# Jamming/flowing transition of a non Brownian suspension.

Maxym BUREL [1*], Olivier BONNEFOY [1]

* Corresponding author: Tel.: +33 (0)4 77 42 02 91; Email: maxym.burel@emse.fr
1 Ecole Nationale Supérieure des Mines, SPIN-EMSE, CNRS:UMR 5307, LGF, 158 cours Fauriel 42023 Saint-Etienne, France

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Many industrial processes require the use of an hydraulic transport with macroscopic particles. Those methods are widely used in mining or food industries. However relatively few studies have been performed on the behavior on the transition between jamming and flowing states. Indeed, for that kind of flow, some intriguing effects are observable such as shear -thickenning or shear – thinning. It appears that fluid-particle interactions and hydrodynamic effects have an important impact on the suspension dynamic (especially for high packing volume fraction). For example, in oil industry, it is possible to observe interfaces problems for heavy oil extraction with sand or for hydrates crystals in off-shore pipe (in this case the hydrates are sedimenting leading to the jamming state).

The jamming phenomenon is not systematic. This is why we have performed a lot of experiments in order to establish a statistical analysis. The experiments provided here intend to characterize the elements responsible for such a phenomenon (dense flow, fluid velocity, hydrodynamic forces…).

We have performed a set of experiments with a rectangular pipe in 2D to investigate the jamming effect. We study the flow of non Brownian particles suspended in a liquid passing through a restriction. With image analysis we were able to count the total number of particles through the restriction between two jamming. We noticed that the total number of particles for different size (length) of restriction could be expressed as an exponential with only one fitting parameter.

# Extended abstract

## 1. Introduction

The physics of granular media is a field of study which appeared in both industry and environment areas. In literature, studies of concentrated suspensions are present but these experiences are difficult to design, that is why many are based on numerical simulations [1].

When particles are no longer free to move (creating a dense network), we can observe jam state. Jamming origin first comes from the amount of particles (dense state). If the number of particle injected in the pipe increases, so the clogging probability also increases. Rheological experiments often use the same configuration (Couette geometry or plane-plane geometry, [2]). However, it is extremely difficult under these conditions to obtain rheological measurements (shear rate). Indeed, shear stress generates hydrodynamic forces that create forces chains i.e. contacts more or less persistent and intense. These chains are harmful for the flow because its increase the viscosity and can lead to jamming [3], which is true when the particle size is of the order of 100 µm. To study this phenomenon, we performed experiments involving suspensions of macroscopic spherical particles flowing in a 2D pipe through a restriction. We varied the key variables such as fluid velocity, solid mass flow rate, but also the size of the restriction. We will see how these parameters can influence the clogging. We changed the morphology (shape) and the cohesion (attraction between particles due to roughness or porosity or surface agent).

## 2. Experiment

A two dimensional system was built to observe the jamming of a suspension of monodisperse spheres in a liquid. This device consists of a main part which corresponds to the label 1 in Figure 1. This label 1 is the pipe of rectangular section whose dimensions are: a height of 7.5 mm, a width of 140 mm and a length of 1000 mm. This central part is connected to two tanks (2 and 3) respectively filled with the stock of beads and liquid. The entire system is made of Plexiglas, which allows us to visualize the behavior of the fluid and the beads in each part of the system.

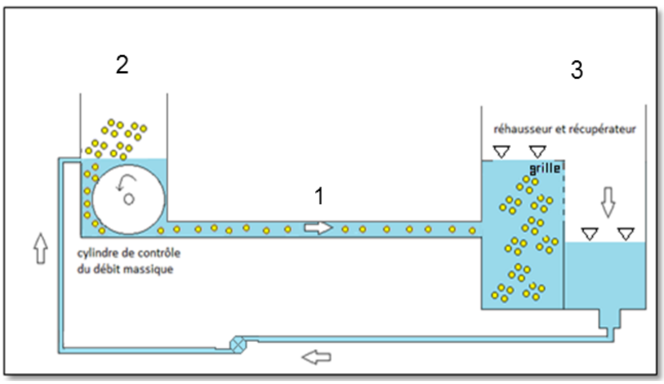


***Figure 1.*** *Schematic view of the tanks (2-3) and the pipe (1)*

To obtain a monolayer (2D system), we use a deformable rotating brush (label 2 in Figure 1). This brush allows us to control the mass flow rate by adjusting the speed of rotation. We take care to always keep some beads and roll submerged to avoid the presence of air bubbles. Those bubbles may be responsible for the formation of gaseous bridge which will modify the particle dynamics in the liquid. We use a peristaltic pump which gives us access to a wide range of flow of the order of ml / min to a few l / min. Finally, to simulate the jamming, we have removable plates (Figure 2), in this way the gap can be precisely controlled.

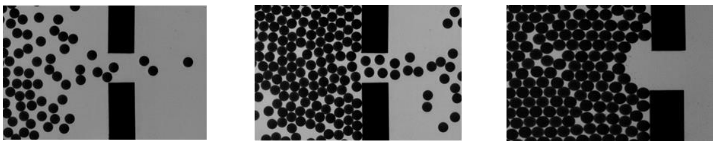

***Figure 2.*** *View of the restriction and a jamming*

## 3. Results and discussion

We will call an avalanche[4] the number of particles flowing through an orifice between two consecutive jams. Furthermore, in order to release or break the arches (see figure 2, last picture on the right), we apply a shock on the upper surface of the pipe. A campaign consisting of 40 avalanches. for several opening ratio R = L / d, where L is the size of the orifice and the d diameter of the grains. In figure 3 we plotted the variable "Cumul Ci" as a function of the number of beads Ti in each avalanche.

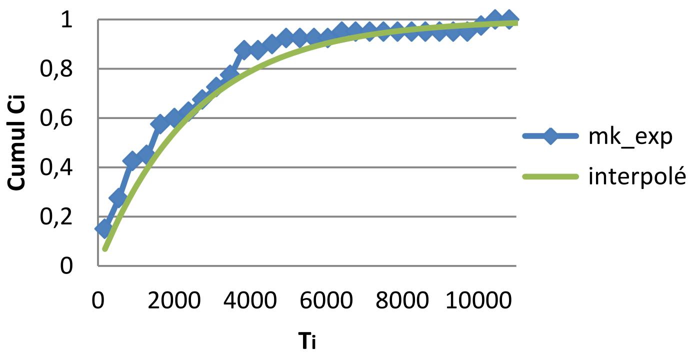


***Figure 3****. Experimental "Cumul" and an interpolate model for R = 3.33.*

The "Cumul" represents the total number of particles included in a specific class. This means that an avalanche belongs to Ci if the number of grains Ti is included between 0 et Tk (where k Є {1 ;….; kmax}).

We have made an interpolation (in green on the figure 3):

$$m_k = f(T_k)$$

$m_k$ is the cumulated frequency, i.e. all of the avalanches belonging to a class k are incleded.

Then,

$$m_k = 1 - \exp\left(-\frac{T_k}{T^*}\right)$$

Where, T* is an adjustable parameter, which corresponds to the characteristic size of the avalanches.

So, we can see that approximatively 80% of the jamming occurs for an average avalanche size of 3000 grains.

We modified the ratio R and we obtained the figure 4.

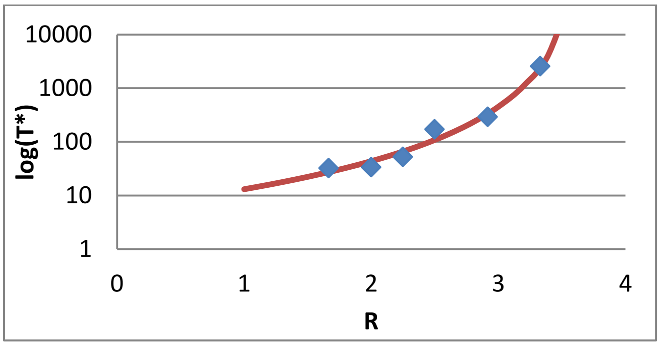


***Figure 4.*** *Evolution of T* as a function of R, in blue square the experimental data, in red line the power law.*

Note that the evolution is linear for small ratios. But when we reach a limit value or threshold (here 3.33) then evolution follows an exponential law. Following two major assumptions - a critical value of R exists and when R tends to this critical value, an exponential law is obtained. According to the literature [5], we can suggest that the evolution law of the size T * follows a power law (red curve in Figure 6):

$$T^* \propto (R_c - R)^{-\gamma}$$

With $R_c$ is a critical value where the number of grains Ti grows exponentially, and γ is an adjustable parameter.

By using the least squares method, we can get the following values:

$R_c = 3.67$ and $\gamma = 2.57$

## 4. Conclusion

We have shown through these experiments that the “Cumul” is independent of the ratio R but depends on a parameter which is T *. However avalanche sizes are dependent on this ratio and tend to reach a critical value jam state is not reachable. We were able to prove that a power law was consistent in order to predict the evolution of avalanche sizes depending on the ratio R. Later, we will conduct experiments involving different particle sizes typically 100 microns to 6 mm where we will vary the solid mass flow rates and fluid.

## 5. References

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