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# NUMERICAL STUDY OF SOLID PARTICLE AXIAL MIXING IN A FIXED CYLINDRICAL DRUM WITH ROTATING PADDLES

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## Abstract

Axial mixture characterization is a widespread problem in granular particle blending processes such as in an horizontal drum mixer. The homogeneous mixture of particles is obtained by blending the particles via rotating paddles in a fixed cylindrical drum. This problem, common to many technological devices, is crucial in the manufacture of a broad variety of industrial products, such as polypropylene. The granular flow behavior in these systems is still poorly understood and the numerical study of such configurations receives increasing academic and industrial attention. In this paper, a study is conducted to investigate the effects of different aspects of the reactor design on the axial transport of monodisperse, uniform density and spherical polypropylene particles. Results show that principally the shape of the paddles is the important design consideration to enhance the axial transport of particles.

## Introduction

Granular mixing of particles is a widespread procedure in many industries such as the plastics production, pharmaceuticals, concrete and food manufacture. The manufacture of many products in these areas strongly depends on the homogeneous mixing of particles such as propylene where the polypropylene particles are produced through the polymerization reactions in fixed cylindrical drums with rotating paddles. The quality of mixing directly determines the quality of the final product (8). To enhance axial granular flow and to obtain a good level of mixing, the shapes of the paddles and operating conditions (angular velocity, solid mass) are important parameters. However, the granular flow inside the drum is not easily accessible for the experimental apparatus and the effects of these parameters on the flow are not easy to measure (5). Computational Fluid Dynamics (CFD) tools are then useful in order to get information about the detailed mechanics of the flow.

This study is a collaboration between the Institut de Mécanique des Fluides de Toulouse (IMFT), and Ineos Technologies. Important part of the investigation is the characterization of the axial mixing of the solid particles. To this purpose, an axial propagation velocity and a diffusion coefficient using this velocity are computed in order to characterize the mixing of particles. The results are in qualitative coherence with the experimental data conducted at the facilities of the industrial partner.

## Mathematical Modeling

The simulations have been performed using the Euler-Euler code NEPTUNE\_CFD. NEPTUNE\_CFD is a multiphase flow solver developed in the framework of the NEPTUNE project, financially supported by CEA, EDF, IRSN and AREVA-NP. In the Euler-Euler approach, mean equations are solved for both phases and are coupled through the interphase transfer terms (mass, momentum and energy). The turbulence of the gas phase is treated by the two-equation “k- $\epsilon$ ” eddy-viscosity model with additional terms taking into account the effect of the presence of the solid phase. Particle phase equations are derived in the general frame of the kinetic theory of granular media supplemented by the interstitial fluid effect (2, 3). Wen-Yu drag model limited by the Ergun’s equation for the dense flows is used for the drag force acting on the particles (1). Apart from the drag force for the solid phase, the Archimedean force and the gravity are also taken into account in the momentum transport equations of both phases. The kinetic theory-based approach for the solid phase is theoretically inadequate for the closely packed dense flows where the particle-particle contacts are of long durations such as observed inside the horizontal drum. Indeed, the long duration contacts lead to the frictional force effects, which cannot be taken into account by hard sphere collision models. Following (4), a semi-empirical model is used in this study in order to compute the frictional stress tensor for the solid phase in the momentum equation. The model has been further developed (7), by taking into account the quasi-static state fluctuations of the strain-rates as discussed in (6). The model coefficients are chosen as in the proposition of (7).

## Numerical Simulations Overview

Four simulations have been performed to investigate the effect of different operating conditions. The simulations are summarized on Table 1. Solid mass is the initial mass of particles inside the domain. There are two paddle types tested, Mixer A and Mixer B. Mixer A is the initial simple paddle shape and Mixer B is with a substantially different paddle shape.

Table 1. Simulations carried out

Simulations	Angular velocity	Solid Mass	Mixer Type
Sim1	40 rpm	31.7 kg	Mixer A
Sim2	40 rpm	45.2 kg	Mixer A
Sim3	15 rpm	45.2 kg	Mixer B
Sim4	40 rpm	31.7 kg	Mixer B

## Mesh

Figure 1 presents 3D perspective view of the mesh generated. The length of the cylinder is one order of magnitude larger than its diameter. Around 40 paddles are present inside the domain that enhances the mixing of the particles. The mesh contains in total 2 500 000 hexahedral cells. The cells have uniform length in axial direction and they are more or less of a cubical shape.

## Initial and Boundary Conditions

Initially, the particles are at rest and there is no gas motion, neither. The paddles start to rotate and to mix the solid phase. The entire domain is enclosed with walls so there is no inlet or outlet. Gas and solid phases have frictional interactions with the walls (no-slip condition).

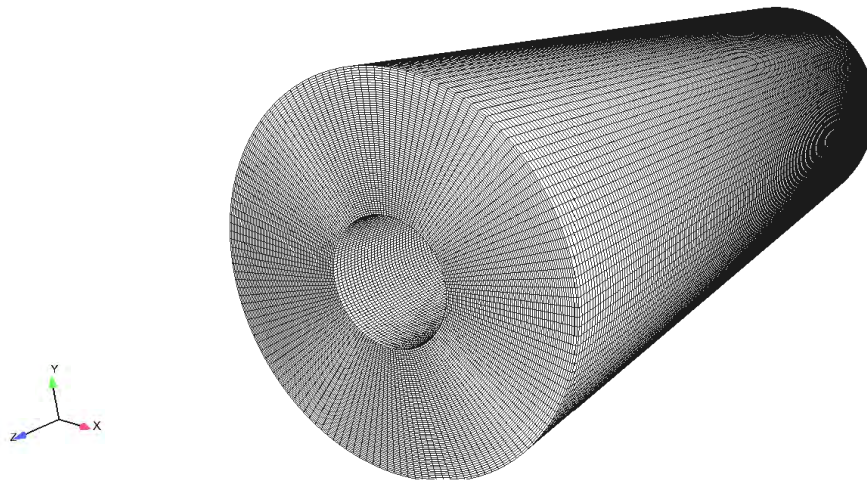


Figure 1. 3D view of the mesh

## Material Properties

Solid phase is composed of monodisperse particles, the diameter is  $700 \mu\text{m}$  and the material density is  $900 \text{ kg/m}^3$ . These characteristics are of polypropylene particles used in the real process. Gas phase is the air with a density of  $1.2 \text{ kg/m}^3$  and the dynamic viscosity is  $1.8 \times 10^{-5} \text{ kg/m/s}$ .

## Performing the Simulations and Computer Performances

Simulations were performed in order to characterize the axial propagation of the colored particles and to estimate a dispersion coefficient. The calculations have been done starting after several complete rotations of the paddles. All the simulations have been performed on the supercomputer CALMIP (Toulouse) on a parallel platform. 60 s of physical time cost almost 45 days with 256 processors. The time step of the simulations is not constant. On the mean, it is around  $5 \cdot 10^{-5} \text{ s}$ .

## Results and Discussion

In order to characterize the axial propagation of particles, colored particles were used. At time  $t=0 \text{ s}$ , the particles in the first axial 10 cm of the domain were colored and their collective motion is predicted using the scalar transport equation. The temporal evolution of these particles' motion gives an idea about the velocity of the axial propagation  $U_c$ . This velocity is calculated by using the convection equation of the colored particles written as:

$$\frac{\partial Y_c}{\partial t} = -U_c \frac{\partial Y_c}{\partial z} \quad (1)$$

where  $Y_c$  is the local colored particle concentration.

For the computation of the gradients in the equation (1), temporal evolution of the concentration profiles are extracted on several axial lines along the length of the domain after each complete rotation. The figures presented in the sections below correspond to only one line, as the results corresponding to different lines were more or less the same. The line is so chosen that the results would not be affected by the presence of the walls such as of the drum and of the paddles. It is to be noted that using the equation (1) to calculate the convection velocity  $U_c$  assumes that the radial distribution of particles is homogeneous.

A diffusion coefficient  $D_t$  can then be calculated as:

$$D_t = -\frac{U_c}{\left(\frac{dY_c/dz}{Y_c}\right)} \quad (2)$$

It should be noted that this definition of the diffusion coefficient is of an empiric nature. More rigorous estimation of the diffusion coefficient requires a well-based definition and a well-defined methodology. Nevertheless as we will see in the following sections, using the formula (2) gives reliable results in terms of the flow qualitative behavior.

### **Effect of the solid mass**

Figure 2 shows the influence of the solid mass. Each line corresponds to one complete rotation of the paddles starting from the one on the top ( $Y_c=1000$ ). Arrows show the direction of the temporal evolution of the concentration profiles. Qualitatively, the profiles are smooth up to 10 cm and between the 30-40 cm. Near the front of the colored particle region (around 20 cm), remarkable oscillations are present. In any case, the profiles are the same after 6-7 rotations. The estimated propagation velocity is around 5 mm/s for both simulations. To conclude on the effect of the solid mass, it does not have a large influence on the axial propagation velocity of the particles.

### **Effect of the angular velocity**

Figure 3 shows the effect of the velocity of rotation. On the left figure, the angular velocity is 15 rpm and on the right, it is 40 rpm. Qualitatively, it is clear from the figure on the left that reducing the velocity results in smoother axial profiles of the particle concentration. As seen on the plots, after 10 rotations, the particle front arrives at 30 cm for both cases. It can be concluded that the velocity of rotation also does not have a large effect on the axial transport of the particles. However, it can be pointed out that the slow motion of the paddles result more flat concentration profiles and temporal evolution of the profiles.

Here, it should be noted that the solid mass of these two simulations are different. However, in the previous sections, it has been shown that the solid mass does not have a large effect on the axial transport.

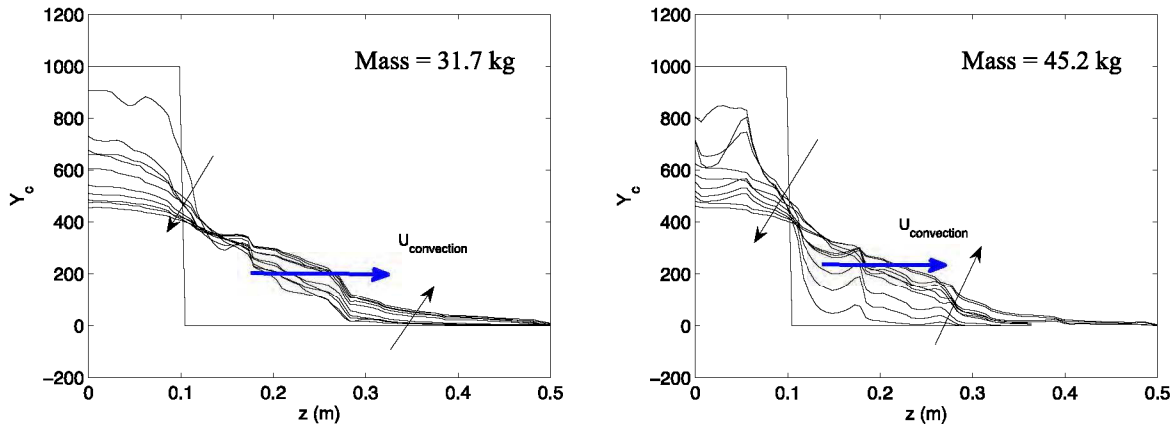


Figure 2. Temporal evolution of colored particle concentration profiles on a line along the axis of the domain: Effect of the solid mass (Mixer A, 40 rpm)

### Effect of the paddle shape

Figure 4 shows the effect of the paddle shape. Two different paddle shapes have been tested. On the left, the results with the initial paddle shape and on the right, the results with substantially different paddle shape are presented. Clearly on the figures, particle front propagates faster for the first paddle shape than the second one. In addition, the profiles are much flatter for the second paddle shape than those for the first paddle. The initial paddle shape enhances the axial propagation largely.

The estimated diffusion coefficients  $D_t$  for the initial and second paddle shapes are, respectively,  $2.0 \times 10^{-3}$  and  $0.5 \times 10^{-3}$   $\text{m}^2/\text{s}$ . We can conclude that the shape of the paddles can largely enhance the axial transport of particles. These results are in qualitative coherence with the experimental results, however, more quantitative comparisons are to be made in the recent future.

### Conclusion and Perspectives

3D simulations of an horizontal fixed drum with rotating paddles have been carried out with the Euler-Euler code NEPTUNE\_CFD. Different operating conditions have been investigated such as the solid mass, velocity of rotation of paddles and paddles' geometrical shape on the axial transport of colored particles. The simulations show that the solid mass and the angular velocity are much less important than the shape of the paddles in terms of the enhancement of the axial transport. However, substantially different paddle shape can increase the transport up to 4 times. Quantitative comparisons with the experimental data provided by the industrial partner will take place in the future in order to verify the validity of the results. However, the proper characterization of the axial particle transport remains an open problem and more efficient methods should be thought of. Results' sensibility to the frictional model coefficients, particle-wall boundary conditions and the polydispersion are in our future prospects. In the context of the collaboration IMFT-INEOS, more realistic representation of the polypropylene production process is in progress where the polymerization reactions are to be taken into account.

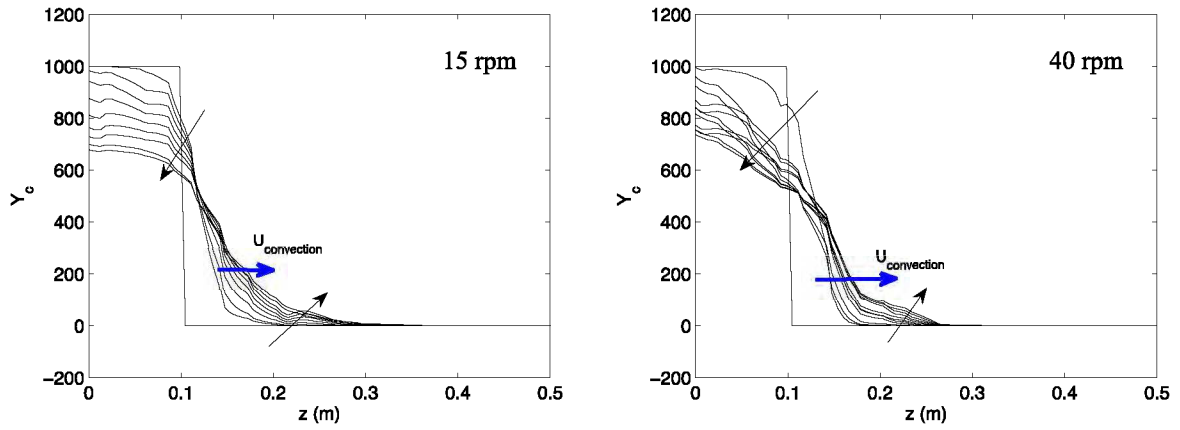


Figure 3. Temporal evolution of colored particle concentration profiles on a line along the axis of the domain: Effect of the angular velocity (Mixer B, solid masses of 45.2 kg and 31.7 kg, respectively)

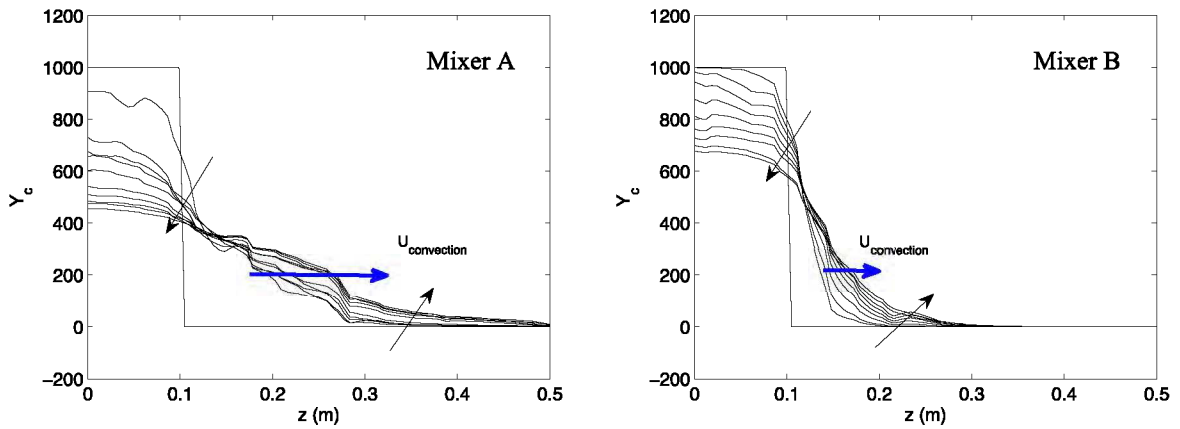


Figure 4. Temporal evolution of scalar concentration profiles on a line along the axis of the domain: Effect of the paddle shape (40 rpm, 31.7 kg)

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