A Stabilized and Parallelized High Order Finite Element CFD-DEM Solver for Multiphase Flows

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Introduction

Multi-phase solid-gas flows are encountered in several technological applications such as pollutant control systems, combustion systems, and drying systems.

- Fluidized and spouted beds are among the common industrial applications which deal with solid-gas flows.
- Experimental techniques to investigate fluidized and spouted beds are generally expensive and sometimes infeasible for complex applications.
- Modeling helps the understanding of the various phenomena occurring in different processes at a much cheaper cost.

Objectives

- **Develop** a stabilized Volume Averaged Navier Stokes (VANS) solver with high order capabilities as high order methods are more accurate for the same mesh.
- **Couple** the VANS solver with the Discrete Element Method (DEM) solver within the open source software Lethe.
- **Validate** the code using different test cases.

Equations

The VANS equations are discretized using the Finite Element Method. These equations are:

Continuity:

$$\rho_f \frac{\partial(\epsilon_f)}{\partial t} + \rho_f \nabla \cdot (\epsilon_f \mathbf{u}) = m'$$

Momentum:

$$\rho_f \left(\frac{\partial(\epsilon_f \mathbf{u})}{\partial t} + \nabla \cdot (\epsilon_f \mathbf{u} \otimes \mathbf{u})\right) = -\epsilon_f \nabla p + \epsilon_f \nabla \cdot \tau_f + \mathbf{F}_{pf} + \rho_f \epsilon_f \mathbf{f}$$

The solid phase is solved using Newton's second law:

$$m_p \frac{\partial \mathbf{u}_p}{\partial t} = \Sigma_{N_p} \mathbf{F}_{p-p} + \Sigma_{N_p} \mathbf{F}_{p-w} + m_p \mathbf{g} + \mathbf{F}_{fp}$$

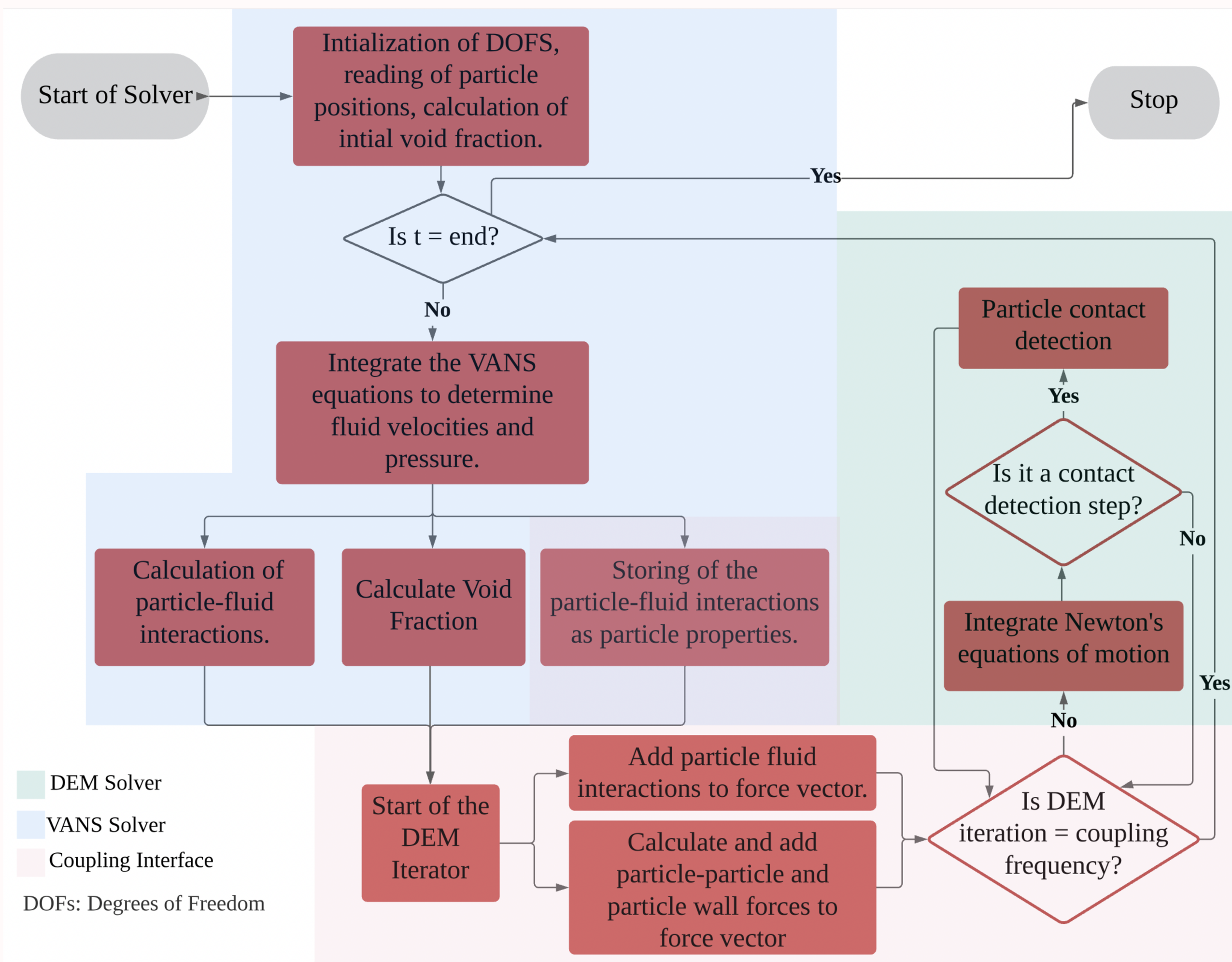
Nomenclature

ρ_f : fluid density	ϵ_f : void fraction	$\mathbf{u}$: fluid velocity
m' : mass source	p : pressure	τ_f : shear stress
$\mathbf{f}$: external forces	$\mathbf{F}_{pf}$: particle-fluid force	h : mixing length
A : Atwood number	α : constant	g : gravity

Methodology

The coupling between CFD and DEM is accomplished by:

- **Void Fraction Calculation:** The void fraction allows the fluid to feel the particles. It is calculated using one of different schemes such as **the particle centered method (PCM) and the divided approach.**
- **Fluid-Particle Interactions:** These forces include **the drag force, the buoyancy force, the shear force, and the pressure gradient force**. During fluidization, the dominant force is the drag force which is determined using one of many frag models (eg: Di Felice, Rong, Beestra, Gidaspow, ...)



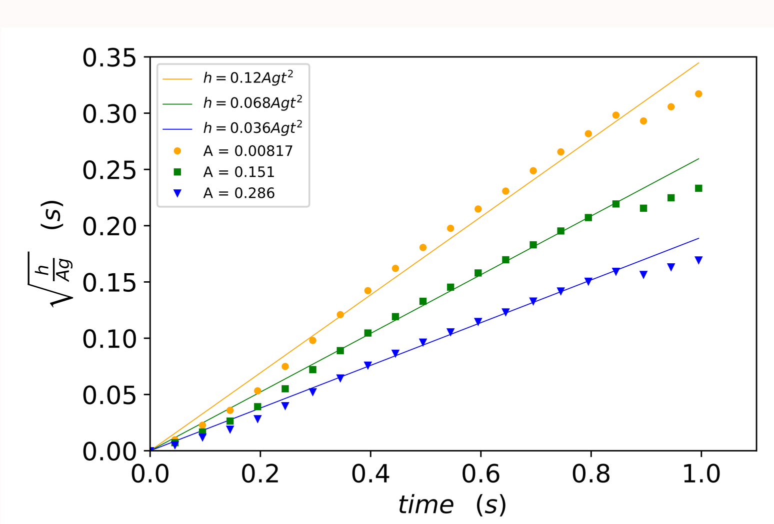
The CFD-DEM coupling scheme

Results

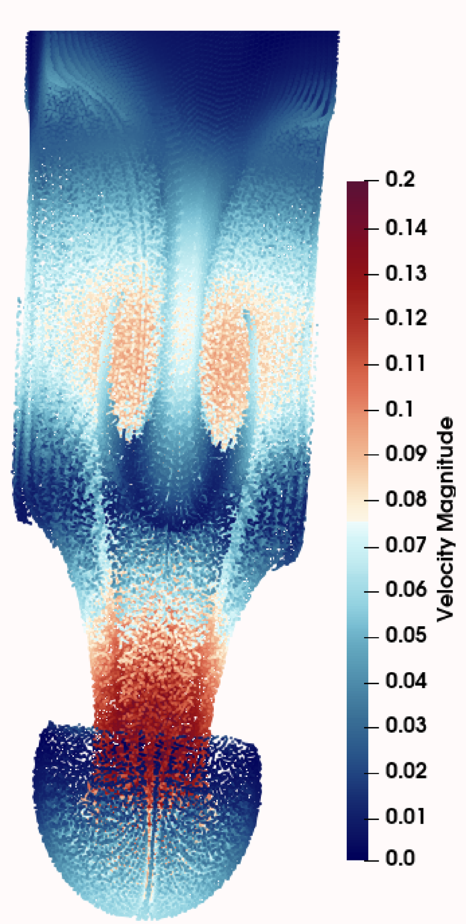
We show the results of a **spouted bed** test case and the **Rayleigh Taylor instability** that were simulated using Q1-Q1 elements.

Rayleigh Taylor Instability

We study the evolution of the Rayleigh-Taylor instability as a function of different fluid and particles' densities. This is a well known case in which a heavy fluid is located above a light fluid. The difference in densities makes this case an inherently unstable problem. In this case, the heavy fluid is a mixture of light fluid and particles. The mixing layer is described as: $h = \alpha A g t^2$

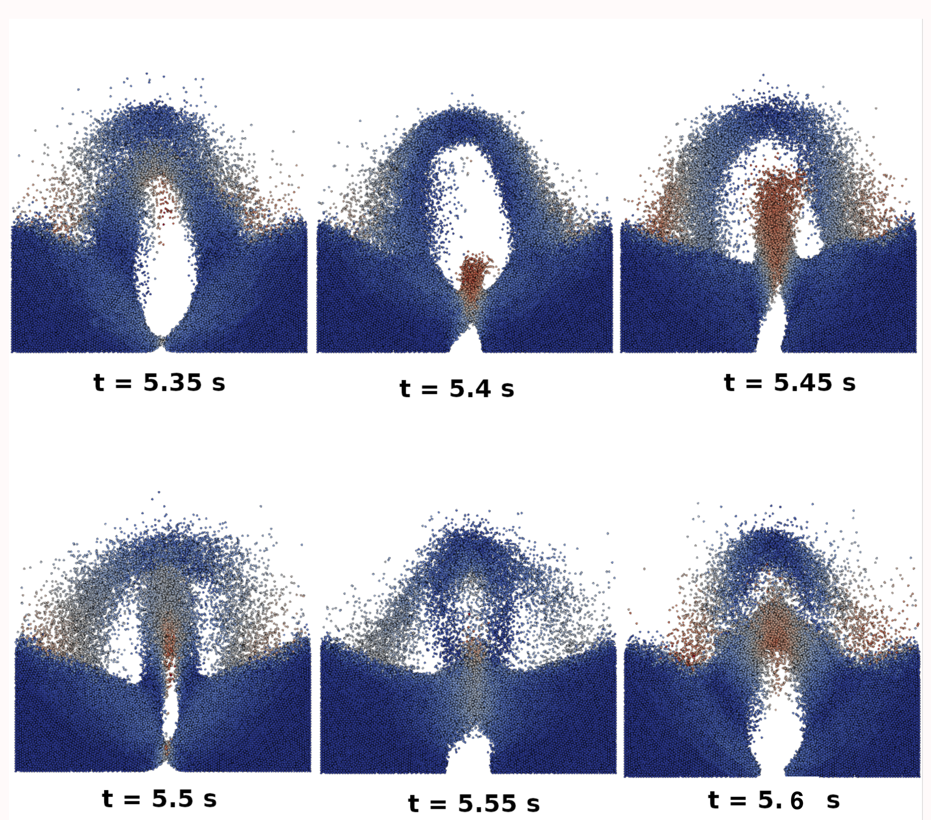


Evolution of the mixing layer



Plumes of Rayleigh Taylor Instability

Spouted Bed



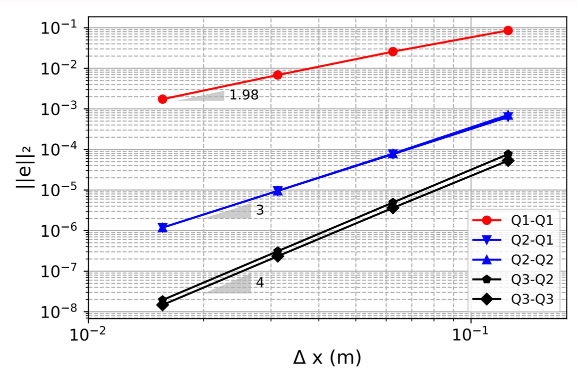
Spouted bed: periodic cycle

We simulate a spouted bed using Q1-Q1 elements. The bed is rectangular with 89700 glass beads of 2.5 mm diameter and a density of 2500 kg/m^3. The fluid used is air and is introduced at the center of the base of the bed.

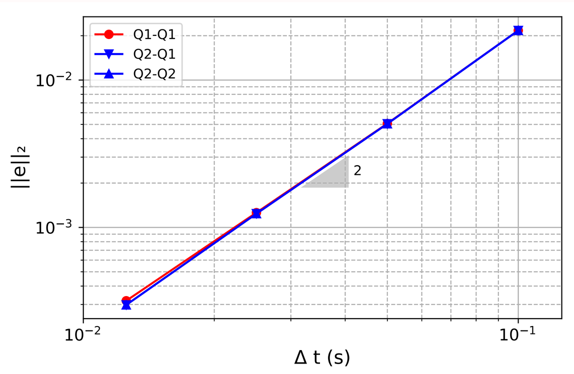
Validation of VANS Solver

The validation is divided in two parts: validation of the VANS solver discussed here and validation of the coupling solver discussed in the results section.

- **Verification using the method of manufactured solution (MMS):**

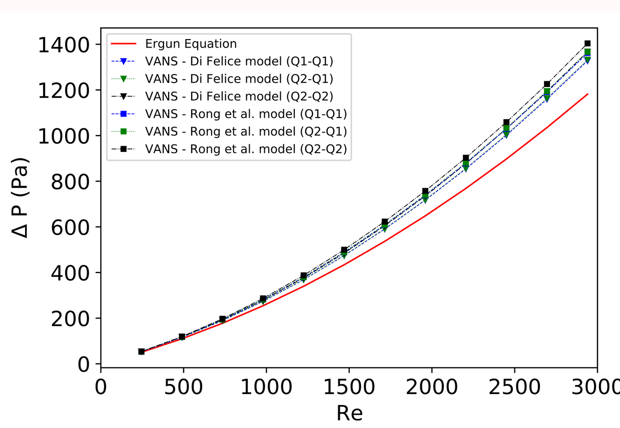


Space convergence of the VANS solver

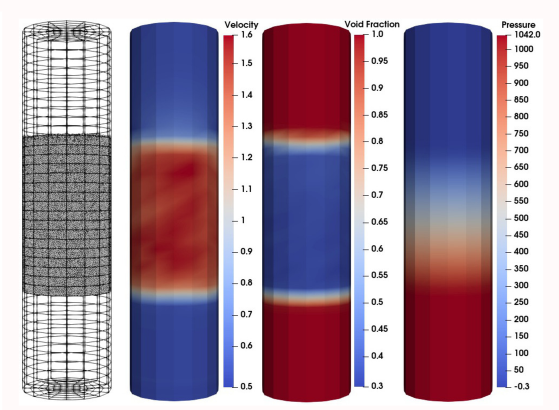


Time convergence of the VANS solver

- **Validation using a packed bed test case:**



Pressure drop as a function of inlet velocity



Packed bed (from left to right): Particles, Velocity, Void Fraction, Pressure

Conclusion

This work presents a verified and validated finite element approach to solve the VANS equations leading to a new coupled unresolved CFD-DEM solver with the following properties:

- Support for **arbitrary finite element orders** due to PSPG and SUPG stabilization.
- **Globally mass conservative** due to grad-div stabilization and void fraction time derivative.
- **Fully parallel** and one of the first CFD-DEM solvers to support **load balancing** between the phases.

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