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Numerical Simulation of Granular Solids' Behaviour: Interaction with Gas

A. Zugliano[*,1], R. Artoni[2], A. Santomaso[2], A. Primavera[1]
[1] Danieli & C. Officine Meccaniche, Italy [2] DIPIC - Università di Padova, Italy
[*] Corresponding author: Via Nazionale 41, 33042 Buttrio (UD), Italy, a.zugliano@danieli.it

Abstract: In previous works [1, 2], a dissipative hydrodynamic model was used to simulate the behaviour of a dense granular solid flowing through silos with simple geometries or with internal devices, showing good agreement with experimental results.

That model has been upgraded taking into account the interaction between the solid itself and a nonreactive gaseous stream flowing countercurrent through it. This has been made by solving for the gas phase the Brinkman equation where the porosity and the permeability of the porous media are derived from the flow field of bulk solid, and for the solid phase solving the same equations of [1,2] in which a volume force raising from the gas pressure gradient is computed.

This upgraded model has been compared with the results coming from an experimental campaign developed at Danieli R&D, and it will be shown that it still gives good agreement with the experimental results obtained.

Keywords: Granular solids, CFD simulations, Rheology, Dense granular flow.

1. Introduction

It has been already shown [1, 2] that a dissipative hydrodynamic model can well represent the behaviour of a bulk solid flowing through a silo, with simple or complex geometries.

We now focused on the interaction that a granular material can have with a gaseous stream flowing countercurrent through it.

To do so, we modelled the gas effect as a volume force acting along the gas phase pressure gradient. The solid velocity was low enough to model the gas phase as flowing through a still porous media with variable porosity.

After setting up the model parameters on a reference case[1], we compared the model results with experimental data obtained with a test facility (figure 1). Such facility had the possibility to have or not internal devices (tubes passing side-to-side in the silo, called flow feeders) and to have (or not) air flowing upwards.

The silo was almost 2.5 meters tall and had a diameter that in the upper part varies from ~0.4m to ~0.5m. The material used was steel grit with a mean particle diameter of 825 μm.

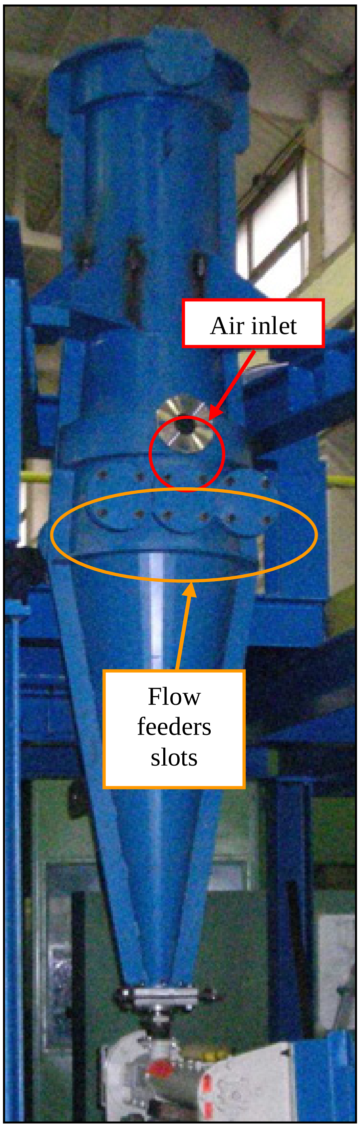

Figure 1. Picture of the experimental facility. The silo was ~2.5m tall and had a ~0.5m maximum diameter.

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[1] The reference case is without internal devices and no air flowing through the silo.

2. Governing Equations

The model equations for the granular phase are those of the pseudothermic model used in previous works ([1, 2]) – the incompressible Navier-Stokes' equation and the heat transfer equation –, with the only addition of a drag force term in the Navier-Stokes equation which becomes as follows:

$$\rho\frac{\partial \mathbf{v}}{\partial t}+\rho\mathbf{v}\cdot\nabla\mathbf{v}=-\nabla p-\nabla\cdot\Pi+\rho\mathbf{g}+\mathbf{F}_D .$$

For the gas phase, instead, we need to solve the Brinkman equation for porous media flow:

$$\rho_g\frac{\partial\bar{\mathbf{u}}}{\partial t}+\frac{\mu_g}{k_p}\bar{\mathbf{u}}=\nabla\cdot\left(-p\mathbf{I}+\mu_g\left(\nabla\bar{\mathbf{u}}+(\nabla\bar{\mathbf{u}})^T\right)\right)+$$

$$+\rho_g\bar{\mathbf{g}}$$

where the permeability isn't constant but depends upon the porosity of the medium.

This relationship can be obtained from both the Darcy and the Ergun equations

$$u_0=k_p\frac{dP}{dx}$$

$$\frac{\Delta P}{L}=150\left(\frac{\mu_g G_0}{\rho_g d_p^2}\right)\frac{(1-\varepsilon)^2}{\varepsilon^3}+\frac{7}{4}\left(\frac{G_0^2}{\rho_g d_p}\right)\frac{1-\varepsilon}{\varepsilon^3}$$

Merging these equation one can relate the permeability to the porosity.

The porosity in a granular solid is higher in correspondence of a higher shear stress. This could be a problem in implementing the gas phase simulation in the pseudothermic model for the bulk solid since one of the base assumptions is that the pseudofluid is incompressible.

To avoid such a problem, we used an algebraic closure. From literature [3, 4], it is known that in the slow motion regime the porosity of the solid is linearly dependent from the inertial number ***I***, defined as follows:

$$I=\frac{|\dot{\gamma}|d}{\sqrt{p/\rho}}$$

$$\varepsilon=\varepsilon_{\min}+bI$$

This way, solving the model for the solid phase it is possible to obtain the values of I in every point of the domain and from this the permeability of the porous medium and then solve the Brinkman equation.

Once solved the Brinkman equations it is possible to solve again the solid phase equations with the new values for the drag force, computed from the gas phase solution. Looping on these two solutions it's possible to compute the results.

3. Boundary Conditions

For the solid phase, the boundary conditions were the same applied in previous work [2]:

- Velocity outlet at the bottom end,
- Pressure inlet at the top,
- Navier Condition on the walls to describe the slip of bulk solid on the boundary [5].

The definition of boundary conditions for the gas phase is simpler since we imposed three pressure conditions:

- Pressure inlet for the inlet nozzles
- Pressure outlet at the top and at the bottom.

A summary of all the boundary conditions used for every one of the three application modes used in simulations is available in figure 2.

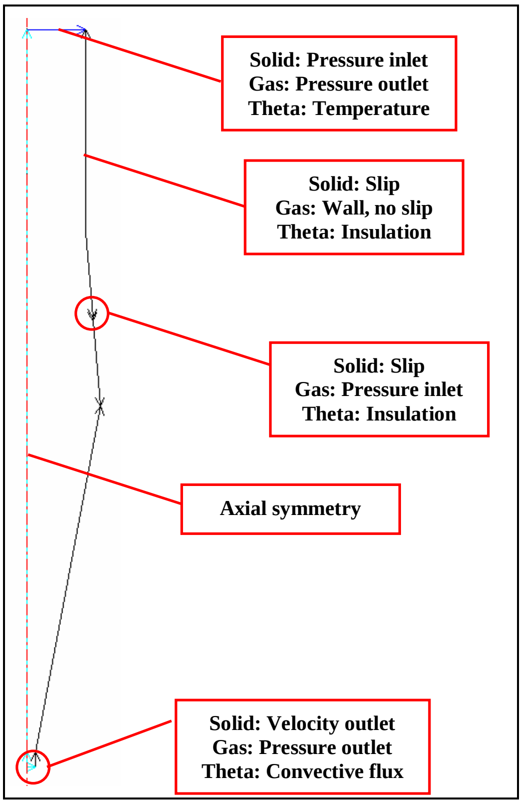
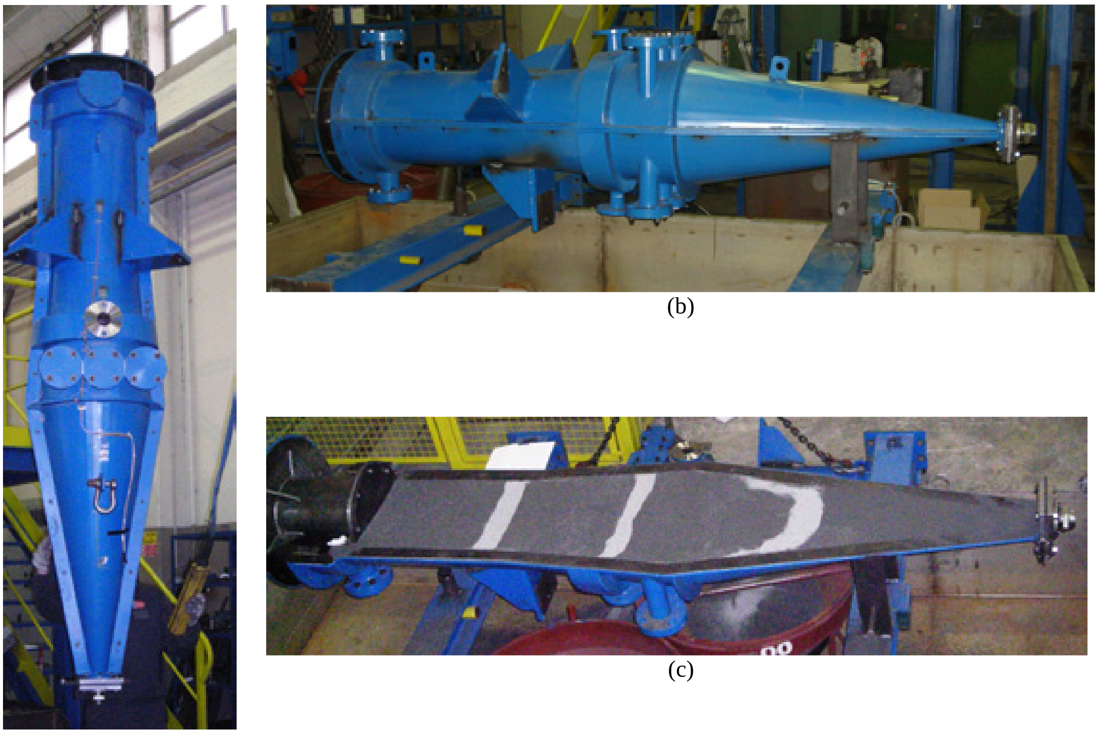


Figure 2. Boundary conditions for the three application modes used. Theta is the "granular temperature".



(b)

(c)

(a)

Figure 3. Pictures from the profiles study phase of the tests. (a) The silo is closed and moved with a crane, then (b) put in horizontal position and finally (c) the material is removed until the middle line is reached.

4. Experimental Method

With the silo in figure 1 an experimental campaign was performed between December 2008 and March 2009.

In each single test, we prepared some tracer bands (of similar material but different colour) at different heights and then we made the material flow downwards by means of a screw conveyor at the bottom end. Meanwhile fresh material was continuously charged at the top with a hopper to preserve the level inside the silo.

Since we were interested in studying the profiles of the tracer bands, at the end of each test the silo was closed on both ends, put in horizontal position, opened along a diameter and the upper part of the material removed to reveal the middle line (figure 3).

We also recorded the wall stresses at 6 different heights by means of strain gages placed on steel sheets strained by the material acting on them. When we performed the tests with the air flowing through the silo, we also recorded the air speed inside the solid bed by mean of a probe at 4 different heights.

During this campaign we made 8 kind of different tests, according to table 1. Each kind of test was repeated at least two times.

Table 1. Main kinds of test performed.

Option	Values
Flow feeders	With/Without
Air	With/Without
Test length & tracer bands	Short (~45min, 3 bands)/Long (~110min, 1 band)

We tried also other configurations, varying the mass flowrate (from 4.5 to 17 kg/min) and the material (steel spheres or sand).

In this way we performed a total of 25 tests.

5. Numerical Simulations

We used three different application modes to solve the problem:

- Incompressible Navier-Stokes (ns) to simulate the solid phase motion,
- General heat transfer (htgh) for the granular temperature,
- Brinkman equation (chns) for the gas phase.

The domain was axysymmetric and we used a total of 3000-4000 elements, depending on the case considered.

We set up the model parameters by tuning he reference case.

6. Results

As in previous works [1, 2] the model results with respect to the material flow field, and thus with respect to the tracer bands profile during descent, showed good agreement with the experimental results. All the errors that can be observed between the two are less than 50 mm (nearly 4% on a 1300mm displacement); this is due to the uncertainty that we could have in creating the bands during the filling of the silo, since the balance we used to weigh the solid had a precision of 20kg (which equals a 40mm error in the upper part of the silo).

In figure 4 it is reported a comparison between the experiments and the simulations that shows the strong agreement between the two.

The asymmetry and the fluctuations in the experimental results are due to the motion of bulk solids, which is not continuous.

Conversely the simulation presents always symmetric profiles due to the fact that the pseudofluid we simulate is a continuous media.

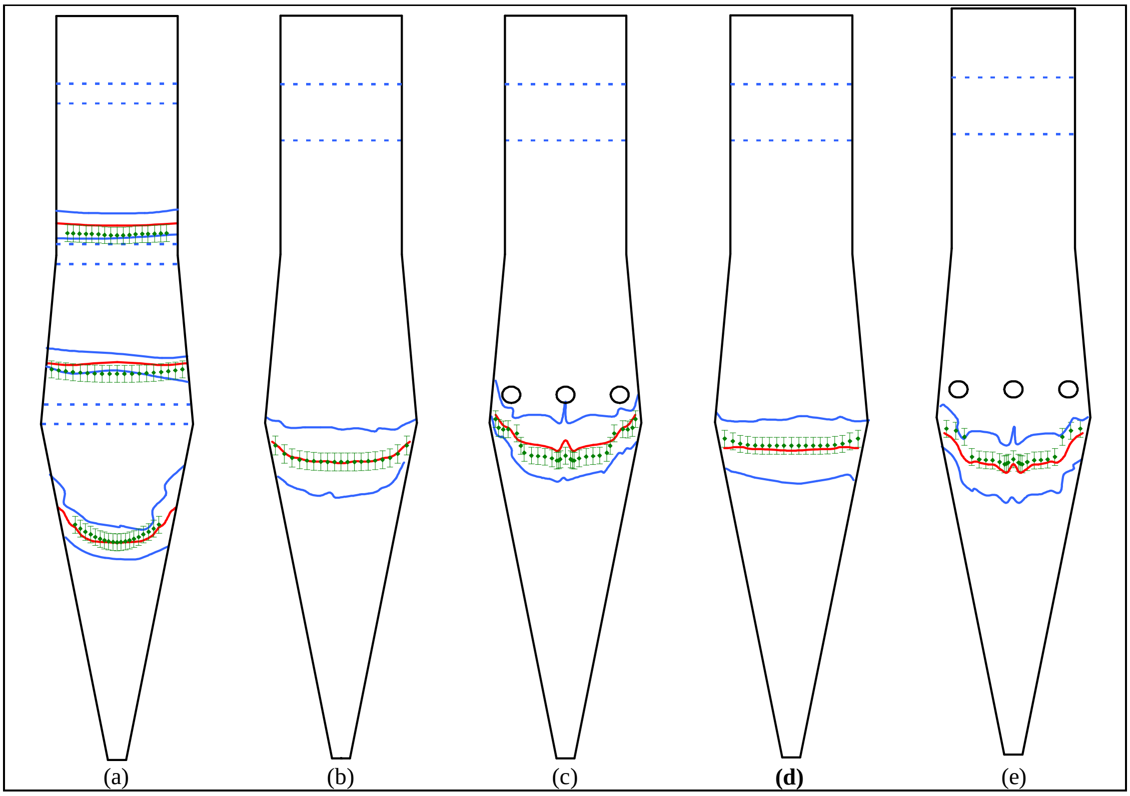


Figure 4. Comparison between experimental and simulation results. (a) and (b) are base cases, with no flow feeders and no air, used for calibration. (c) is the case with flow feeders but no air, (d) with air but no flow feeders and (e) with both flow feeders and air. Blue dashed lines are tracer stripes position at experiment start time, blue solid lines position at the end of the test, red solid lines stripes middle line at the end and green diamonds are simulation results. Error bars are 30mm long, because this is the uncertainty on the tracer starting height.

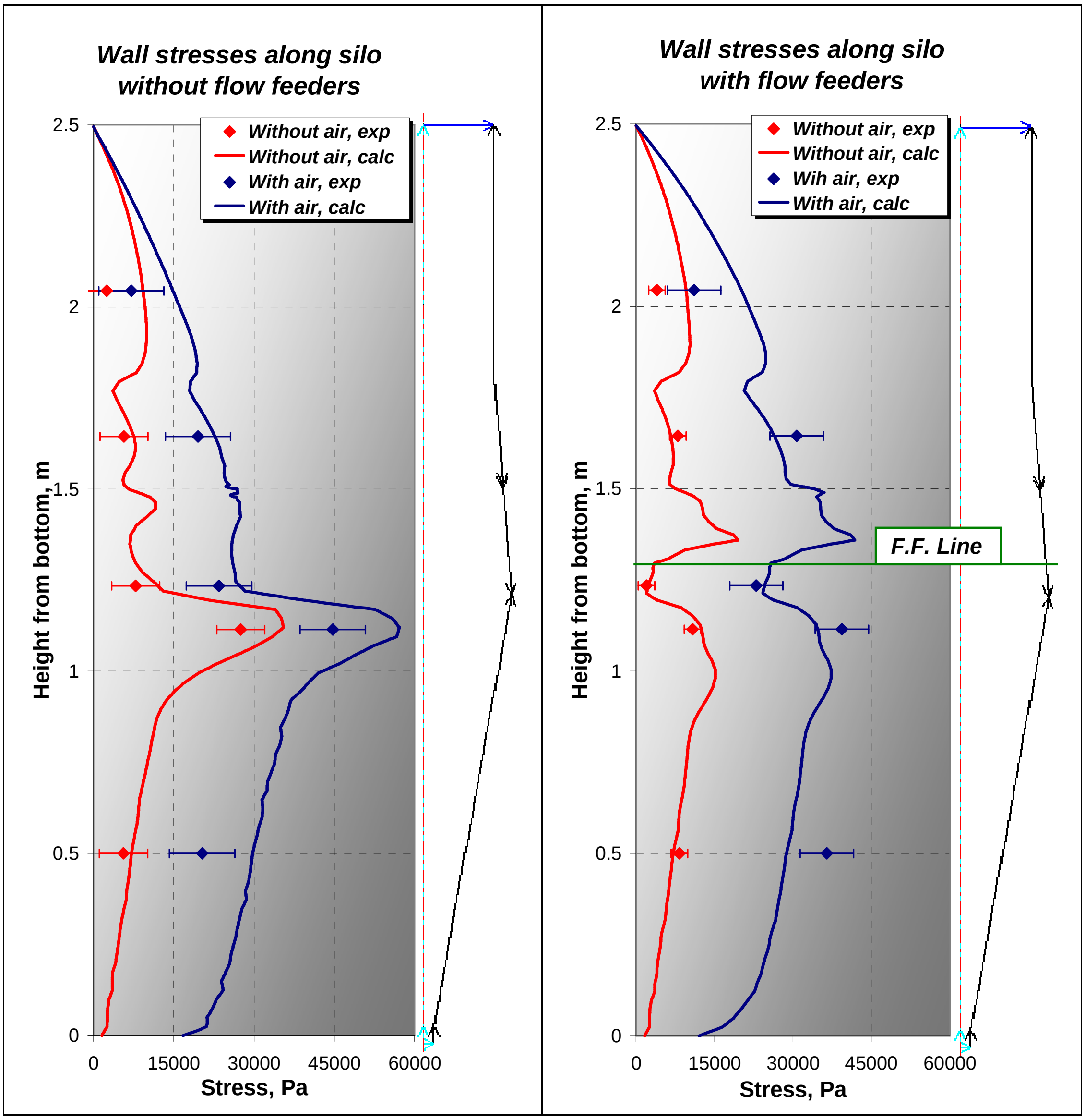


Figure 5. Wall normal stresses along the silo in the "no flow feeders" (left) cases and in the "with flow feeders" ones (right). Error bars represents standard error on experimental measure.

The wall stresses profiles also show a good approximation of the experimental results even though the model overestimated wall stresses in the "no flow feeders" cases and underestimated them in the "with flow feeders" ones (figure 5).

As in previous works [1, 2] the model predicts correctly the wall stress when there is no air flowing through the silo. The upgraded model reproduces well enough – at least with regard to the shape of wall stresses profiles – also the case in which the air is flowing through material.

The gas velocity profiles are well represented by the model, as can be deduced from figure 6.

The experimental results are biased by an error of ±0.25 m/s due the scale of the anemometer used, a Schiltknecht Miniair I.

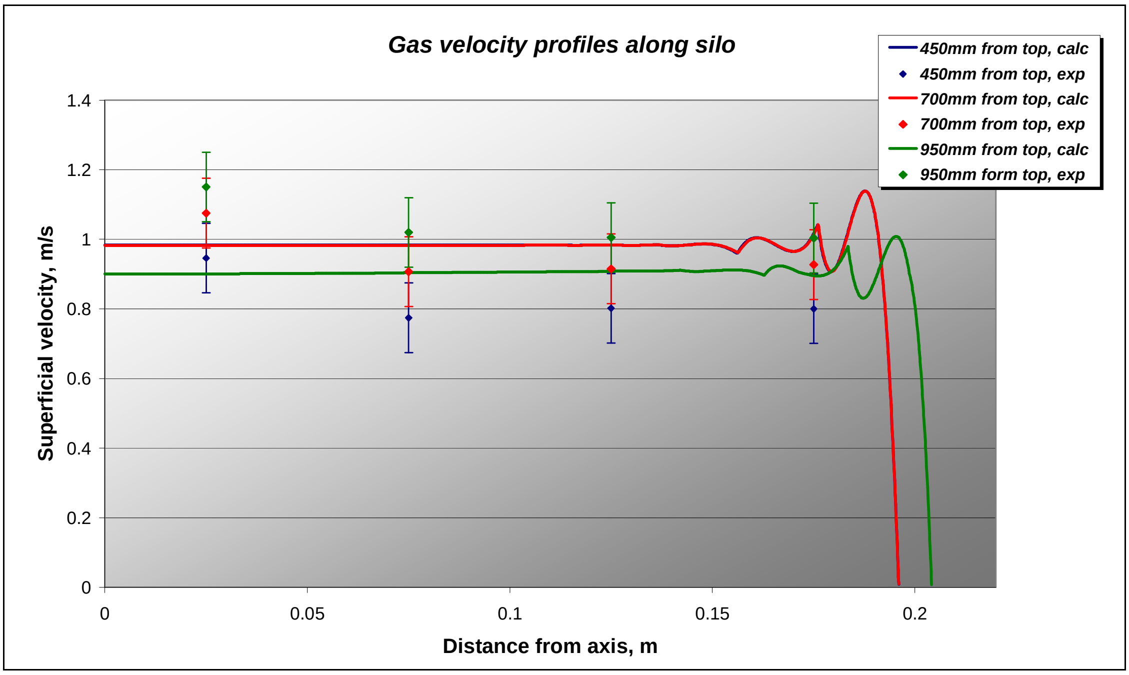


Figure 6. Gas velocity profiles at various deeps in the silo. Error bars on experimental values are of the same order of magnitude of the anemometer scale, ±0.1m/s. Calculated values at 450 and 700 mm from the top are identical.

Experiments showed that the gas velocity decreased from the injection point to the top.

This is due to small gas leakages in the middle plane separating the two shells of the silo. We were not able to estimate such leakages.

7. Conclusions

In this work we upgraded the dissipative hydrodynamic model taking into account the interaction between the bulk solid descending through a silo and a gaseous stream flowing upwards.

The model showed a good agreement with the experimental results we have obtained during the test campaign held in Danieli R&D.

The model well estimates solid phase flow field as well as the gas phase flow. Wall stresses are qualitatively well predicted too.

The next steps of the study will be to consider the compressibility of the gas phase, to take into account thermal as well as chemical interactions between the two phases and also to perform a 3D simulation to avoid geometrical problems related with the flow feeders representation in an axysymmetric simulation.

8. References

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