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# NUMERICAL ANALYSIS OF DUST EMISSION BY POWDER DISCHARGE AND JET EXPANSION

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## ABSTRACT

The paper deals with the Euler-Euler numerical simulation of an experimental study (Ansart et al., 2009 [1]) of freely falling granular jet for investigating the dispersion of dust. The configuration is a bunker, where quasi-static particulate flow takes place, and a free-fall chamber. As a first step, a frictional viscosity model developed by Srivastava and Sundaresan (2003) [2] is implemented to take into account the frictional effects occurring in the quasi-static particulate flows. Without the frictional model for the viscosity, the numerical simulations overpredict the solid mass flow rate at the outlet of the bunker. When using the frictional viscosity, the solid mass flow rate is in better accordance with the experimental value. However, the solid velocity is overestimated in numerical simulations.

## INTRODUCTION

The handling of free-fall powder or granular structures in jet flows remains a core activity in many industrial processes. The unstructured falling particle stream can generate dust emission, might be harmful for workers and cause health and safety hazards. Mastering these elements relies on the understanding of the mechanisms governing the spreading granular jet. However, this remains challenging due to the several interactions involved, not just between the particles but also gas/particle and polydispersion effects.

To perform a thorough analysis of the granular jet expansion, it is necessary to consider an effective range of solid volumetric fraction; from quasi-static flows into bunker to very dilute flows. Besides, one may refer to experimental studies carried out on air entrainment during the free-falling granular jet process [1, 3-5]. When considering fine particles ( $d_p < 100 \mu m$ ), it has been

proved that the interplay between particles with the surrounding air is not negligible [1, 4]. Part of the surrounding air is entrained into the particle stream and could then modify its behaviour.

In the first section, the experimental set-up used in this study is presented. This experiment corresponds to a freely falling granular jet based on a recent study of Ansart et al. (2009) [1]. It comprises: two vents on the top, a bunker on the middle and it ends with a free-fall chamber. The goal of the experiment was to examine the discharge of particle plumes in stagnant air. A dust lateral dispersion associated to the interaction effect between particles and the surrounding air has been observed.

The present paper is based on an Euler n-fluid modelling approach of a fluid-particle turbulent polydisperse flow. This formulation is described in the second section. It follows the kinetic theory of granular flows [6] and has been extended by [7, 8] with the aim of dealing with interstitial fluid effects and particle/turbulence interactions. This approach entails an additional closure term for the solid stresses accounting for the particle packing in dense and quasi-static regime.

The third section describes the numerical setup, which includes the two chimneys, the bunker and the free-fall chamber. Simulation results are provided in Section four. The dependence to wall boundary conditions and parameters of the frictional model will be addressed.

## EXPERIMENTAL CONFIGURATION

The geometry of the free-falling configuration conducted by Ansart et al. (2009) [1] is shown in Fig. 1. It consists in a bunker filled with particles which flow out through the orifice into the free-fall chamber. It consists of two parts: (i) the first part allows the spreading of granular jet in static air, (ii) the second part corresponds to the granular jet impact on the particles heap. Six vents have been placed in the experiment to prevent the

depression created by the induced air flow (this is represented by (+) for inward flow and (-) for an outward flow).

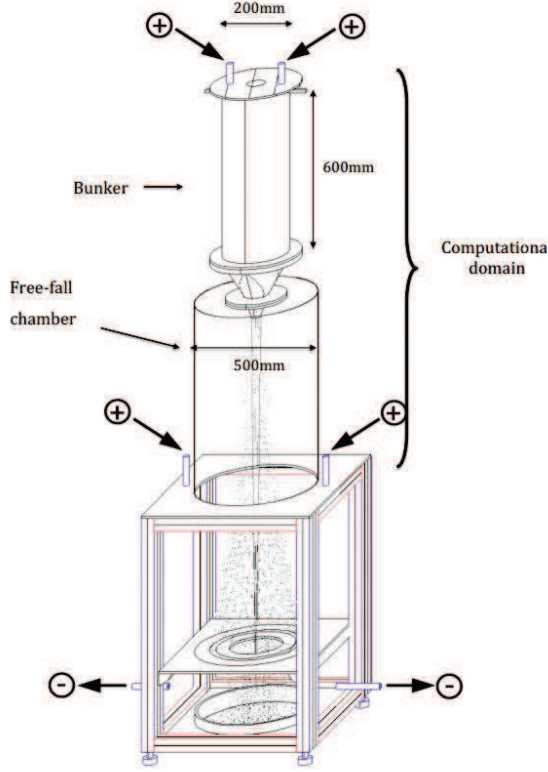


FIGURE 1. SKETCH OF THE EXPERIMENTAL SET-UP

To characterize the fine particles, Ansart et al. used a Particle Image Velocimetry (PIV) methodology. This allows to observe the spreading of granular particles that might be associated to the streaming air entrained into the plume. Operating conditions from experiment are shown in Tab. 1.

TABLE 1. EXPERIMENTAL SET-UP

Variable	Symbol	Value
outlet diameters	$D_o$	10 mm
mean diameter	$d_p$	60 $\mu\text{m}$
particle density	$\rho_p$	1000 $\text{kg} \cdot \text{m}^{-3}$
air density	$\rho_f$	1.2 $\text{kg} \cdot \text{m}^{-3}$
air dynamic viscosity	$\mu_f$	$1.85 \cdot 10^{-5} \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
outlet mass flow rate	$Q_m$	$1.44 \cdot 10^{-3} \text{ kg} \cdot \text{s}^{-1}$

## MODELING APPROACH

Three dimensional numerical simulations of free-falling granular jet have been carried out using an Eulerian n-fluid modelling approach for gas-solid turbulent polydisperse flows developed and implemented by IMFT (Institut de Mécanique des Fluides de Toulouse) in the NEPTUNE CFD V1.08@Tlse version. NEPTUNE CFD is a multiphase flow software developed in the framework of the NEPTUNE project, financially supported by CEA (Commissariat à l'Énergie Atomique), EDF (Electricité de France), IRSN (Institut de Radioprotection et de Sécurité Nucléaire) and AREVA-NP. The numerical solver has been developed for High Performance Computing [9, 10]. Separate mean transport equations of mass and momentum are solved for each phase. The transport equations are derived by phase ensemble averaging for the continuous phase and in the frame of kinetic theory of granular flows [6] for the dispersed phase but extended to account for interstitial fluid effects and particle-turbulence interaction [7, 8]. The fluid-particle momentum transfers are taken into account by the model proposed by Gobin et al. [14]. The turbulence of the gas phase is computed using the  $k-\epsilon$  model, and particle agitation is treated by the  $q_p^2 - q_{fp}$  model for dense flows (Simonin, 1996 [7]).

Solid volume fraction, in particular case of the hopper, is sufficiently high for the particles-particles and particles-wall interactions to be ruled by friction with long-term contacts. In order to take the quasi-static regime into account, [11, 12] propose to add a frictional contribution to the effective stress tensor, in the following form:

$$\Sigma_{k,ij}^{eff} = \Sigma_{k,ij} + \Sigma_{k,ij}^{fric} ,$$

with the frictional stress tensor,

$$\Sigma_{p,ij}^{fric} = P_p^{fric} \delta_{ij} - \mu_p^{fric} \tilde{D}_{p,ij}$$

where  $P_p^{fric}$  and  $\mu_p^{fric}$  are the frictional pressure and viscosity. The solid strain tensor,  $\tilde{D}_{p,ij}$  reads:

$$\tilde{D}_{p,ij} = \frac{\partial U_{p,i}}{\partial x_j} + \frac{\partial U_{p,j}}{\partial x_i} - \frac{2}{3} \frac{\partial U_{p,k}}{\partial x_k} \delta_{ij} .$$

The frictional pressure is written according to [12, 13],

$$P_p^{fric} = \begin{cases} Fr \frac{(\alpha_p - \alpha_{p,min})^r}{(\alpha_{p,max} - \alpha_p)^s} & \text{if } \alpha_p > \alpha_{p,min} . \\ 0 & \text{otherwise} \end{cases}$$

$Fr$ ,  $r$  and  $s$  represent empirical material constants of the model. For glass beads this constant are taken to be  $Fr = 0.05$ ,  $r = 2$ ,  $s = 5$  and the threshold volume fraction for friction  $\alpha_{p,min}$  is 0.5.

A frictional viscosity model has been developed by Srivastava and Sundaresan (2003) [2]. At the critical state, one assumes no volume change during the deformation of the granular medium. This model can be written as:

$$\mu_p^{fric} = \begin{cases} \frac{\sqrt{2} P_p^{fric} \sin(\phi)}{\sqrt{I_{2D} + \frac{8}{3} \frac{q_p^2}{d_p^2}}} & \text{if } \alpha_p > \alpha_{p,min} \\ 0 & \text{otherwise} \end{cases}$$

where  $\phi$  is the angle of internal friction, set to  $28.5^\circ$  for glass beads, and  $I_{2D}$  is the second invariant of the strain rate tensor.

## DESCRIPTION OF NUMERICAL SIMULATIONS

The computational domain corresponds to the top of the experimental set-up. The domain consists of two parts: a bunker with a very dense particulate flow, and a free-falling zone where the particulate flow is dilute. The geometry of the bunker is a cylinder with a diameter of 200 mm and a length of 600 mm. The bottom part of the bunker is a cone with a height of 190 mm and a semi-angle of  $30^\circ$ . Two chimneys (inlet of the surrounding air) can be found at the top of the bunker. The free-fall chamber is a squared box of 500 mm in length and 600 mm in height.

Fig. 3 shows the mesh used for the numerical simulations. It contains 37 000 hexahedral cells for the bunker and 418 000 hexahedral cells for the chamber. In the free-fall chamber, the cells are locally refined close to the central axis (see Fig. 2) to capture the spreading of the granular jet. The outlet of the bunker, also called the injector, is meshed with 25 grid cells ( $\Delta_x = \Delta_y = 0,4$  mm).

The initial particle volume fraction in the silo is equal to 0.6. The computation is divided into three steps. First the outlet of silo is closed by a fictitious wall for 10s. In this phase, the particles are compacting. The second step corresponds to the transient state after removing the fictitious wall (around 20s). Finally, variables are averaged over an established regime which lasts about 20s.

The two chimneys at the top of the domain are free outlets. The bottom of the computational domain is also a free outlet and the hydrostatic pressure has been taken into account. Wall friction boundary conditions have been applied to the gas phase, while no-slip, or free-slip wall boundary conditions have been chosen for the solid.

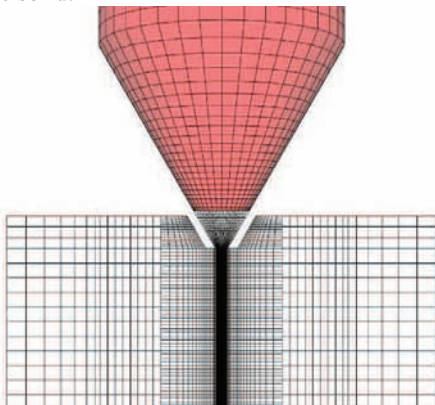


FIGURE 2. VIEW OF THE MESH

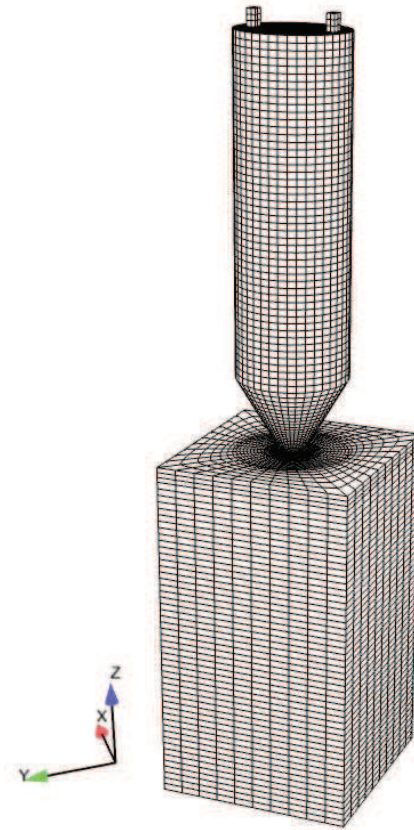


FIGURE 3. THREE DIMENSIONAL VIEW OF THE MESH

## RESULTS AND DISCUSSION

Three dimensional simulation with and without frictional viscosity are considered. The results will focus on the outlet of the bunker and the dependence to wall boundary conditions is carefully examined. The influence of frictional parameters introduced by Ocone et al. (1993, [15]) is evaluated thereafter. Finally, the threshold volume fraction for the activation of the friction parameter is studied.

Figure 4 and 5 show the solid mass flow rate measured at the outlet of the bunker. Case 1 is a numerical simulation without frictional viscosity model and no-slip wall boundary condition for the solid. Case 2 has been performed with the frictional viscosity model and no-slip wall boundary condition. Case 3 has been carried out with the frictional viscosity model and free-slip wall boundary condition. The particle mass flow rates are compared with the one measured in the experiment (1.44 g/s). When the injector is open ( $t=10s$ ) two different behaviours are observed. Without frictional viscosity (Case 1), the numerical simulation predicts a very large value of the solid mass flow rate (up to 0.12 kg/s) that is about 100 times larger than the one in experiment. The numerical simulation performed with frictional viscosity exhibits much smaller solid mass flow rate which is in better accordance with the experiment.



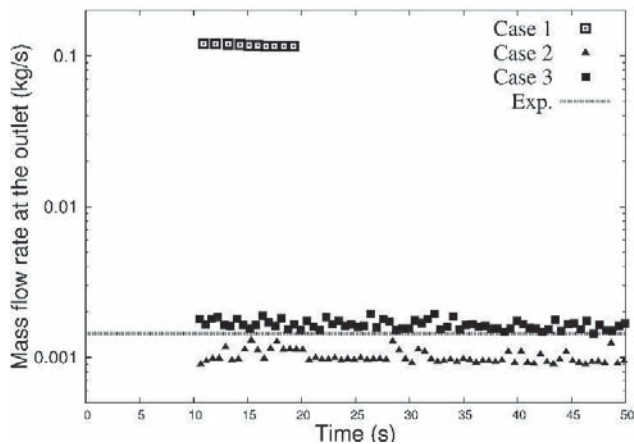


FIGURE 4. PARTICLE MASS FLOW RATE

The effect of the wall boundary condition is shown by comparing Case 2 and Case 3. No-slip wall boundary conditions lead to a smaller solid mass rate at the outlet of the bunker than free-slip conditions. Such result was expected because in the case of no-slip wall boundary condition the particle-wall friction is enhanced. Solid mass flow rate from numerical simulation with free-slip wall boundary condition matches experimental value. It is worth mentioning that all simulations exhibit temporal fluctuations of the mass flow rate.

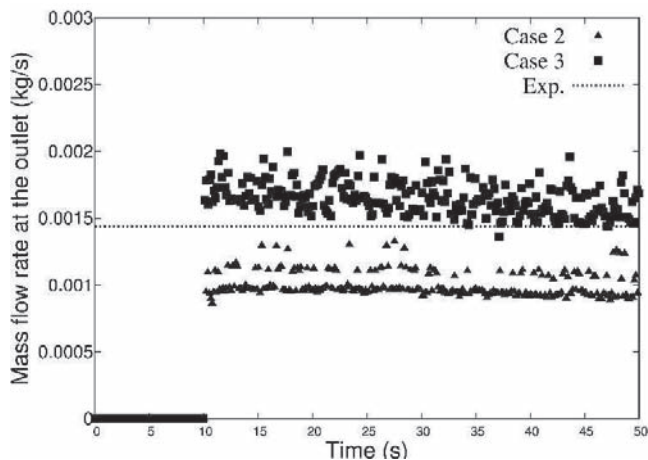


FIGURE 5. PARTICLE MASS FLOW RATE ZOOM ON CASE 2 AND CASE 3

Figure 6 shows the mean particle velocity measured along the  $z$ -axis, in the free falling zone. The comparison between the particle fall velocities show how the drag force has a non-negligible effect on particles. However, the drag is not strong enough to prevent particles from falling, having little effect on the particle speed. The huge amount of particles falling prevents the atmospheric air from interacting radially.

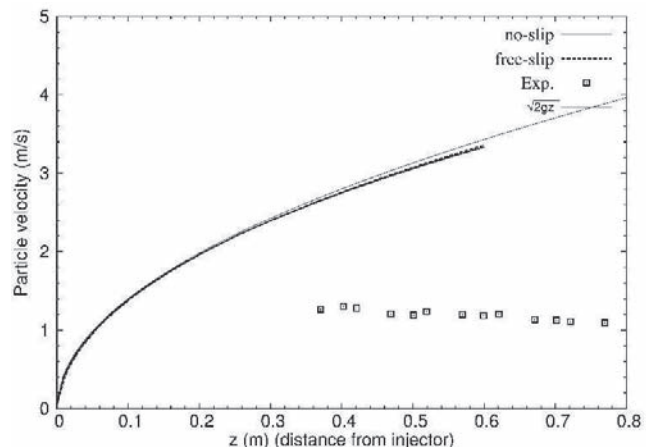


FIGURE 6. MEAN AXIAL PARTICLE VELOCITY

Figure 7 shows the mean particle volume fraction for Case 3. The particles fall in the free fall chamber without interaction with surrounding air.

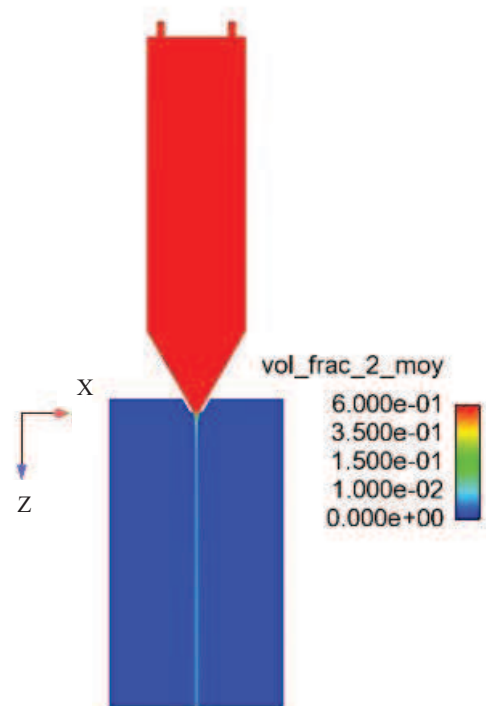
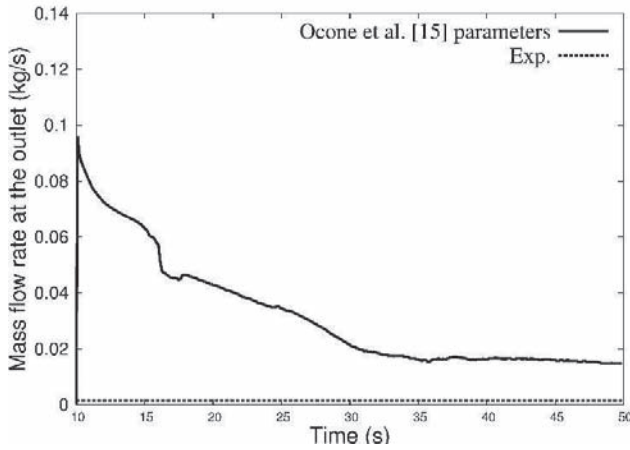


FIGURE 7. SIDE VIEW OF MEAN PARTICLE VOLUME

In the following, all simulations have been performed with no-slip BC for walls. In the literature, different coefficients are proposed for the modelling of frictional effects. Ocone et al. (1993, [15]) use the following values:  $Fr = 0.05$ ,  $r = 2$ ,  $s = 3$ ,  $\alpha_{p,min} = 0.5$  and the angle of internal friction  $\phi = 28^\circ$ .

These parameters have been studied in fluidized bed [16], as well as bubbling operating air injection in fluidized bed [17]. To the best of our knowledge, these parameters have not been analysed on a jet spreading experiment.

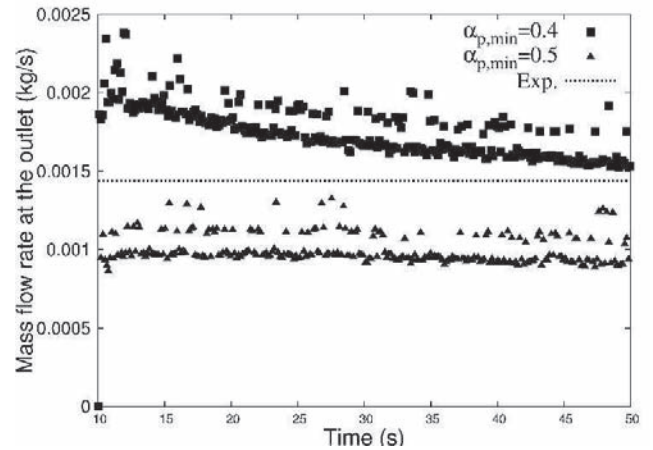
Figure 8 shows the particle flow rate at the injector outlet, using parameters from Ocone et al. [15]. This set of parameters overestimates the mass flow rate at the outlet (almost 10 times higher than the experimental value). Previously, it has been showed that frictional viscosity diminishes the particle flow rate. The pressure used by Ocone is smaller than Srivastava et al. [2], leading to a reduction of frictional viscosity. Decreasing frictional effects allows increasing the compactness inside the bunker (value of volume fraction inside the bunker is  $\alpha_p = 0.636$  for Ocone et al. [15] and for Srivastava et al. [2]  $\alpha_p = 0.6$ ). Thus, it seems natural that the flow rate value increases.



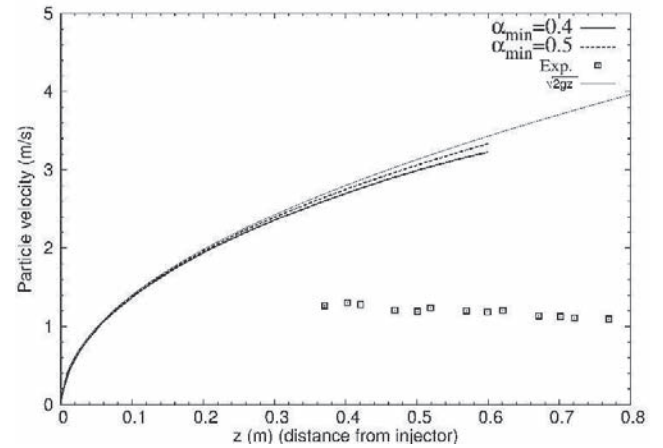
**FIGURE 8.** PARTICLE MASS FLOW RATE WITH OCONE ET AL. [15] PARAMETERS

In the modelling proposed by [2], it is not completely acquired that frictional effects occur only above the limit of  $\alpha_{p,min} = 0.5$ . Therefore, a parametric study on the threshold volume fraction for friction is proposed. Figure 9 shows  $\alpha_{p,min}$  for two values 0.4 and 0.5. When the parameter is equal to 0.4, the flow rate is very close to the experimental value (<10 %). The case of  $\alpha_{p,min}=0.4$  is not completely converged, it tends to the experimental value.

Figure 9 and 10 show the average axial velocity of particles and gas for  $\alpha_{p,min} = 0.4$  and  $\alpha_{p,min} = 0.5$ . The mean particle velocity along the z-axis for  $\alpha_{p,min} = 0.4$  is lower than  $\alpha_{p,min} = 0.5$ . The frictional effects are not totally negligible in the chamber. Additional studies will be needed to totally understand the influence of the parameters by refining the mesh.



**FIGURE 9.** PARTICLE MASS FLOW RATE OBTAINED FOR DIFFERENT THRESHOLD VOLUME FRACTION FOR FRICTIONAL EFFECTS



**FIGURE 10.** MEAN AXIAL PARTICLE VELOCITY

## SUMMARY AND CONCLUSIONS

The results show that the frictional viscosity model captures the particles mass flow rate at the orifice. But it is not enough to slow the particles and provoke a lateral dispersion. This might be explained through different reasons associated to the lack of physical effects. One explanation relies on the mesh representation or the model for frictional viscosity.

A first study on the choice of the boundary wall condition shows the particle mass flow rate at the outlet is reduced by no-slip boundary condition. Then, the Ocone et al. [15] parameters overestimate the mass flow rate up to ten times more than results with Srivastava et al. [2]. Finally, the choice of the threshold volume fraction for friction equal to 0.4 better captures the flow rate of particles at the outlet of the silo. It also allows reducing the speed of the falling particles. However, a value for the highest threshold volume fraction for friction is necessary to see air lifts inside the silo, this was noticed in the experiments conducted by

Ansart.

It would certainly be interesting to analyse the frictional viscosity models to look more finely granular jet transition in a very dense regime to a more diluted one [18, 19]. Encouraging results were obtained by Chialvo et al. [18, 19] applied to a new kind of model based on DEM type methods. The advantage of this type of analysis is to compare different parameters effects that can influence the behaviour of granular media.

In future work, a way to destabilize the entrained air in three dimensional simulations will be investigated. Indeed, it is possible that in the entrained air vortices lead to disruption and granular structures in the periphery of the jet. Finally, the work currently underway at the IMFT on the modelling of a fluidized bed can be interesting for this project. This work shows that a very refined mesh is required to obtain granular structures in a fluidized bed. For a coarser mesh, these structures disappear. Parmentier et al (2012) [20] developed a sub-grid model for particles to obtain these structures in simulations even with a coarse mesh. In the case of granular jet, it is possible that the mesh sizes used are not fine enough to obtain granular structures within the same jet, particularly close to the injector, which could then cause instability. The transition from quasi-static regime of dense and dilute regime will be influenced in the model by selecting the threshold volume fraction for friction.

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