Evaluation of scaling laws for gas/solids fluidized beds with computational simulations

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Motivation

- **Previous studies (e.g., presentation by van Ommen *et al*, 2004) indicate simulations do not scale as expected (e.g., according to Glicksman's dimensionless groups)**
  - **Counter intuitive results that full-set yields poorer dynamical similarity than reduced-set**
    - **Are additional physics used in the code?**
    - **Are numerical errors involved?**
    - **Is there a problem with algorithm implementation?**
- **Can scaling studies be used as CFD software verification?**

The dimensionless scaling groups proposed by Glicksman have been widely used for fluidized beds

- **Theoretically derived from equations of motion (including kinetic theory closure relations*)**
- **Verified experimentally****
- **Provides logical approach for sensitivity analysis and scaling devices**
- **Should be possible to extrapolate bed design/operation over large changes (e.g., extrapolate a process from earth to the Moon or Mars)**
  - **If additional physics is not introduced which does not scale with these groups**

***Hrenya, C. et al., Powder Technology 116 2001 190–203**

****Louge, M. et al., Chemical Engineering Science 59 (2004) 2633 – 2638**

Original dimensional analysis produced 5+ key groups*, but Glicksman proposed reduced set of 4+

- **Full Set***

Very important parameter

$$\frac{G_s}{\rho_g U_g};\quad Fr = \frac{U_g^2}{gD};\quad Ar \approx \frac{\rho_s \rho_g d_p^3 g}{\mu_g^2};\quad \frac{\rho_g}{\rho_s};\quad \frac{d_p}{D};$$

Glicksman combined these two parameters into one

- **Simplified set***

$$\frac{G_s}{\rho_g U_g};\quad Fr = \frac{U_g^2}{gD};\quad \frac{U_g}{U_{mf}};\quad \frac{\rho_g}{\rho_s};$$

Also included: bed geometry; particle sphericity, size distribution

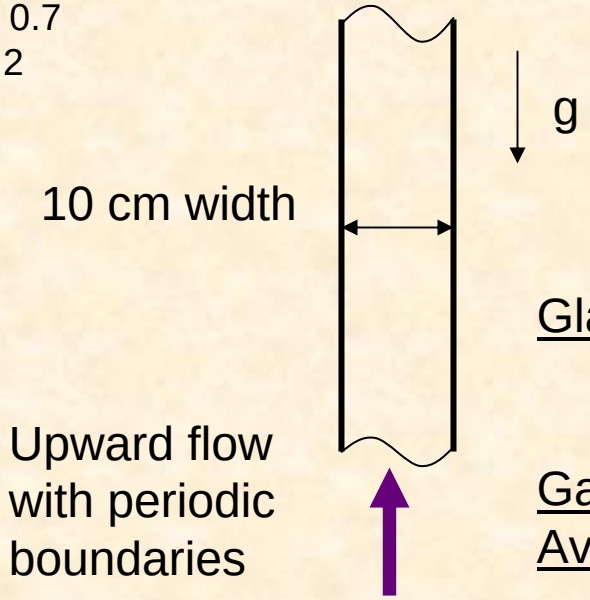
We are using MFIX to evaluate consistency with the Glicksman scaling groups for selected fluidization cases

- **Cases:**
  - **1) Fully developed upward dilute solids flow in a channel**
  - **2) Uniform bubbling bed**
  - **3) Bubbling bed with a single jet**
- **Approach:**
  - **We pick a reference case of each of the above applications**
  - **Vary particle properties, gas properties or gravity to match the non-dimensional groups according to Glicksman's full set**
  - **Compare the results with properly scaled time (time ~ length/velocity)**

Case 1: Fully-developed upward dilute gas/solids flow in a 1-D channel

1-D channel has 1 computational cell in flow-wise direction.

Jenkins wall BC parameters:
Particle-wall rest. coef. = 0.7
Coefficient of friction = 0.2

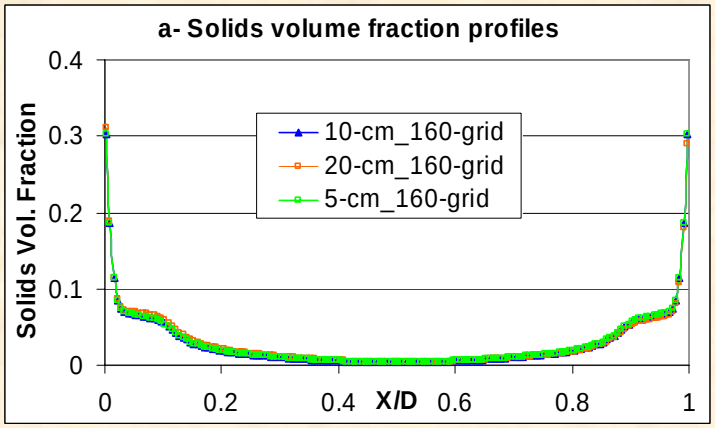


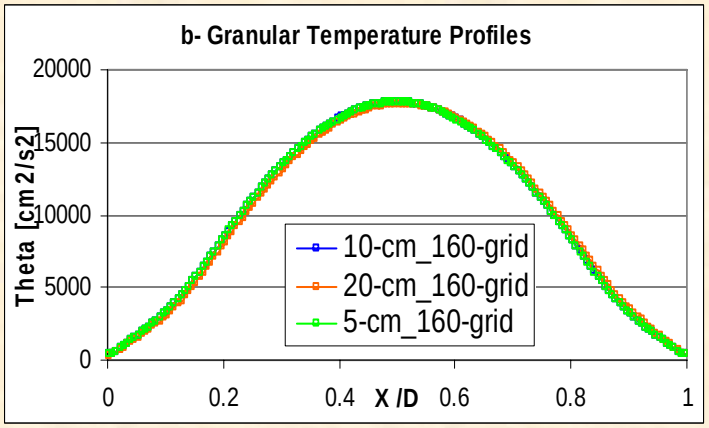
Glass beads : 2.4 g/cm3 density
120 micron diameter
0.95 restitution coef.

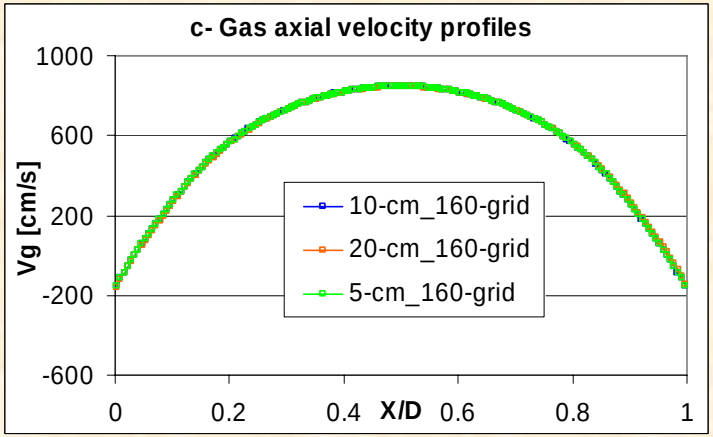
Gas sup. Velocity fixed at: 5.0 m/s

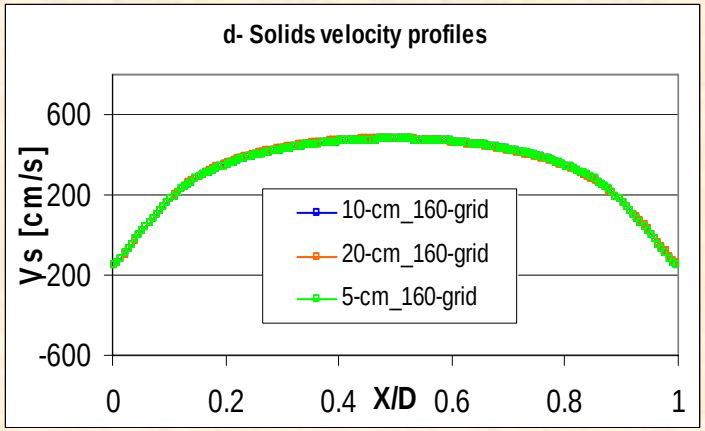
Avg Solids volume fraction fixed at: 3%

The scaling laws are verified for the simple channel flow

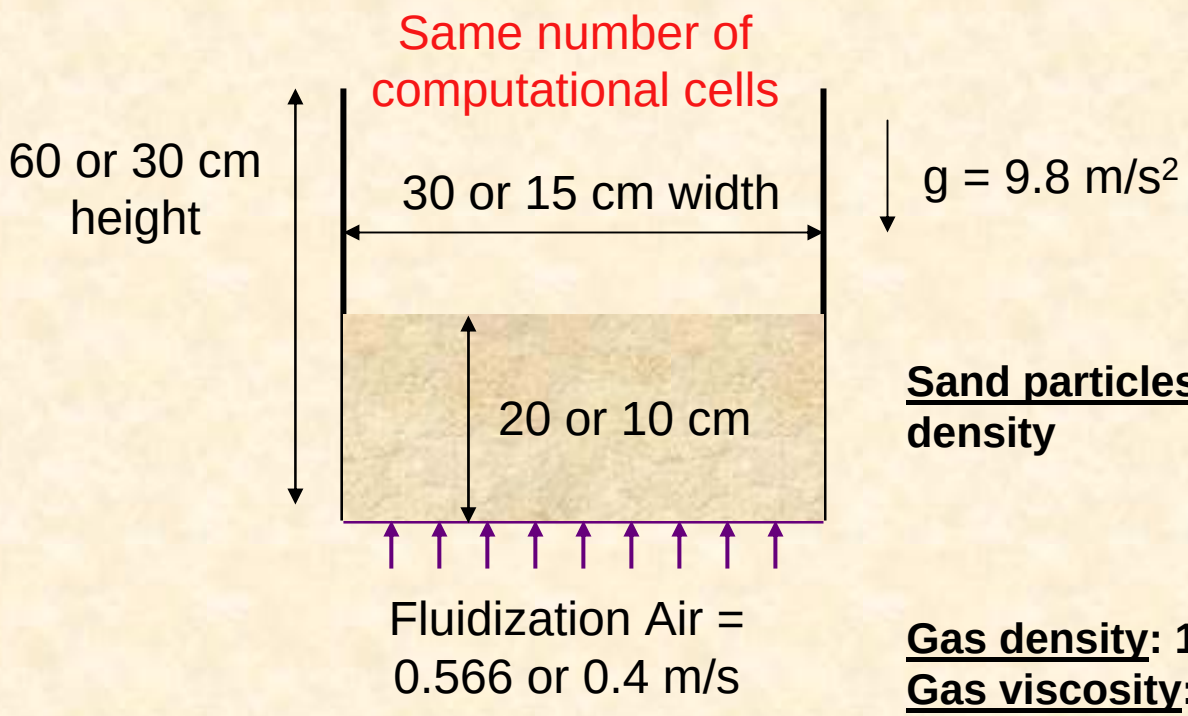








Case 2: 2D Uniformly bubbling fluidized bed*



<u>Sand particles</u> : $2.6 \cdot 10^3$ or $2.01 \cdot 10^3$ kg/m^3 density

396 and 198 μm diameter

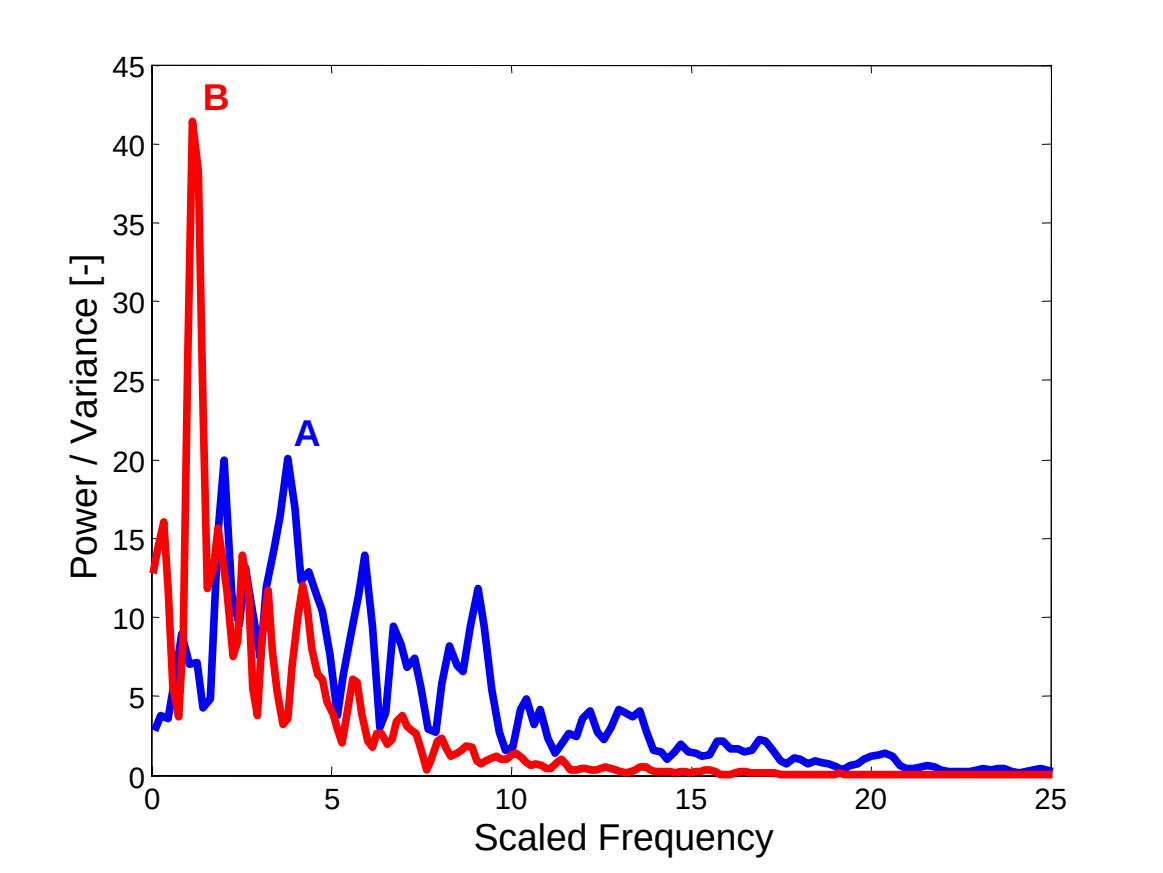
0.8 restitution coef.

<u>Gas density</u>: 1.2 or 0.93 kg/m^3

<u>Gas viscosity</u>: $1.82 \cdot 10^{-4}$ and $4.98 \cdot 10^{-4}$ poise

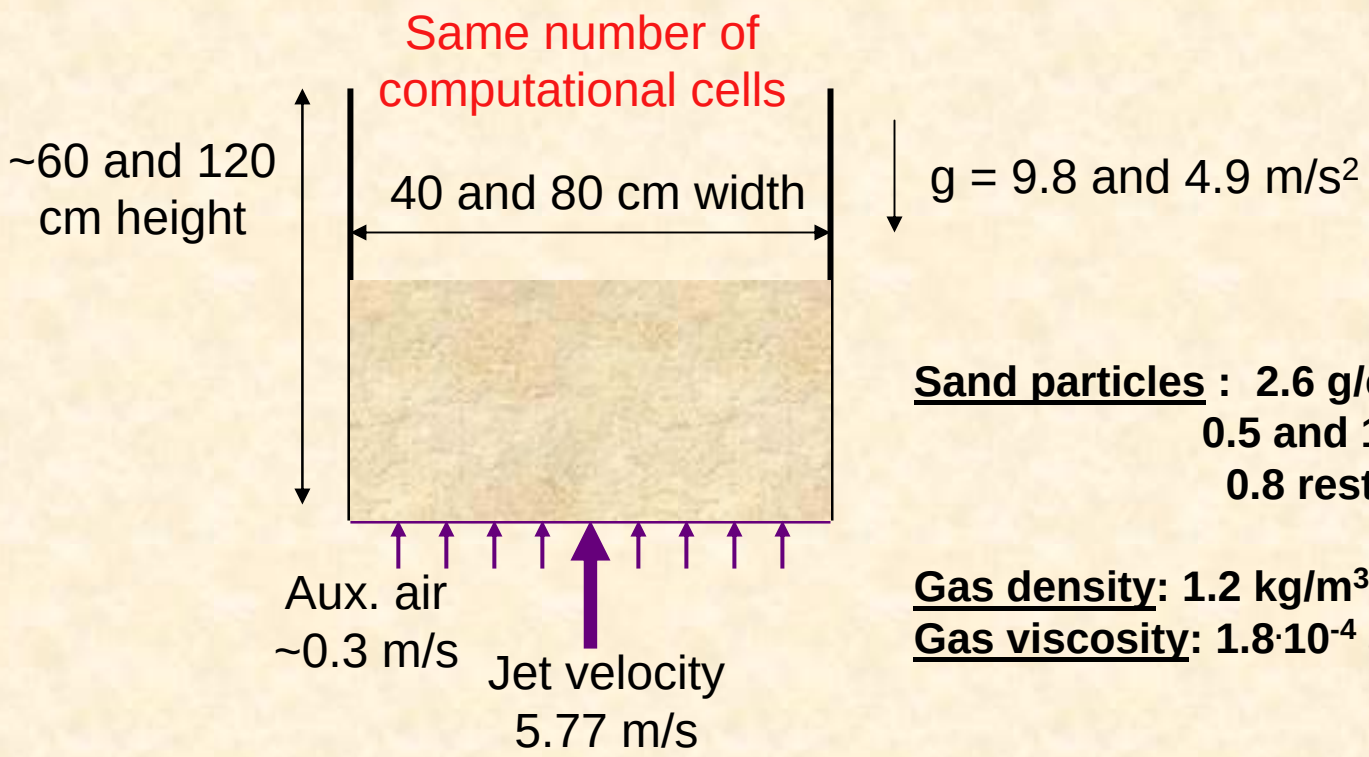
***van Ommen et al, 2004 AIChE annual meeting**

Power Spectrum Density (PSD)



- **Reference and scaled beds are not dynamically similar**
- **To explore this discrepancy we will now look at a simpler system**

Case 3: 2D bubbling fluidized bed with a single jet*

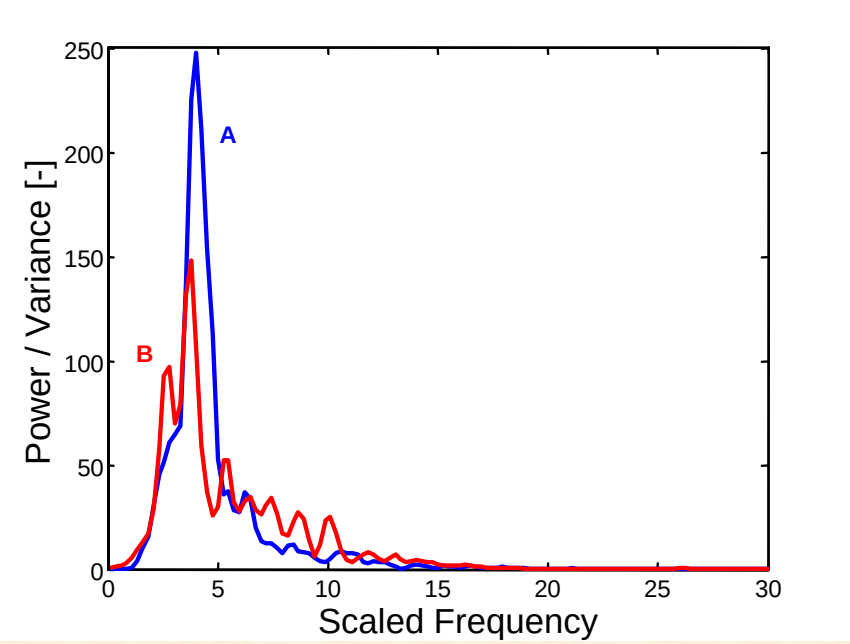


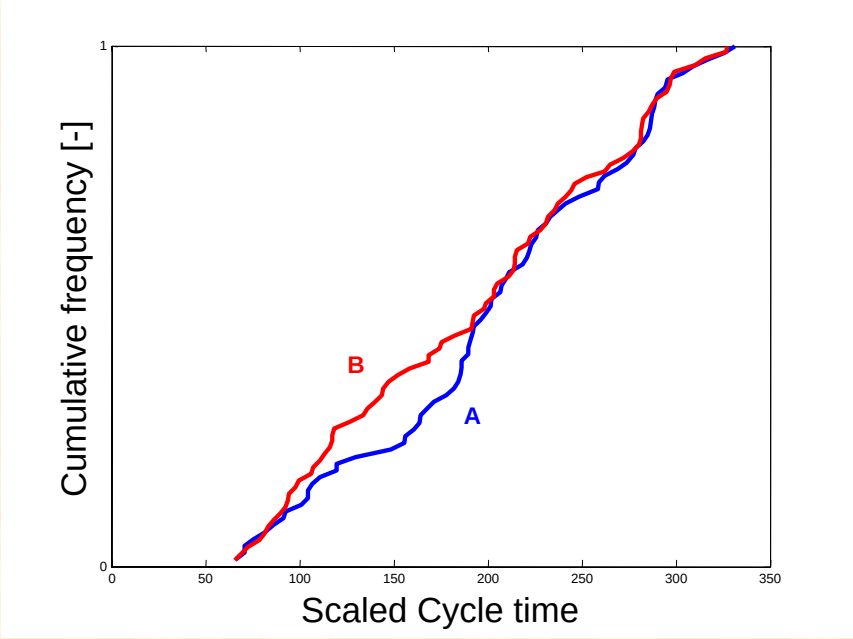
<u>Sand particles</u> : 2.6 g/cm^3 density
0.5 and 1 mm diameter
0.8 restitution coef.

<u>Gas density</u>: 1.2 kg/m^3
<u>Gas viscosity</u>: $1.8 \cdot 10^{-4}$ and $3.6 \cdot 10^{-4}$ poise

*Gidaspow, D.,1994. Multiphase flow and fluidization, pp. 158-162

Time Series Analysis (PSD and CDF for cycle times)

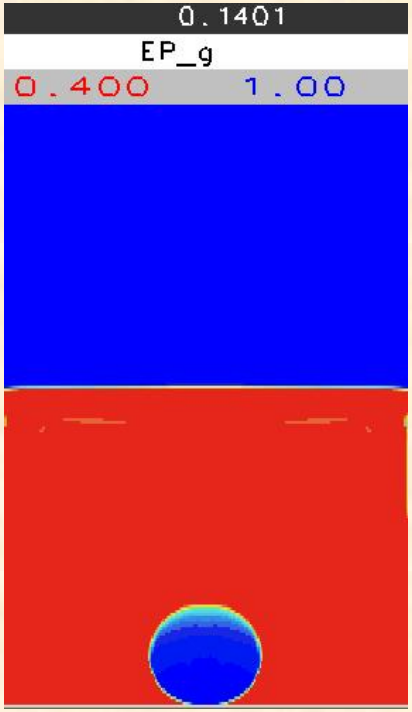




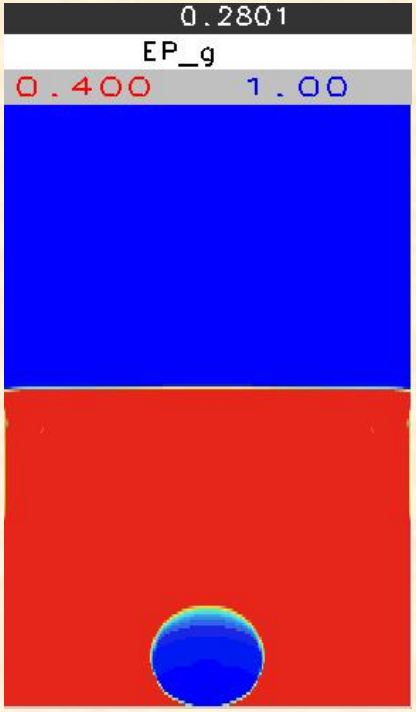
P-value – 0.37

Why are these different even for a simple system?

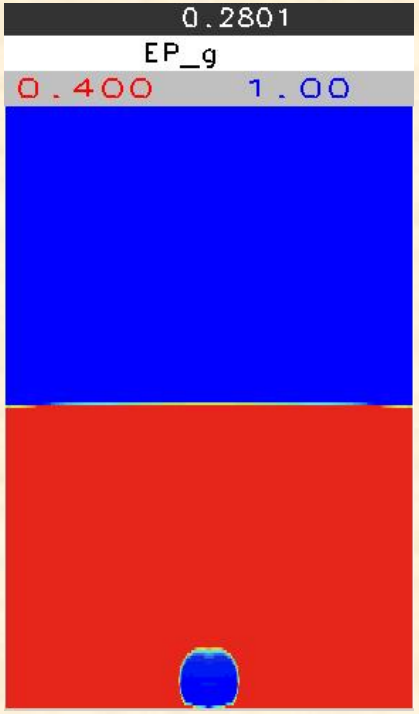
Bubbling fluidized bed with a jet – Initial bubble formation



Standard case
L

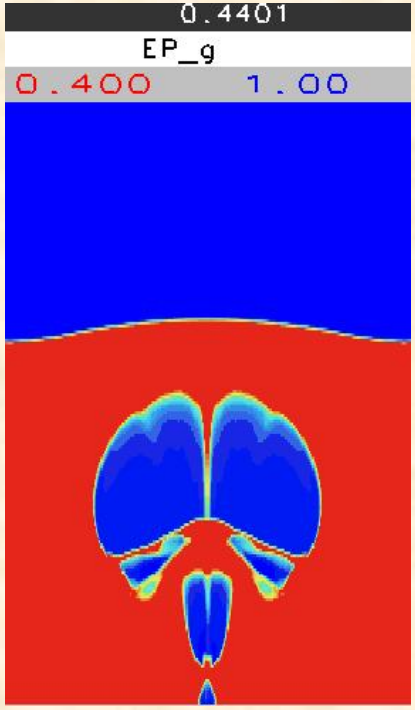


Full set
2 x L

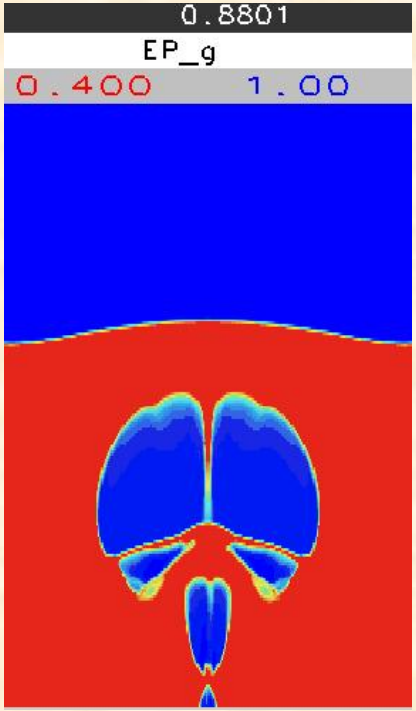


Ar mismatched
2 x L

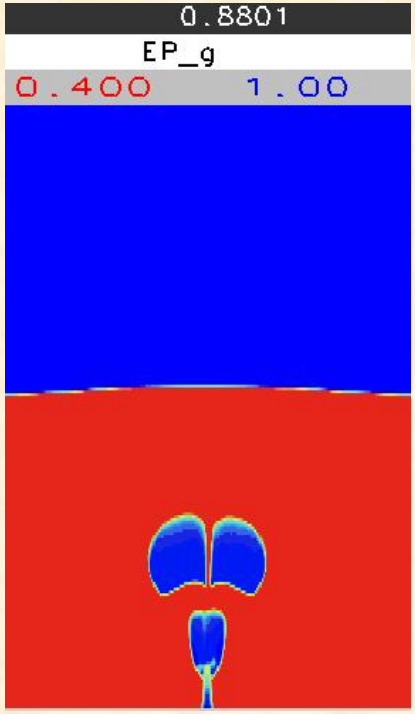
Bubbling fluidized bed with a jet - subsequent breakup and interaction



Standard case
L

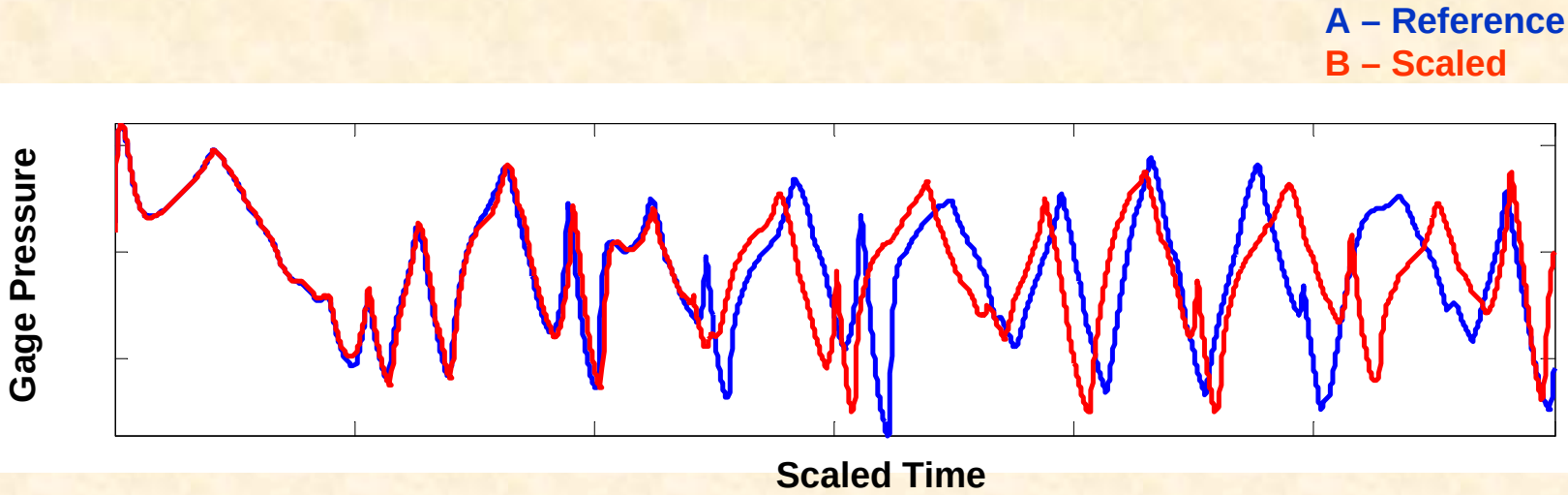


Full set
2 x L



Ar mismatched
2 x L

Time-series



- What can be the source of this discrepancy?
- Are there constraints in the code not considered in Glicksman's scaling rules?

Current Viscous and Plastic Theory Implementation

$f(x) = 1$

Plastic Regime

Slow flow

Strain rate independent

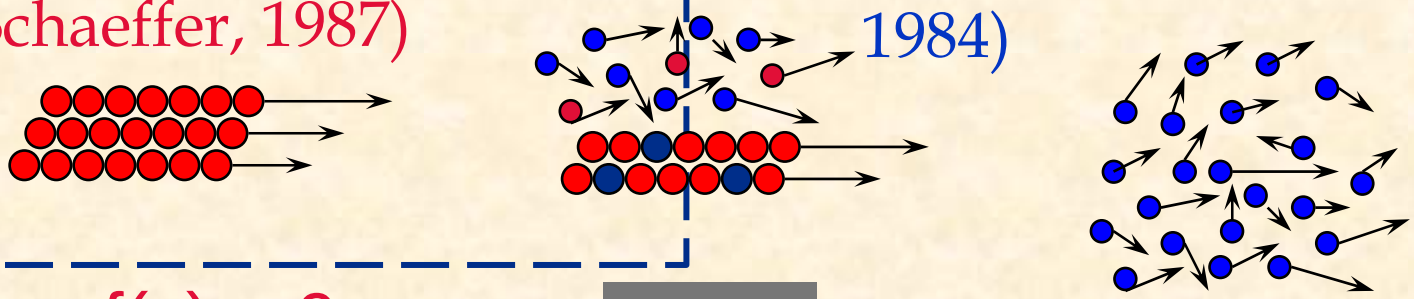
Soil mechanics (Schaeffer, 1987)

Viscous Regime

Rapid flow

Strain rate dependent

Kinetic Theory (Lun, 1984)

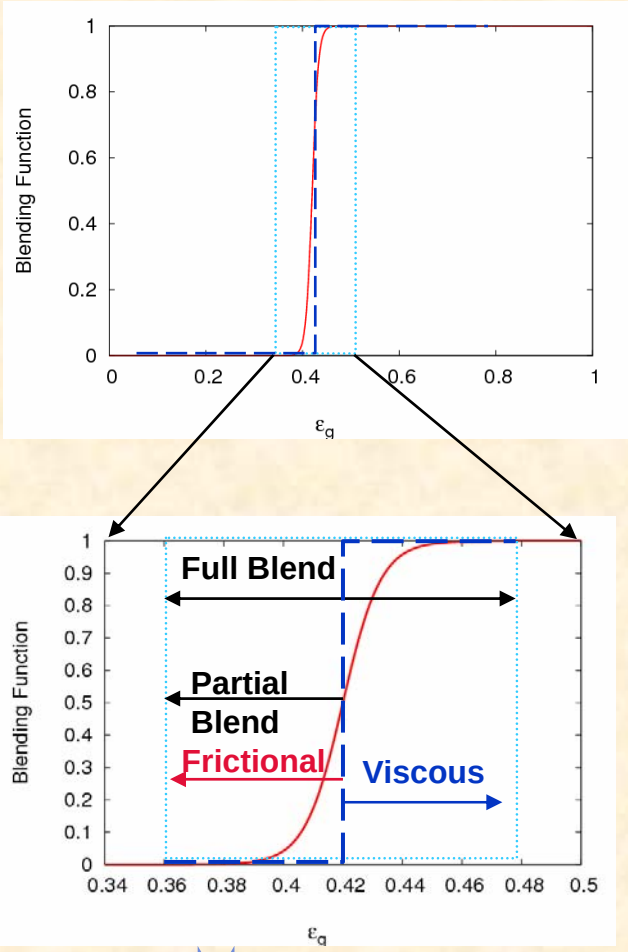


$f(x) = 0$

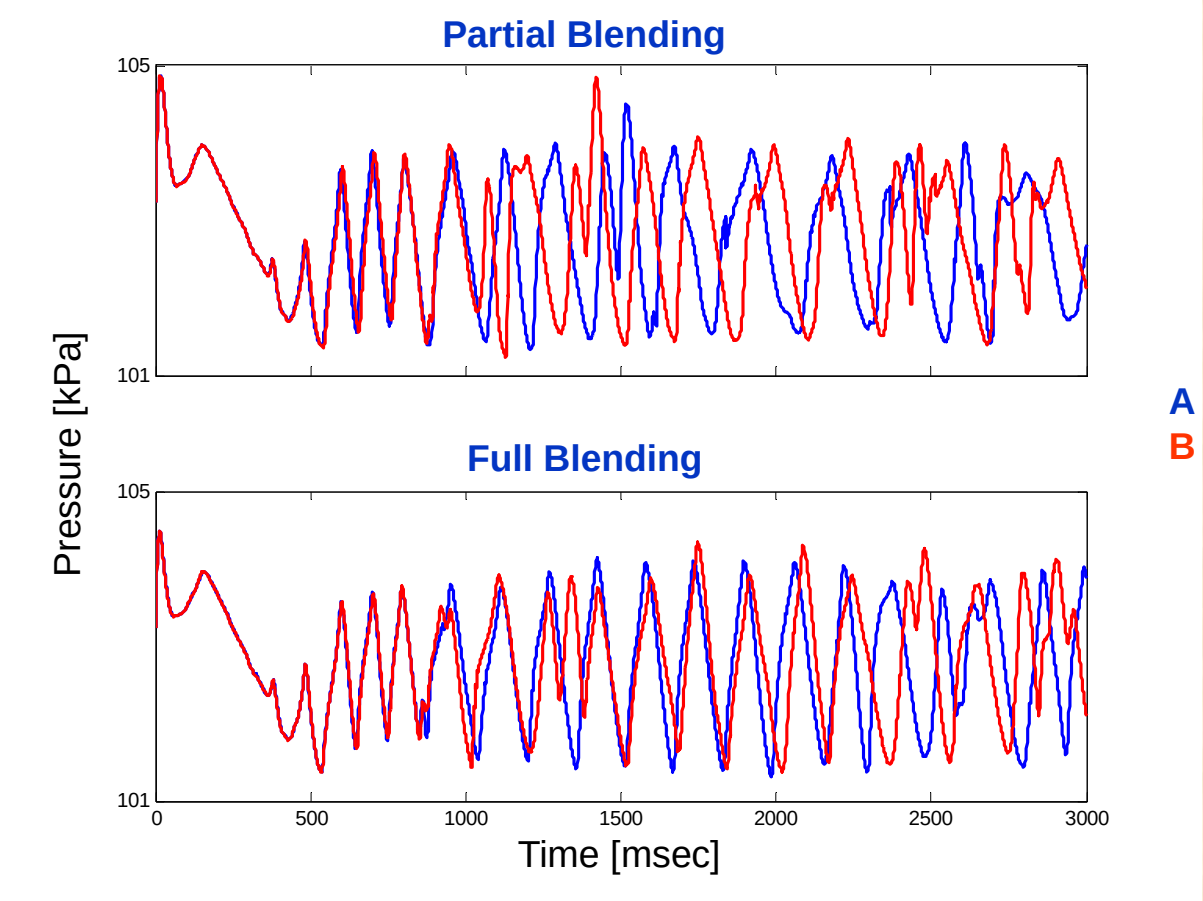
$\varepsilon_g = \varepsilon^*$

Is the step discontinuity contributing to the scaling discrepancy – can we use a blending function?

- **Blending function**
  - **Smoother transition**
  - **Still preserving the viscous/frictional stress formulation**
  - **Bridge to address the transition region**
- **Benefits**
  - **Improved convergence (papers 284d & 301a)**
  - **Reduced artificial non-linearity**
  - **Increase stability**
  - **Possibly address the scaling discrepancy?**
  - **Reduce the infinite states of the system**



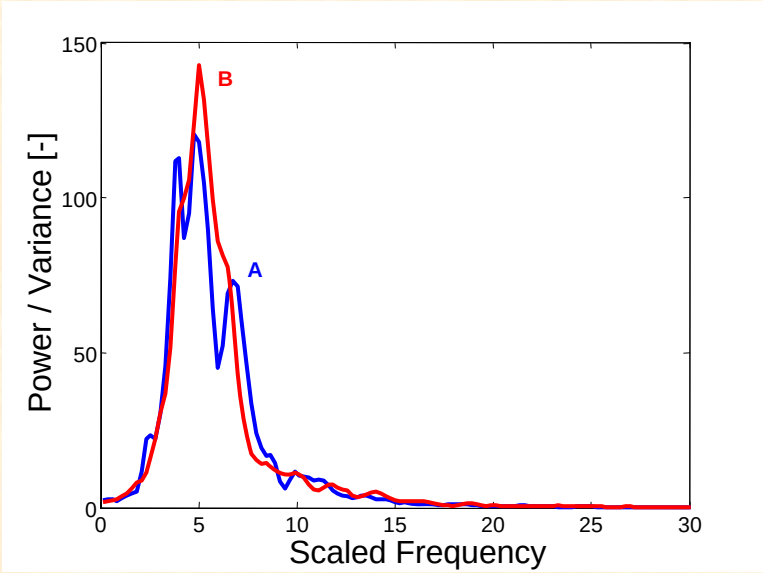
Bubbling bed with a jet: Did blending viscous and plastic stresses help?



A – Reference
B – Scaled

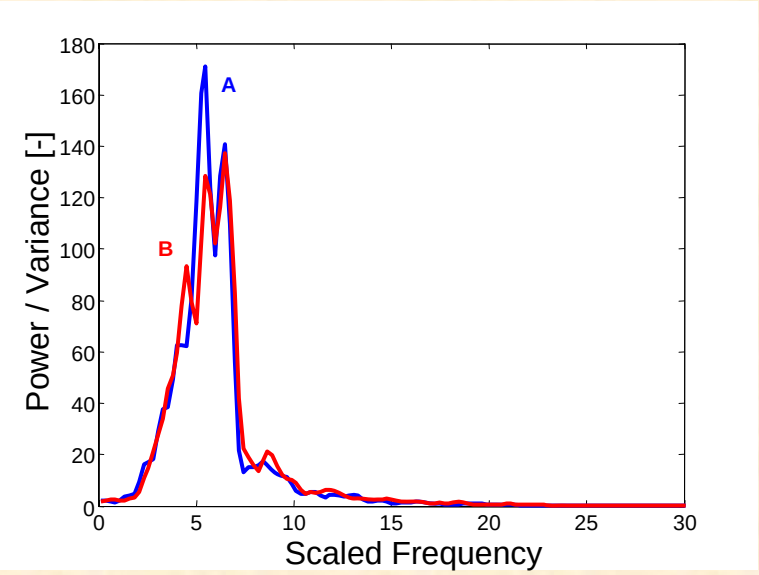
Bubbling bed with a jet: Did things change with blending viscous and plastic stresses? Effect on PSDs

Partial Blending



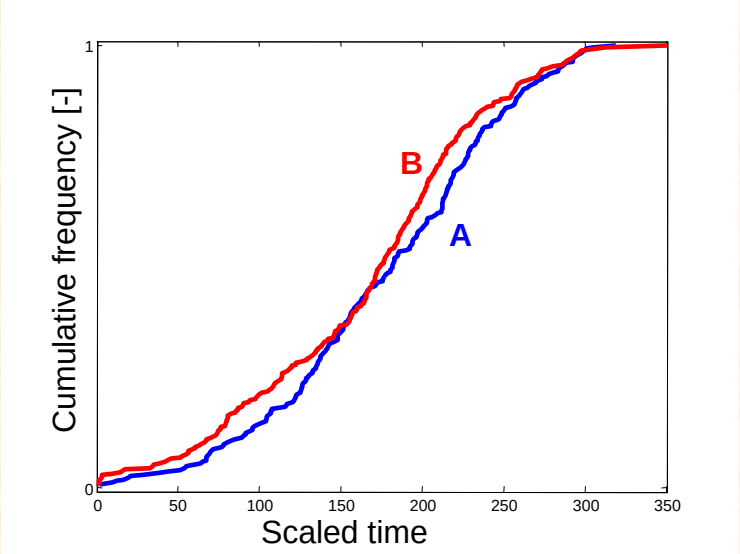
A – Reference
B – Scaled

Full Blending



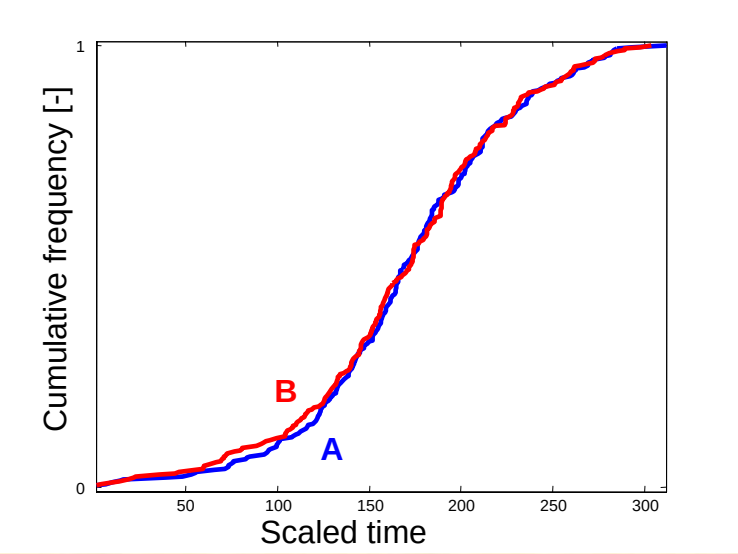
Did things change with blending viscous and plastic stresses? Effect on CDF of cycle times

Partial Blending



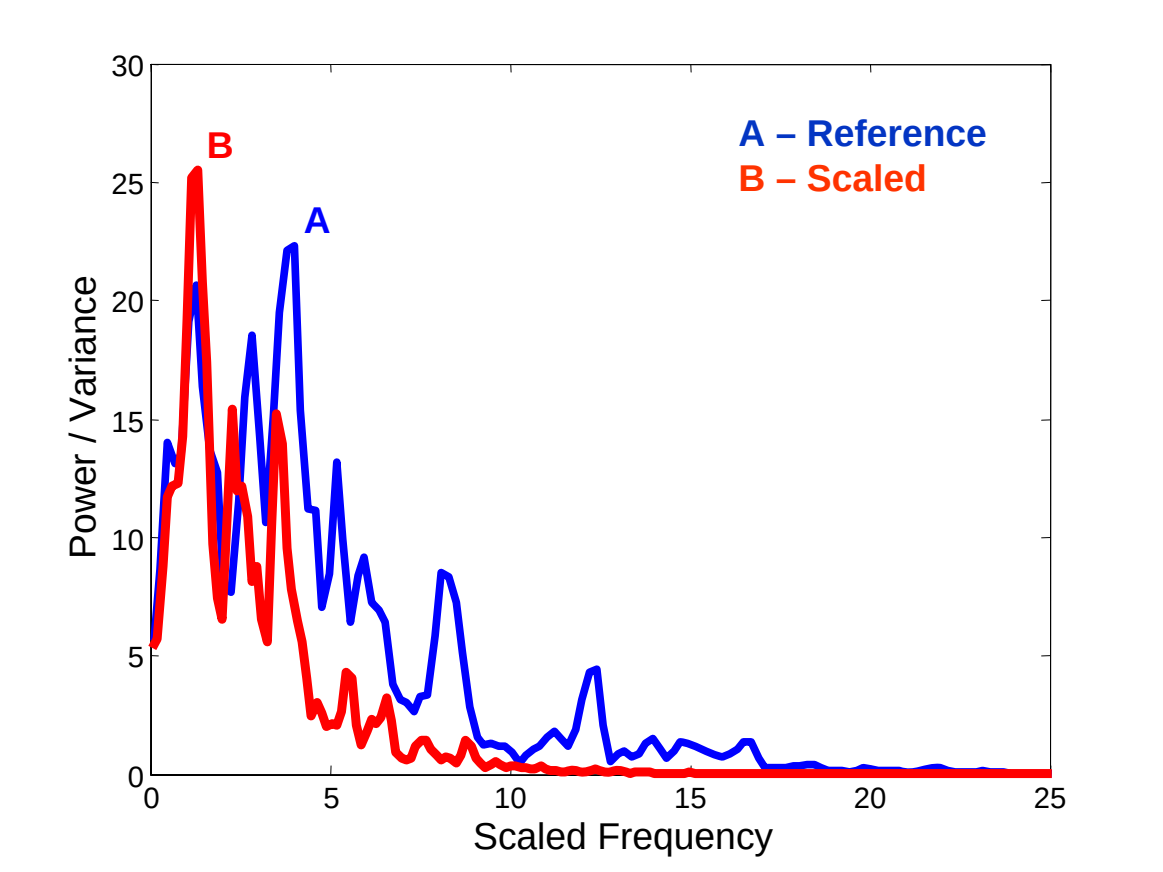
A – Reference
B – Scaled

Full Blending



- **Reference and scaled beds are dynamically very similar**
- **Discrepancy:**
  - **Resolution – numerical errors?**
  - **Longer time-series?**

How does this change effect freely bubbling bed?



- Reference and scaled beds are still not dynamically similar but look closer
- Gas compressibility?
- Resolution – numerical errors?
- Longer time-series?
- Is $\boxed{P_0 / \rho_s u_0^2}$ a problem?
- Is $\boxed{A / \rho_s u_0^2}$ a problem, A is pre-exponent for plastic solids pressure?

Conclusions and future work

- **Observed similar problems as reported by van Ommen with a different simulation tool (MFIX)**
- **Specific results:**
  - **Good scaling in upward dilute solids flow in a channel**
  - **Bubbling bed with jet with stress blending achieves very good similarity**
  - **Uniform bubbling bed fails to achieve dynamic similarity**
  - **Viscous-frictional step change in dense phase may be critical model parameter**
- **General issue:**
  - **Need standard way to evaluate scaling behavior of codes that accounts for both time-averaged and dynamic features**

Thank you for your attention!!

http://www.mfix.org

MFiX