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SIMULATION OF THE SETTLING OF SOLIDS IN A NON-NEWTONIAN FLUID

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Settling of particles in non-Newtonian fluid is important in the field of mining and dredging. A CFD code is adapted to simulate the settling of particles under shear. Different rheological models are implemented. The simulations are compared with experiments.

KEY WORDS: Non Newtonian flow, Shear Settling.

1. INTRODUCTION

The flow of mixtures of coarse solids in a non-Newtonian fluid occurs in many industrial applications, mining and dredging. Both the behaviour in pipelines and in disposal sites is important since it determines energy and water consumption as well as the strength development of disposal sites.
In this study, it is investigated whether the open source CFD OpenFOAM is capable to simulate these complex flows.

2. GOVERNING EQUATIONS

2.1 MASS AND MOMENTUM

The flow is solved using a Volume of Fluid method using an adopted icoFoam solver of OpenFOAM. The momentum equation reads:

$$\frac{\partial U}{\partial t} + \nabla.(UU) - \nabla.\frac{\mu}{\rho}\nabla U - g = -\frac{1}{\rho}\nabla p \qquad (1)$$

The continuity equation takes the form:

$$\nabla.U = 0 \qquad (2)$$

Here ρ is the density of the carrier fluid. The viscosity μ is calculated using a Bingham Plastic model, where the sand fraction influences both yield stress τ_Y and plastic viscosity μ_p, following Talmon et al (2016):

$$\mu_p = \mu_{p,c} e^{\beta\lambda}$$
$$\tau_Y = \tau_{y,p} e^{\beta\lambda} \tag{3}$$

Where $\mu_{p,c}$ and $\tau_{y,c}$ are the rheological parameters of the carrier fluid alone , β is a constant (in this study a value of 0.27 is chosen) and λ the linear concentration defined as:

$$\lambda = \frac{1}{\left(\frac{c_{\max}}{c_s}\right)^{\frac{1}{3}} - 1} \tag{4}$$

The sand fraction c_s is being transported by the fluid fraction using the drift flux approach:

$$\frac{\partial c_s}{\partial t} + \nabla.(U_s c_s) = 0 \tag{5}$$

Where the sand particles have a velocity U_s which is simply calculated with

$$U_s = U + w_s \tag{6}$$

2.2. SETTLING VELOCITY

The settling velocity is calculated using Talmon and Huisman (2005):

$$w_s = (1 - c_s)\frac{1}{18}\frac{(\rho_s - \rho)gd}{\mu} \tag{7}$$

Where the first term between brackets denotes the hindered settling effect and μ is the apparent viscosity without the effect of the sand fraction.

3. NUMERICAL IMPLEMENTATION

The relative simple icoFoam solver of OpenFOAM is used as a basis for the new solver. In icoFoam a non Newtonian viscosity model already can be used. The available models however do not include the influence of the sand fraction on rheology as indicated above.

Therefore a new Bingham Plastic model is included. Furthermore the transport Eq. (5) is added to the solver.

4. VALIDATION

4.1. 2D CHANNEL FLOW

The Bingham Plastic model is compared with the analytic solution using a simulation of a channel flow with a flow depth h = 0.1 m, a depth averaged velocity $\bar{u}$ = 0.4 m/s, τ_Y = 10 Pa and μ_p = 0.2 Pa.s. Total length of the simulated channel is 20 m. The profile is captured at x = 15 m (distance from the inlet zone). The analytical solution is constructed using the pressure gradient determined from the numerical solution.

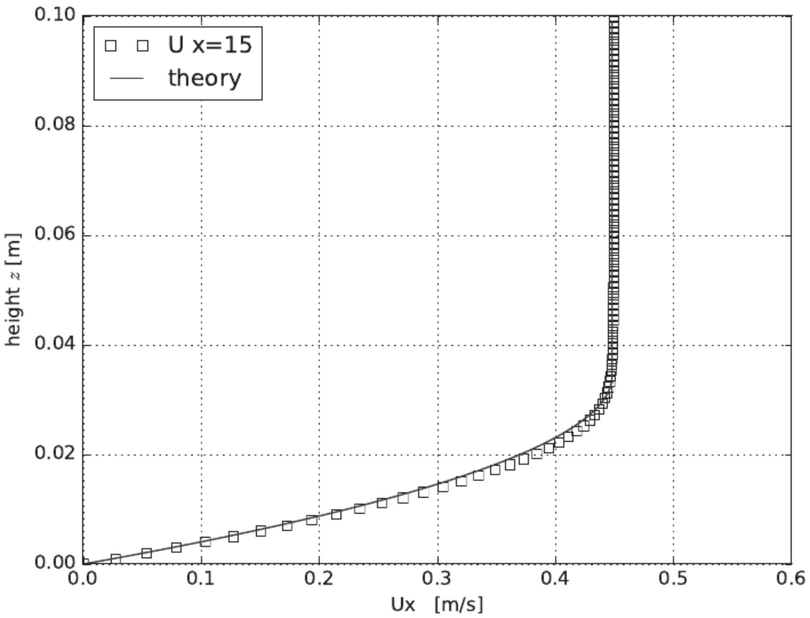

Fig.1 Calculated and analytical solution of the velocity profile at x = 15 m

Figure 1 shows that there is a perfect agreement between the numerical and analytical solution.

4.2. 3D FREE SURFACE PIPE FLOW

Spelay (2007) experiments in a half open round pipe are reported. One of the experiments on thickened tailings is simulated. The pipe diameter is D_p = 0.1567 m. The inflow concentration for sand c_s = 0.12. Particle size d = 188 micron. Inflow discharge is 5 lit/s. The yield stress of the carrier fluid τ_Y = 47.3 Pa and plastic viscosity μ_p = 0.0214 Pa.s. The measured flow depth is 0.0968 m. Since the adopted icoFoam does not have a free water surface, the flow depth and mesh is fixed at this value of the mixture depth. Figure 2 shows the grid as used for the solver created with blockMesh.

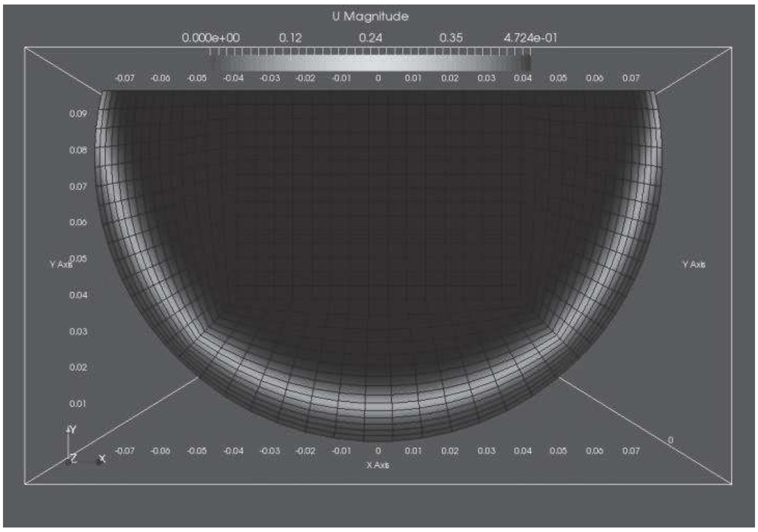

Fig.2 Grid used for computations. Flow velocity at z = 15 m

Figure 3 shows the sand concentration distribution at a vertical cross section in the symmetry plane of the pipe. Note that the y - axis is distorted with a factor 40, hence the height of the vertical axis is actual 0.1 m. The labels at the axes are wrong due to rotation of the figure.

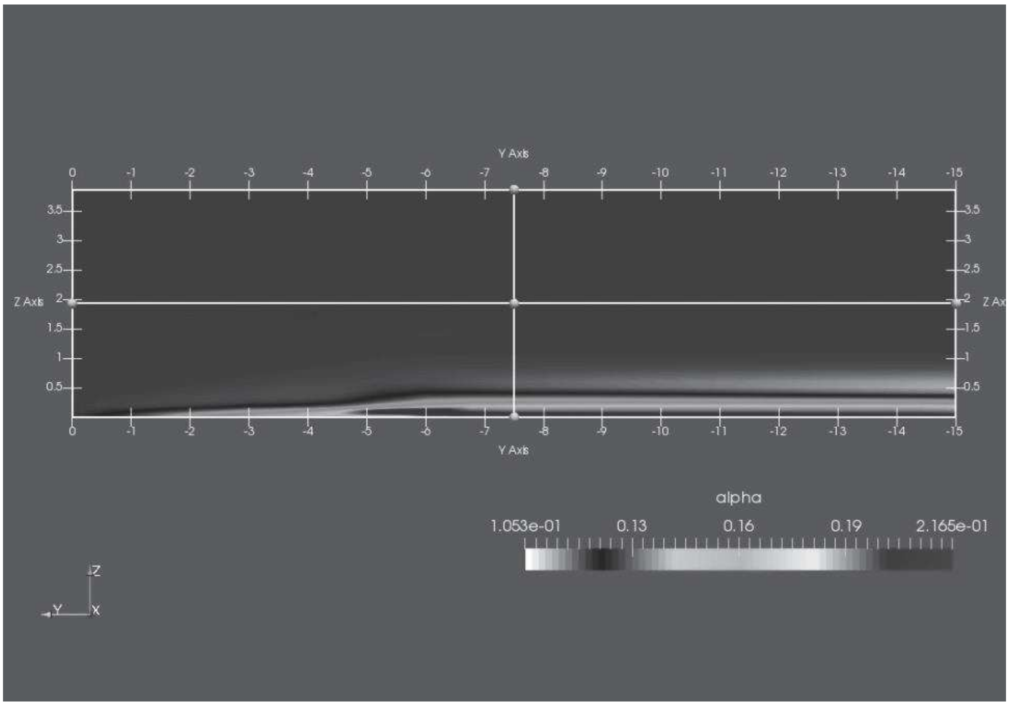

Fig.3 Sand concentration distribution along the vertical symmetry plane in the pipe

The inflow is at the left side of the figure and it is clear that a higher concentrated layer of sand forms at the bottom of the pipe. The concentration distribution is after approx. 300 s of simulation.

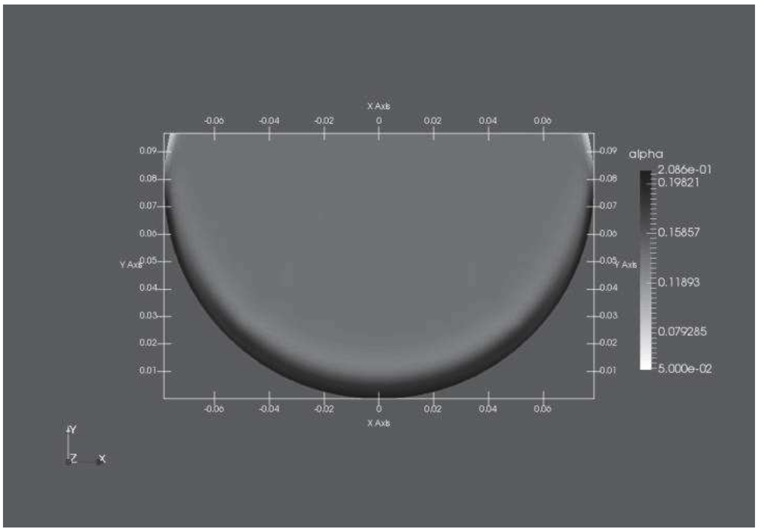

Fig.4 Sand concentration distribution at z = 15 m

Just above the layer with higher concentration an area with a slightly lower concentration is visible. In this area most of the shear is concentrated and therefore the viscosity is lower and sand settles from this region. This lower concentrated zone is also visible in Fig. 4 which shows the concentration distribution in a cross section.

Figure 5 shows a vertical concentration and velocity profile, located in the centre of the pipe.

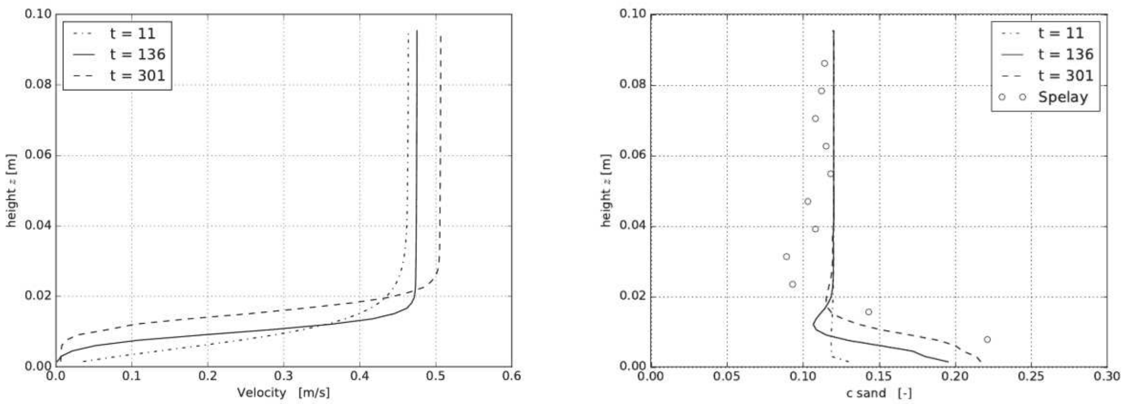

Fig.5 Sand concentration and velocity distribution at z = 15 m at different time after the start of the simulation

Note that sand settles at the bottom of the pipe. Since the sand concentration increases the yield stress and plastic viscosity at the bottom will be increased also and the shape of the velocity profile changes. For reference the measured sand concentrations are also plotted. The shape of the calculated concentration profile is similar in comparison with the experiments. However the experiments show a larger dip in the concentration in the shear zone compared with the calculations.

5. CONCLUSION

The adapted icoFoam solver is capable to capture the settling process of solid particles in a non-Newtonian flow pipe and channel flow. The paper only shows a first attempt. In the future different settling models and rheological models will be tested. In addition, a free mixture surface is needed to simulate the settling in open pipe and channel flow.

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