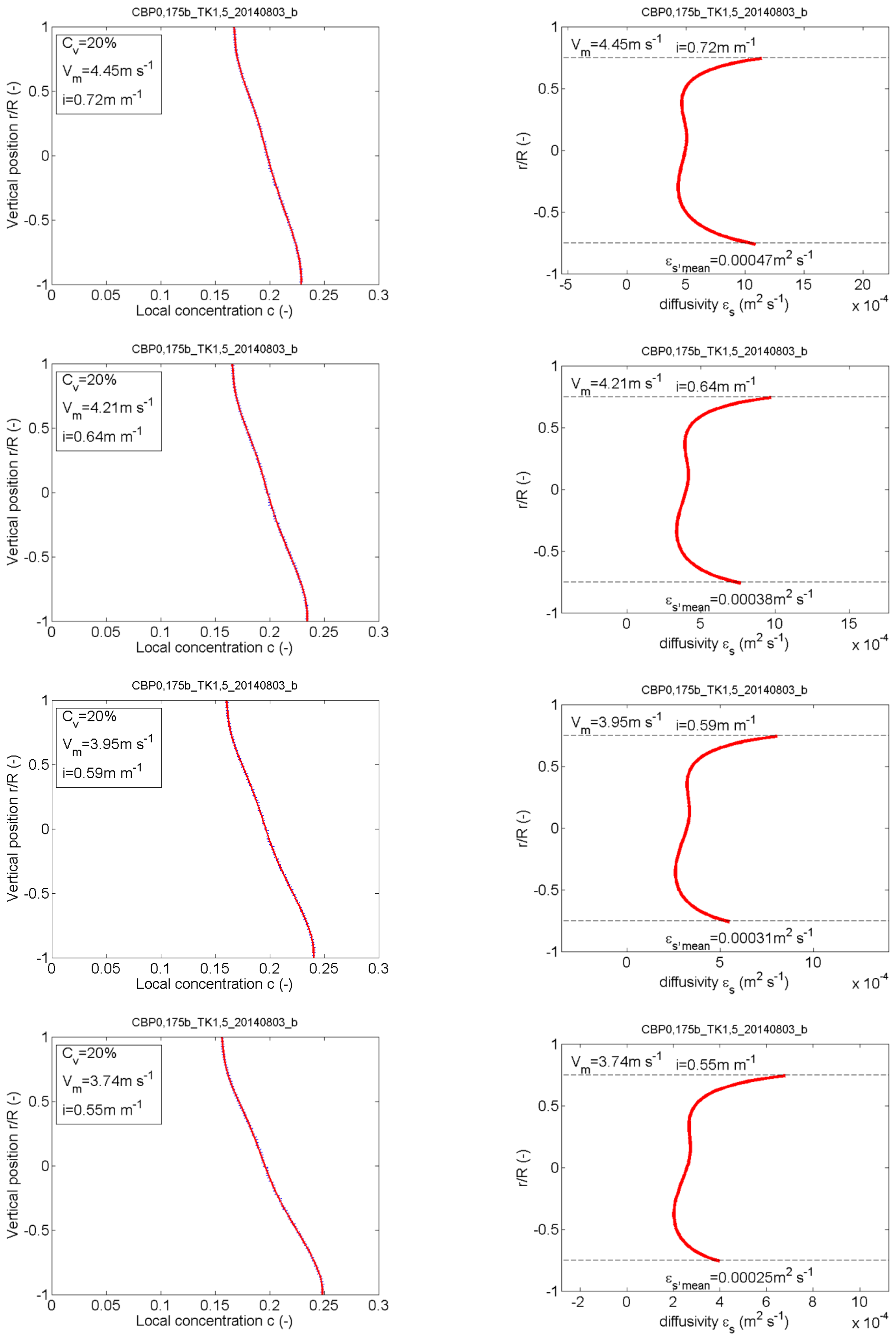

Figure 3. Measured concentration profile and evaluated particle diffusivity.

The dimensionless average particle diffusivity was obtained by normalizing $\varepsilon_{s,mean}$ with the flow shear velocity and the pipe inner radius, $\varepsilon_{s,mean}/(u_* * R)$. The shear velocity was calculated from the measured hydraulic gradient i,

$$u_* = \sqrt{g \frac{D}{4} i} \quad (3)$$

Figure 4 shows the dimensionless diffusivities obtained for different test series.

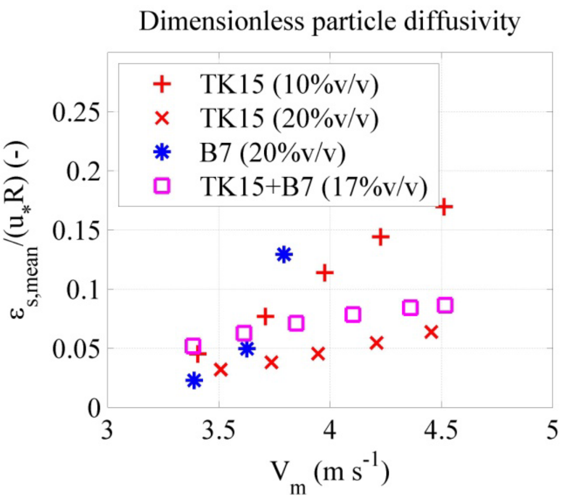

Figure 4. Dimensionless diffusivities obtained for all test series.

5 Discussion

Figure 4 indicates that the dimensionless turbulent diffusivity of particles in mildly viscous Herschel-Bulkley fluid is sensitive to flow velocity, solids concentration and fluid rheology. It also indicates that the diffusivity values are of the same order of magnitude as in a Newtonian carrier. An experimentally determined average value for the diffusivity in flows of sand-water mixtures through a 150-mm pipe was found equal to approximately 0.12 [10], other experiments suggested a value of 0.08 for the centre of the solid-water flow [6]. Compared to the Newtonian case in [10], the diffusivity in the non-Newtonian carrier seems to be considerably more sensitive to the velocity and concentration.

6 Conclusions

The turbulent diffusivity was evaluated in coarse mixture flows within Herschel-Bulkley carrier. The evaluations indicate that the dimensionless diffusivity of particles is of the same order of magnitude in flows of slurry based on a mildly viscous non-Newtonian carrier as in slurry flows with an equivalent Newtonian carrier.

The dimensionless average particle diffusivity appears to be sensitive to carrier rheology, average velocity of mixture and average concentration of coarse particles in the mixture. The data base needs to be extended further to serve as a basis for an appropriate correlation.

The evaluated particle diffusivity can be used in a turbulent diffusion model in order to predict a 1-D concentration distribution of coarse particles in turbulent flow of non-Newtonian carrying liquid.

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