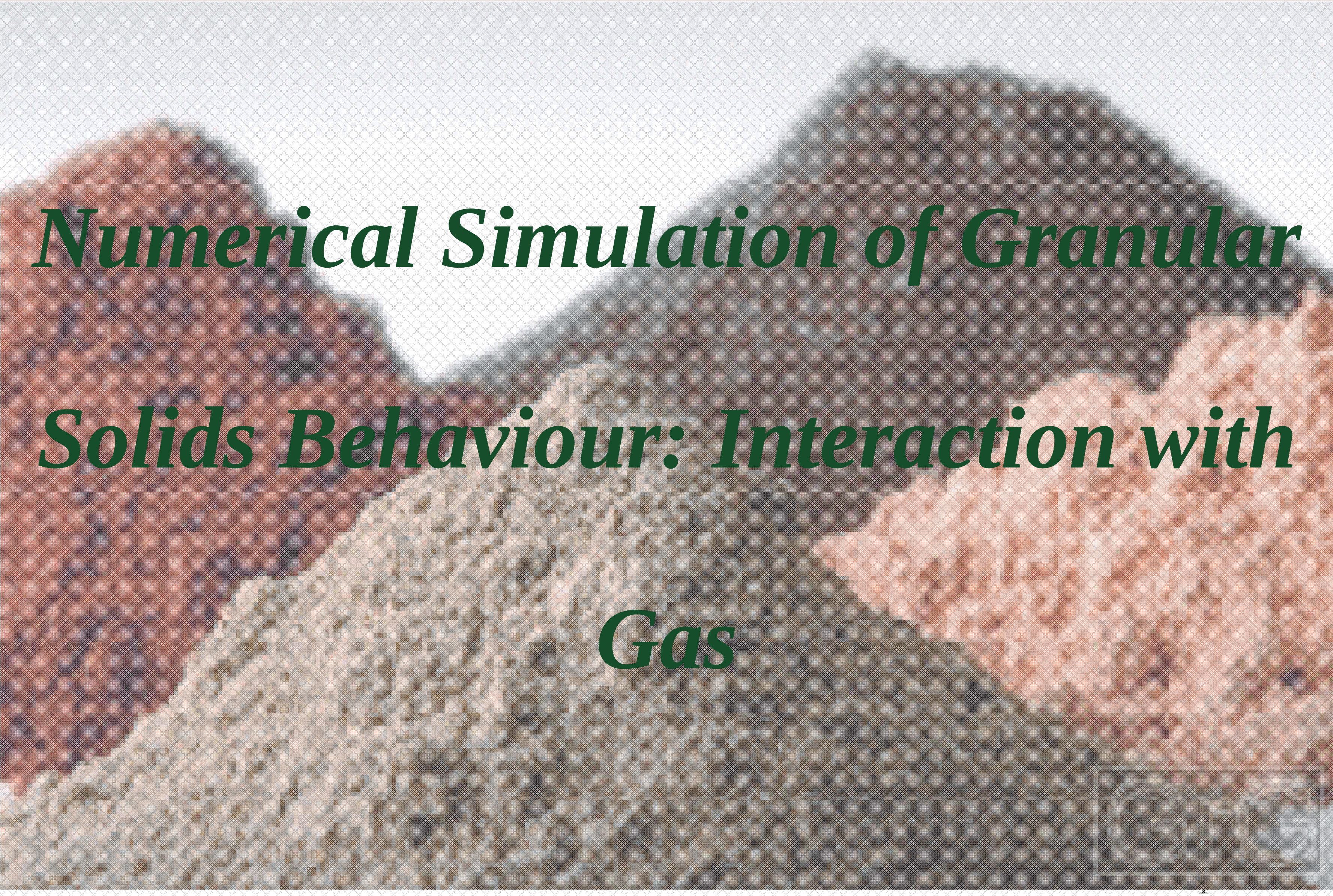

Numerical Simulation of Granular Solids Behaviour: Interaction with Gas

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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.

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

Governing Equations

The bulk solid is simulated as a continuous pseudofluid using the dissipative hydrodynamic model shown in [1,2]. In the Navier-Stokes equation we added a drag term for taking into account the effect of the gas countercurrent motion through the solid:

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

The gas phase behaviour instead is simulated with the Brinkman equation, where the porosity and the permeability of the media aren’t constants.

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

Governing Equations

The media permeability depends upon the porosity. That can be seen putting together the Darcy and the Ergun equations

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

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

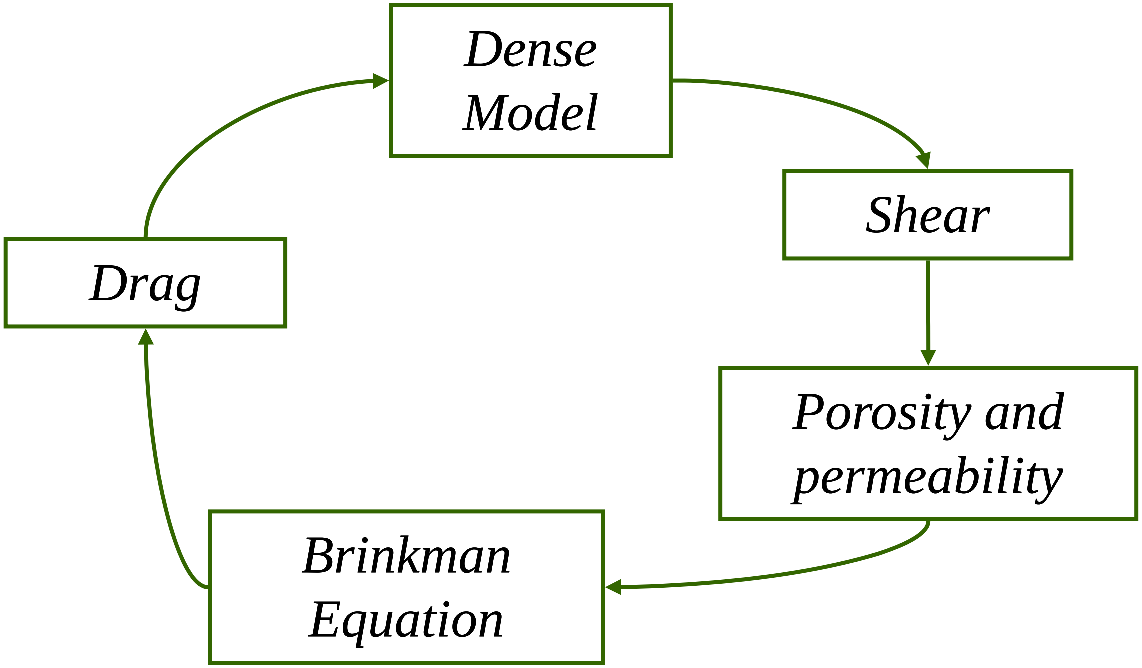
$$\downarrow$$

$$k_p = \left(\frac{150\mu_g(1-\varepsilon)^2}{d_p^2\varepsilon^3} + \frac{1.75u_0\rho_g(1-\varepsilon)}{d_p\varepsilon^2}\right)^{-1}$$

The media porosity instead depends upon the shear rate: where this shear is higher, the porosity is higher, making bulk solid flow better

Governing Equations

One of the assumption made writing the model is that the solid is incompressible. This could be a problem considering that the porosity, and hence the density would change now. Instead of making the model compressible, we made an algebraic closure of this kind



Dense Model

Shear

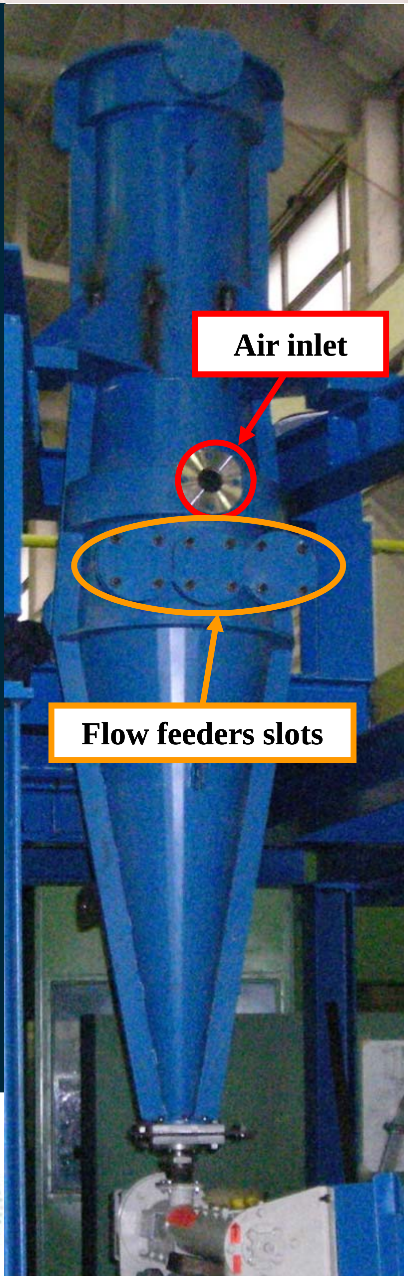
Porosity and permeability

Brinkman Equation

Drag

This can be only done if the changes in the porosity are small enough

Experimental Method



To set up and validate the model, we compared its results with those coming from an experimental campaign held in Danieli R&D between December 2008 and March 2009

During this campaign we studied the behaviour of a bulk solid in the silo that can be seen in figure. We used three different kind of solids : steel grit, zinc grit and sand.

This silo was ~2.5m tall and had a diameter of ~0.4m. It also had the possibility to have the injection of air and to have internal devices called flow feeders.

Those internal devices are three tubes passing from side to side of the silo.

Experimental Method

During each test, we prepared zinc tracer bands in a bed made of steel grit and made the material flow downwards. Meanwhile fresh material was continuously charged on the top of the silo.

We performed eight test kinds, combining the options in the table

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.

Experimental Method

For each test we recorded the wall stresses, the air velocity in the bed and the profiles of the tracer bands at the end of the test. To do so, we closed the silo on both ends, put it in horizontal position, opened along a diameter and the upper part of the material was removed to reveal the middle line

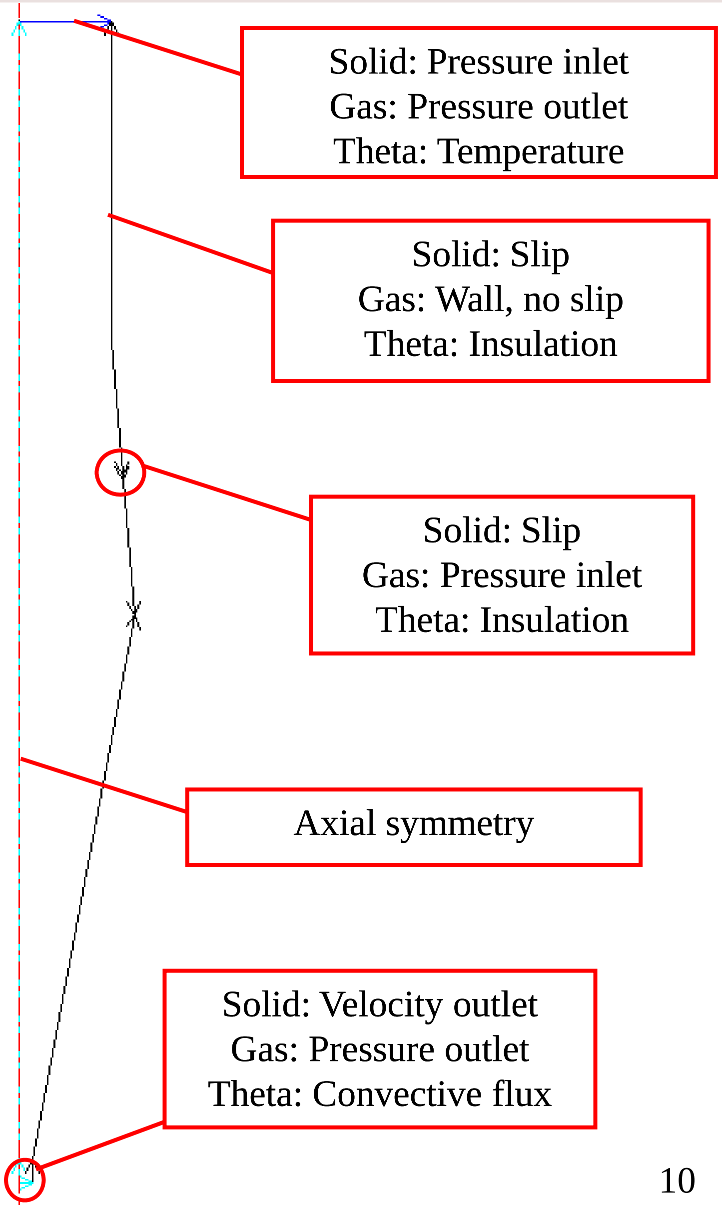
Boundary Conditions

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.



Solid: Pressure inlet
Gas: Pressure outlet
Theta: Temperature

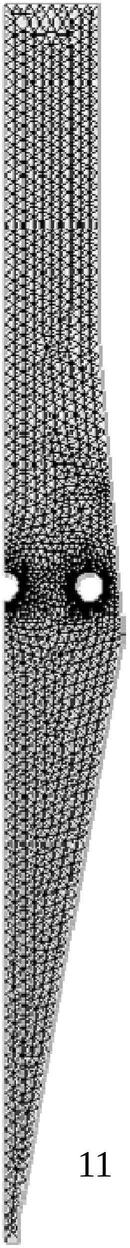
Solid: Slip
Gas: Wall, no slip
Theta: Insulation

Solid: Slip
Gas: Pressure inlet
Theta: Insulation

Axial symmetry

Solid: Velocity outlet
Gas: Pressure outlet
Theta: Convective flux

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 axisymmetric 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, which was the one without internal devices and air.

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.

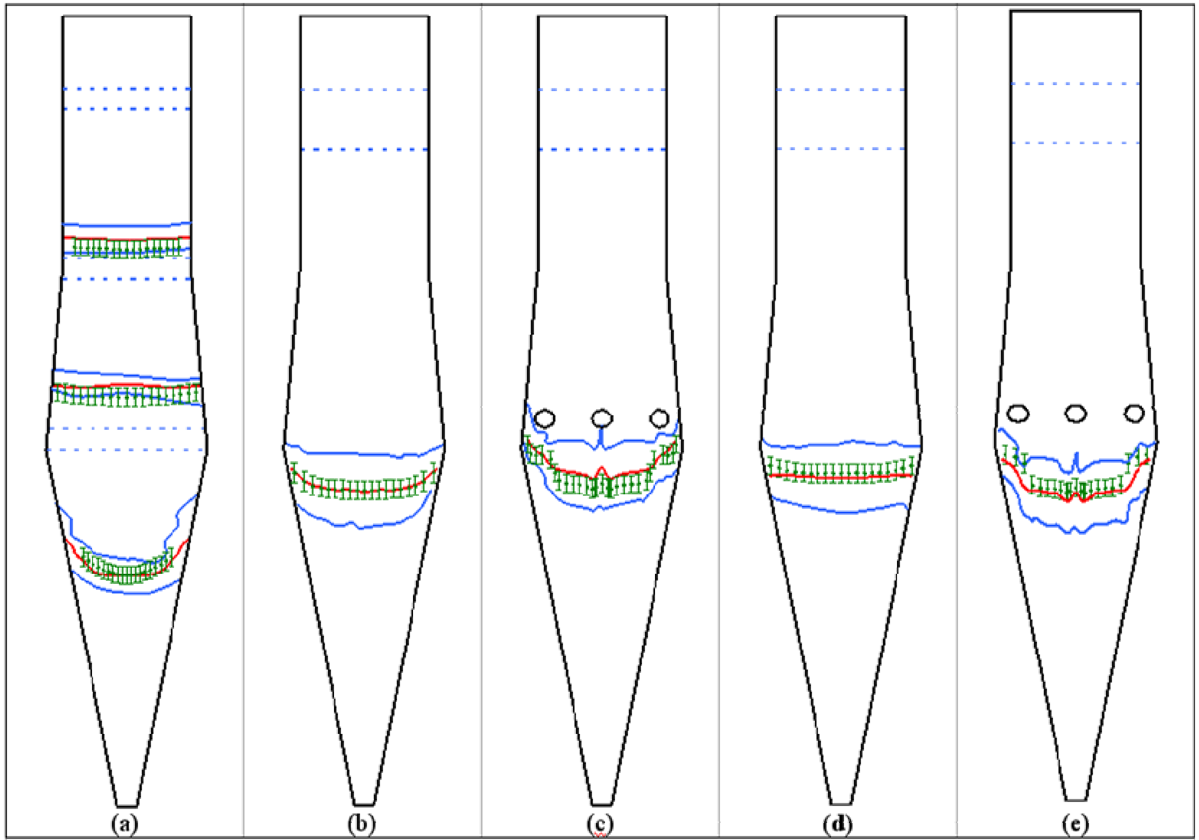


Figure 4. Comparison between experimental and simulation results. (a) and (b) are base cases, with no flow feeders and no air, used for calibration. (c) is the case with flow feeders but no air, (d) with air but no flow feeders and (e) with both flow feeders and air. Blue dashed lines are tracer stripes 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.

Results

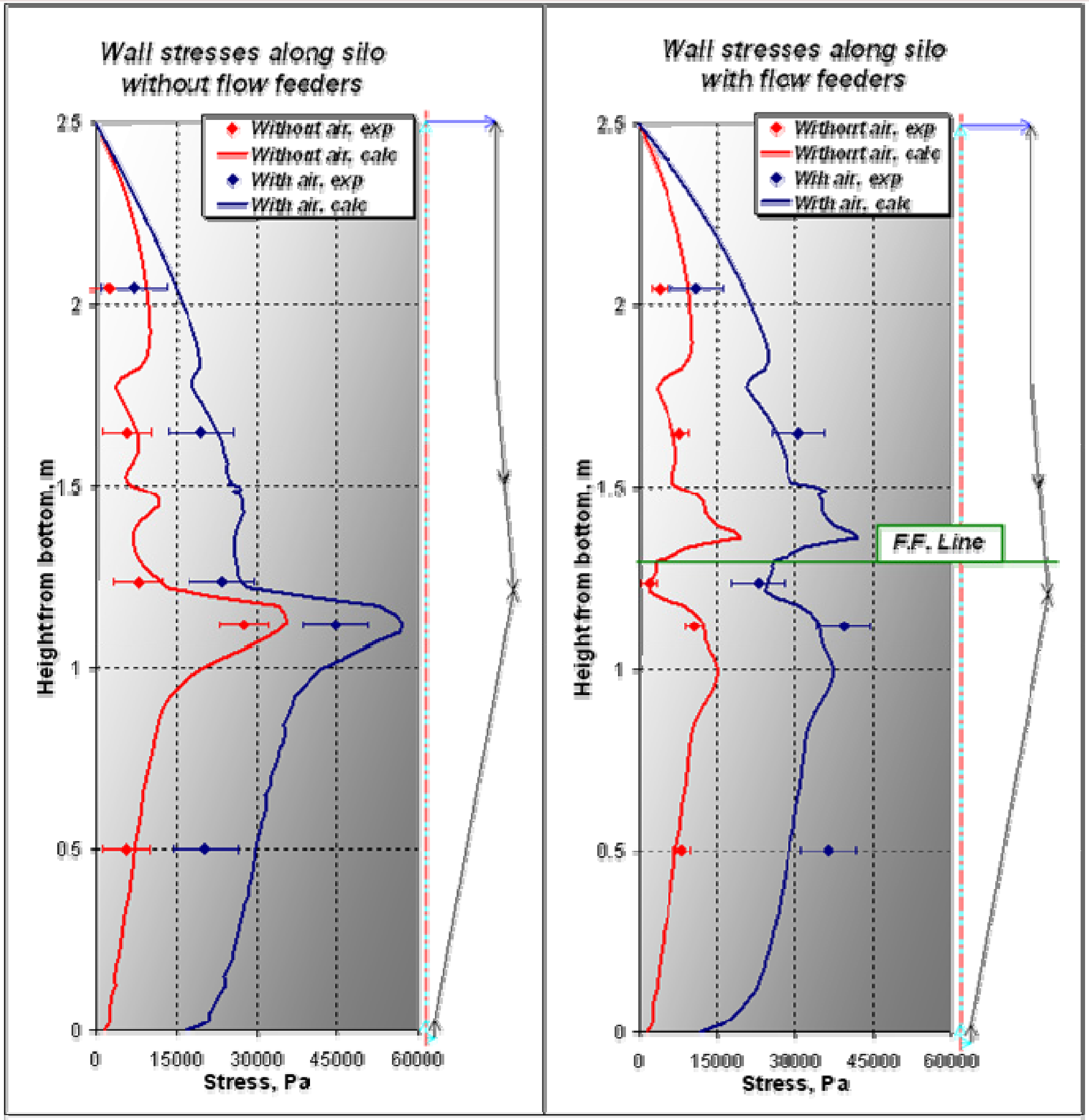


Figure 5. Wall normal stresses along the silo in the "no flow feeders" (left) cases and in the "with flow feeders" ones (right). Error bars represents standard error on experimental measure.

In previous works [1, 2] was shown that the model predicts correctly the wall stress when there is no air flowing through the silo.

The upgraded model reproduces well enough also the case in which the air is flowing through material.

Results

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

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

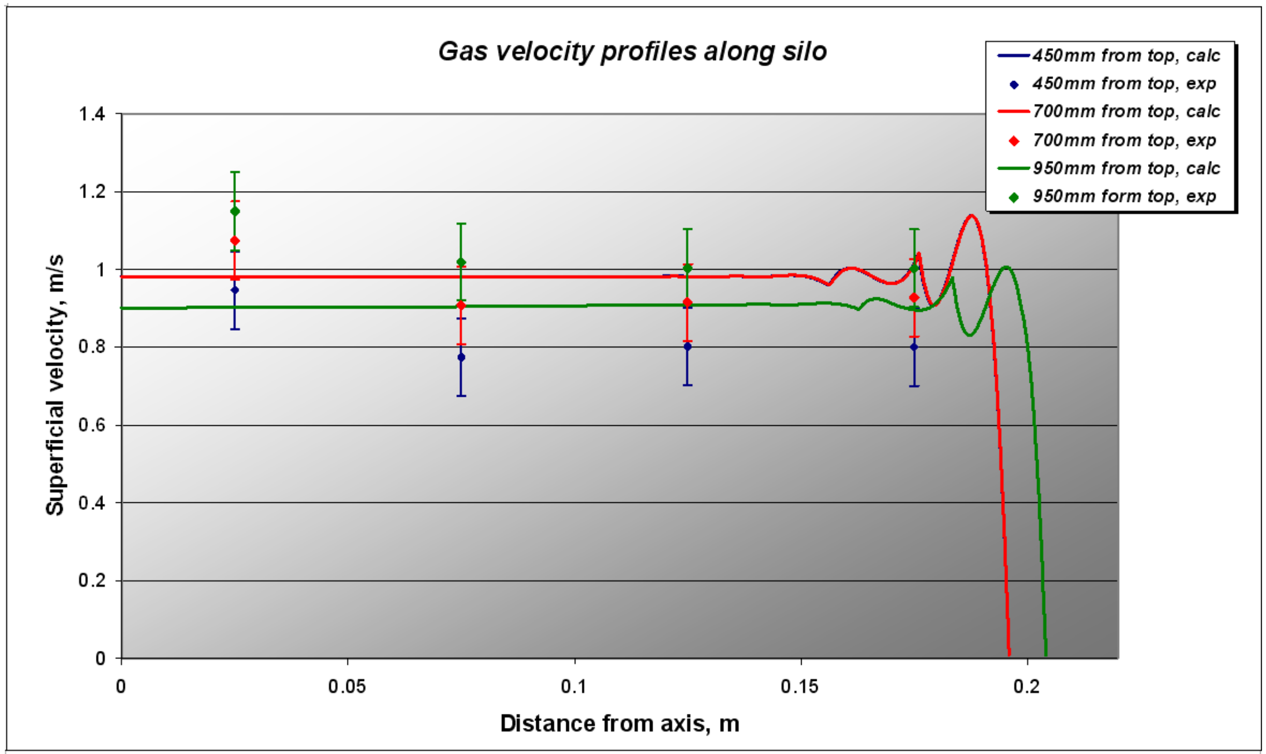


Figure 6. Gas velocity profiles at various deeps in the silo. Error bars on experimental values are of the same order of magnitude of the anemometer scale, ±0.1m/s. Calculated values at 450 and 700 mm from the top are identical.

Conclusions

We upgraded the dissipative hydrodynamic model [1,2] 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:

- consider the compressibility of the gas phase
- take into account thermal as well as chemical interactions between the two phases
- perform a 3D simulation to avoid geometrical problems related with the flow feeders representation in an axisymmetric simulation

Thank you for your attention

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