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► **To cite this version:**

Agathe Bignon, Mathieu Renouf, Emilien Azéma. Systematic description of the effect of grain elongation in silo discharge. 9th International Conference on Discrete Element Methods (DEM9), Sep 2023, Erlangen, Germany. DEM9 Book of Abstracts. hal-04209698

HAL Id: hal-04209698

<https://hal.science/hal-04209698v1>

Submitted on 8 Nov 2023

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Non-linear effect of grain elongation on the flow rate in silo discharge

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Objectives : We aim to elucidate how the flow properties in a silo are affected by the shape of the grains. More specifically, we look for a behaviour law describing the flow as a function of grain elongation for a fixed aperture. To do so, we used 2D numerical simulation based on Contact Dynamics, by systematically varying the grain aspect ratio and aperture size in an “perpetual” flow condition.

Model : Following the work of Janda [1], we can express the flow as :

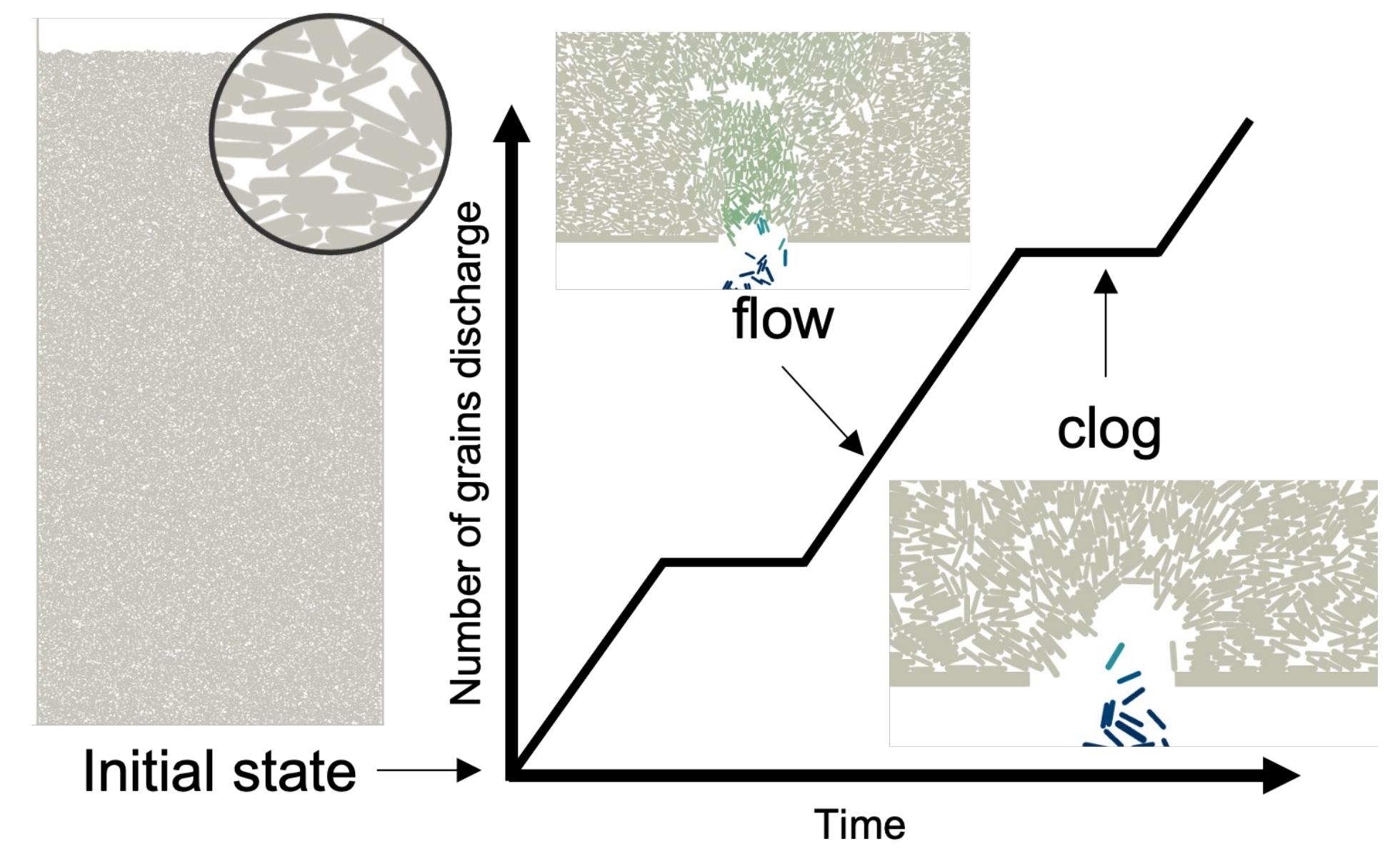
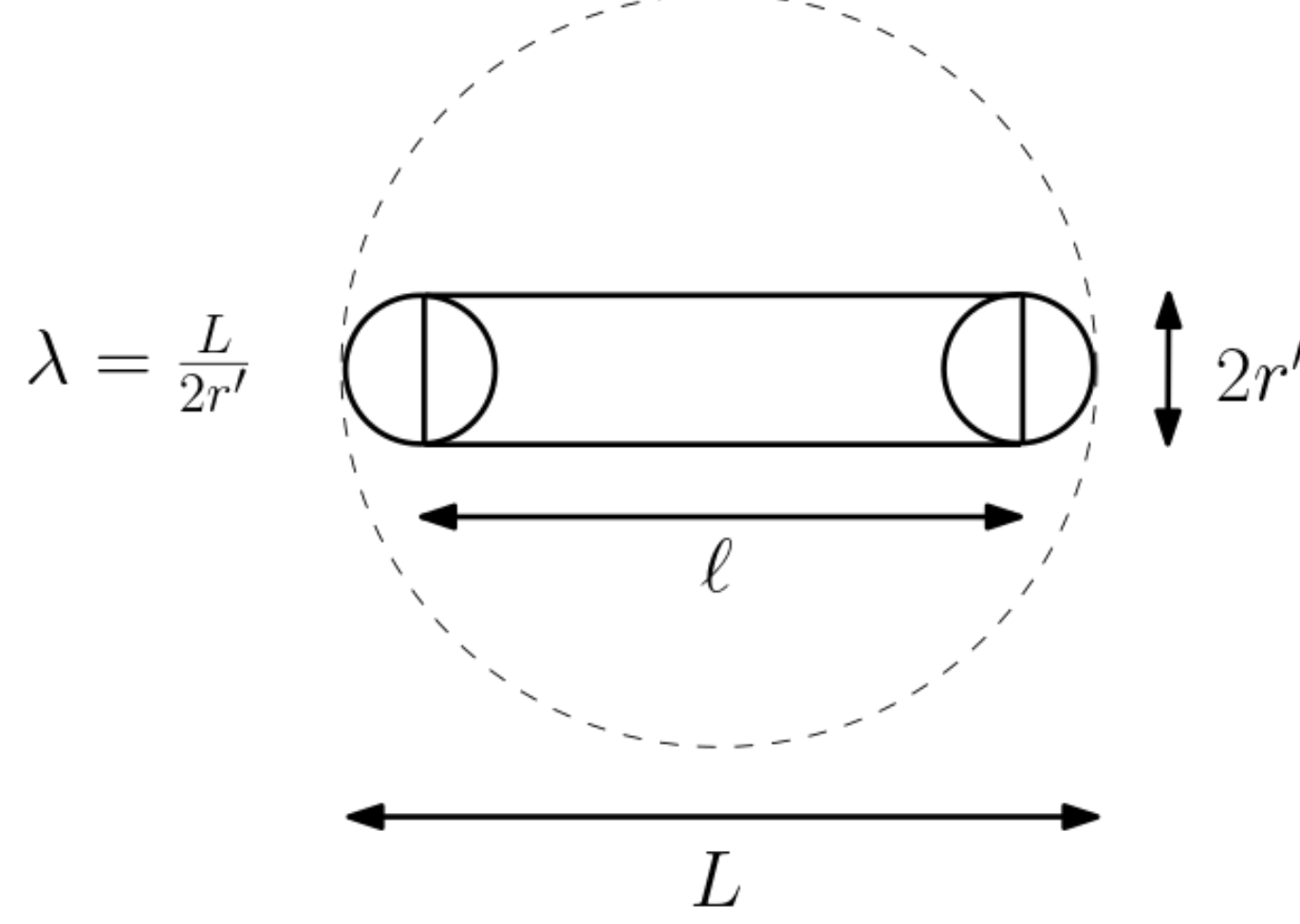
$$Q = \frac{2}{m} \int_0^{D/2} \sigma \phi(x) v(x) dx \quad (a)$$

where D is the aperture, m mass of the grain and σ surface density. $v(x)$ and $\phi(x)$ stand for the velocity and packing fraction profile along the aperture.

Find the expression of $v(x)$ and $\phi(x)$ to find the master equation of the flow Q as a function of λ for a given α (and vice versa for α with a given λ but the development is not present here).

For both profile (v and ϕ) : decomposition into a product of the data at the center of the orifice by the data as a function of x normalized by the data at the center of the orifice.

Grains and system construction

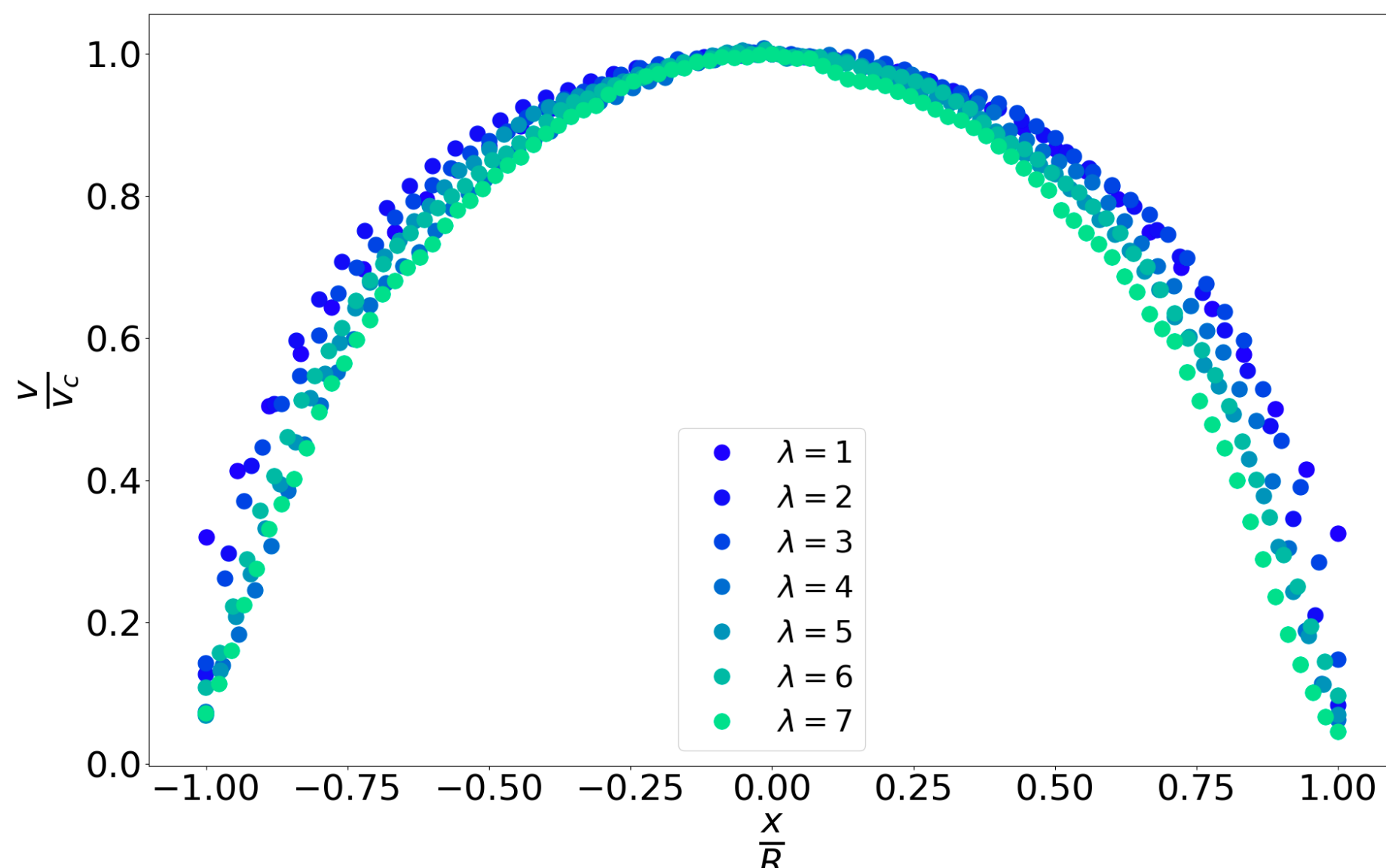
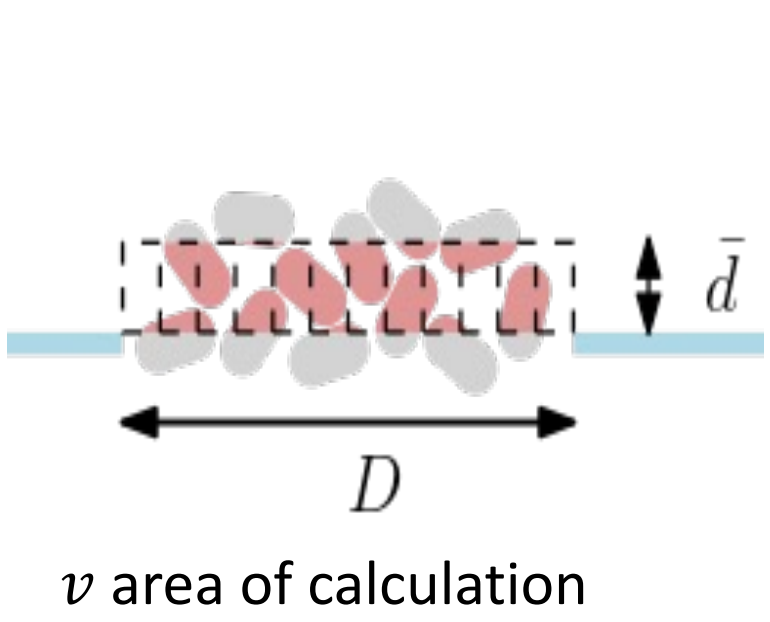


Parameters

Silo width & height	$W, H = 2W$
Orifice size	D
Diameter of disks	d
Circumscribing diameter of RCR	$\bar{d} \equiv L$
Grain elongation ratio	$\lambda = L/(2r')$
Aperture width to grain length ratio	$\alpha = D/\bar{d}$



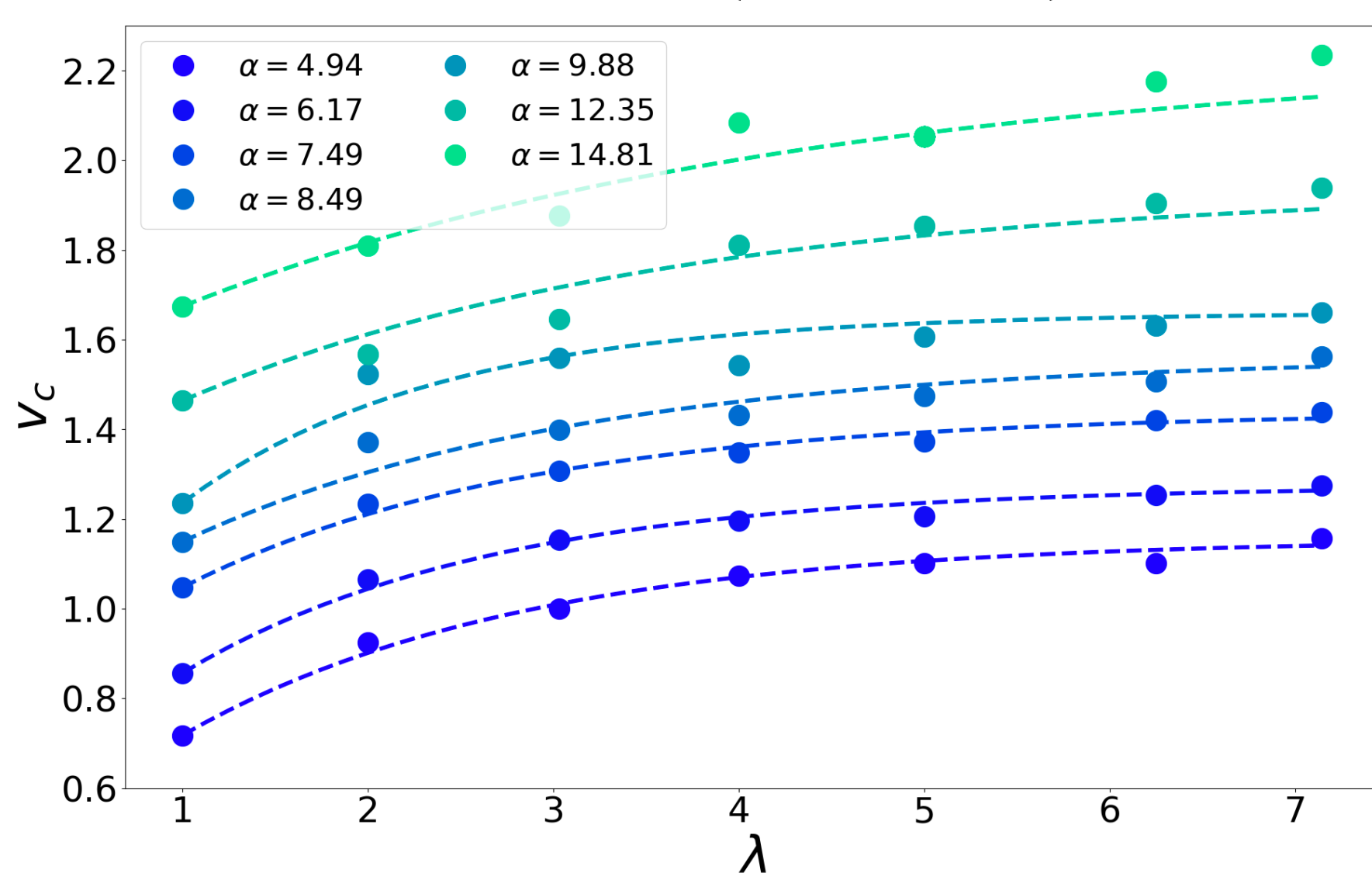
Velocity v



$$v(x) = v_c^\alpha(\lambda) f\left(\frac{x}{R}\right)$$

$$f\left(\frac{x}{R}\right) = \frac{v}{v_c} = \left(1 - \left(\frac{x}{R}\right)^2\right)^{-\mu_\lambda}$$

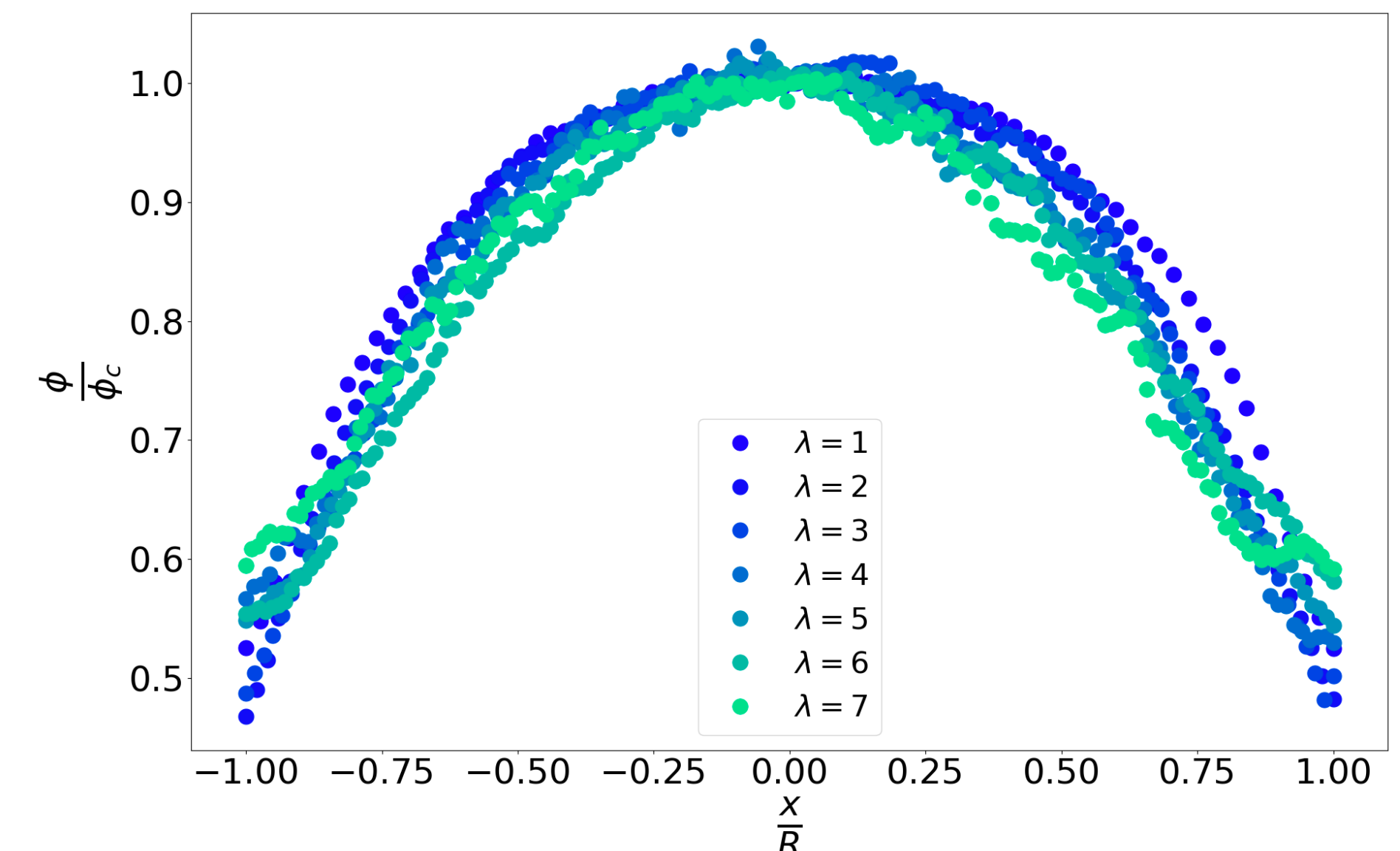
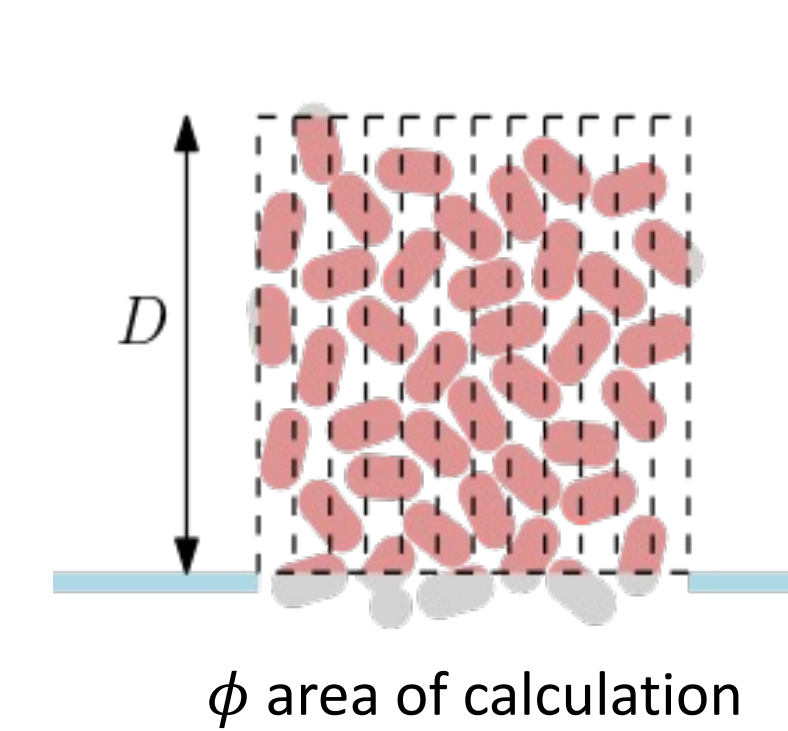
$$v_c^\alpha(\lambda) = v_c^{\alpha,1} + (v_c^{\alpha,\infty} - v_c^{\alpha,1}) \left[1 - e^{-\frac{\lambda-1}{\lambda^\alpha}}\right]$$



Value extract from simulation : $v_c^\alpha(\lambda)$ (value for a given α at the center of orifice)

Fitting parameters : μ_λ

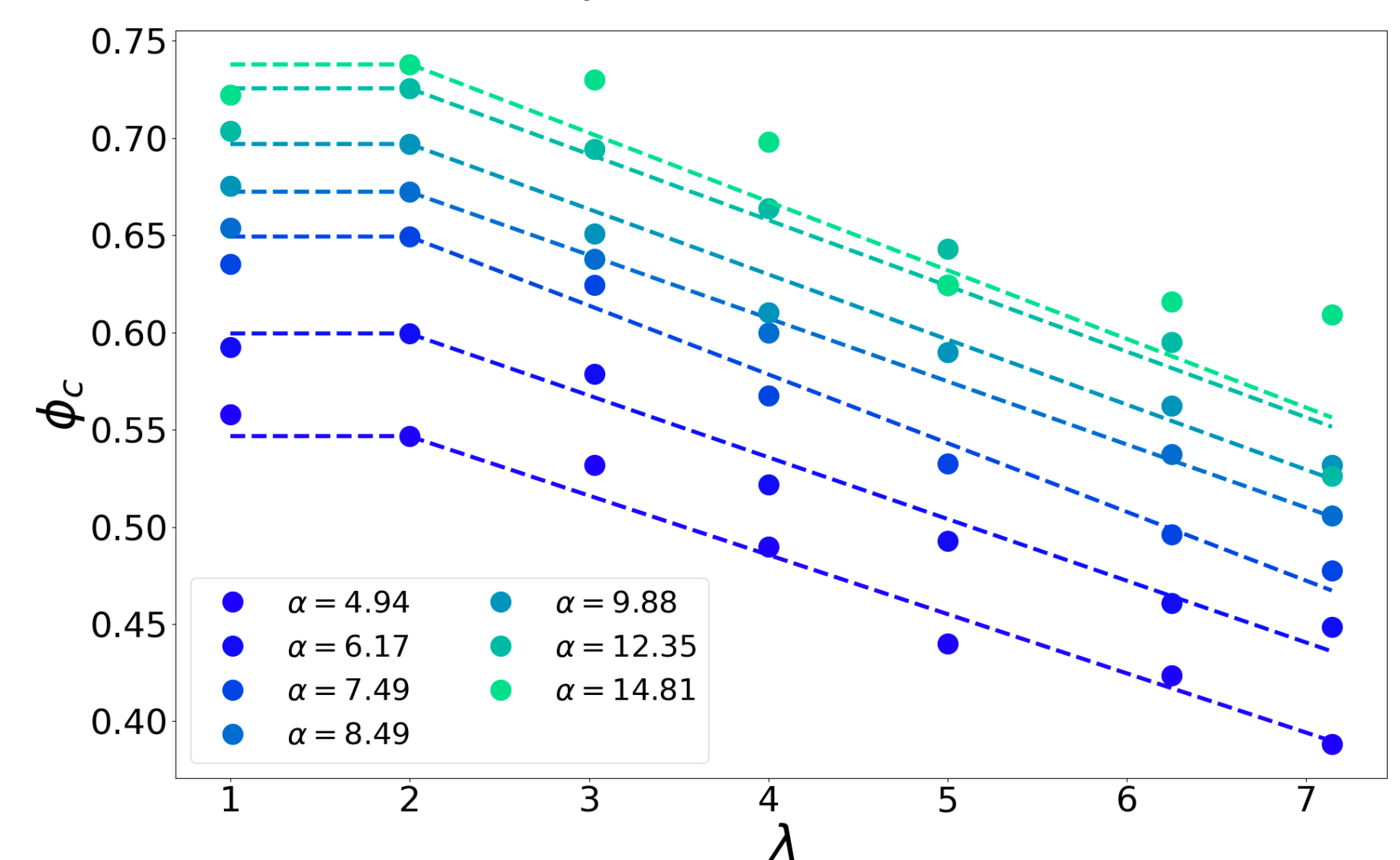
Packing fraction ϕ



$$\phi(x) = \phi_c^\alpha(\lambda) g\left(\frac{x}{R}\right)$$

$$g\left(\frac{x}{R}\right) = \frac{\phi}{\phi_c} = \left(1 - \left(\frac{x}{R}\right)^2\right)^{-\nu_\lambda}$$

$$\phi_c^\alpha(\lambda) = \phi_c^{\alpha,1} + \beta_3(\lambda - 1)\delta_{\lambda>2}$$



Value extract from simulation : $\phi_c^\alpha(\lambda)$ (value for a given α at the center of orifice)

Fitting parameters : β_3, ν_λ

Flow

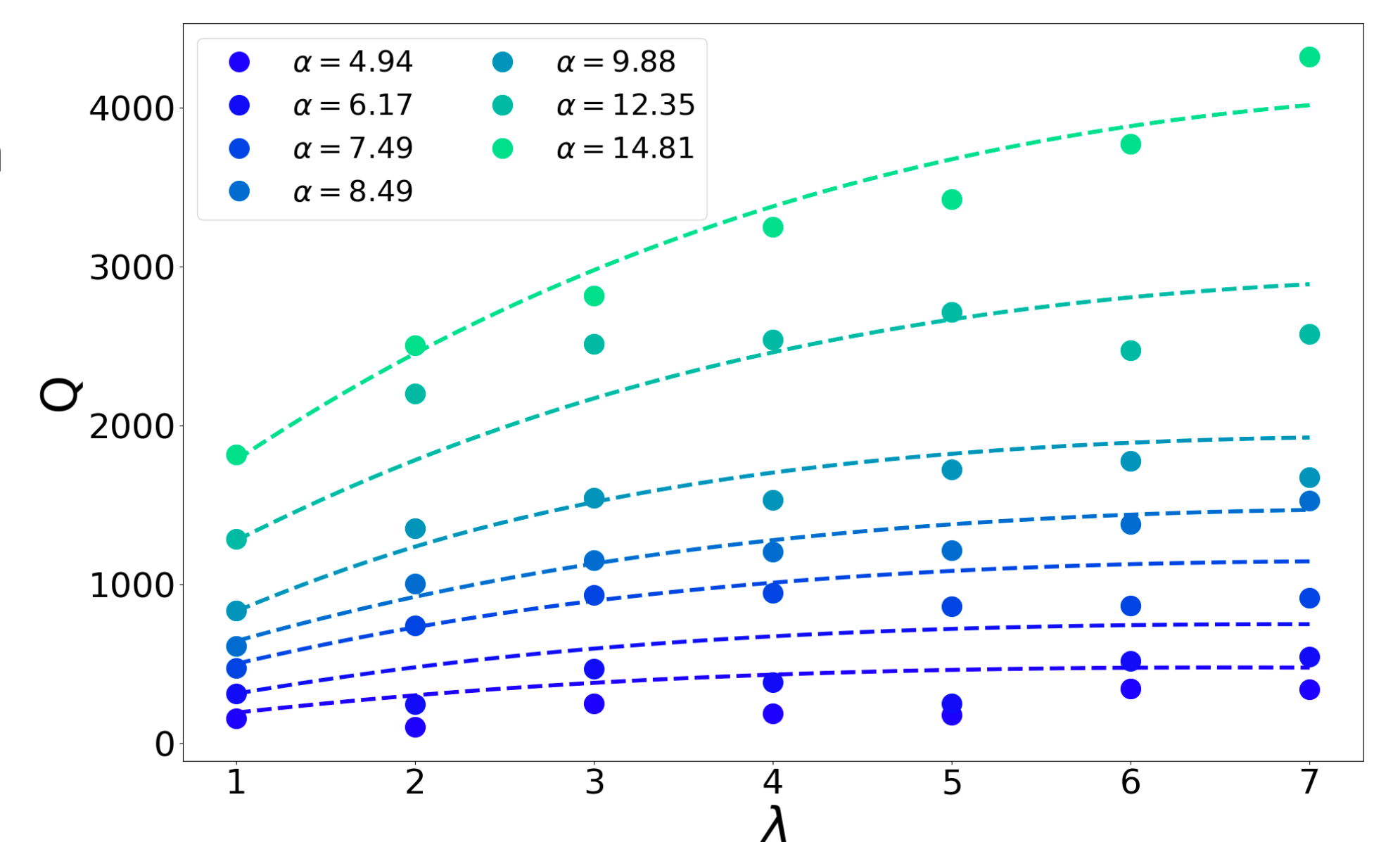
By replacing all the expressions in the equation (a). We can now express the flow rates as a function of λ for a given α :

$$Q_\alpha(\lambda) = \frac{2}{\mathcal{A}} v_c^\alpha(\lambda) \phi_c^\alpha(\lambda) \int_0^R \left[1 - \left(\frac{x}{R}\right)^2\right]^{\frac{\nu_\lambda + v_\lambda}{\nu_\lambda + v_\lambda}} dx$$

By using the beta function integration :

$$Q_\alpha(\lambda) = \psi'' \left\{ v_c^{\alpha,1} + (v_c^{\alpha,\infty} - v_c^{\alpha,1}) \left[1 - e^{-\frac{\lambda-1}{\lambda^\alpha}}\right] \right\} \left\{ \phi_c^{\alpha,1} + \beta_3(\lambda - 2)\delta_{\lambda>2} \right\} \frac{\alpha}{2}$$

Where $\psi'' = \frac{1}{\mathcal{A}} \beta \left(\frac{1}{2}; \frac{\nu_\lambda + \mu_\lambda}{\nu_\lambda \mu_\lambda} + 1\right) \bar{d}$, \mathcal{A} is the area of a grain



Conclusion : This work show that considering the flow rates as a function on the grain elongation, it first increase and then reach a plateau. Those variations can be explain by the evolution of packing fraction & velocity at the orifice center. The competition between both quantities explain the non linear variation of the flow rates as a function of grain elongation.

Perspectives : The main perspective of this work is to extend to the 3D. Equations will be more complexe to integrate du to increasing intermittent flow as the aspect ratio of grain is increased. 3D simulations are currently underway with rod-like grains to address this issue.

Reference : [1] A. Janda, I. Zuriguel, and D. Maza, Physical Review Letters, vol. 108, p. 248001, June 2012.

