A Step Forward in the Use of Computational Fluid Dynamics Simulation as a Tool for the Engineering Handling of Slurry Pipeline Systems

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A STEP FORWARD IN THE USE OF COMPUTATIONAL FLUID DYNAMICS SIMULATION AS A TOOL FOR THE ENGINEERING HANDLING OF SLURRY PIPELINE SYSTEMS

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KEY POINTS

- *A two-fluid model is developed in Ansys Fluent™ for simulating slurry flows in pipelines*
- *The applicability conditions are clearly defined and can be verified a priori*
- *The model requires calibration of a single empirical coefficient*
- *The level of accuracy is satisfactory for slurry flows in horizontal pipes at the laboratory scale*
- *Long-term goal is to use the model for simulating complex pipeline components such as slurry pumps*

1 BACKGROUND AND LONG-TERM RESEARCH GOALS

Pipeline transport of granular material in the form of slurry over long distances has been a well-established technology in the mining industry for a long time (*Thomas & Cowper*, 2017). Traditionally, the design of slurry pipelines has mostly been based on best practices gathered from previous experience. Additionally, empirical models obtained from laboratory data allow gross estimation of the key parameters to ensure efficiency and safety of slurry transport (*Wilson et al.* 2006). In the last few decades, mechanistic models have been developed, which take the structure of the flow into account and allow for deeper insight, but still rely on simplifying assumptions and thus require calibration of several coefficients based on laboratory experiments (*Wilson* 1976). More recently, Computational Fluid Dynamics (CFD) has opened up new possibilities in the field of slurry pipe transport, also thanks to the advances in the computer technology and capability of simulation codes. The paradigm shift brought by CFD requires abandoning a global vision of the slurry flow in favor of a local one, in which the focus is on the key physical processes governing particle transport, such as particle-turbulence interactions or inter-particle collisions, rather than on macroscopic quantities such as a bulk velocity or the hydraulic gradient (*Messa et al.* 2021). Such change of perspective has a tremendous impact on slurry pipeline technology, as it has potential to treat problems that cannot be addressed using traditional approaches, including the prediction of the flow in large-diameter (> 500 mm) pipes or in complex components of the pipeline system, such as the slurry pumps. In addition, a CFD simulation provides much more information on the flow compared to laboratory experiments, and it allows investigating relevant phenomena extremely hard or even impossible to characterize experimentally, such as particle degradation or erosive wear.

However, several challenges must be solved to make CFD a useful tool for the engineering handling of slurry pipelines. These include modelling and numerical issues. To be practically solved, CFD models rely on assumptions and simplifications, which increase in number and strength with the complexity of the simulated phenomena; in the end, all CFD models face a certain degree of empiricism, making experimental data necessary for calibration and validation. For slurry pipe flows, only the hydraulic gradient and the vertical solid concentration profile in horizontal pipes with relatively small diameter (typically < 150 mm) can be measured accurately enough. Thus, a big challenge is how to assure that a CFD model calibrated and validated with respect to small pipe laboratory experiments preserves its good predictive capacity when applied to large pipes or complex pipeline components. Another challenge is the need for a suitable "engine" for the numerical solution of the equations. The issue is not so much finding appropriate solution algorithms, which are nowadays relatively well established, but rather having access to advanced numerical utilities that are necessary to handle complex geometries, such as for local mesh refinement, dynamic mesh generation, etc.

The long-term objective of the authors' research is to develop a CFD framework that can be used as an engineering-effective tool for the optimized design of complex slurry pipeline components, such as the slurry pumps. With this goal in mind, a slurry flow model has been built within the Ansys Fluent™ code, which is widely used by professional engineers also because of its capacity of efficiently handling complex flows. On the grounds of the previous considerations, Ansys Fluent™ was judged an appropriate "engine" to build the fluid dynamic model on, and efforts were devoted to defining the appropriate set of equations and closures as well as their applicability conditions. In this preliminary study, the focus was on slurry flows in which the main transport mechanism is the interaction between the solids and the turbulent flows, whereas particle-particle interactions can be ignored; this typically occurs for very fine solids, say smaller than 40 microns. In order to calibrate and validate the model, reference is still made to experimental data for horizontal pipe flows, shelving the application to complex geometries to a next stage of the work.

2 TWO-FLUID MODELLING FRAMEWORK

Slurry pipelines are generally characterized by high amounts of solids, say well above 10% in terms of in situ concentration. Therefore, the selected modelling approach was the "two-fluid" one, in which both phases are interpreted as interpenetrating continua and modeled in the Eulerian, cell-based framework (*Messa et al.* 2021). Simulating the flow in the Eulerian-Lagrangian framework, in which the trajectories of the individual solids are calculated, would not be feasible for reasons of computational costs.

A two-fluid model was built starting from submodels and parameters already embedded in Ansys Fluent™, avoiding the need of implementing user defined subroutines. This would increase the impact of the model in a professional environment, as introducing new elements through user programming might produce implementation or convergence issues. The key settings of the proposed model are summarized in Table 1.

Feature of slurry flow model	Setting
Modelling approach	Eulerian multiphase
Turbulence model	k-ε standard – dispersed
Near wall treatment	Standard wall functions
Turbulent dispersion	Diffusion in VOF
Drag force model	Schiller and Naumann
Wall boundary condition of solid phase	No slip

Table 1. Specific settings of the slurry flow model built into Ansys Fluent™; others are left default. The reader is referred to the Ansys Theory Guide for more information and detailed equations.

One of the most important features of the model resides in the use of the "Diffusion in VOF" option to account for the turbulent dispersion of the solids. In this option, a turbulent diffusion term is added to the mass conservation equation of the solid phase, which, for steady-state calculations takes, the following form

$$\nabla \cdot (\alpha_s \rho_s \boldsymbol{U}_s) = \nabla \cdot \left(\frac{\mu_{t,s}}{\sigma} \nabla \alpha_s \right) \tag{1}$$

where the subscript "s" denotes the solid phase, and α, ρ, $\boldsymbol{U}$, and μ_t are the volume fraction, the density, the velocity vector, and the eddy viscosity, respectively. The symbol σ indicates a dimensionless empirical coefficient called "turbulent Schmidt number for volume fractions" and, since the value of σ was found to have a strong influence on the predicted concentration distribution, this was regarded as the main tuning coefficient of the model, which must be determined through a calibration procedure.

3 DEFINITION OF THE APPLICABILITY CONDITIONS OF THE TWO-FLUID MODEL

The applicability conditions of the two-fluid model built in Ansys Fluent™ were inferred from those of another existing model, namely, the β-σ two-fluid model for fully-suspended flow developed within the authors' lab in recent years and implemented into the PHOENICS™ code. In *Messa & Matoušek* (2020), the applicability limits of the β-σ two-fluid model have been assessed in the form of three validity conditions which can be verified a priori, and basically set an upper bound to the particle size, d_p, an upper bound to the in-situ solids concentration, C_{vi}, and lower and upper bounds to the bulk velocity, V_m. The attempt made was to use the degree of agreement between the solutions of the proposed two-fluid model (in Ansys Fluent™) and of the existing β-σ two-fluid model (in PHOENICS™) as a criterion to define the range of validity of the former.

Although both the β-σ two-fluid model and the proposed one apply to slurry pipe flows dominated by particle-turbulence interactions, there are some differences between the two in terms of their mathematical structure. For instance, in the β-σ two-fluid model the turbulent diffusion terms are not included only in the mass conservation equation of the solid phase, but in all conservation equations of both phases, and a more elaborated treatment is provided for the wall boundary condition of the solid phase and for the momentum exchange between the two phases. Nonetheless, several simulations on horizontal pipe flows indicated that, up to an in-situ concentration of about say 20%, the solutions of the two models were rather similar to each other, as partially exemplified in Figs. 1a. At higher concentrations, the model in Ansys Fluent™ produces a different concentration profile, as seen in Fig. 1b. Indeed, this finding was not surprising, because the β-σ two-fluid model uses an inter-phase friction coefficient that makes it appropriate for high concentration flows, which is not the case for the model in Ansys Fluent™.

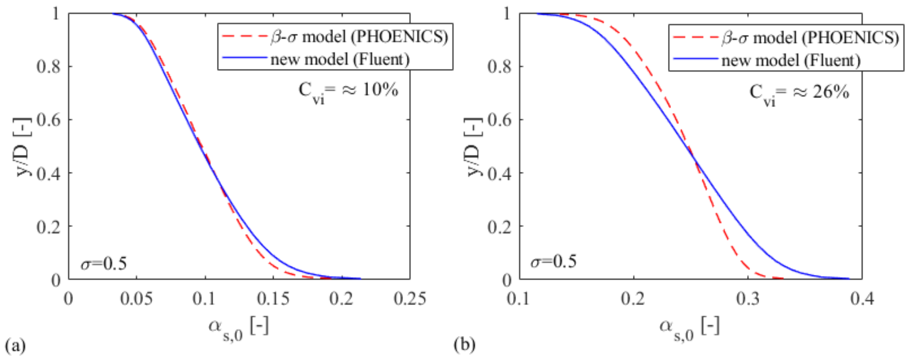

Figure 1. Comparison of the concentration profiles obtained by the earlier β-σ two-fluid model (in PHOENICS) and the current two-fluid model (in Ansys Fluent™) for two values of C_{vi}. Symbols *y, D,* α_{s0} are the vertical elevation over the pipe bottom, the pipe diameter, and the local solid concentration in the vertical pipe axis, respectively.

Based on the these results, the applicability conditions of the two-fluid model described in Section 1 were established as follows: (1) $d_p^{+B} < 30$, where d_p^{+B} is the ratio between the particle size and the viscous length scale obtained by Blasius' correlation for turbulent single-phase flows in straight pipes; (2) $V_m > 1.5\, V_{dl}^T$, where V_{dl}^T is an estimate of the deposition limit velocity, that is, the value of V_m at which solid deposit is first observed, obtained using the empirical correlation of *Thomas* (2015); (3) $C_{vi} < 20\%$.

4 PRELIMINARY VALIDATION FOR HORIZONTAL PIPE FLOW

As already mentioned, the solution of the two-fluid model is strongly dependent upon the value of the turbulent Schmidt number for volume fractions, σ, which must be calibrated based on experimental data. Particularly, among the fluid dynamic variables of most engineering interest in slurry pipe flows, the concentration distribution (quantified by the concentration profile along the vertical diameter in horizontal pipe flows) is the one which is mostly affected by σ, whereas, for instance, the hydraulic gradient and the velocity field are nearly insensitive to this parameter. Thus, the strategy adopted was to find out an appropriate σ based on a limited set of experimentally determined concentration profiles (calibration phase), and to verify that the same value of σ allows accurate prediction of the concentration profile also for other data series out of the calibration range, clearly within the applicability limits (validation phase). Additionally, the predicted hydraulic gradients, i_m, were compared with the measured values for all test cases. The reader is referred to the M.Sc. Thesis of *Malinverni* (2021) for all the information concerning the numerical setup of the simulations.

For the calibration phase, reference has been made to the experimental data reported in *Matoušek et al.* (2013) concerning fine glass bead slurries with d_p=0.18 mm flowing in a 100-mm diameter pipe at three velocities (V_m≈2.26, 3.00, 3.99 m/s) and C_{vi}≈10%. Good agreement was obtained between the calculated and the three measured concentration profiles with σ=0.3 (an example is reported in Fig. 2a). Using this value of σ, validation was performed using other experimental data from *Matoušek et al.* (2013) and experimental data reported in the PhD thesis of *Gillies* (1991), concerning fine sand slurries with d_p=0.18 mm flowing in 53-mm and 459-mm diameter pipes at different velocities in the range 3 to 4 m/s and different concentrations in the range 6 to 15%. Farly good agreement was obtained for all concentration profiles, as partially exemplified in Fig. 2b, suggesting that σ is a robust regards to particle material, pipe diameter, and concentration. Even the deviation with respect to the measured hydraulic gradient (lower than about 15% for all cases) indicated that the two-fluid model meets the typical accuracy requirements of slurry pipeline applications.

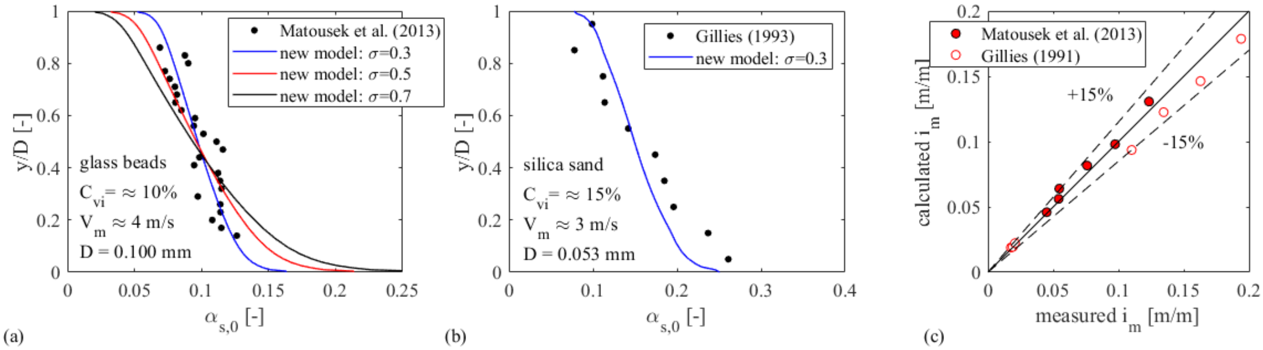

Figure 2. (a) calibration of σ based on a concentration profile in *Matoušek et al.* (2013); (b) model validation based on a concentration profile in *Gillies* (1991); model validation based on hydraulic gradient data in *Matoušek et al.* (2013) and *Gillies* (1991).

5 CONCLUSIONS AND NEXT STEPS OF THIS RESEARCH

A two fluid model has been built in the Ansys Fluent™ code for the simulation of pipe flows of fine particle slurries dominated by particle-turbulence interactions. The model uses options embedded in Ansys Fluent™, without the need for implementing user-defined functions. The validity conditions of the model have been clearly defined, and expressed in the form of three applicability constraints that can be verified a priori. The model include a main empirical coefficient, σ, which mostly affects the concentration distribution and requires calibration based on experimental data. A preliminary study carried out referring to previous laboratory tests on horizontal pipe flows suggested that the value of σ obtained in the calibration phase allows for reliable predictions even outside the calibration range, that is, for other particle materials, pipe diameters, velocities, and concentrations. The accuracy is satisfactory for typical slurry pipeline applications. Next steps of this research include: (1) extending the validation of the model; (2) improving the model to account for particle-particle interactions, which play a key role for coarser particle slurries, (3) applying the model to simulate complex components of a slurry pipeline system, such as the slurry pumps.

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