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SUSPENDED PIPEFLOW WITH OPENFOAM

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In dredging applications, deep sea mining and land reclamation projects typically large amounts of sediments are transported through pipes in the form of hyper concentrated (40% sediment or more) sediment-water mixtures or slurry. These slurries can flow at three different regimes. 1: fully suspended (homogeneous and stratified) 2: partially suspended with a sliding bed 3: partially suspended with a fixed bed. At the moment it is hard to predict the transport regime, the volume flux of particles and the pressure drop (friction factor) of these slurries within these regimes. The goal is to establish a model 3D continuum model that is able to predict the aforementioned aspects of slurry flow in a wide range of slurry flow conditions. In this paper it is investigated how well an existing CFD-model is able to model velocity and concentration profiles of suspended sediment in a pipeline. The CFD-model that is used is TwoPhaseEulerFoam which is part of OpenFOAM. This Euler-Euler solver treats both the phases as a continuum with its own momentum and continuity equations. The phases are coupled with coupling terms such as the drag force.

KEY WORDS: slurry transport, CFD, two-phase flow, pipeline

NOTATION

C	coefficient
M_k	Interaction forces acting on phase k
P_k	Pressure of Phase k
U_k	Velocity of phase k
α_κ	Concentration of phase k
ρ_κ	Tensile stress (MPa)
σ_κ	Turbulent Schmidt number
τ_κ	Shear stress (MPa)
$\nu_{\tau\kappa}$	viscosity

1. INTRODUCTION

In dredging applications, deep sea mining and land reclamation projects large amounts of sediments are transported through pipes. Hyper concentrated sand-water mixtures or slurries are pumped through the system where the volume concentration of the sediments can be as high 40% in the suspended regime. The sediment has to be kept in suspension by the turbulent flow. Three different regimes can be distinguished depending on the flow and sediment characteristics. The sediment is either in (a) full suspension, (b) partially

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suspended in the presence of a sliding bed at the pipe bottom or (c) partially suspended with a fixed bed at the pipe bottom. It is challenging to accurately predict the dynamic change in transport regime for the wide range of operating conditions found in practise. As a result, it is also challenging to predict the volume flux of particles and the pipe friction factor.

The transport of slurries has been researched since the third decade of the 20th century. Rouse (1937) and O'Brien (1933) predicted the concentration distribution of low concentration slurries flowing through an open channel with a diffusion model. Some modification to this model were made by Ismael (1952) who correlated the shear velocity gradient to the coefficient of mass transfer. Many other researchers proposed models to predict the concentration profile for slurry flows. Amongst these researchers are Shook and Daniel, (1965), Shook et al. (1968), Gillies and Shook (1994), Gillies and Shook (2000) and Kaushal and Tomita (2002).

Apart from the concentration profiles another aspect of flows through a pipeline is the pressure drop over the length of the pipeline. This gives an indication of the loss of energy due to friction and is directly linked to the friction factor. Pressure drop is investigated in the next notable studies. Durand (1953), Turian and Yuan (1977), Schaan et al. (2000), Matousek (2002), Wilson et al. (2002), Kaushal and Tomita (2003), Kaushal et al. (2005), Matousek (2009) and Talmon (2013). Also, the change in transport regimes has been studied previously. The deposition limit velocity, the bulk velocity at which a bed starts to form at the bottom of the pipeline, has been studied widely. The following literature has some notable contributions for the deposition velocity Sinclair (1962), Wasp and Aude (1970), Oroskar and Turian (1980), Turian et al. (1987), Miedema (2016) and Gillies et al. (2000). The limit deposition velocity gives the velocity at which the bed starts to form. It does not give an indication whether the bed is sliding or if the bed is fixed. The previously mentioned research and models are all based on bulk velocities and description of local phenomena. In reality, the pipeline is not always operating in one transport regime. To predict these dynamic changes accurately another approach is needed. Increase in computer power makes simulations with Computational Fluid Mechanics (CFD) software more attractive.

Ekambara et al. (2009) used a transient three-dimensional model in ANSYS-CFX that simulates slurries of sand with a two-phase model with the kinetic theory of granular flows for the sand fraction. The simulations were compared with experimental data available in literature. Comparison to experimental data of (Gillies and Shook, 2000) showed overall good agreement for fully suspended flows with heavy stratification. They investigated the effect of grain size on the concentration profile, solid and liquid velocity profiles and pressure loss. They found that the asymmetry of grain distribution depends on the grain size and increases with increased grain size. Chen et al. (2009) modelled a coal-water slurry with a Eulerian multiphase approach based on the kinetic theory of granular flows. The coal-water slurry is modelled as a slurry with a bimodal distribution with two solid-phase fractions. The regime of flow is fully suspended or lightly stratified. Simulations give fairly good results for the concentration and the pressure drop when compared to corresponding experimental results. Gravity difference between different grain sizes and the strong solid interactions between grains has a visible effect on distribution of solid concentrations and its velocity. Kaushal et al. (2012) used a two-phase Euler-Euler approach and a mixture model in FLUENT to simulate a slurry of glass beads and compared the CFD results with experimental results. The pressure drop for clear water is in agreement for both models. However, if the concentration of sediment is increased the pressure drop calculated with the mixture model fails to predict this drop correctly. The Eulerian model gives reasonable outcomes for both the pressure drop and the concentration profile. They also presented the slip-velocity obtained by the CFD simulations for higher concentrations. and concluded that the slip velocity drags most of the particles to the core of the pipeline. Gopaliya and Kaushal (2015) simulated a three-dimensional sand-water slurry with a two-phase Eulerian model with the kinetic theory of granular flows. In these simulations it is seen that at higher concentrations and at bigger grain sizes the solids concentration at the bottom of the pipe do not match the measurements. The highest solid concentration is near to the lower wall of the pipe but keeps shifting upwards with increase of grain size. They also found that the secondary flow velocity increases when the grain size is increased. Kumar et al. (2016) did a three-dimensional CFD analysis of two-phase slurry (sand-water) flows. Use was made of a two-phase Eulerian model with for the granular pressure the kinetic theory. The simulations are compared to experimental results and show reasonable agreement for concentration and velocity. Pressure gradient is shown to increase with increasing solid concentration and follows the trend seen in literature but is not validated by experimental results. Also, the effects of turbulent viscosity, turbulent kinetic energy, granular pressure and dissipation of turbulent kinetic energy have been analysed. Kumar et al. (2017) used CFD code based on the Euler-Euler approach. The slurries that are simulated are iron-ore slurries with a mean diameter of 12 micrometre. It is seen in the results that the pressure drop deviates as soon as the slurry is not uniform.

In the previous section it can be seen much research has been done in simulating slurry flows through pipelines with CFD. However, most research focusses on fully suspended slurries and leaves out beds and bed formation. A 3D continuum model based on averaged equations for hyper concentrated sediment will be developed for transport through a horizontal pipeline. The aim of the 3D multiphase model is to predict the transition from the suspended flow, the sliding bed and the fixed bed regime for the range of pipe diameters (high bulk Reynolds numbers), particle sizes and mass density ratios that are typical for dredging applications. Previous papers did not yet demonstrate to be able to simulate these transitions. In this paper the model that is in development will be described. To show that the current model is capable of simulating cases with sediment in full suspension, simulations of pipeline flow will be shown and compared to experimental data.

2. COMPUTATIONAL METHOD

TwoPhaseEulerFoam is a solver that is available in the open source CFD package OpenFOAM (Greenshields (2015)). The solver is a Euler-Euler solver and is used because it takes into account particle-particle interactions which are important in dense suspensions but needs less computational power than Euler-Lagrangian methods. It assumes that the slurry flow consists of a fluid phase f and a solid phase s which form interpenetrating continua. The volumetric concentration of the fluid phase is denoted α_f and of the solid phase α_s which together will be $\alpha_f+\alpha_s=1$. For each individual phase the laws of conservation of mass and momentum are satisfied. The coupling between the phases is accomplished by pressure and interphase exchange forces such as the drag coefficients. The code of TwoPhaseEulerFoam (OpenFOAM 4.x) is based on the code of van Wachem (2000). The momentum equation for each phase:

$$\frac{\partial \alpha_k \rho_k U_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k U_k U_k) = -\nabla(\alpha_k P_k) + \nabla(\alpha_k \tau_k) + \alpha_k \rho_k g + M_k \tag{1}$$

where ρ is the density, U denotes the velocity, t represents time, P is the pressure, τ represents the viscous stresses, g is the gravitational constant and M are the source terms in which the coupling of the phases is handled. The subscript k indicates the phase which can be either f for fluid or s for solids. The continuity equation is of the following form:

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k U_k) = 0 \tag{2}$$

The shear stress for the fluid phase is modeled with a k-ε turbulence model. The shear stress in the particle phase is modeled with the kinetic theory for granular flows. The coupling forces M_k contain the following contributions. The Drag force which is modeled according DiFelice (1994). The lift force which is modeled according Tomiyama et al. (2002) The added mass force which is modeled according Lamb (1895) and the Turbulent dispersion force for which the model of Burns (2004) is used and is written as:

$$M_{\alpha_p}^{TD} = -C_{\alpha_p} \frac{v_{t\alpha_p}}{\sigma_{\alpha_p}} \left(\frac{1}{\alpha_p} + \frac{1}{(1-\alpha_p)} \right) \nabla \alpha_p \tag{3}$$

3. SIMULATION

To assess the performance of the model that was presented in the previous section simulations are compared to experimental work. The first set of simulations represent the experimental work of Roco & Shook (1983) with denser sediment suspensions. The second set of simulations are the experiments by Gillies (2004).

Roco & Shook (1983) performed experiments in a pipeline with a wide range of diameters. The sediment they used was sand that had a particle diameter of $1.65 * 10^{-4}$ m and a density of 2640 kg/m^3. Measurements were made at different average concentrations. They measured solids concentration distribution. Gillies (2004) performed experiments in a pipeline with a diameter of 0.103 m. The sediment they used had a particle diameter of $0.9 * 10^{-4}$ m with a density of 2640 kg/m^3. Measurements were made at different average concentrations. They measured solids concentration distribution.

The domain of the pipeline is modeled according to the physical dimensions reported in the papers of the simulated cases. An overview of these dimensions and other relevant parameters are given in Table 1. The flow is calculated in a periodic domain. The velocity of the fluid is maintained at a constant average velocity by a driving force. The pipe wall is modelled as a no slip wall for the velocity of the fluid phase. For the particle phase a slip boundary condition is implied. The law of the wall is implied with wall functions for ε, k and μ_t. The pressure is set zero-gradient. The initial velocities for both the particle and the fluid phase have been given the values stated in Table 1. The initial concentration of particles in the domain is uniformly distributed and set to the value that corresponds to the measurements of the delivered concentration. A cross-section of the pipe mesh is shown in Figure 1.

Table 1

Parameters for simulations

	D (m)	C (%)	V(m/s)
Roco & Shook (1983) B	0.0515	9-33	3.5
Roco & Shook (1983) C	0.495	10-33	3.78-4.33
Gillies (2004)	0.103	9-33	3

In Figure 2 the concentration profiles for the aforementioned of Roco & Shook's experiments are shown. For the two different pipe diameters the concentration profiles show good overall agreement. In the graph of simulation set C it is seen that the concentration profiles obtained from the simulations are matching the corresponding measurements very well. For simulation set B the results are a little bit more of than the result of simulation set C. Especially the 19% case shows a mismatch in the bottom of the pipeline. The concentration in this part is lower than the measurements. Except from that deviation the simulations still match the experiments quite well.

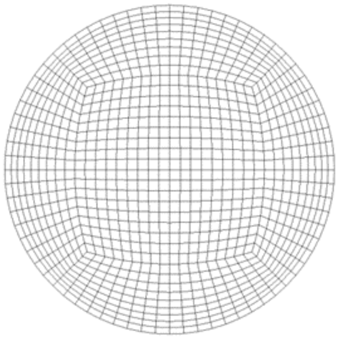

Figure 1. Mesh cross section

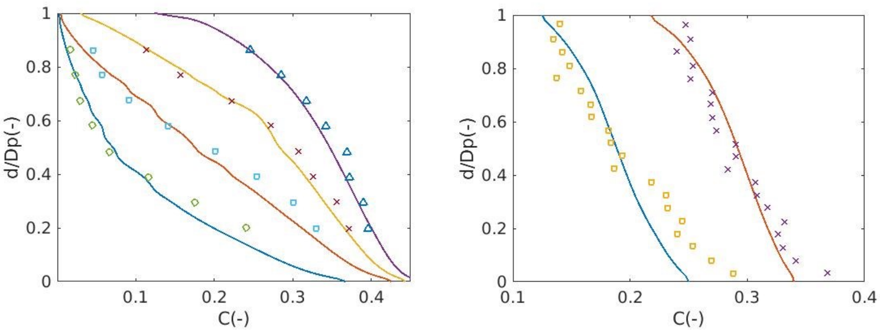

Figure 2. Concentration distribution along the pipe vertical centerline. Left: Roco & Shook (1983) C. C_{vd}: ○ 9%, □ 18%, x 26%, Δ 33%. — Simulations. Right: Roco & Schook(1983) B. C_{vd}: □ 19%, x 26%, — Simulations

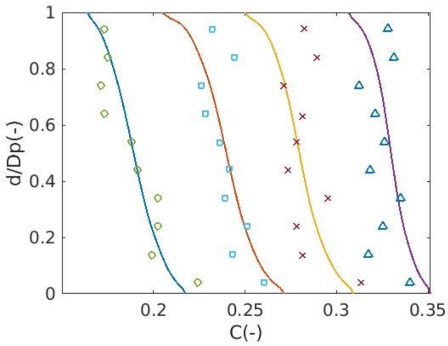

Figure 3. Concentration distribution along the pipe vertical centerline of Gillies (2004). C_{vd}: ○ 19%, □ 24%, x 28%, Δ 33%. — Simulations.

In Figure 3 the results of the simulations for Gillies (2004) are shown and compared to the experimental measurements. The experimental measurements show an almost vertical distribution of concentration along the pipe vertical axis. The simulations for 19% and 24% sediment concentration show good agreement with the experimental data over the full vertical axis. The Simulations with a concentration of 28% and 33% show good agreement in the middle section of the vertical axis but tend to deviate at the top and the bottom of the pipeline. Although there is some deviation the results are still within reasonable range.

Although these simulations show good agreement with experimental results there is a point of discussion. The current model lacks important properties of a turbulent sediment laden flow. Calibration via the turbulent dispersion force is therefore needed to get correct results. The turbulent dispersion force is calibrated with the turbulent Schmidt number ranging from 1 for Gillies (2004) up to 2.5 for Roco and Shook (1983).

4. CONCLUSIONS

In this paper a CFD model was described that is able to simulate sand-water mixtures. Both the sand and water phase were modeled as a fluid and were coupled using coupling terms for interphase forces. The shear stress for the solid phase was modeled with the kinetic theory for particulates. This model was then tested with simulations of multiple sediment laden flows through a pipeline.

The domain of the pipeline is subjected to flows laden with different flow velocities and mean concentrations. Also, the diameter of the sand particles as well as the diameter of the pipeline was varied. After calibrating the simulations with the turbulent Schmidt number in the turbulent dispersion model. The simulation shows good agreement with available experimental data.

The goal of this model is to simulate sediment transport through a pipeline. Although the presented model is capable of reproducing concentration profiles, the additional calibration makes it impossible to use the current model as a tool for predicting slurries.

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