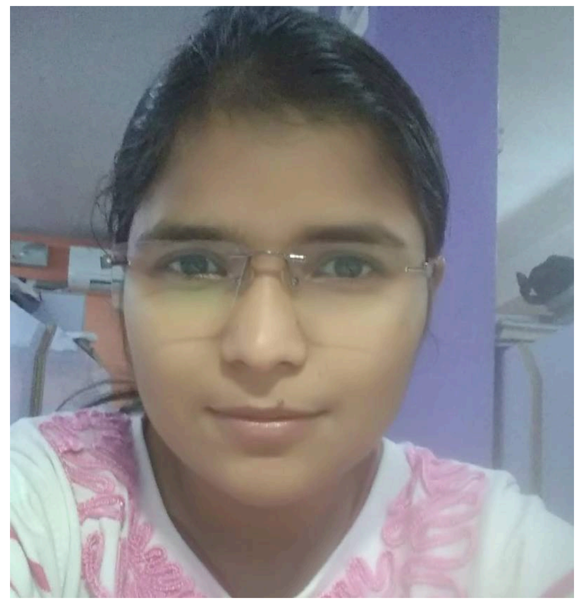
Modelling powder flow through screw feeders

Prabhu Nott



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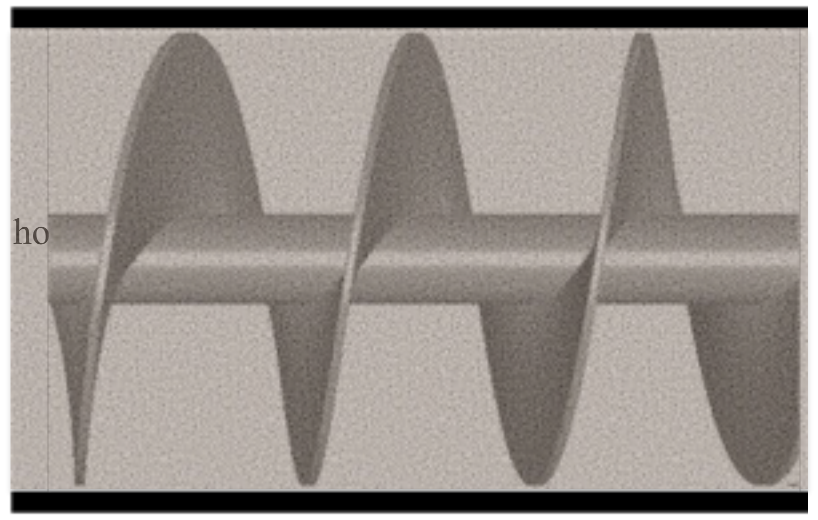
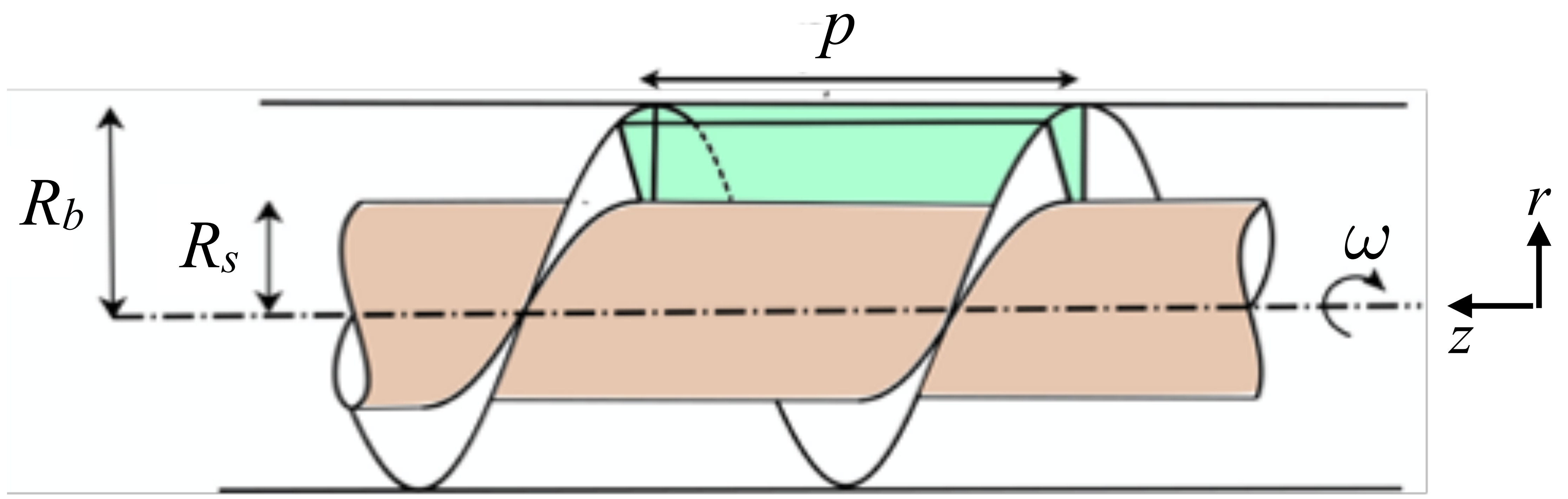


Objectives

- Develop a theoretical model of flow through screw feeders
- Test model predictions against experimental measurements
- Conduct DEM simulations to validate and refine theory, and guide experimental measurements.

Project commenced on October 2019

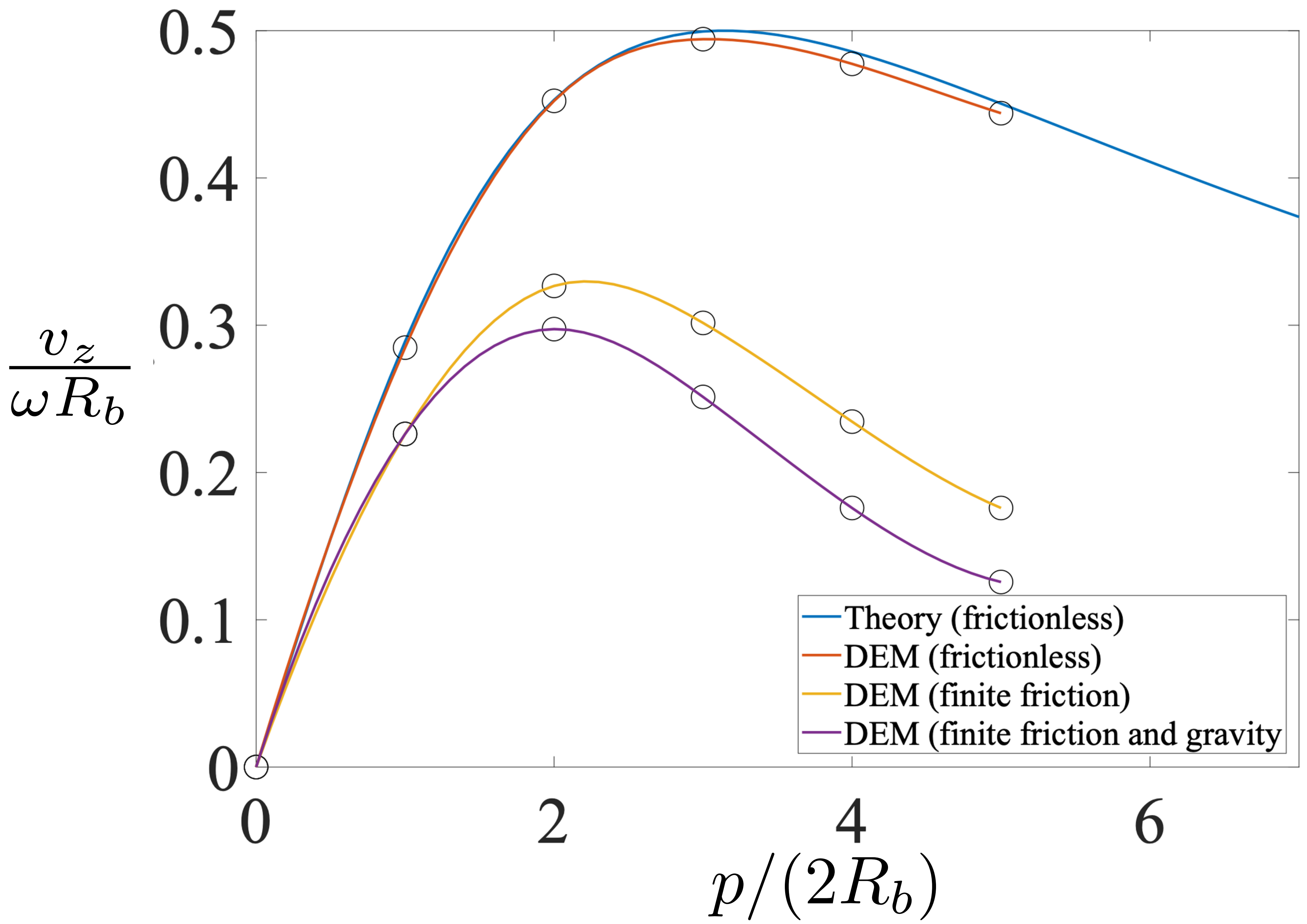
Quick recap of previous years' work



Assuming plug-like (solid body) motion, force and toque balances on the wedge-shaped element yields the relation for the feed rate:

$$Q = \nu \omega R_b f(p/R_b)\pi(R_b^2 - R_s^2)$$

for *frictionless* screw and shaft surfaces.

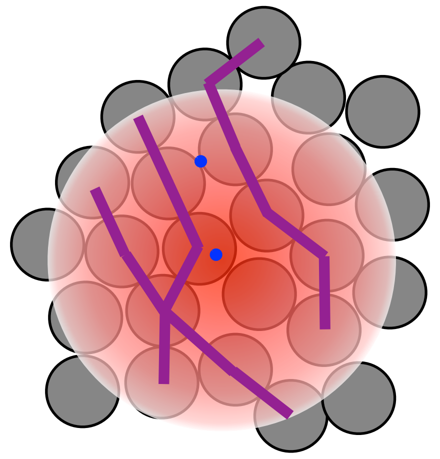


When compared to DEM simulations:

- Excellent agreement for frictionless shaft and screw without gravity
- Same qualitative trend for frictional surfaces, and with gravity
- An optimum value of p/R_b at which discharge rate is maximum

DEM simulations give detailed spatial variation of stress and velocity, which compare well with experimental data

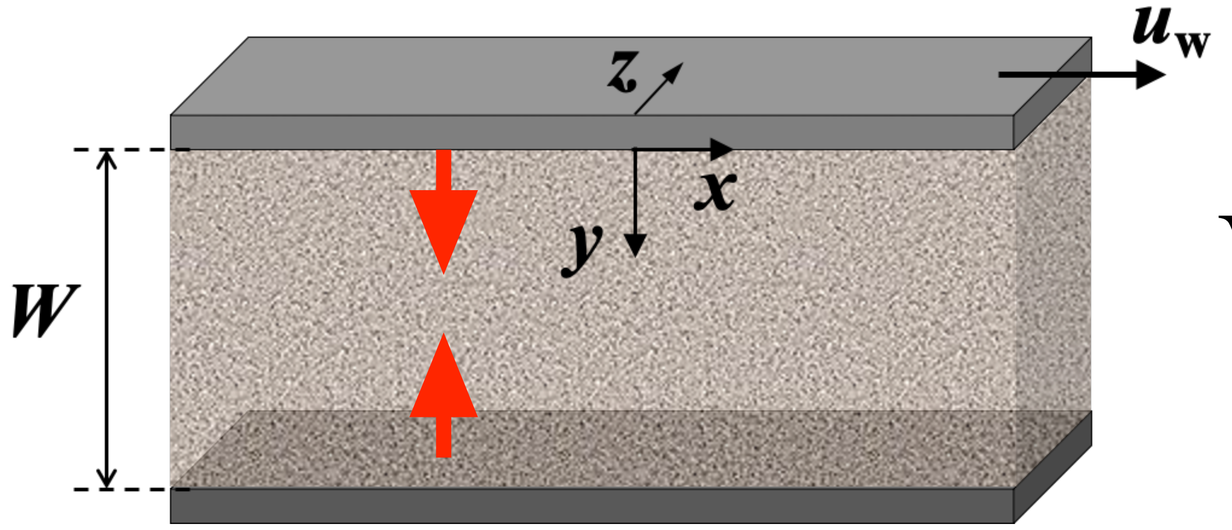
Non-local model that resolves kinematic indeterminacy and incorporates dilatancy



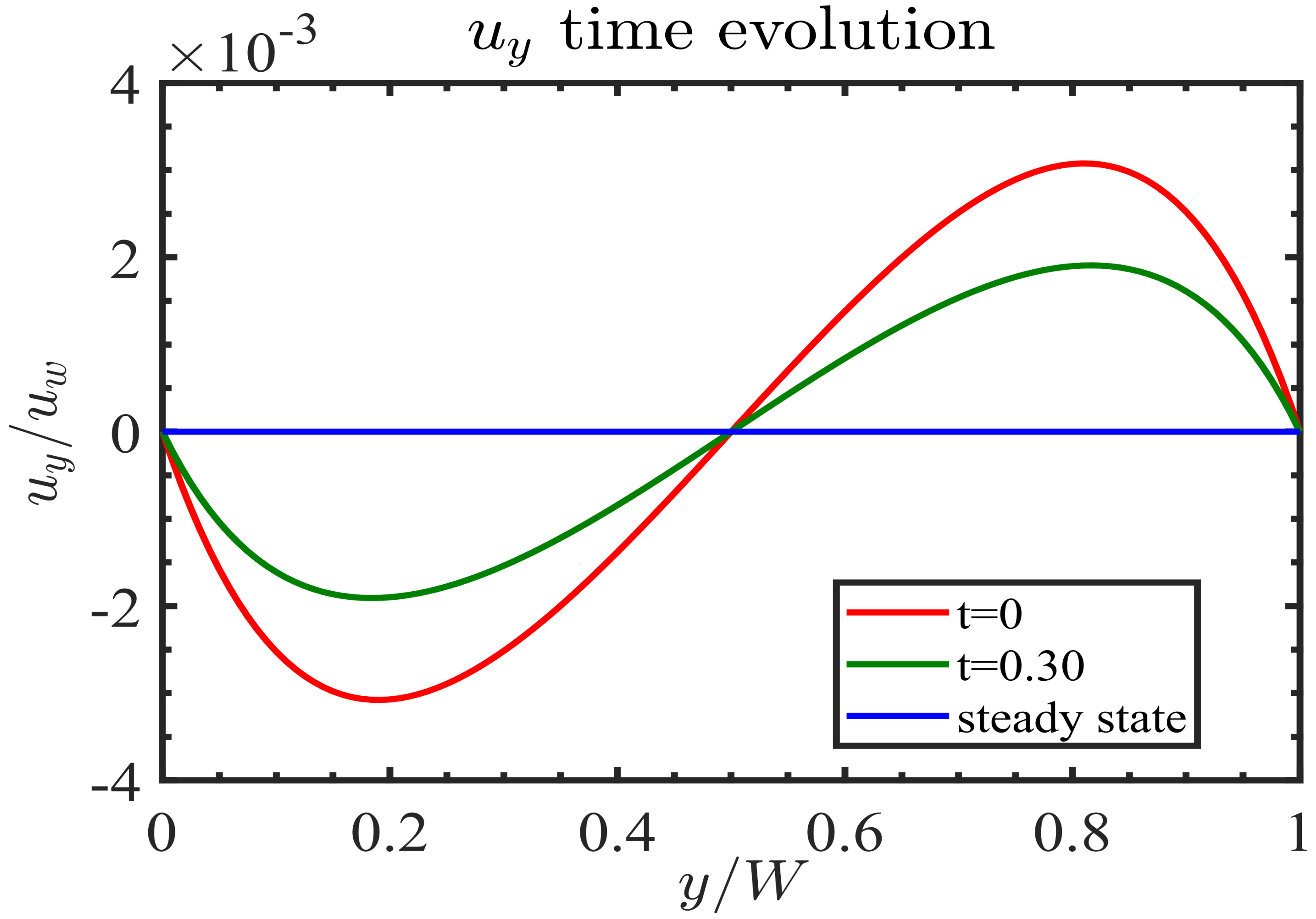
$$\boldsymbol{\sigma} = -p\,\boldsymbol{\delta} + \frac{2\mu}{\dot{\gamma}}\left(p_{\rm c}\,\boldsymbol{D}' - \underline{\ell^2\,\Pi\,\nabla^2\boldsymbol{D}'}\right), \qquad p = p_{\rm c}\left(1 - \frac{\mu_{\rm b}}{\dot{\gamma}}\boldsymbol{\nabla}\cdot\boldsymbol{u}\right) - \underline{\ell^2\,\Pi\,\frac{\mu_{\rm b}}{\dot{\gamma}}\nabla^2\boldsymbol{\nabla}\cdot\boldsymbol{u}}$$

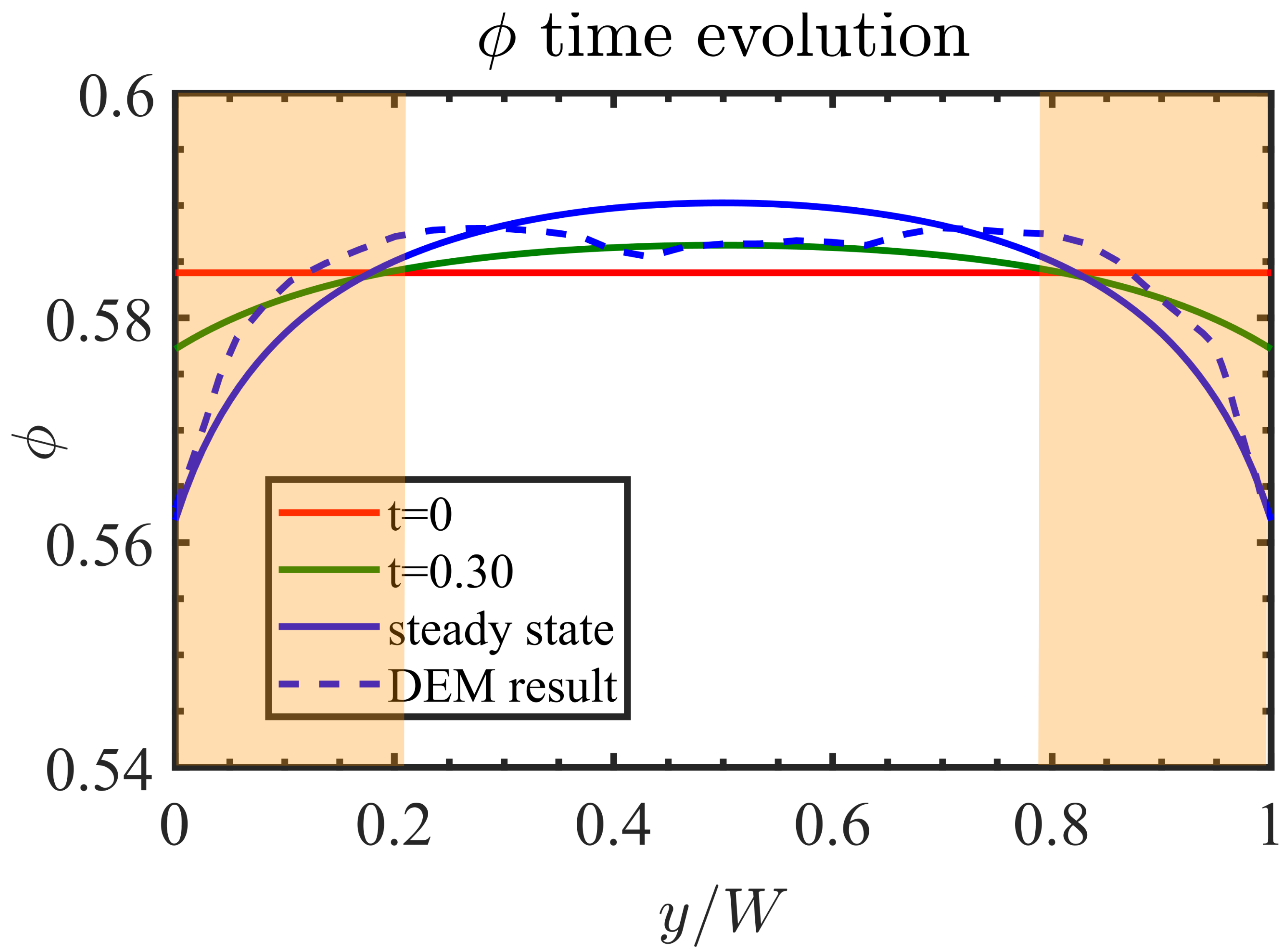
$$p_{\rm c} = \Pi - \underline{\ell^2\,\frac{{\rm d}\Pi}{{\rm d}\phi}\,\nabla^2\phi},$$

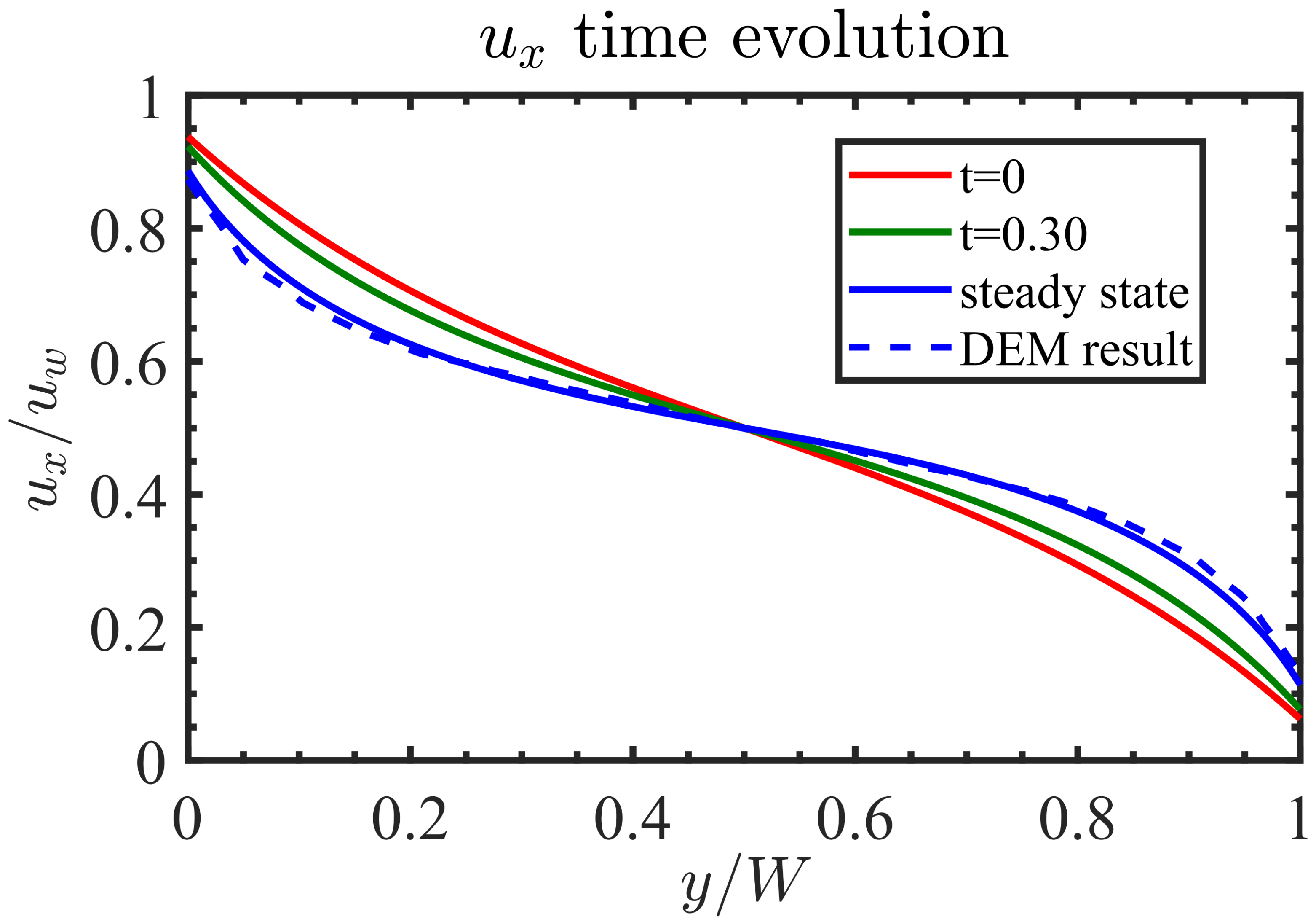
Dsouza & Nott (*J. Fluid Mech.* 2020)



Validation: unsteady plane shear in the absence of gravity

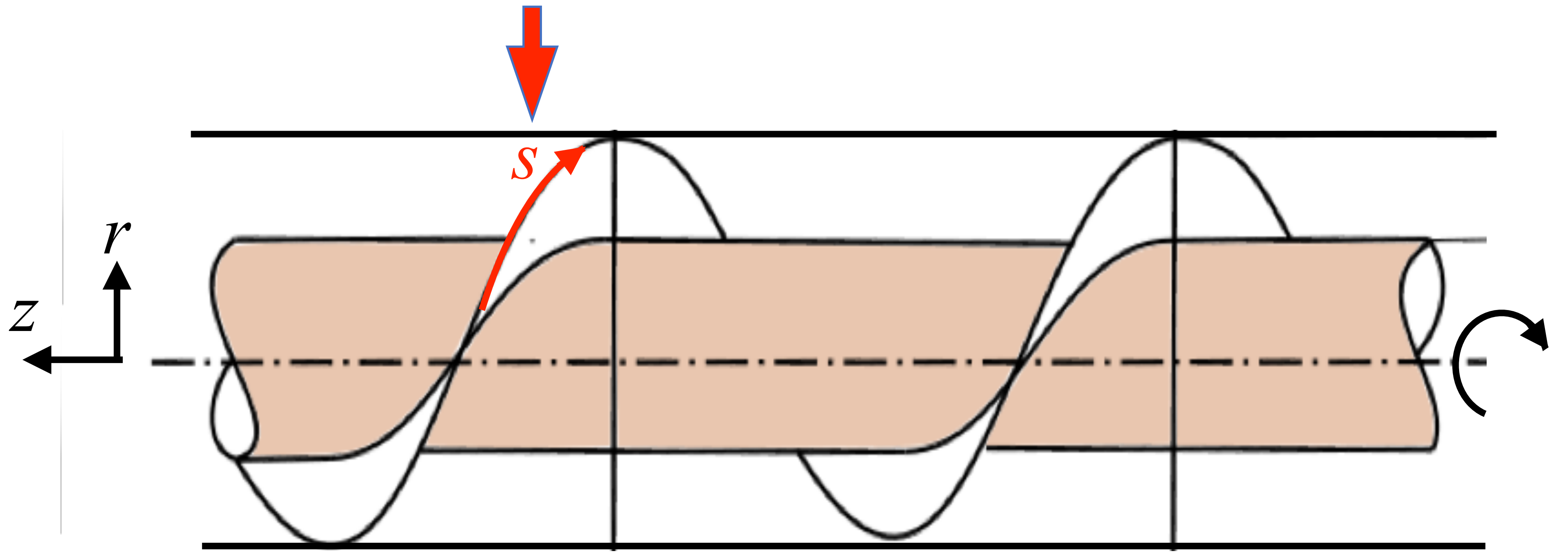






Excellent agreement with DEM results at steady state

Application of the nonlocal model to the screw feeder

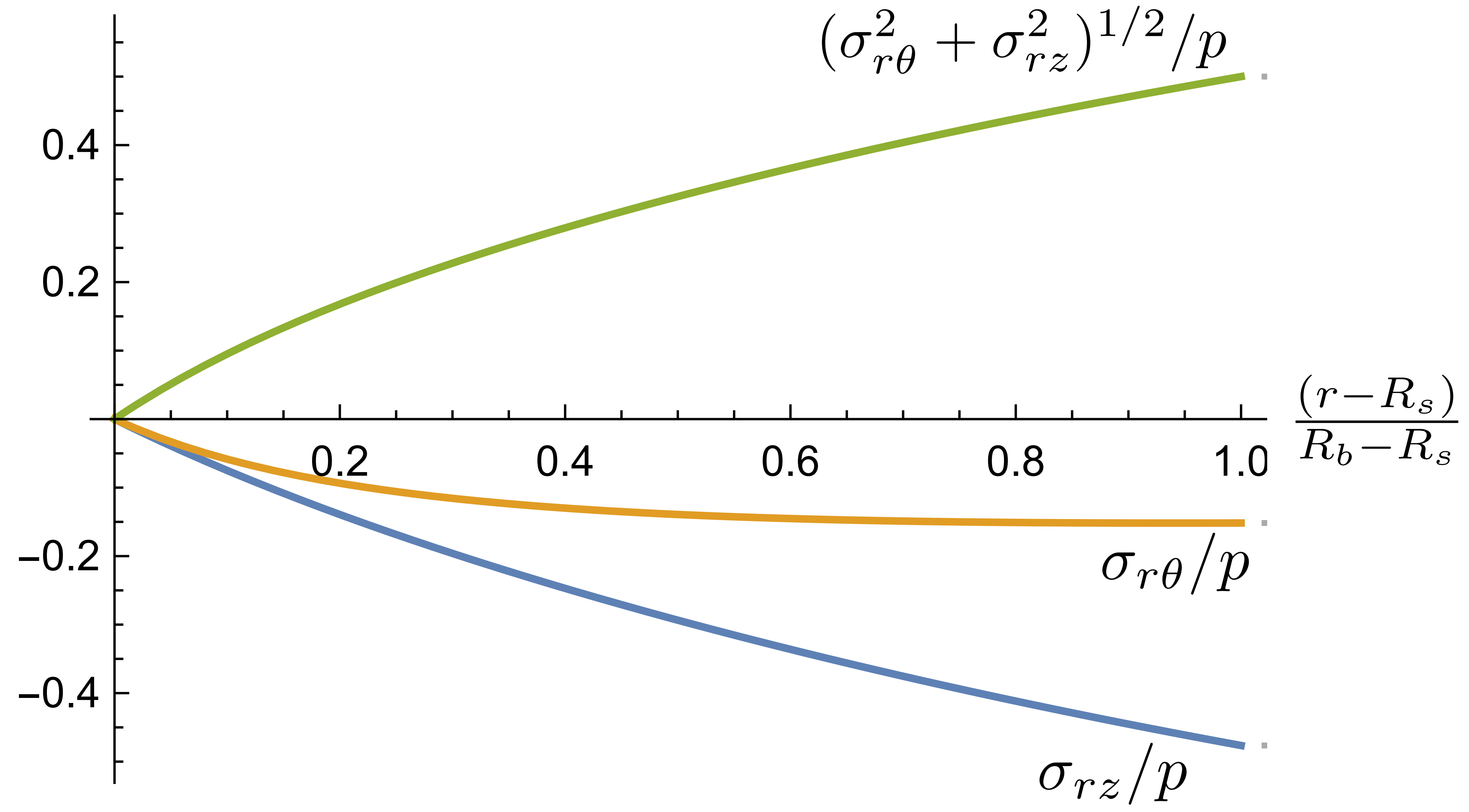


For fully developed flow $\left.\dfrac{\partial \mathbf{u}}{\partial s}\right|_r = 0$

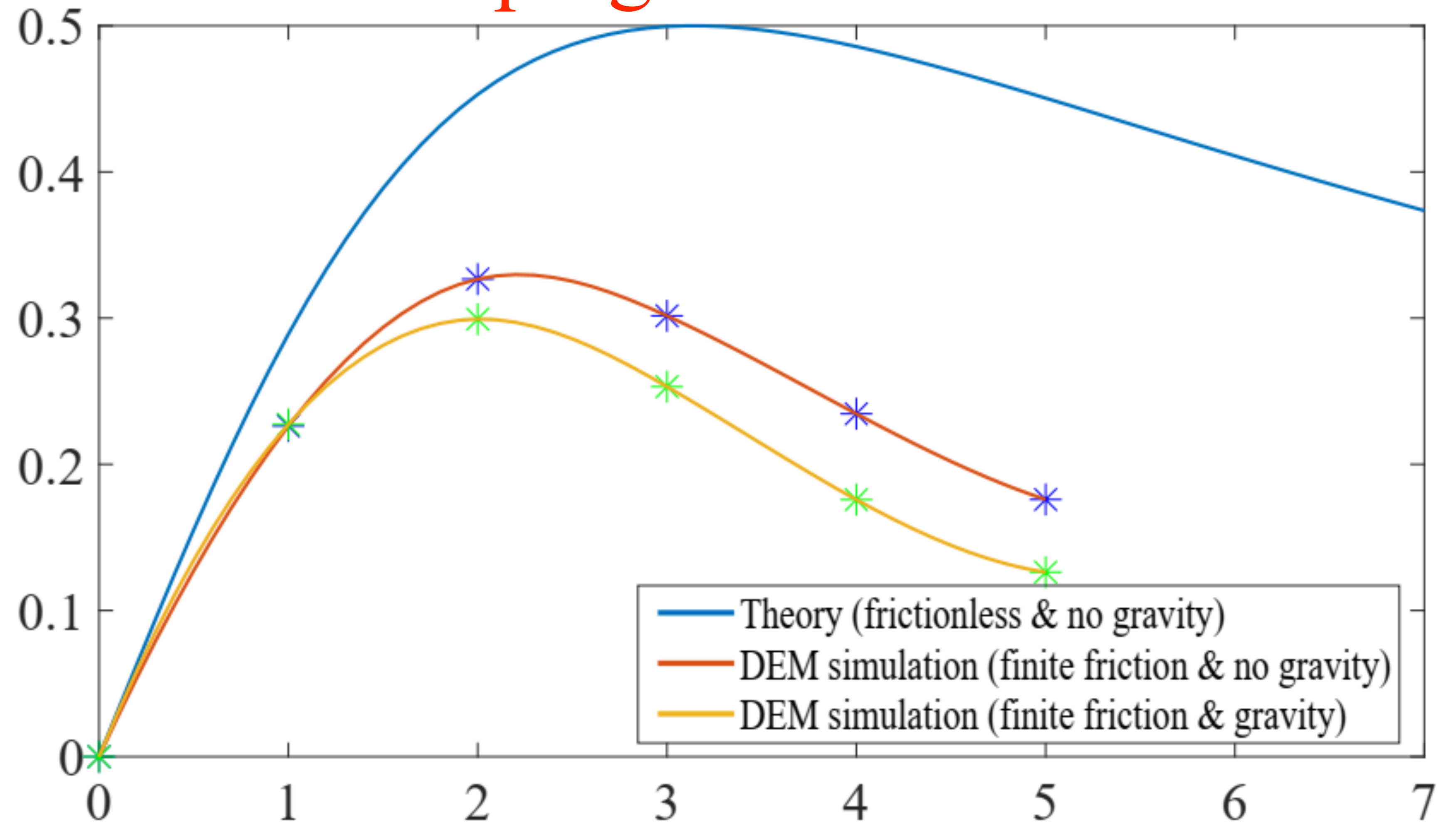
With the additional assumption $\dfrac{\partial \mathbf{u}}{\partial z} = 0$

as suggested by DEM simulations, the velocity field is

$u_z = u_z(r),\ u_\theta(r)$



For frictionless screw and shaft the velocity is constant, and we recover the plug flow solution obtained earlier!

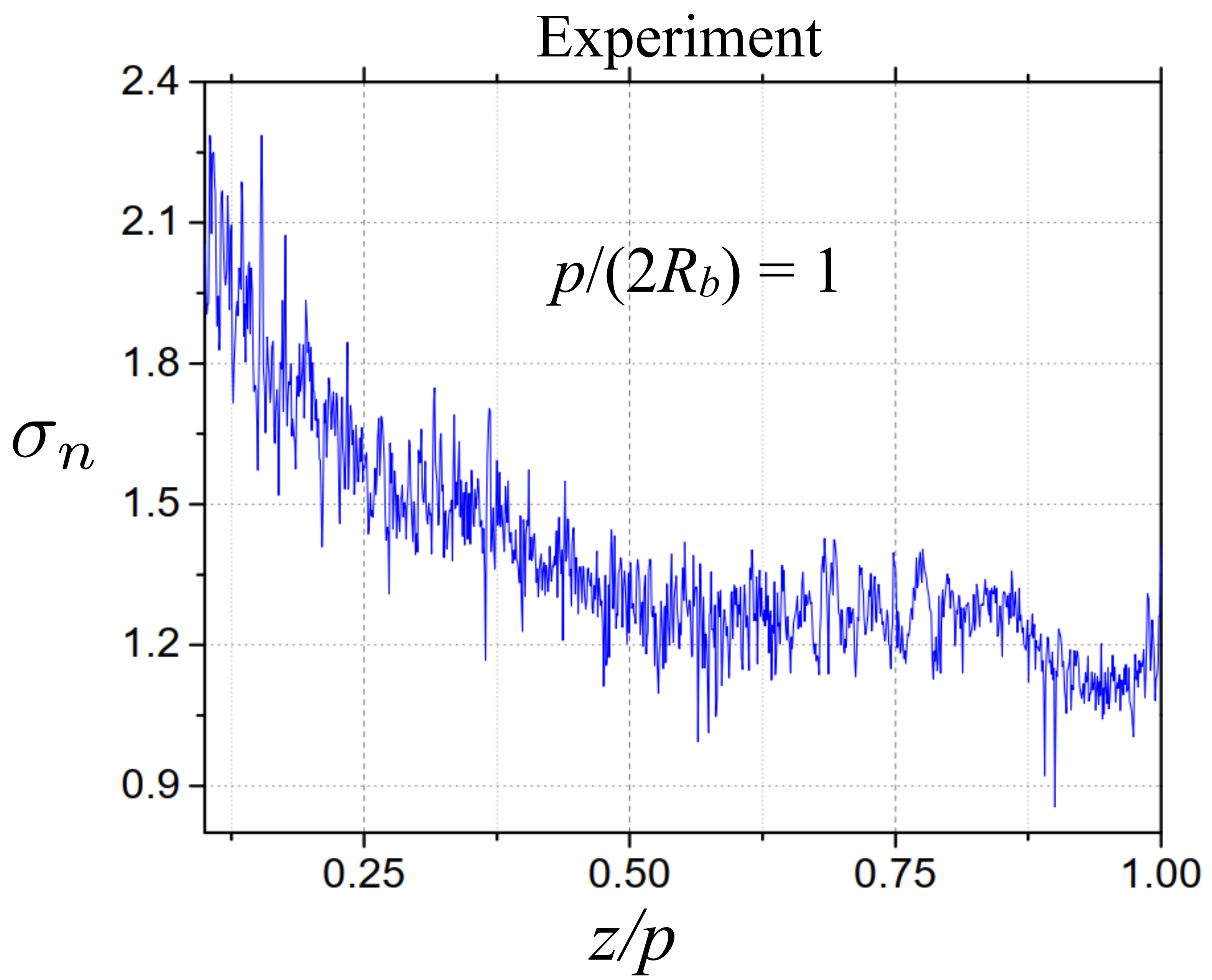


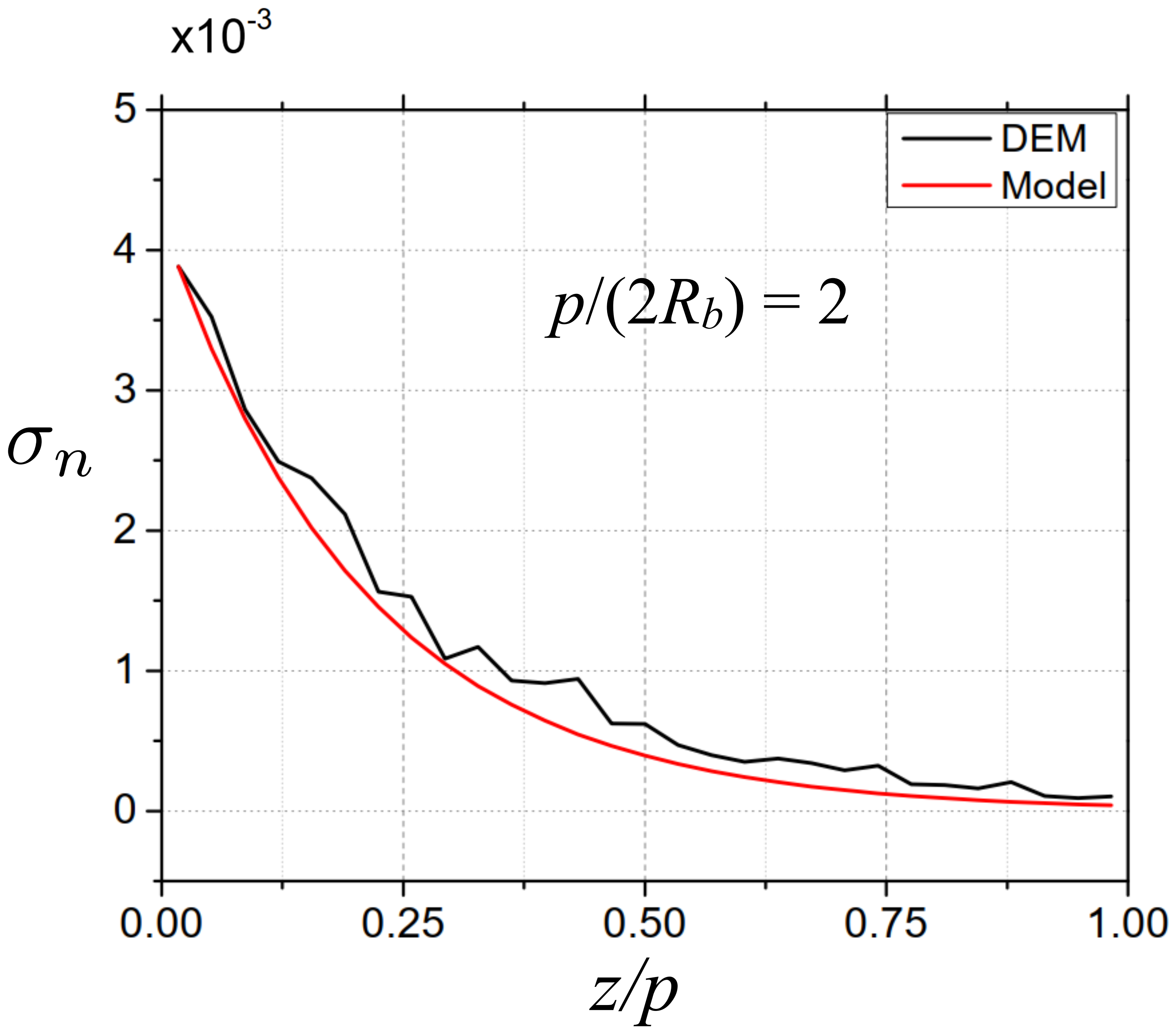
Gupta et al, in preparation (2022)

Solutions for frictional screw & shaft, partially fill, etc. more involved – in progress

Experimental screw feeder assembly

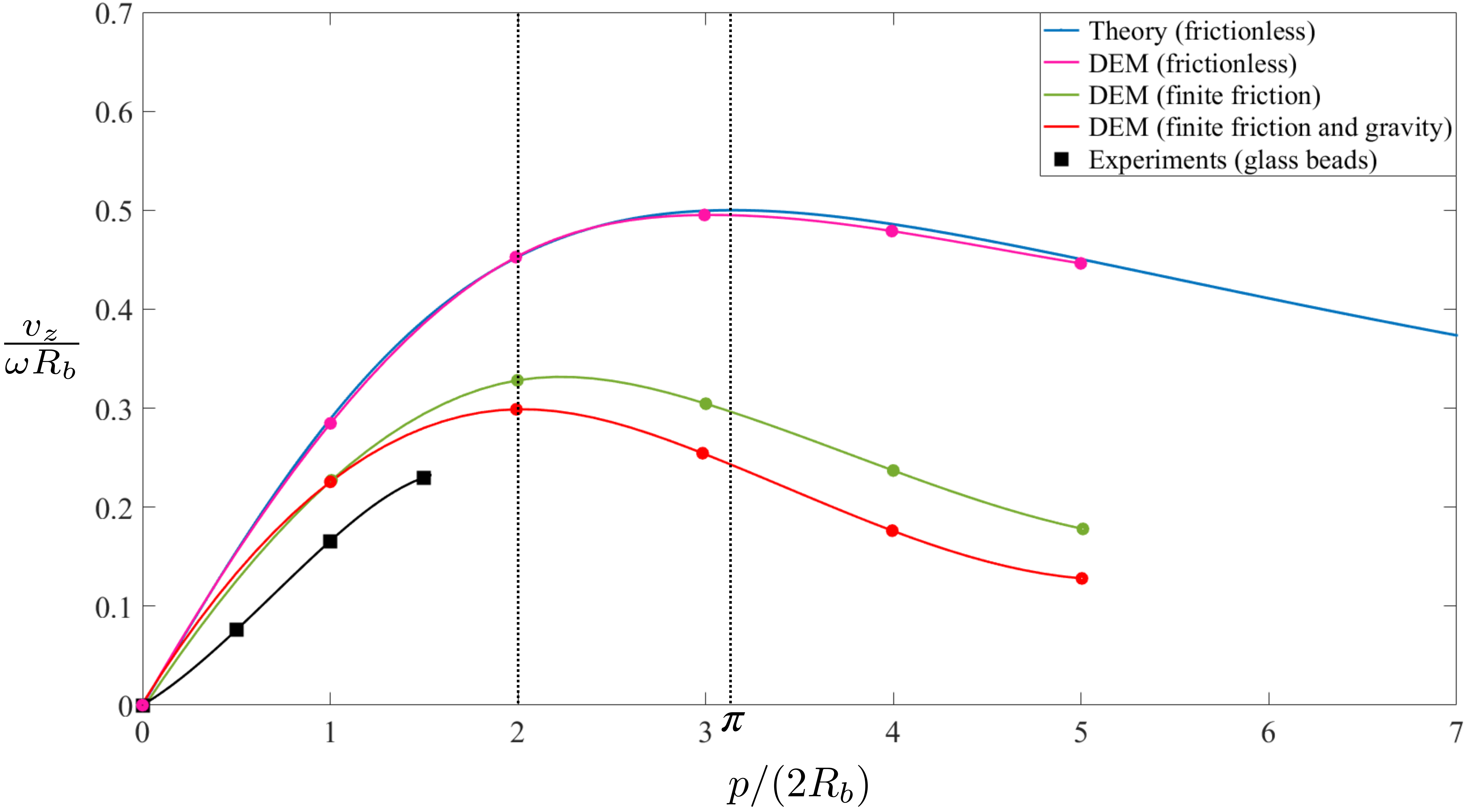
- Transparent front face for imaging
- Stress measurement on back face
- Modular: accommodates screws of different *p*, with length = 5*p*





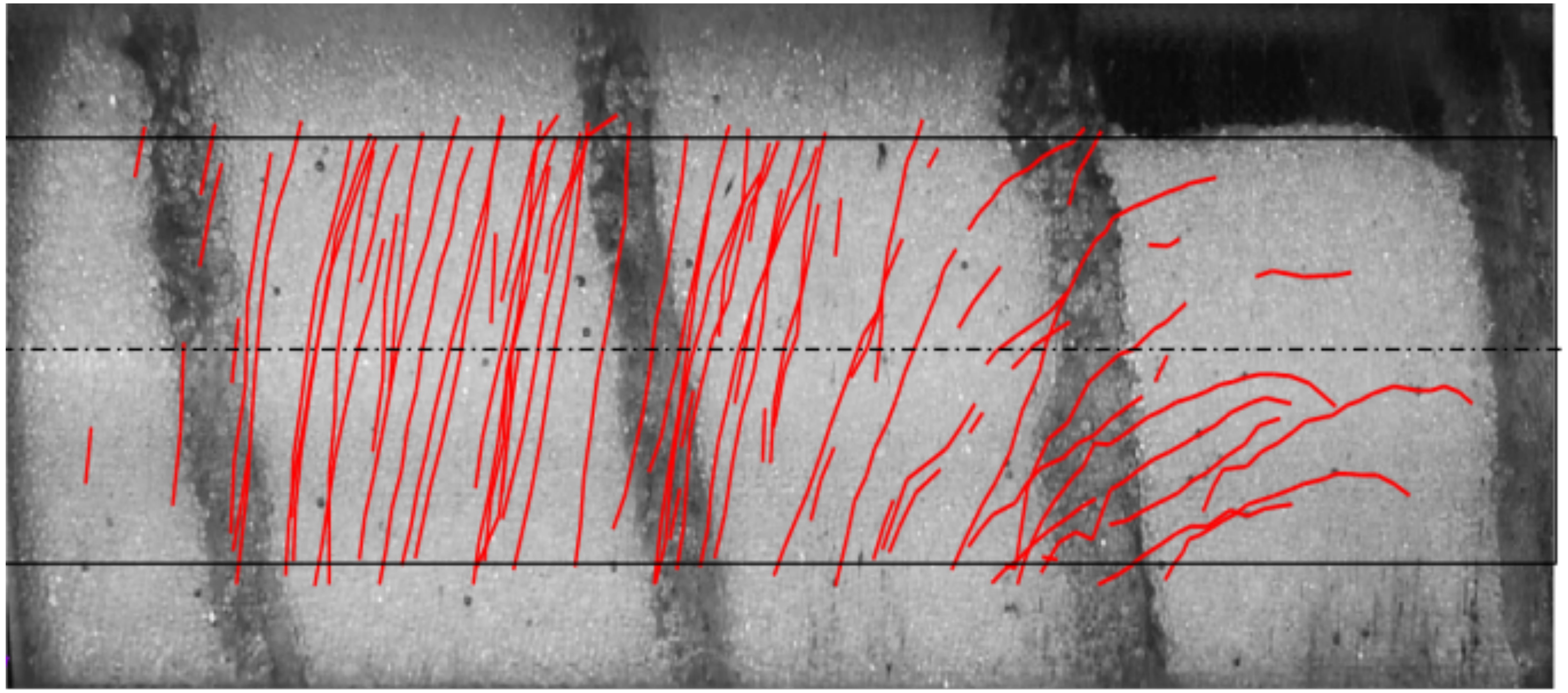
- Good qualitative agreement between experiments and model.
- Nearly perfect agreement between DEM results and model.
- Exponential decay similar to the Janssen saturation of stress in silos

Experimental measurements of the flow rate for glass beads



Good agreement between experiments, model and DEM simulations. Experiments validate the prediction of maximum flow rate at an optimum value of $p/(2R_b)$.

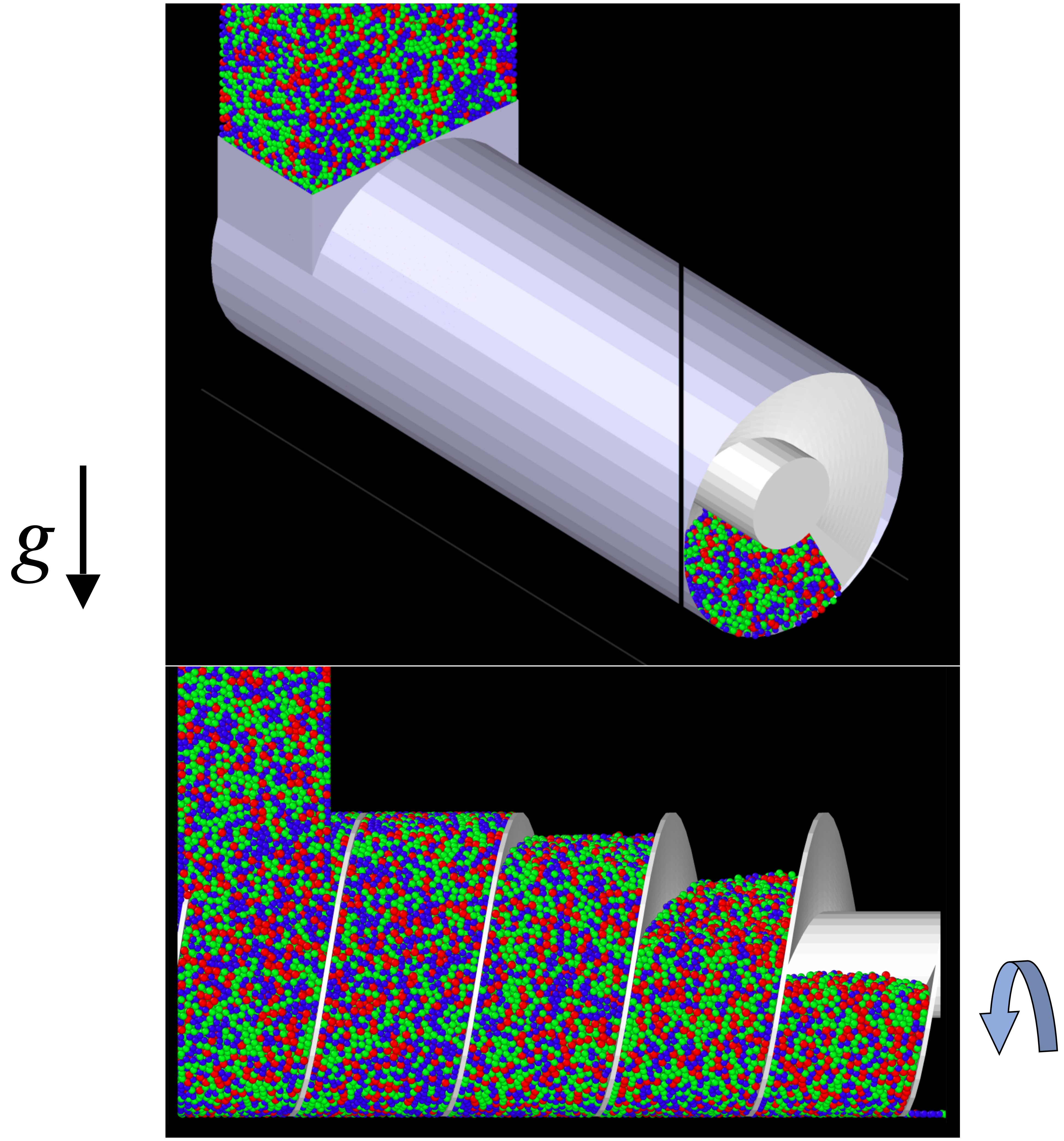
Particle tracking velocimetry

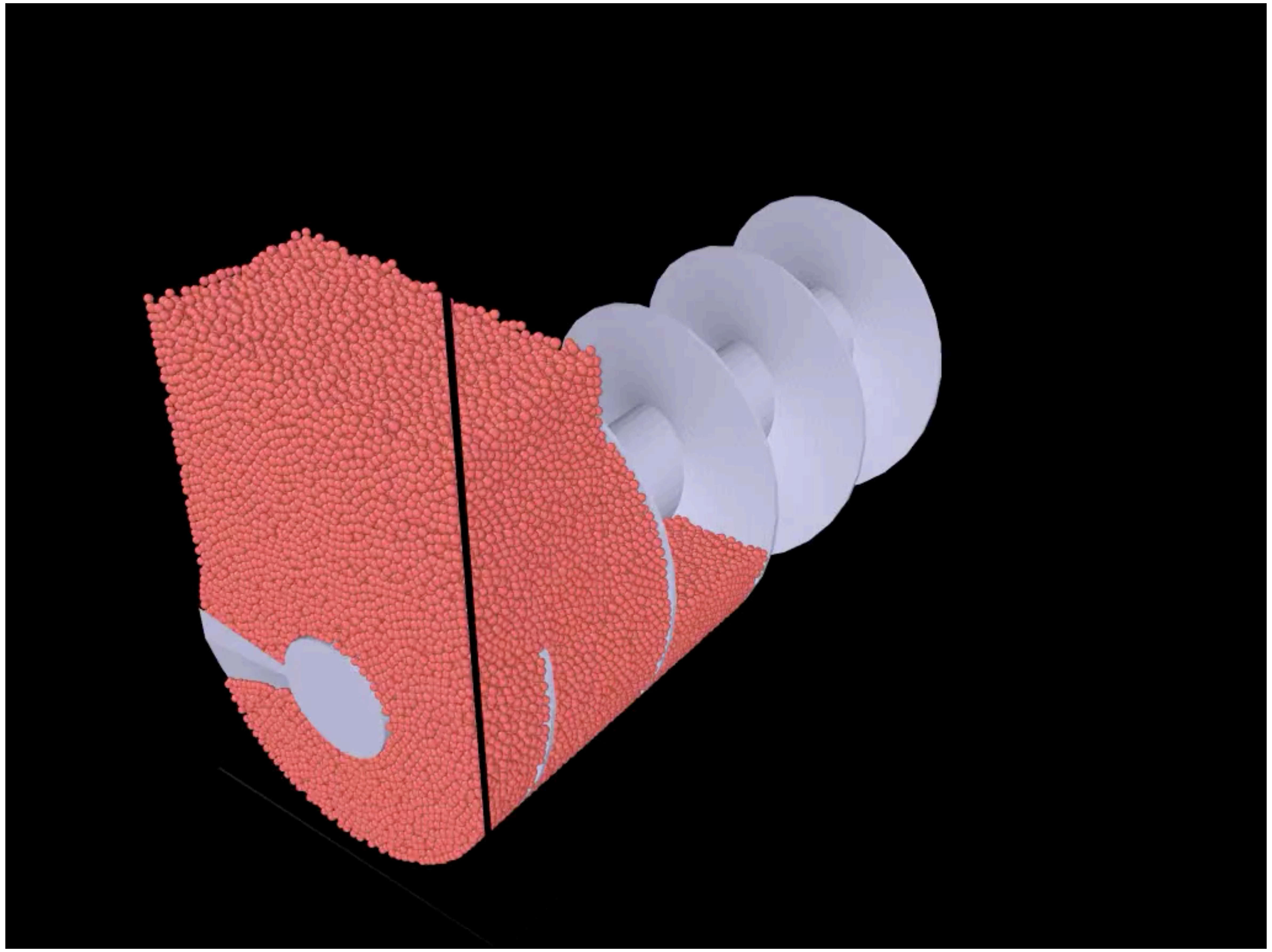


Velocity at the transparent boundary shows a combination of azimuthal and axial flow, with considerable slip at screw surface. No slip boundary condition incorrect.

DEM simulation of inlet hopper coupled with screw feeder

$p/(2R_b) = 0.5$

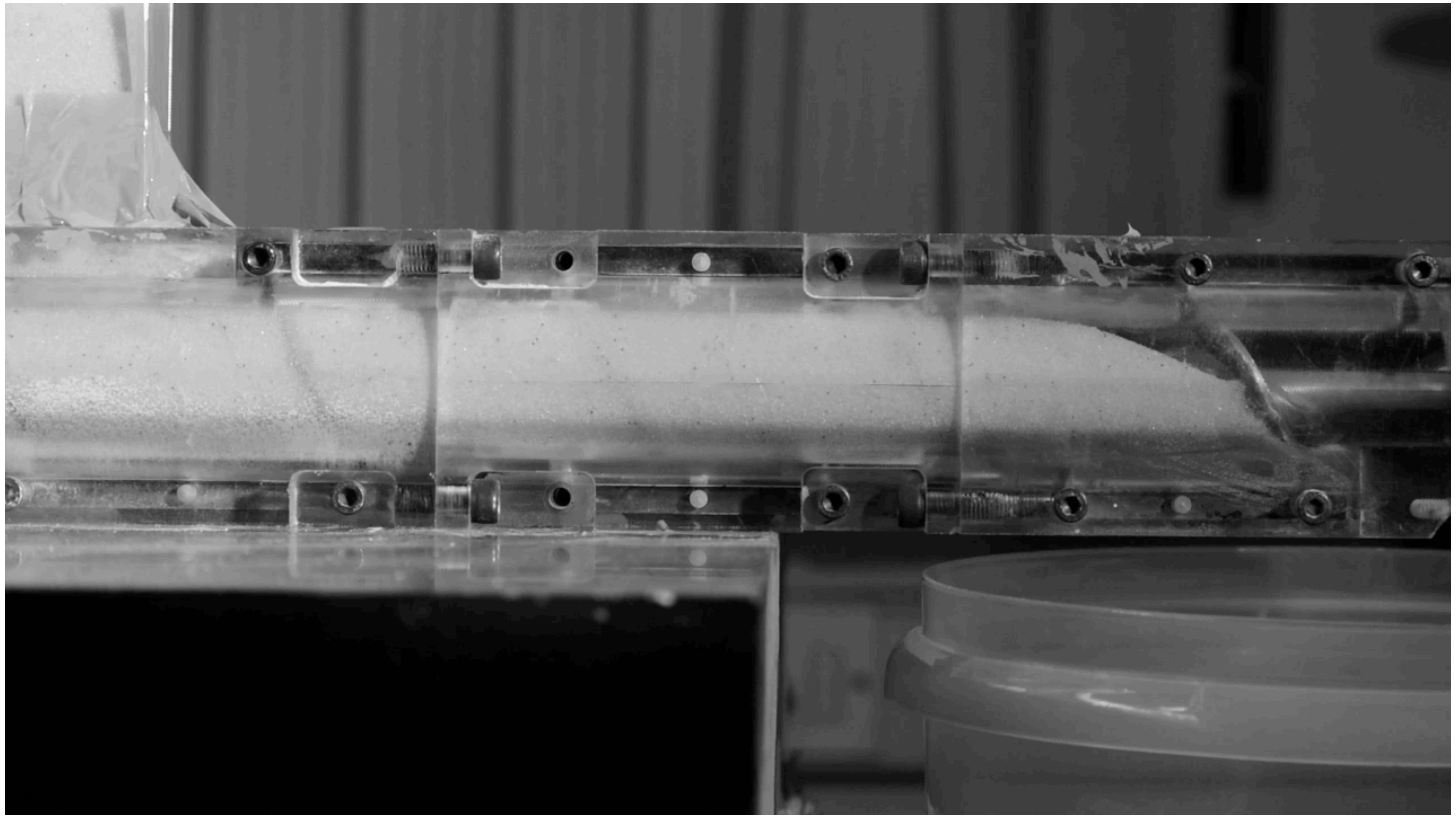


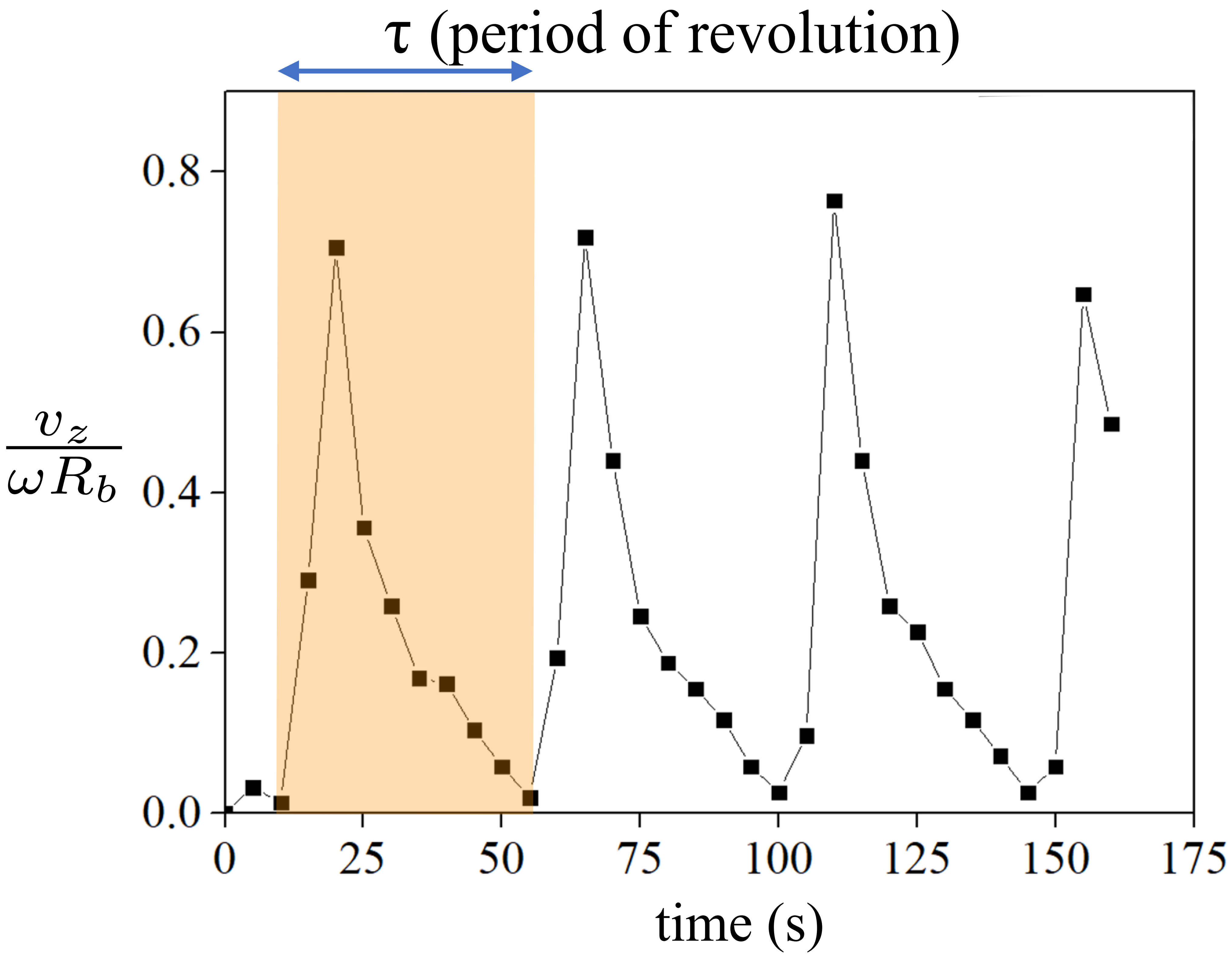


Computationally intensive, but gives an idea of the variation in the axial direction.

Axial variation: Flow imaging of glass beads

$p/(2R_b) = 1.5$

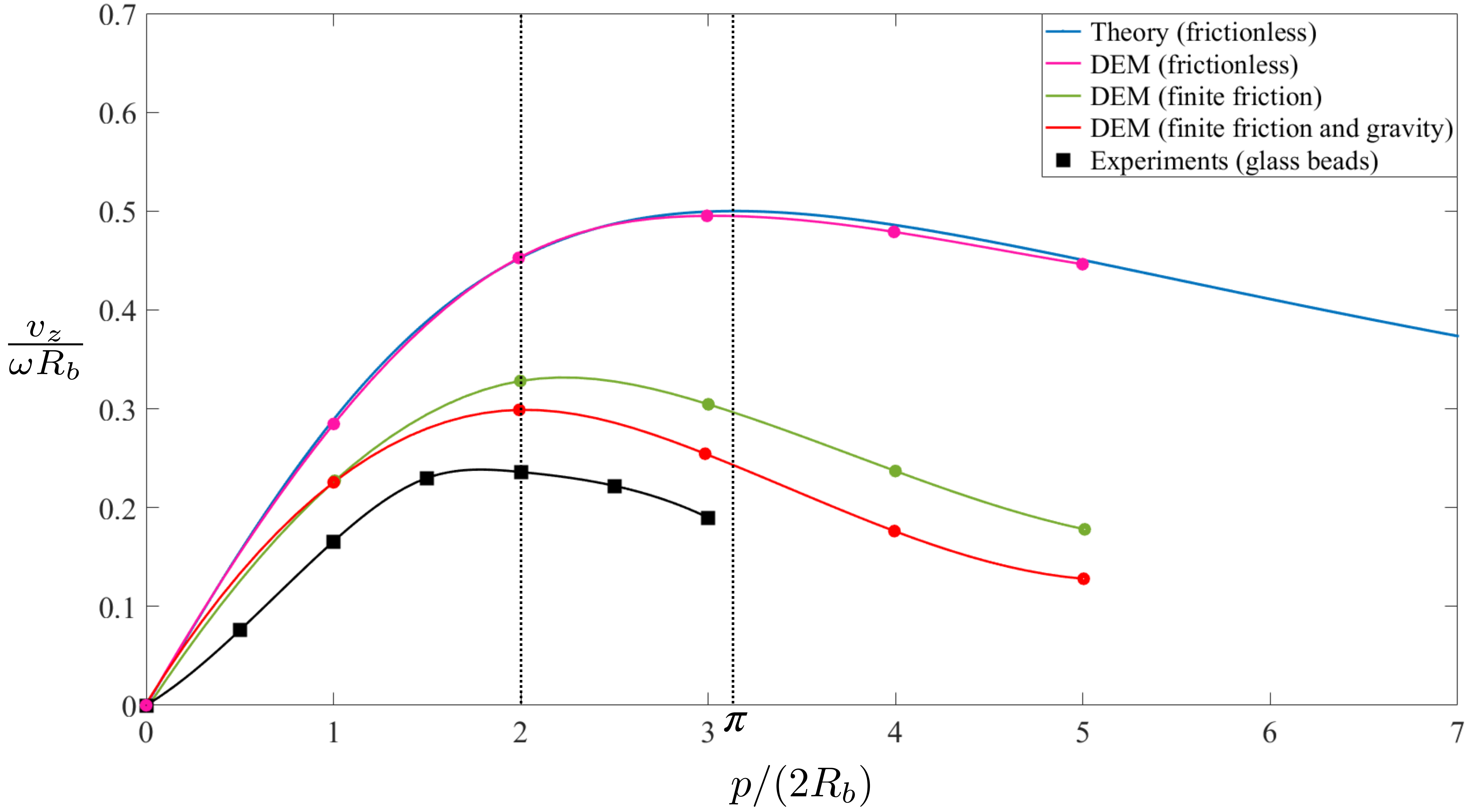




Flow rate well-defined when averaged over ~ 3τ

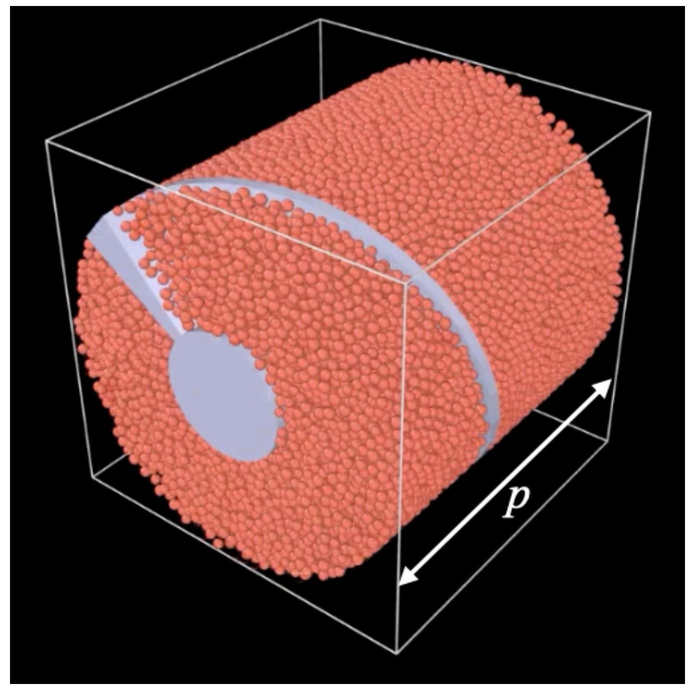
Fully filled except near the exit; periodic variation in flow rate.

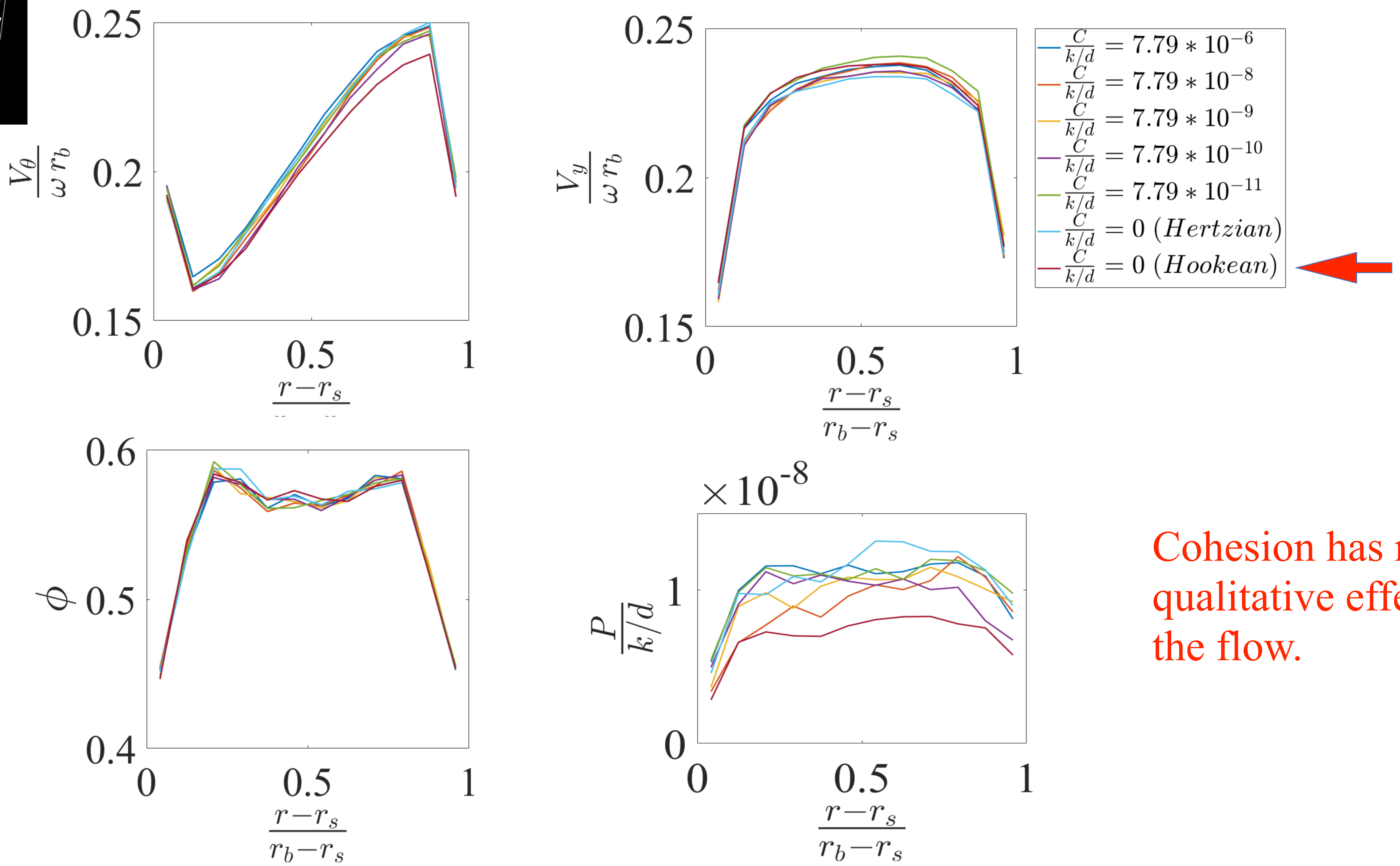
Experimental measurements of the flow rate for glass beads



Flow rate measured over several multiples of τ, hence reproducible and well-defined.

Effect of cohesion on flow: DEM simulations

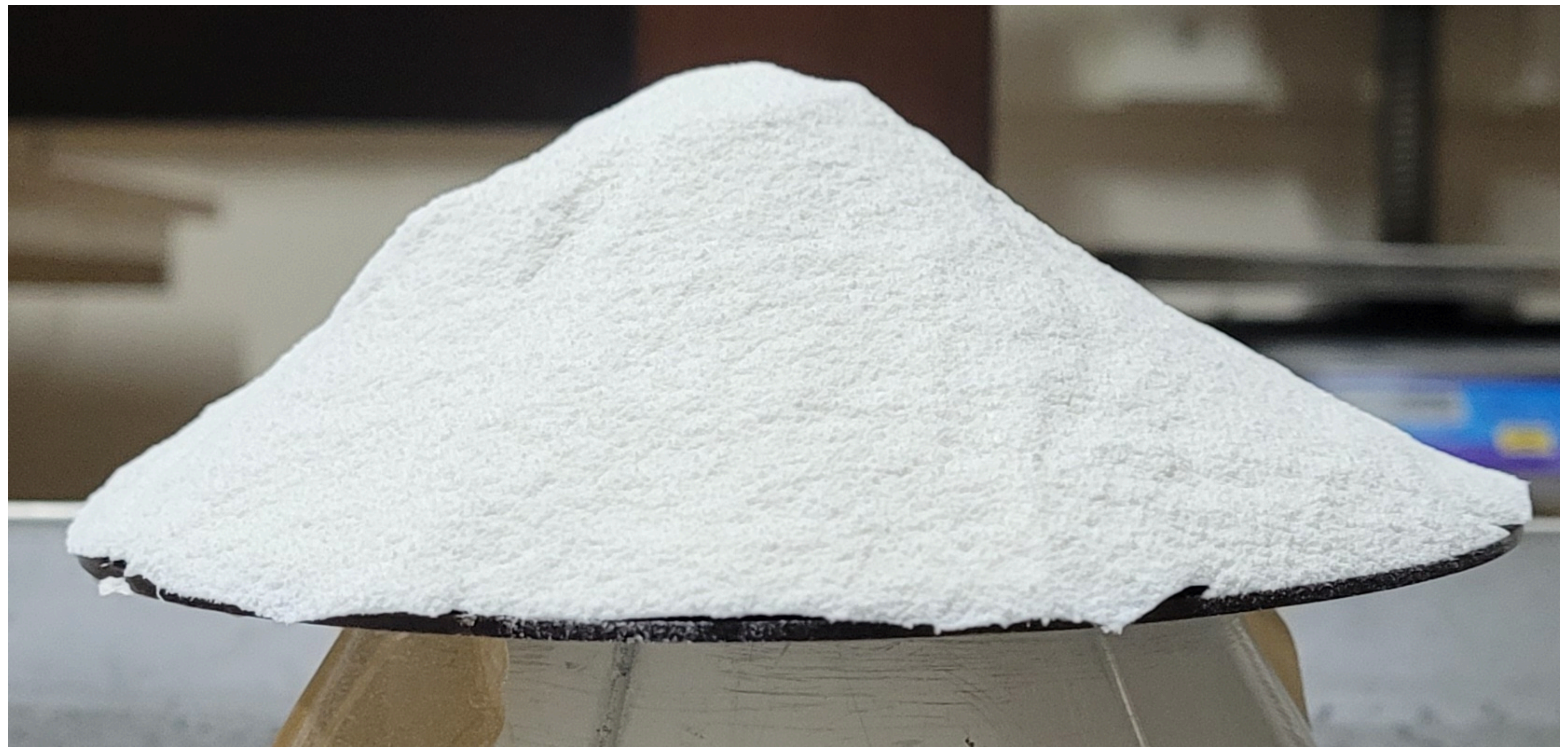




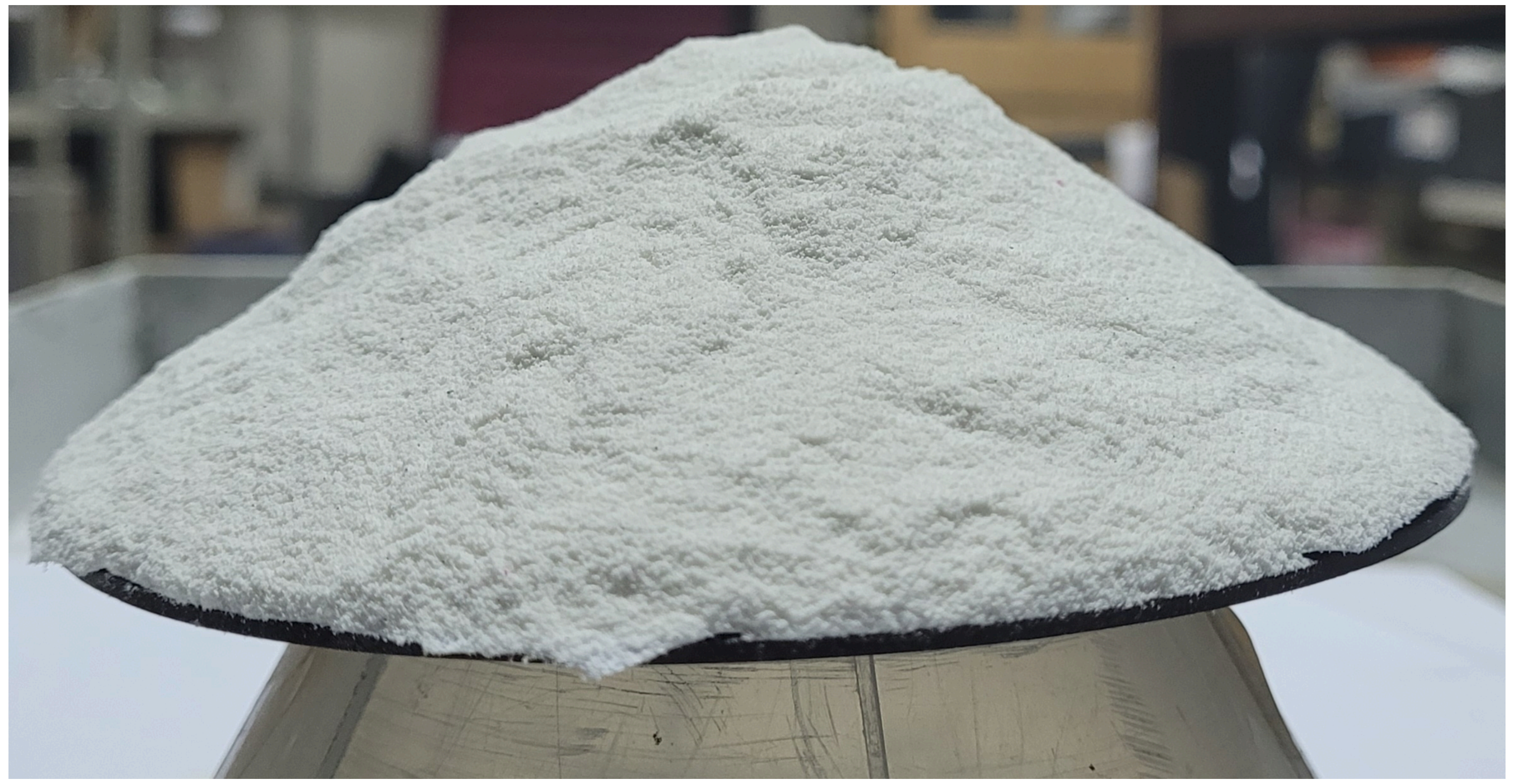
Cohesion has no qualitative effect on the flow.

Experimental studies on cohesive particles: samples from Pauline Janssen, DFE Pharma

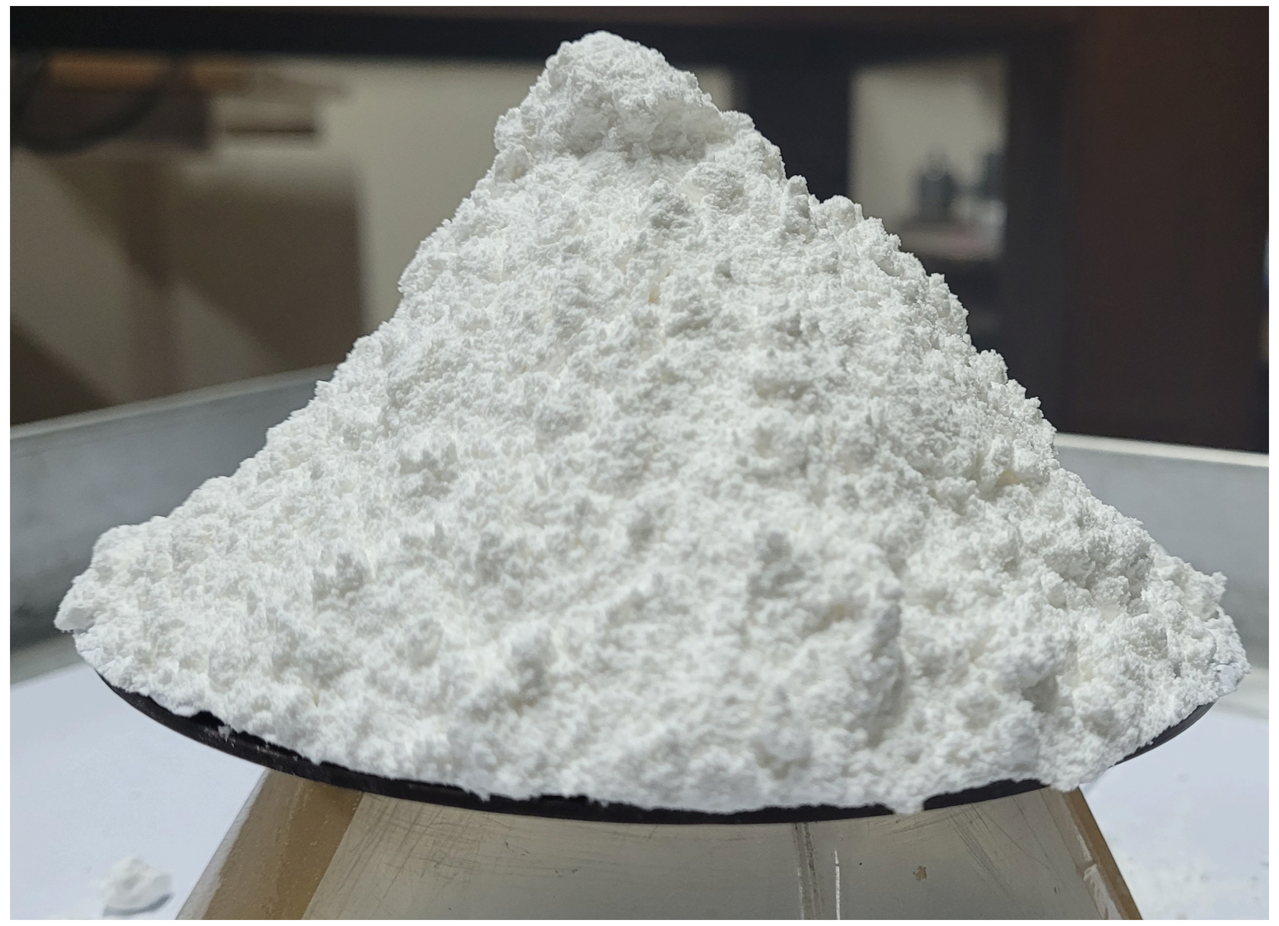
Spray dried lactose



Microcrystalline cellulose



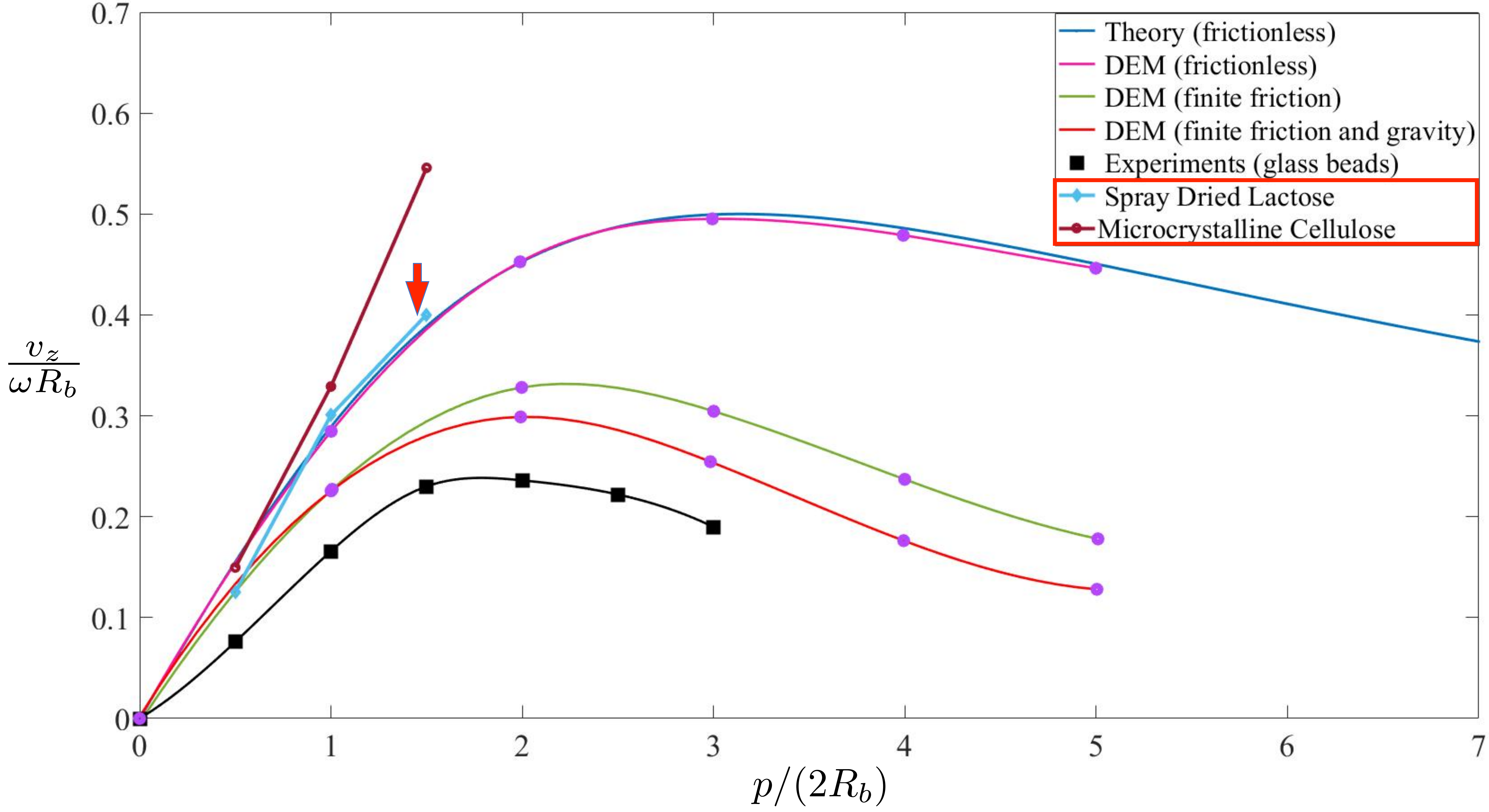
Moderately cohesive



“Lactopress” – Anhydrous fine Lactose

Much more cohesive

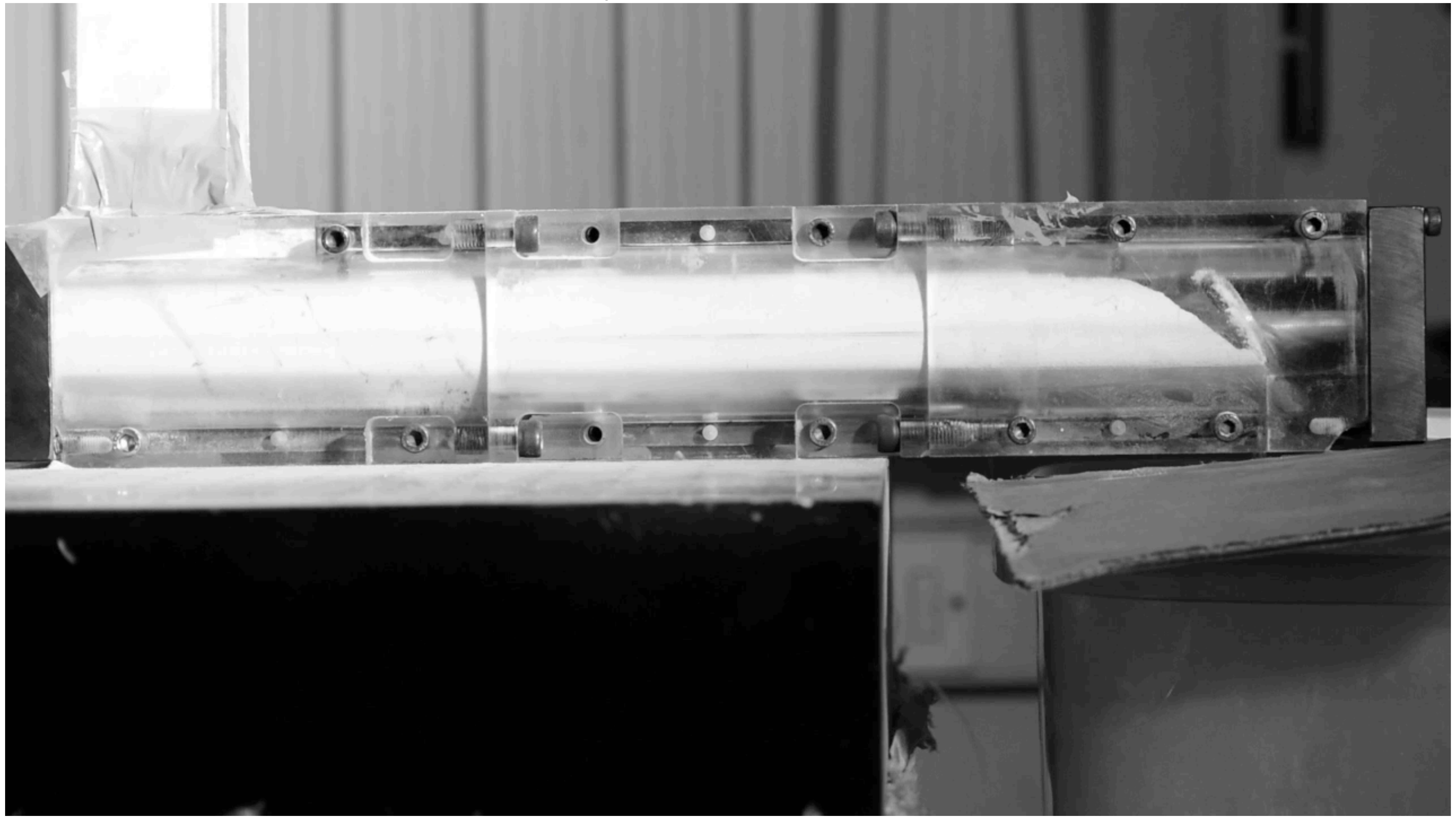
Flow rate versus $p/(2R_b)$ for cohesive powders

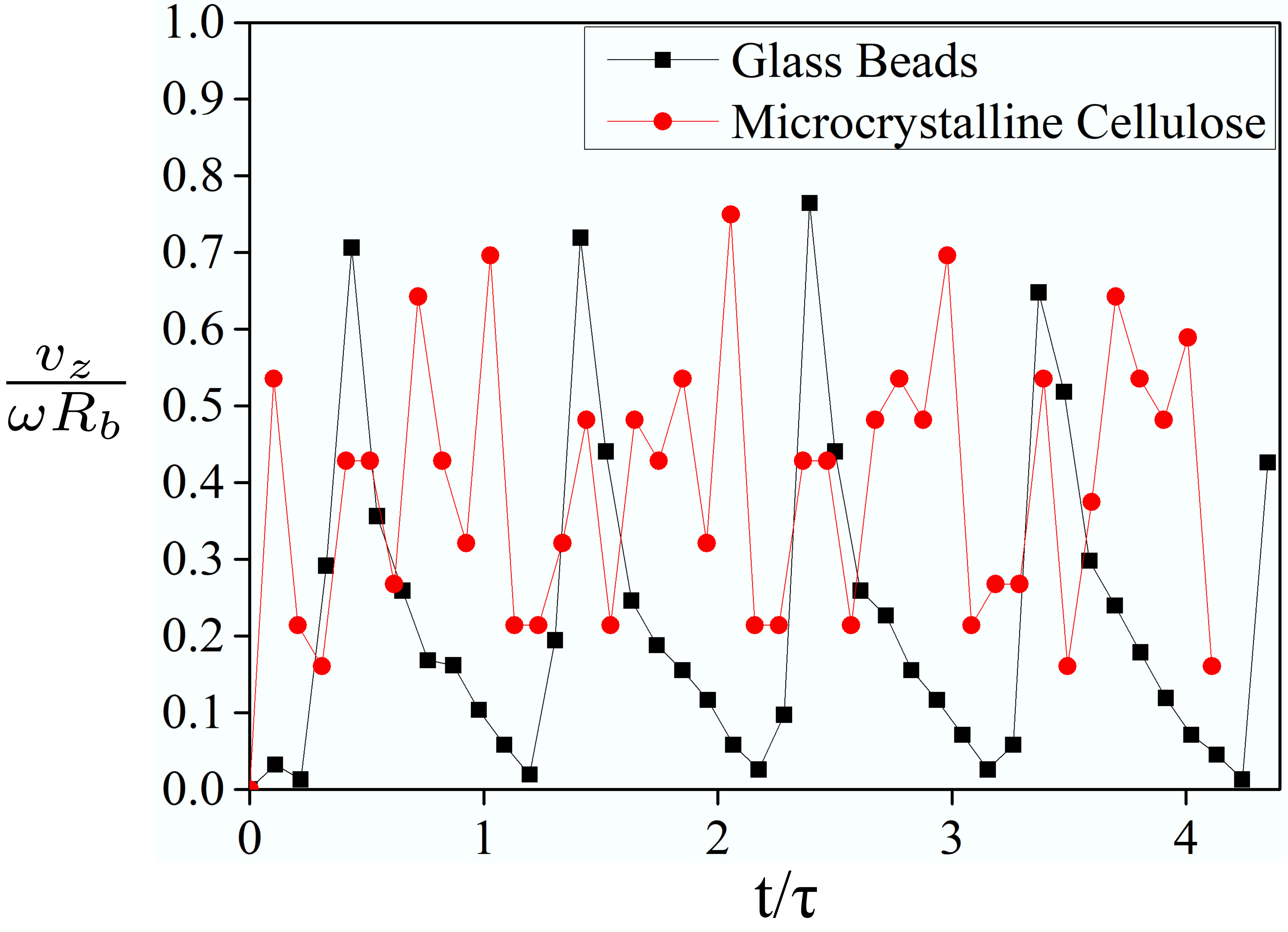


Flow rates for cohesive powders significantly higher than for glass beads.
Lactopress does not flow into the feeder from the inlet hopper.

Axial variation: Flow imaging of (cohesive) microcrystalline cellulose

Microcrystalline cellulose





Flow rate intermittent, but well-defined when averaged over ~ 3τ

Little variation in fill level, but intermittency in flow due to avalanching at exit

Conclusion

- Experiments for a larger range of $p/(2R_b)$ clearly show flow rate reaching a maximum at a particular value of $p/(2R_b)$. End effects are important – leads to fluctuations in the flow rate.
- Experiments conducted for cohesive powders. Flow rate fluctuations are erratic, due to intermittent avalanching at exit. Feeder is fully filled if it is long enough except near the exit.
- Particle tracking velocimetry measurements reveal considerable slip at the screw surface – in agreement with theory. Theory able to capture unsteady development of velocity and solids fraction.
- Non-local plasticity model shows promise. Validated for frictionless screw & shaft. Needs to be solved for frictional surfaces, partial fill, unsteady flow.
- Future work: modelling and experiments on inclined and conical feeders, effect outlet constriction, etc.