State-of-the-Art of Gas-Solids Flow – an Industrial Perspective

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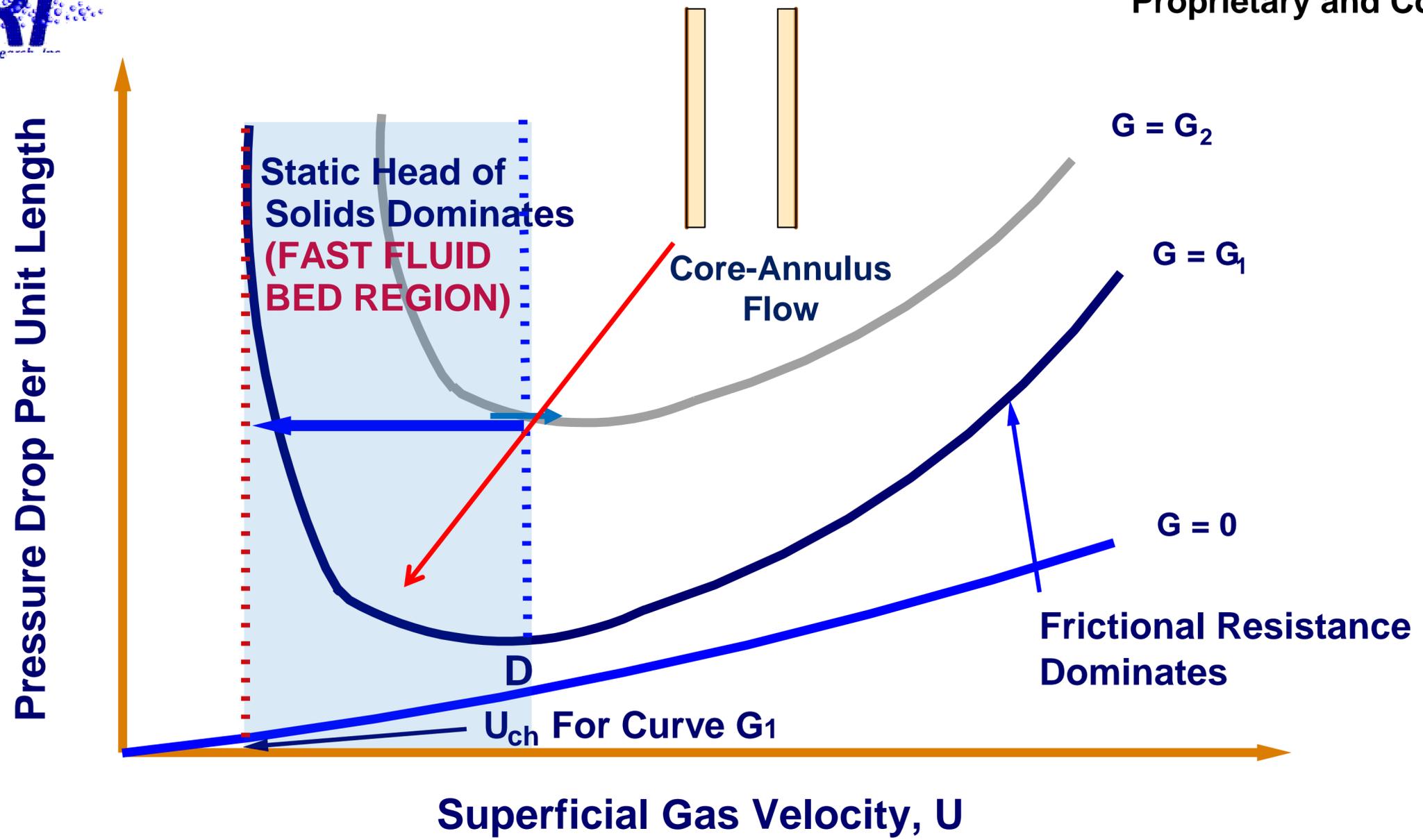**[1]Particulate Solid Research, Inc.**
[2]Origin Materials

June 9, 2023

Pneumatic Conveying

- **Dense-Phase Conveying is a Less Mature Technology Than Dilute-Phase Conveying – Would Recommend Testing Solids in a Dense-Phase Conveying Test Rig to Obtain Best Results for Design**

- **Dilute-Phase Conveying (both Horizontal and Vertical) is More Mature. Can Use Existing Correlations to:**

    -- Define Lower Limit for Dilute-Phase Conveying: 1) *Saltation Velocity* **for Horizontal Conveying and 2)** *Choking Velocity* **for Vertical Conveying**

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Pneumatic Conveying (cont'd)

- **Choking Velocity and Saltation Velocity Correlations are Satisfactory to Determine The Dense/Dilute Boundary Within About ± 25%**

- **There is Still Some Contention in the Field About Where the Boundary *(Choking Velocity)* is Between the Turbulent (Dense-Phase) and Fast-Fluidization (Dilute-Phase) Regimes**

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Pressure Drop Per Unit Length (y-axis)

Superficial Gas Velocity, U (x-axis)

Static Head of Solids Dominates (FAST FLUID BED REGION)

Core-Annulus Flow

$G = G_2$

$G = G_1$

$G = 0$

Frictional Resistance Dominates

D

U_{ch} For Curve G_1

$$\Delta P_{Total} = \Delta P_{friction} + \Delta P_{static\ head}$$

$\Delta P_{gas/wall\ friction}$
$\Delta P_{solids/wall\ friction}$
$\Delta P_{gas/solids\ friction}$

ΔP Required to Support Solids

REGION WHERE STATIC HEAD OF SOLIDS DOMINATES IS THE FAST FLUIDIZED BED REGION

Circulation Systems

- **We Now Understand Circulation Systems Better Than 20 Years Ago– Especially Those Containing Underflow Standpipes**

- **Most People Think That the Purpose of a Standpipe is to Build Pressure in a Circulation System.**

- **A Standpipe Does This, but it's Purpose is More Complex. Its Actual Purpose is to Balance the Pressure Drop Loop in a Circulation System.**

- **So, the Standpipe Can Build Pressure (Mostly) but it Can Also Dissipate Pressure if the Circulation System Requires it.**

Another Standpipe Function

The Standpipe ΔP adjusts to Balance the ΔP Around a Loop

P Balance in the System at Left:
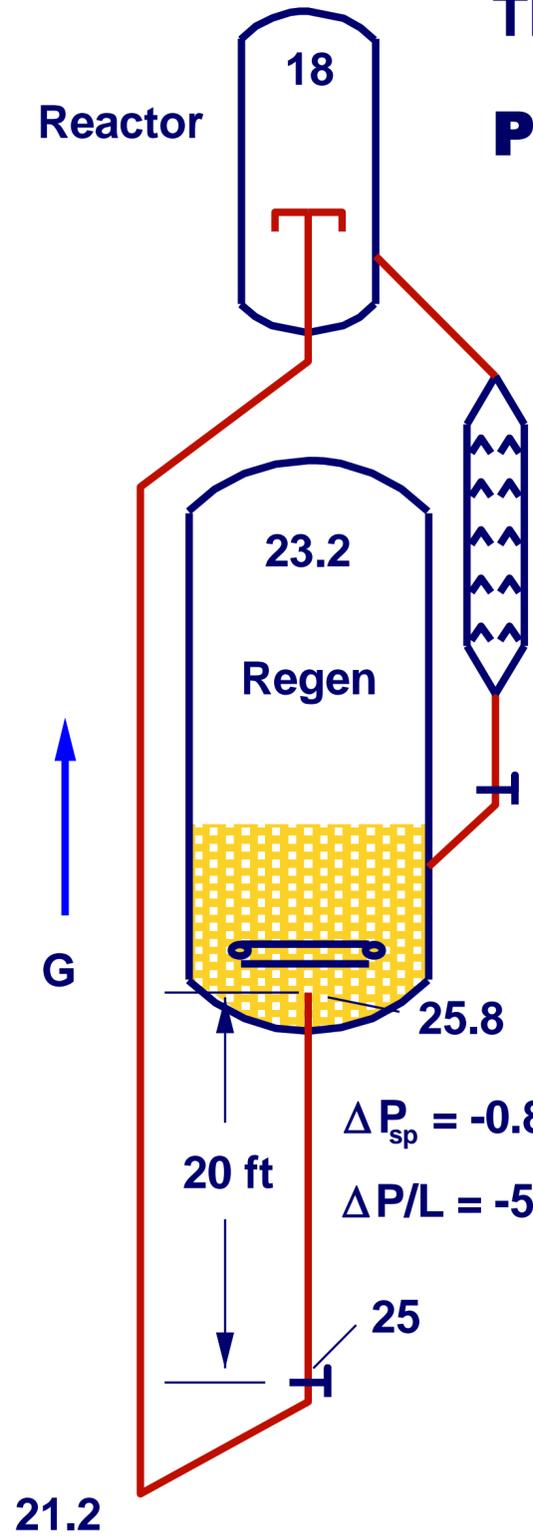
$$\Delta P_{sv} + \Delta P_{riser} - \Delta P_{R/Reg} - \Delta P_{bed} = \Delta P_{sp}$$
$$3.8 \text{ psi} + 3.2 \text{ psi} - 5.2 \text{ psi} - 2.6 \text{ psi} = -0.8 \text{ psi}$$

The Standpipe ΔP Will Adjust so That the Pressure Balance Around the Loop is Satisfied. The Standpipe ΔP Can be Positive *(Builds 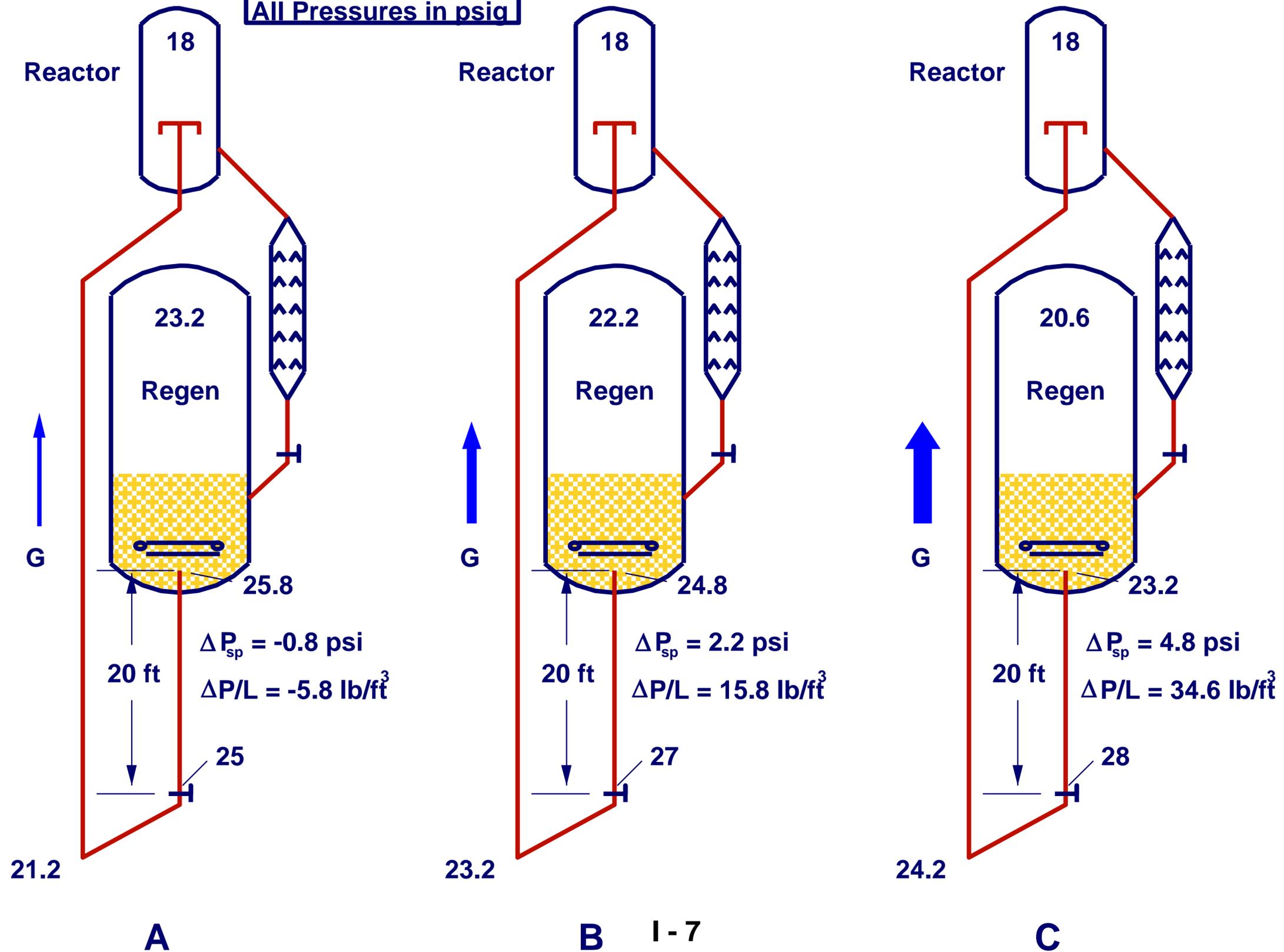Pressure)* or Negative *(Dissipates Pressure).* The Standpipe on the Left is *Dissipating* Pressure so That the Pressure Balance is Satisfied. Therefore, a Standpipe Does Not Always Build Pressure as it was Designed to Do. If a Standpipe is Not Building Pressure at Its Fluidized Density, it Does Not Mean That it is Operating Poorly. *The Pressure Balance Needs to be Checked!*
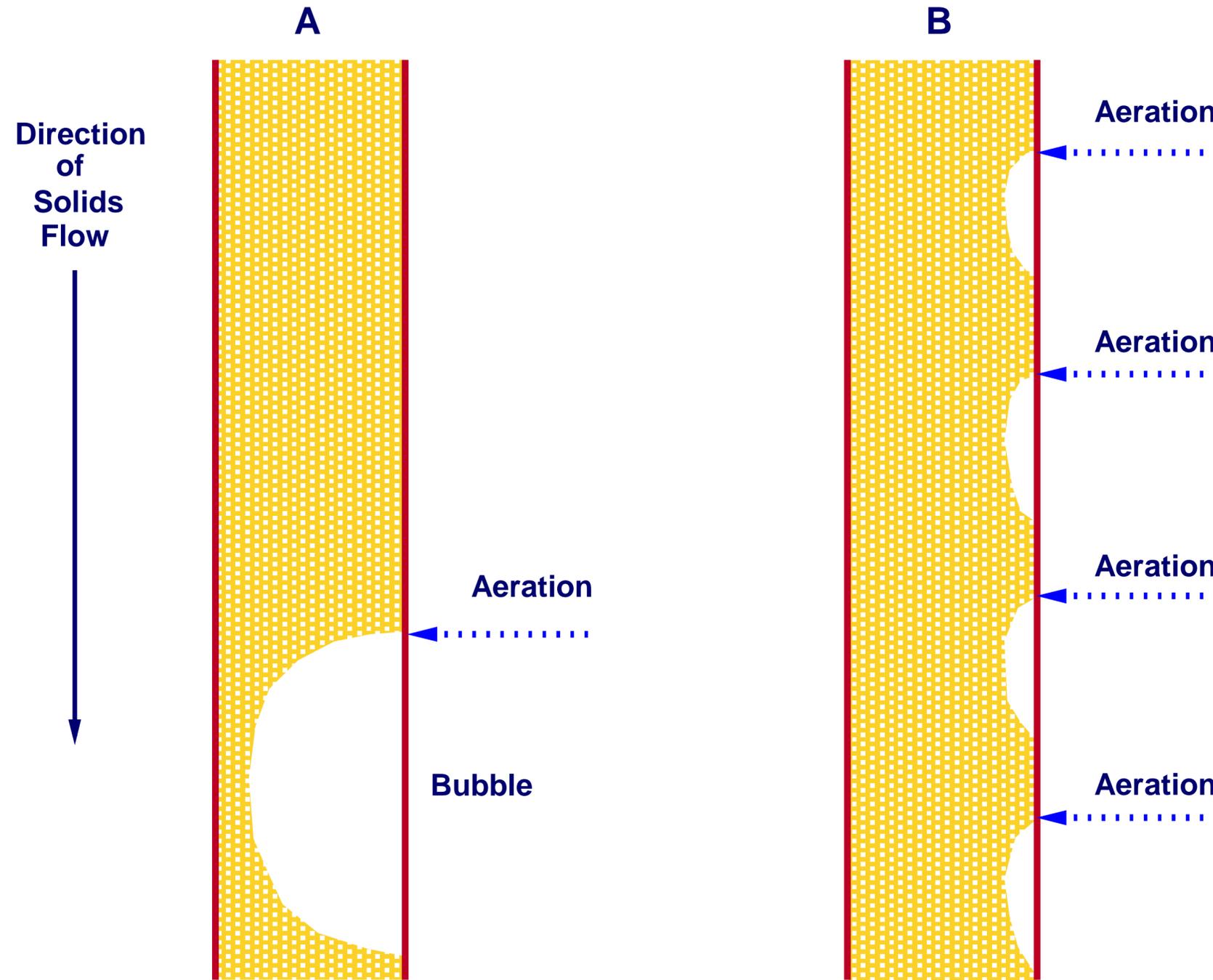
Reactor

18

23.2

Regen

G

25.8

ΔP_{sp} = -0.8 psi

$\Delta P/L$ = -5.8 lb/ft^3

20 ft

25

21.2

Another Standpipe Function

All Pressures in psig

A

Reactor — 18

Regen — 23.2

25.8

G ↑

20 ft

25

21.2

$\Delta P_{sp} = -0.8$ psi

$\Delta P/L = -5.8$ lb/ft^3

B

Reactor — 18

Regen — 22.2

24.8

G ↑

20 ft

27

23.2

$\Delta P_{sp} = 2.2$ psi

$\Delta P/L = 15.8$ lb/ft^3

C

Reactor — 18

Regen — 20.6

23.2

G ↑

20 ft

28

24.2

$\Delta P_{sp} = 4.8$ psi

$\Delta P/L = 34.6$ lb/ft^3

I - 7

Practical Aspect of Standpipe Permeability for Group A Solids

Standpipe Aeration

Another Practical Aspect of Real-World Permeability Effects

Gas Bypassing
(In Group A Powders)

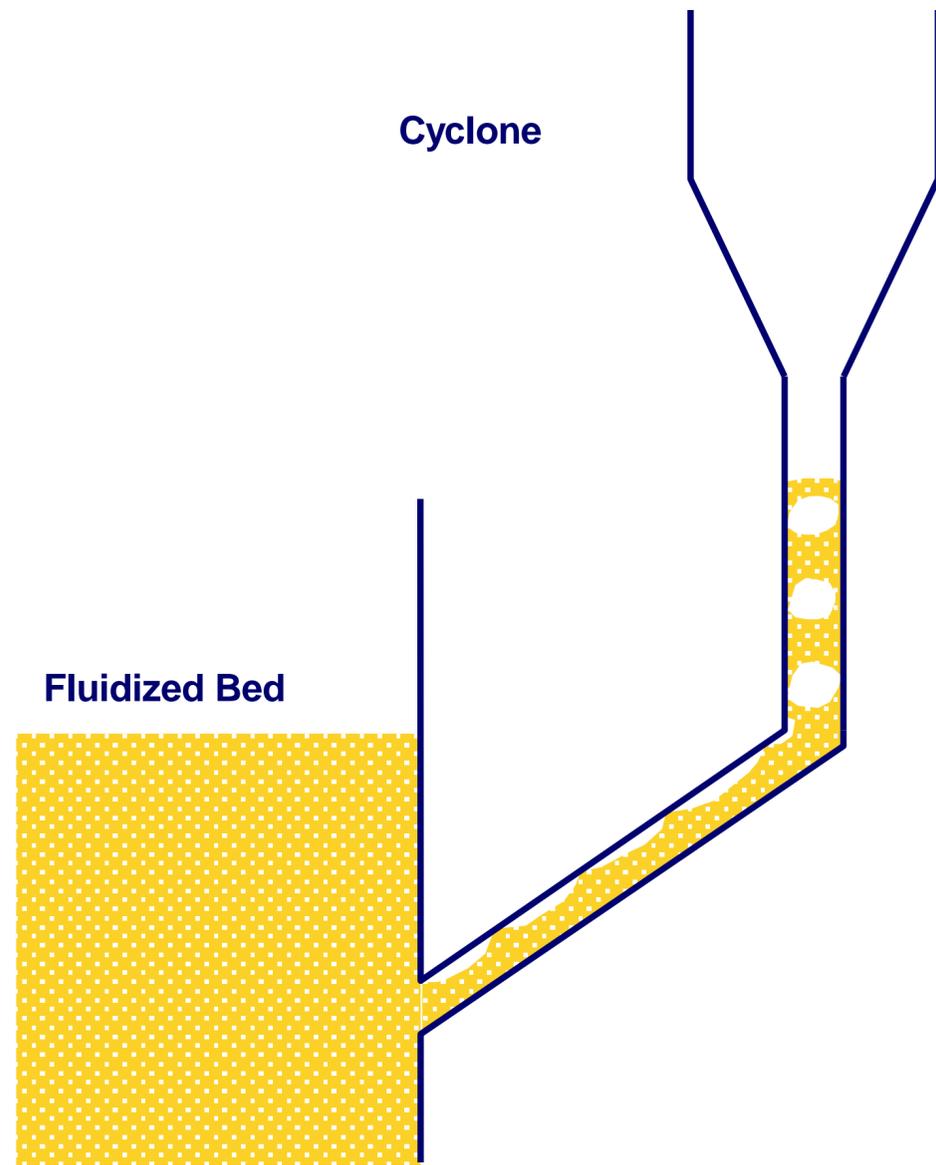**Easier for Gas to Bypass Than to Permeate the Defluidized Solids**

Gas In
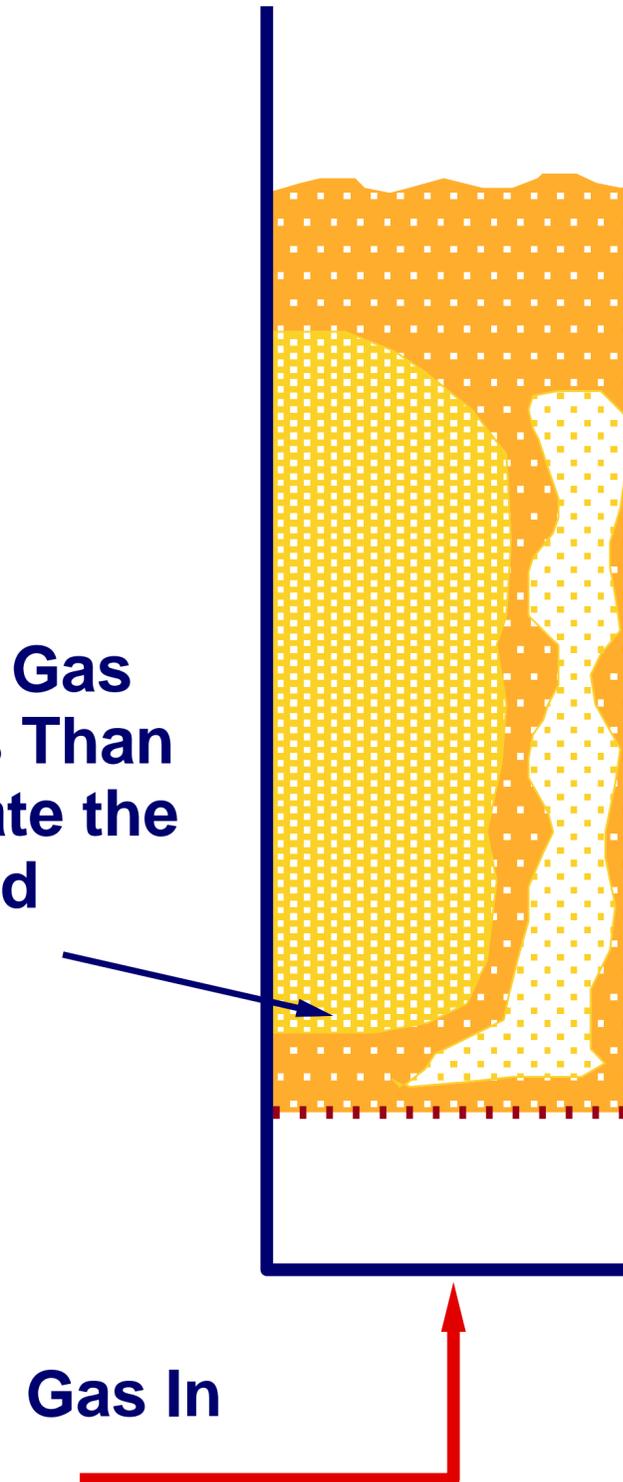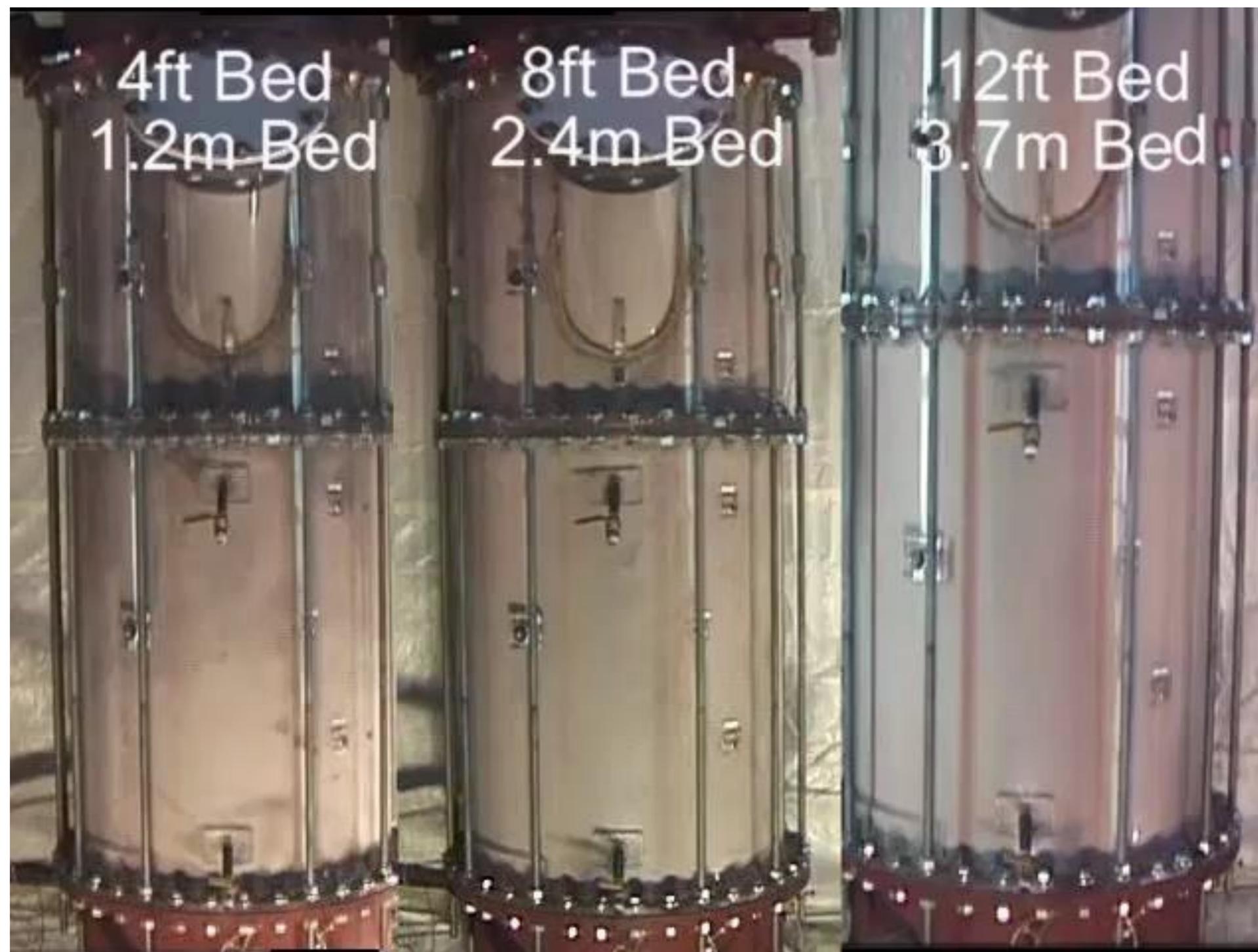
Gas Bypassing: U = 0.46 m/s; D_{bed} = 0.9 m; FCC Catalyst
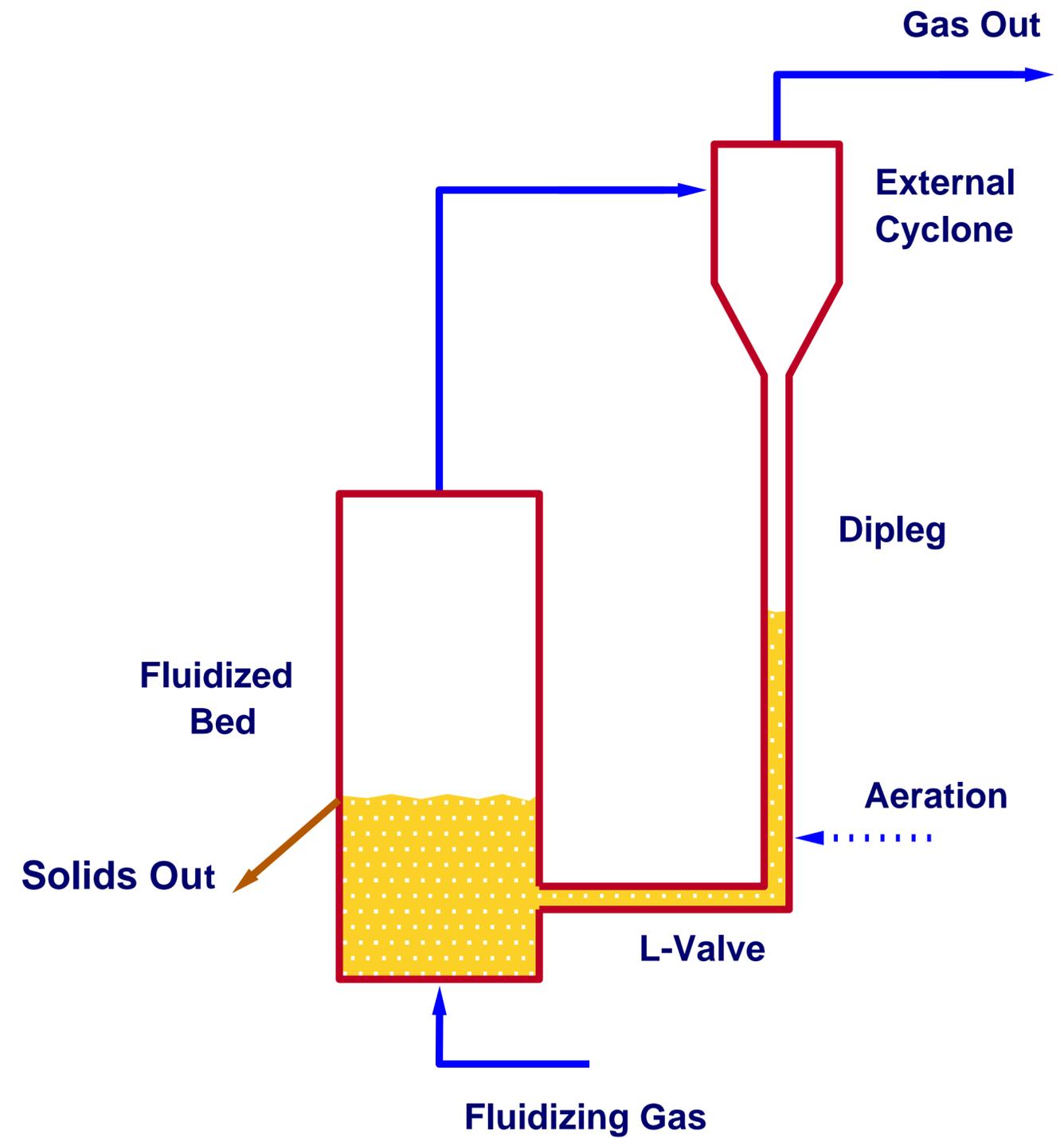
Feed and Discharge Systems

- **In General, Feeding into Fluid-Particle Systems Can be Designed Using a Variety of Methods: 1) Standpipes, 2) Screw Conveyors and Rotary Valves, 3) Pneumatic Conveying, 4) Nonmechanical Valves and 5) Hoppers, etc.**

- **Discharging from Beds Can be Done Using 1) Water-Cooled Screws, 2) Rotary Valves, Standpipes, Nonmechanical Valves and Pneumatic Conveying, etc. Progress in This Area Has Been Slow.**

- **We Now Know That Returning Solids to a Fluidized Bed from a Primary Cyclone Dipleg is More Reliable Using an Automatic L-valve or a Loop Seal Than Using an Angled Pipe**

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Slugging in a Hybrid Fluidized Overflow Standpipe

Cyclone

Fluidized Bed

Angled Dipleg

Gas Out

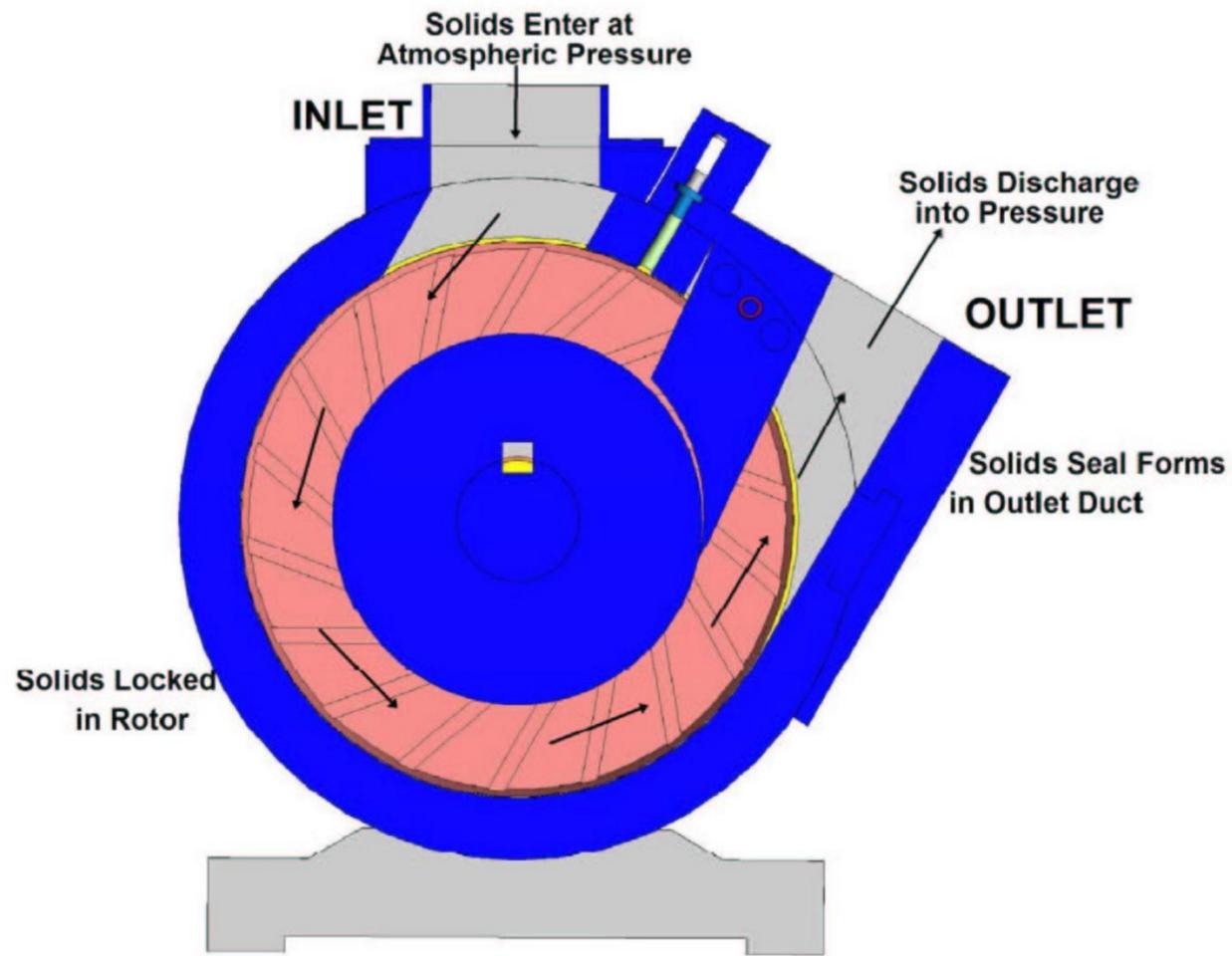External Cyclone

Dipleg

Fluidized Bed
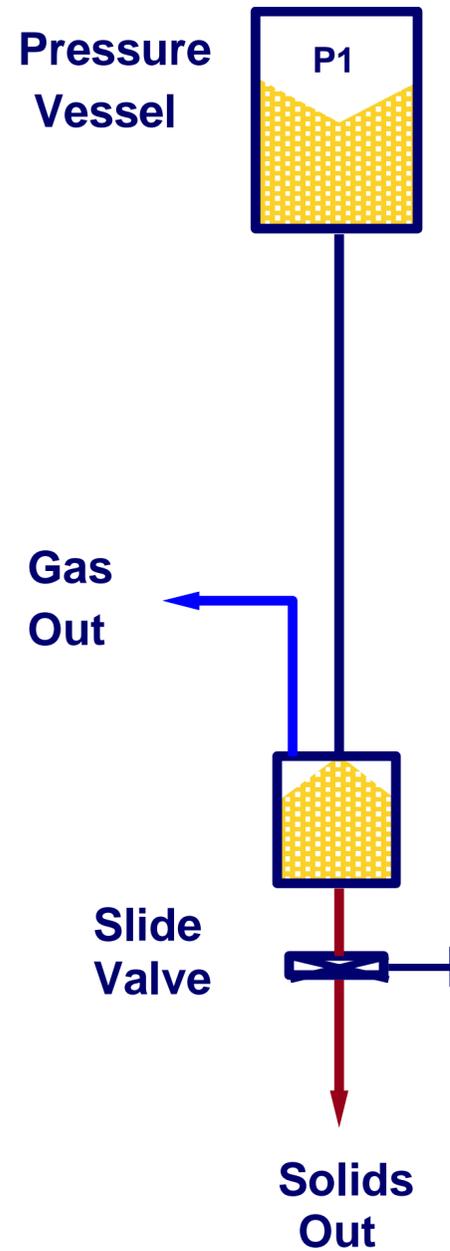
Aeration

Solids Out

L-Valve

Fluidizing Gas

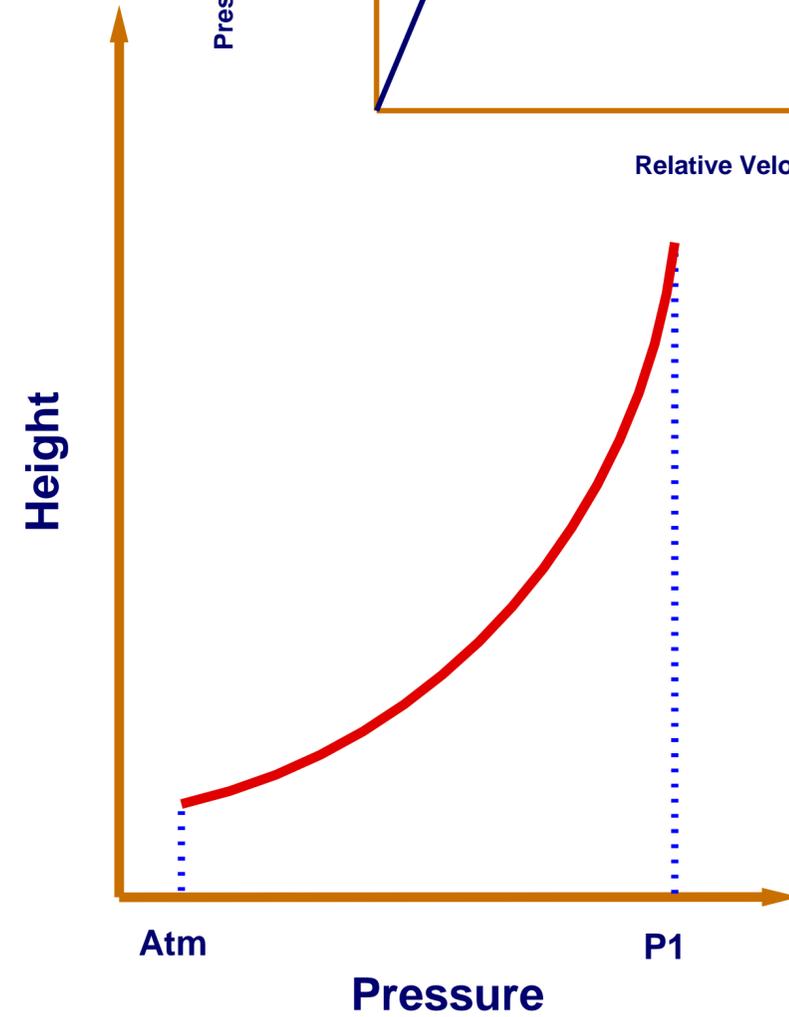**Automatic L-Valve**
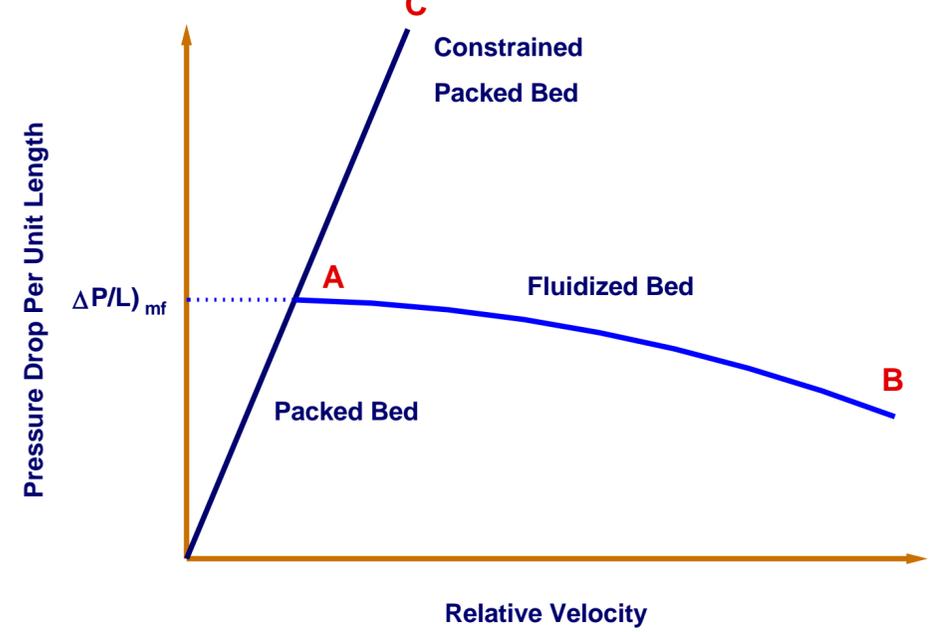
Feed and Discharge Systems

- **Feeding Into High-Pressure Environments Can be Done Using Lock Hoppers, Tapered Screws, Pumping Solids in Slurries or With a Dry Solids Pump (STAMET).**

- **Discharging Solids from High-Pressure Systems can be Done Using Lock Hoppers or a Restrictive Pipe Discharge System (RPDS).**

- **In General, Feeding and Discharge Systems are in a Satisfactory State of Development, with Several Options Available for Feeding Solids from Group A Through Group D and Even Group C.**
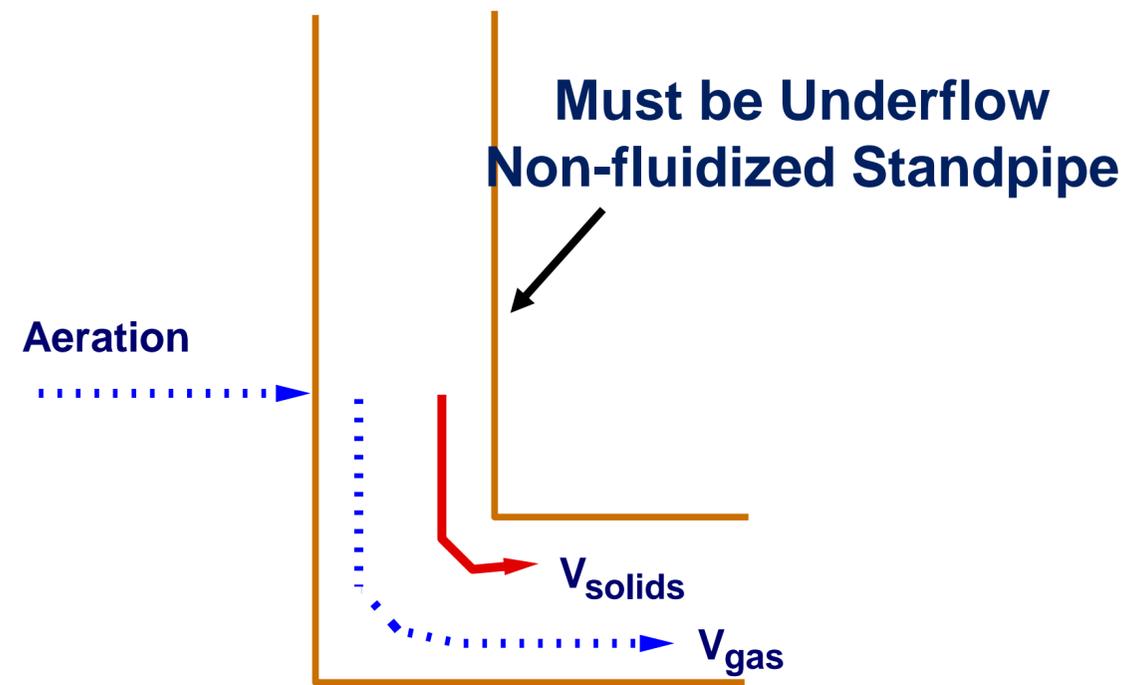
STAMET Dry Solids
Posimetric Feeder

Pressure Vessel — P1

Gas Out

Slide Valve

Solids Out

Restricted Pipe Discharge
System (RPDS)

Pressure Drop Per Unit Length

C
Constrained
Packed Bed

$\Delta P/L)_{mf}$

A

Fluidized Bed

Packed Bed

B

Relative Velocity

Height

Atm

P1

Pressure

Nonmechanical Solids Flow Devices
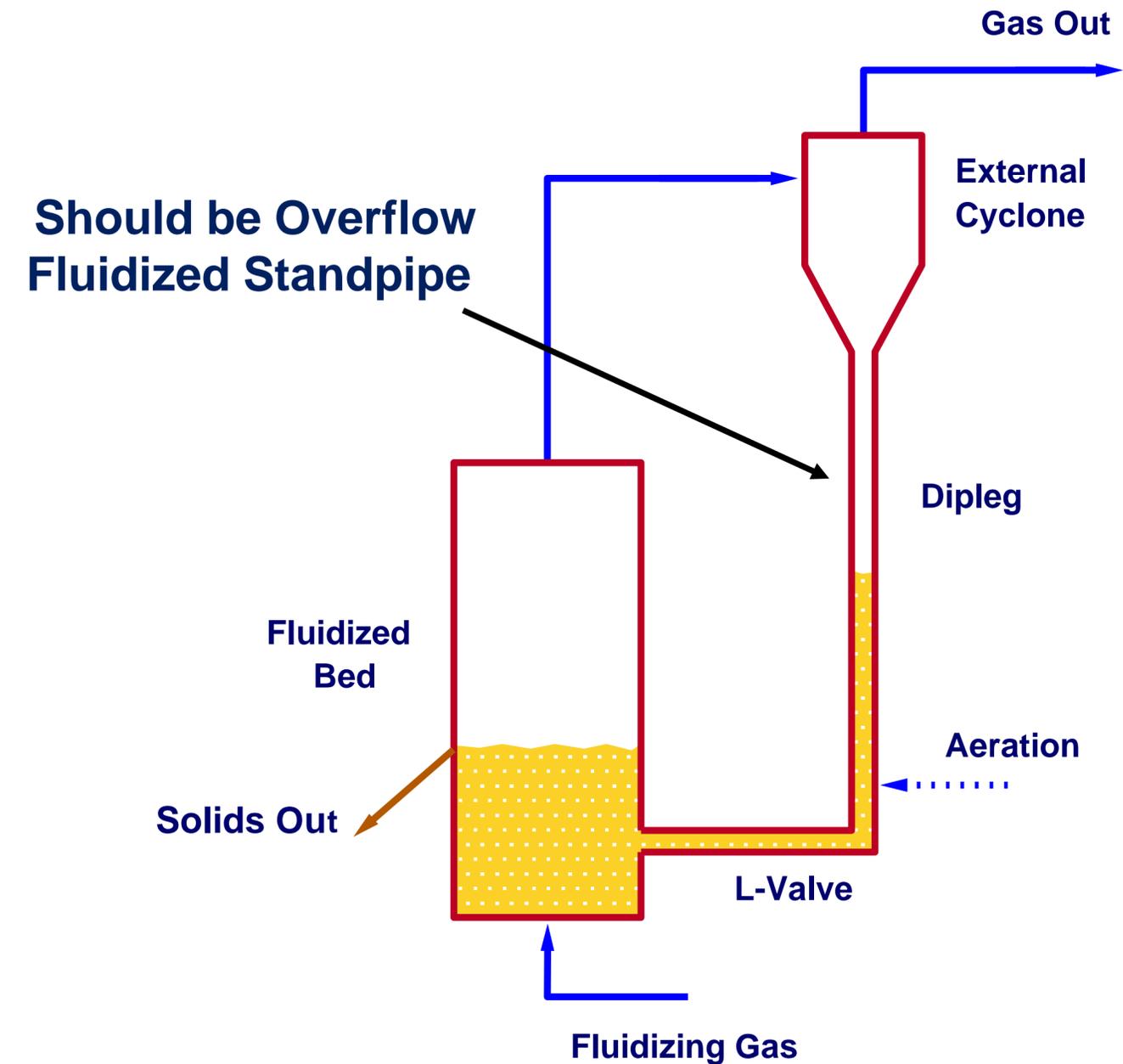## *(Great for High-Temperature Operation)*

- **Nonmechanical Solids Flow Control Devices can be Used to Feed and/or Control Solids in Groups B and D.**

- **Nonmechanical Non-Control Devices (Automatic L-valve, Loop Seal) can be Used to Return Solids From a Cyclone Back into a System (Geldart Groups A, B and D – and cohesive Geldart Group C Solids if They can be made to flow through pipes via pulsing, etc.) A Minor Problem is That Many People in Industry do not Know About and/or Understand the Design and Operation of These Devices.**

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Must be Underflow Non-fluidized Standpipe

Aeration

V_{solids}

V_{gas}

- **Solids Flow Through Nonmechanical Valves Because Gas Drags the Solids Around A Constricting Bend**

Nonmechanical L-Valve Used for Solids Flow Control

Should be Overflow Fluidized Standpipe

Gas Out

External Cyclone

Dipleg

Aeration

L-Valve

Fluidized Bed

Solids Out

Fluidizing Gas

Automatic L-Valve – Non-Control Nonmechanical Device

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Nonfluidized Systems

- **CFD is better being applied to dilute-phase systems, risers, etc. It does not do as good a job predicting the hydrodynamics of very dense-phase systems (especially non-fluidized systems) with wall effects, etc. as I understand it.**

- **It would be great to have a tool to model and troubleshoot these systems (hoppers, entrances to standpipes, flow across slide valves, flow in non-mechanical valves) as they are important in designing commercial systems.**
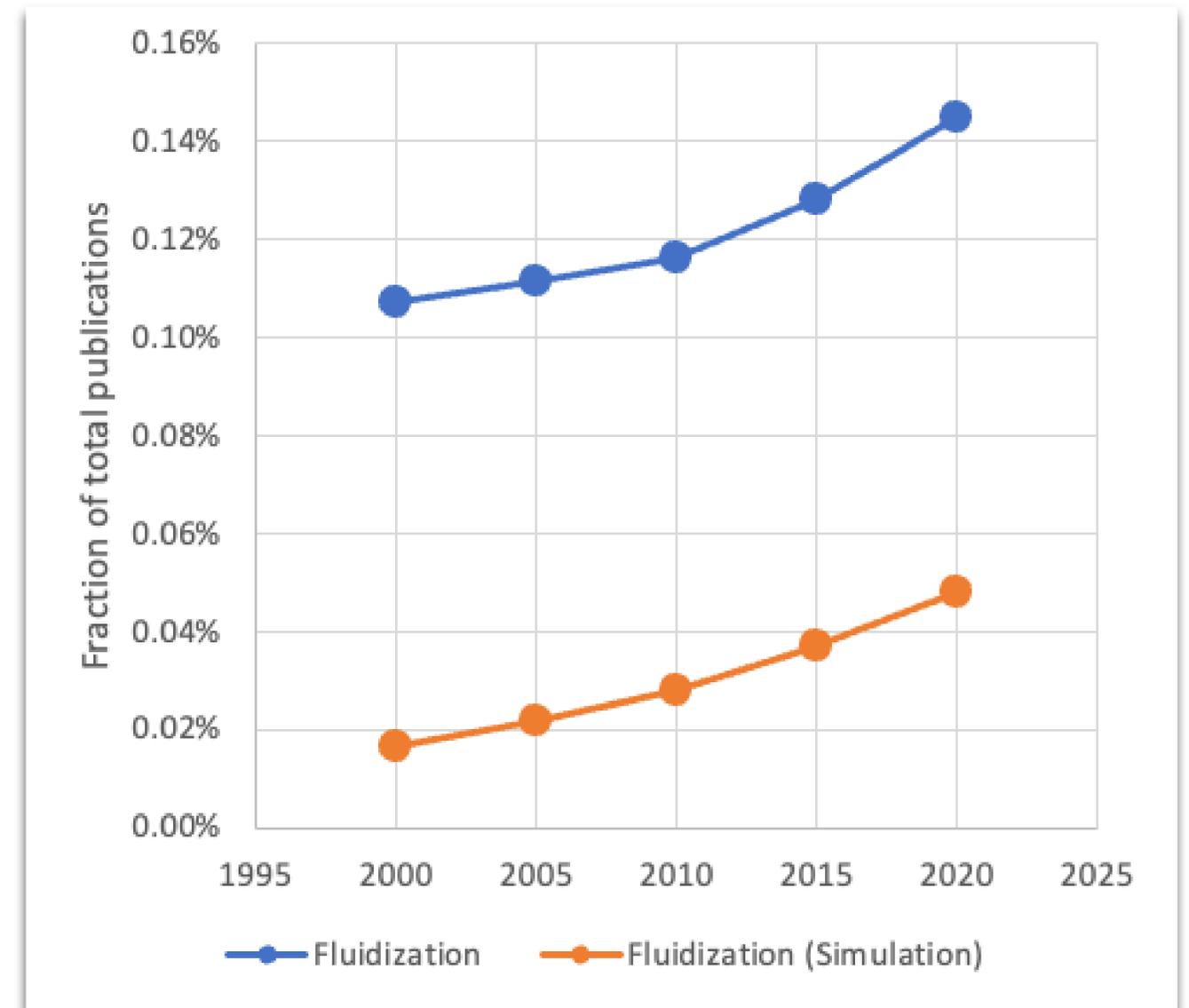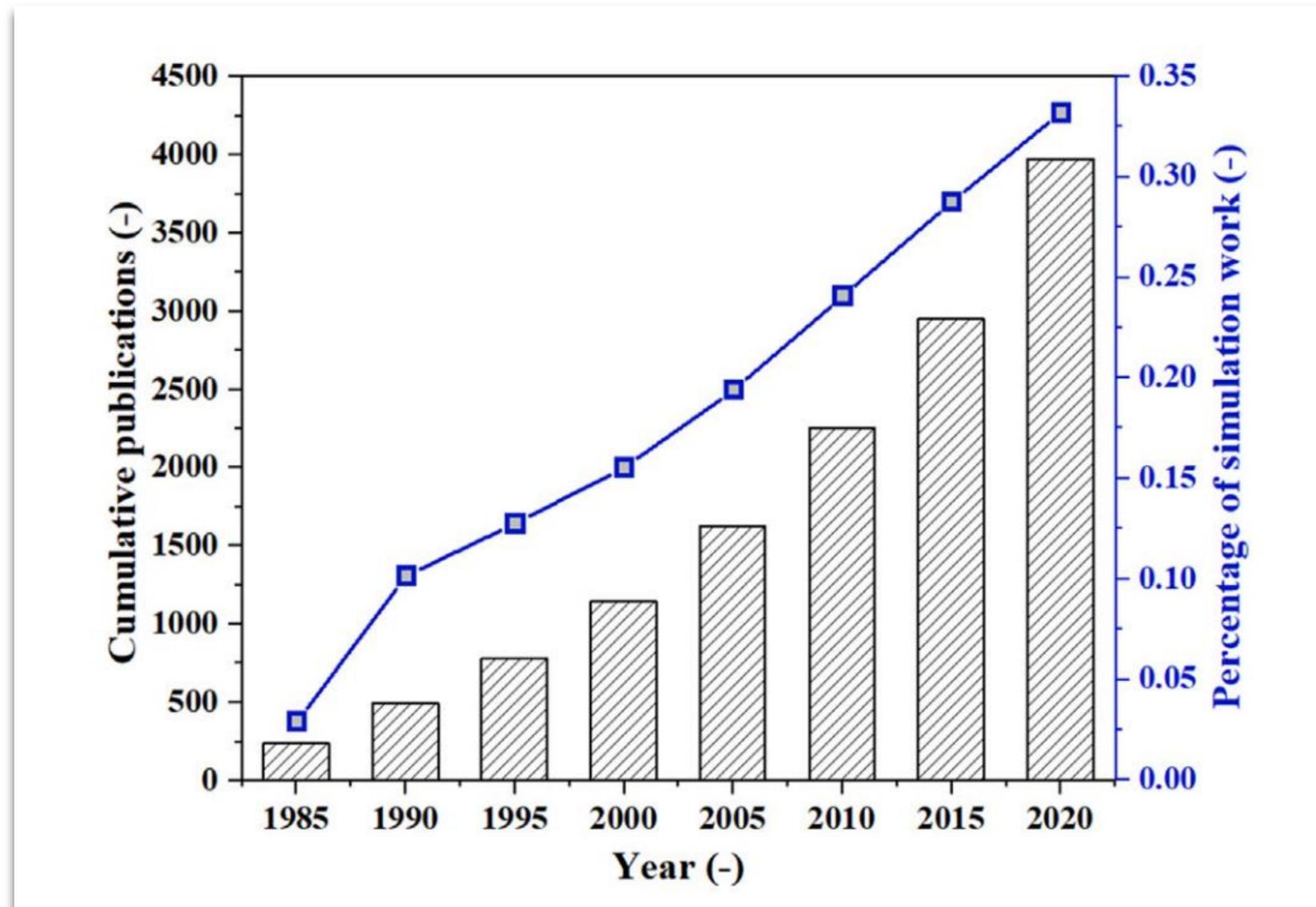
Cohesive Particles

- Some Things can be Done to Make These Solids Fluidize/Flow. A High-Shear Gas Distributor and/or Microjets (100 to 150 microns in diameter) can be Used to Fluidize Most of These Materials. Pulsing Gas Into a Standpipe can be Used to Cause Cohesive Solids to Flow in Standpipes and Diplegs. In Addition, ppm Quantities of fumed silica (average size 0.1 microns) can be Added to These Particles to Make Them Fluidize/Flow. However, the fumed silica may not be able to be used because the fumed silica in the Final Solids Produced May not be Tolerated by the End User.

- This is an Area Which Needs Much More Practical Study/Research Into Interparticle Forces and How to Neutralize/Overcome Them. The work should be done to develop techniques that can be used in commercial-sized units.

- In Addition, More Work Needs to be Done on Low-Permeability Group A Materials as Well (What is also lacking is studies at temperature).

Applying the Fundamentals

Three Questions/Recommendations

1) State-of-the-Art of Solids Flow (described above)
2) How can Qualitative Predictions Evolve Towards a Quantitative Understanding That will Allow System Designs on an Industrial Scale? (Can Scale Up and Design Units Now, but it would help to have a Relatively simple modeling tool for non-gas-supported flows for hopper flow, entrances to standpipes, flows across slide valves and Nonmechanical valves, etc.)
3) Areas that IFPRI and Other Funding Agencies can/should Promote
i)   Develop *practical* models that have stress terms that can be applied to non-gas-supported flows
ii) Direct more attention to the practical operability aspects of low-permeability materials in gas/solid flows (especially for Group A and Group C particles)
iii) Develop Simpler Models – Most Engineers Use Excel not CFD or DEM
iv) Look at the effect of temperature on solids flow (voidage/expansion, etc.)

Comments on research activity

Wang, Shuai, et. al. "Multi-Scale Numerical Simulation of Fluidized Beds: Model Applicability Assessment." *Particuology* 80 (September 1, 2023): 11–41.
National Science Board. "Publications Output: U.S. Trends and International Comparisons," December 17, 2019.

Gas-Solid Simulation

Gas ⟵⟶ **Gas**

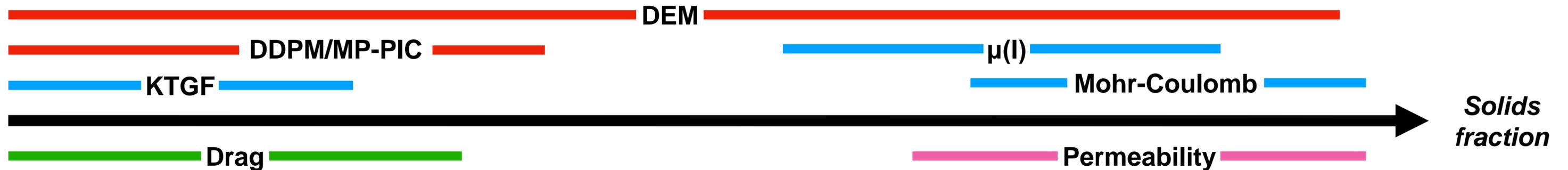**Gas** ⟵⟶ **Solid**

Solid ⟵⟶ **Solid**

Navier Stokes

Drag

Discrete

LBM

Permeability

Continuum

Well studied

Clustering

Closures
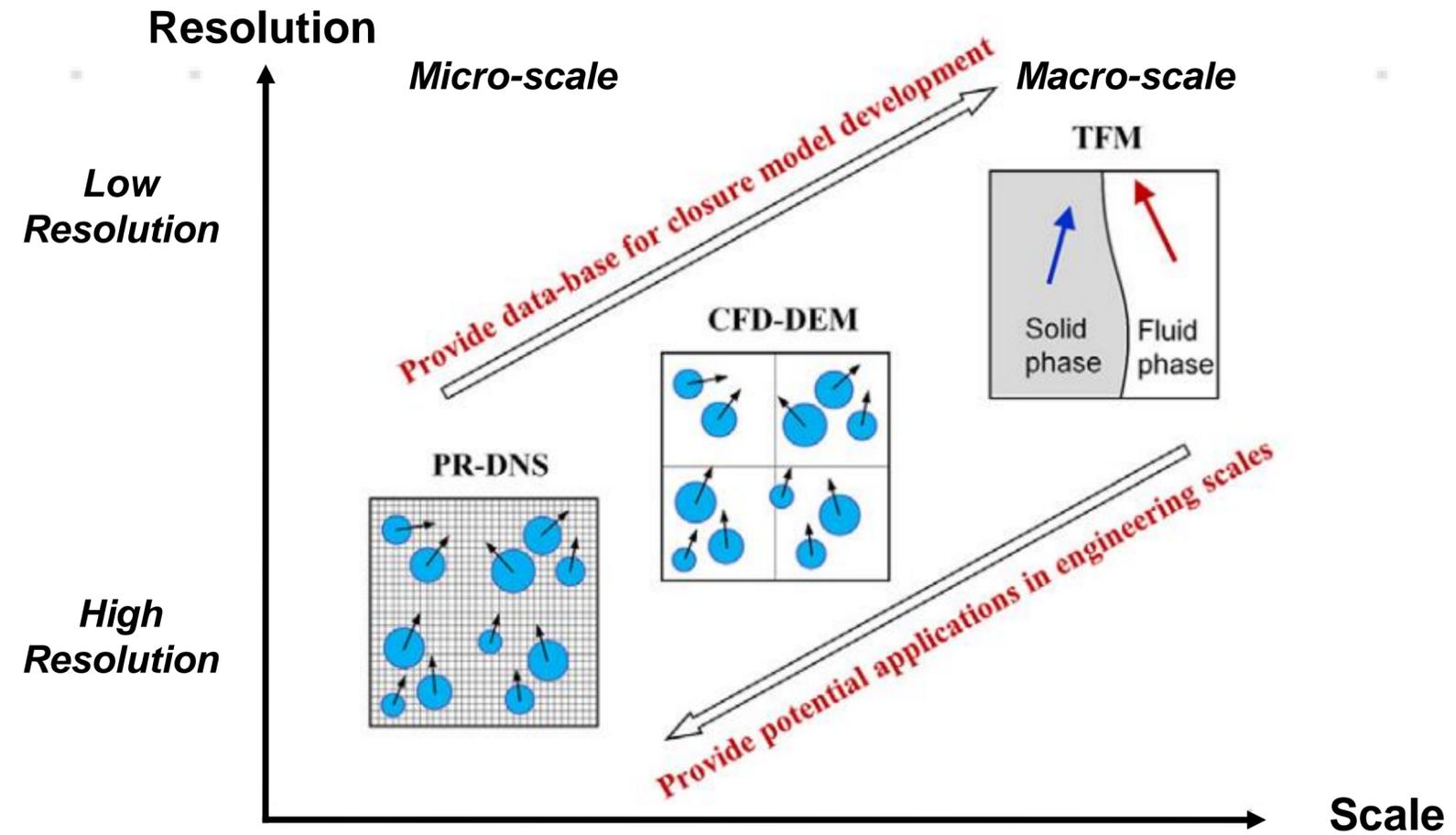
DEM

DDPM/MP-PIC

μ(I)

KTGF

Mohr-Coulomb

Solids fraction

Drag

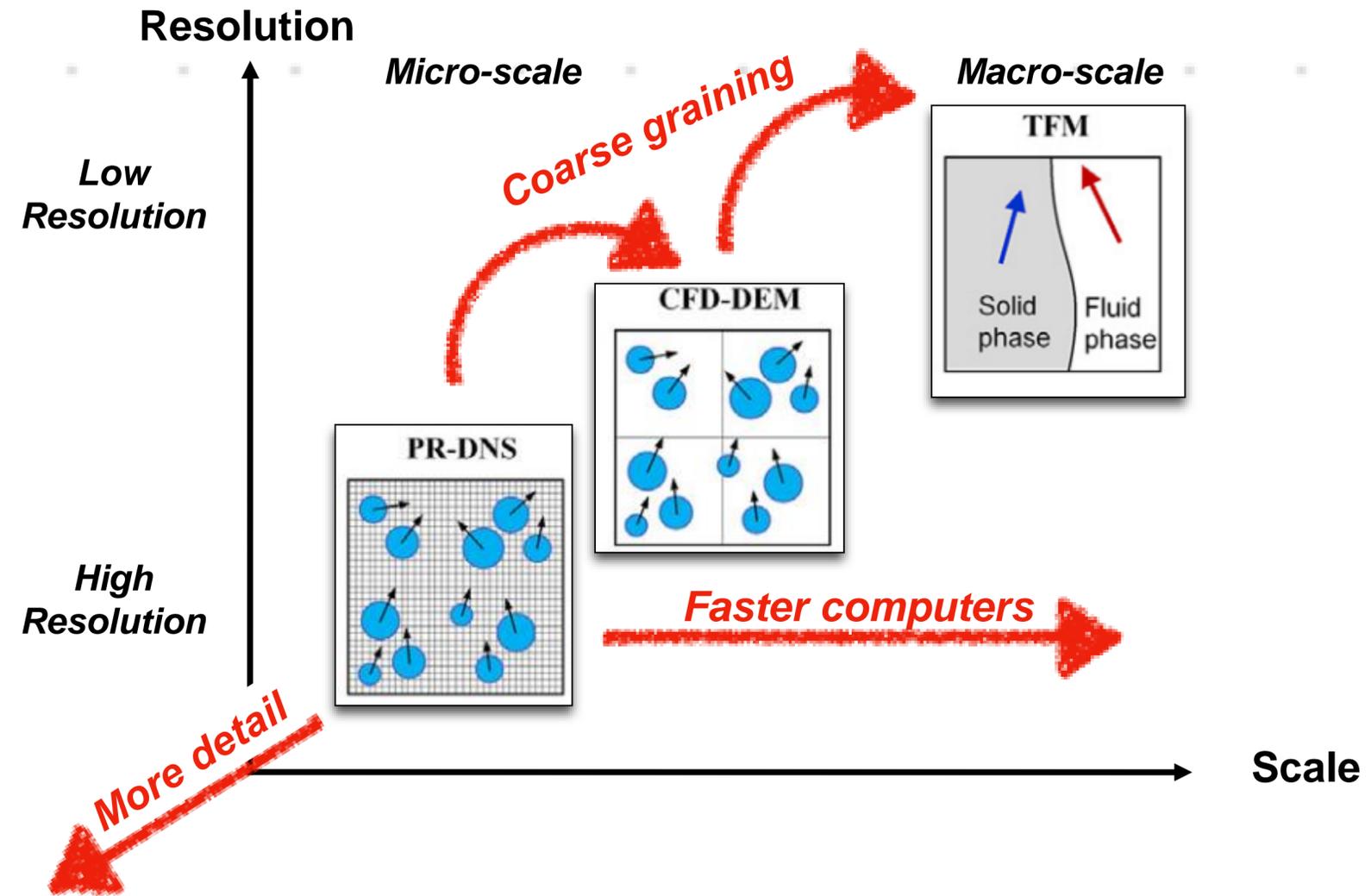Permeability

Resolution and Scale
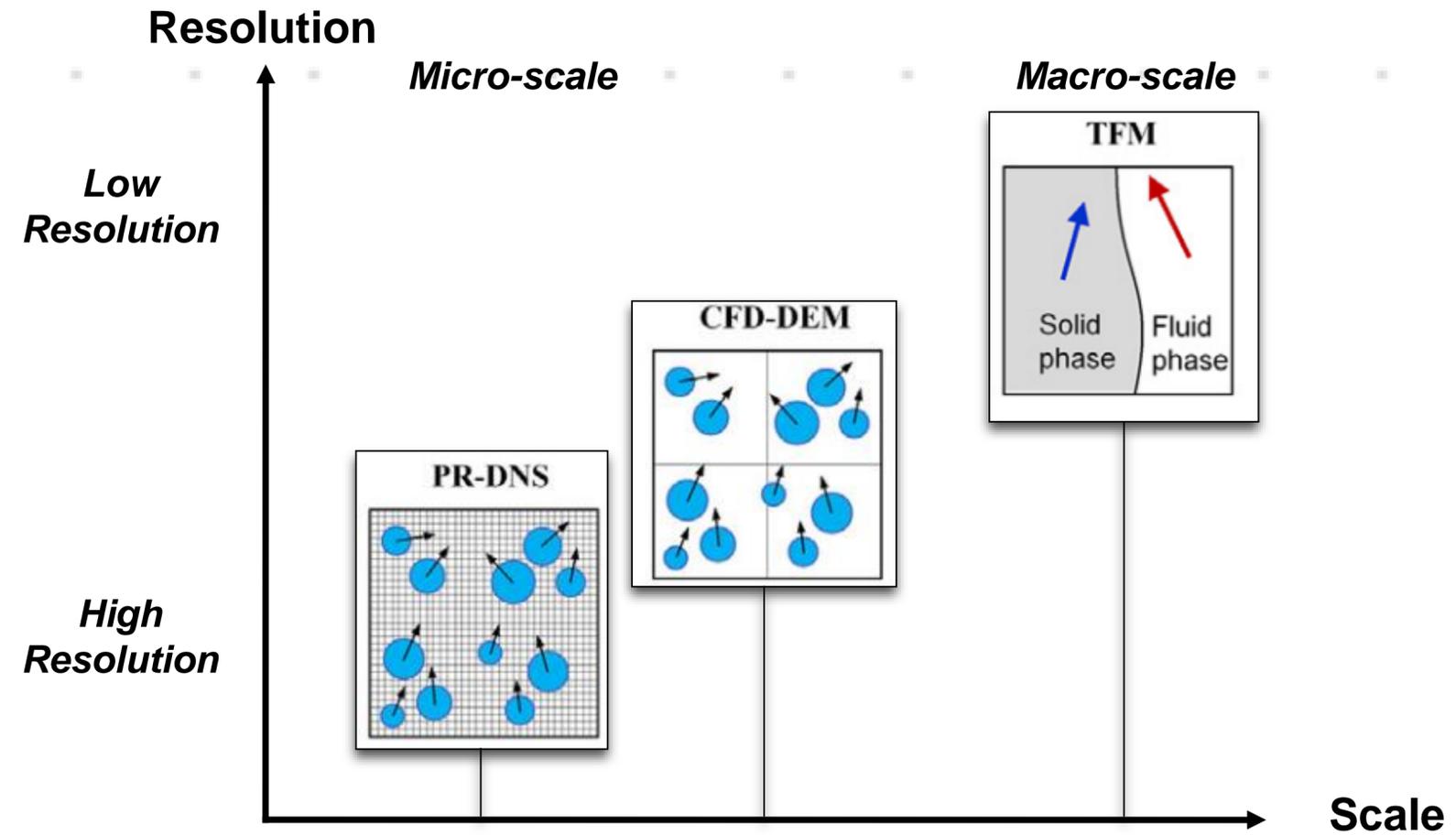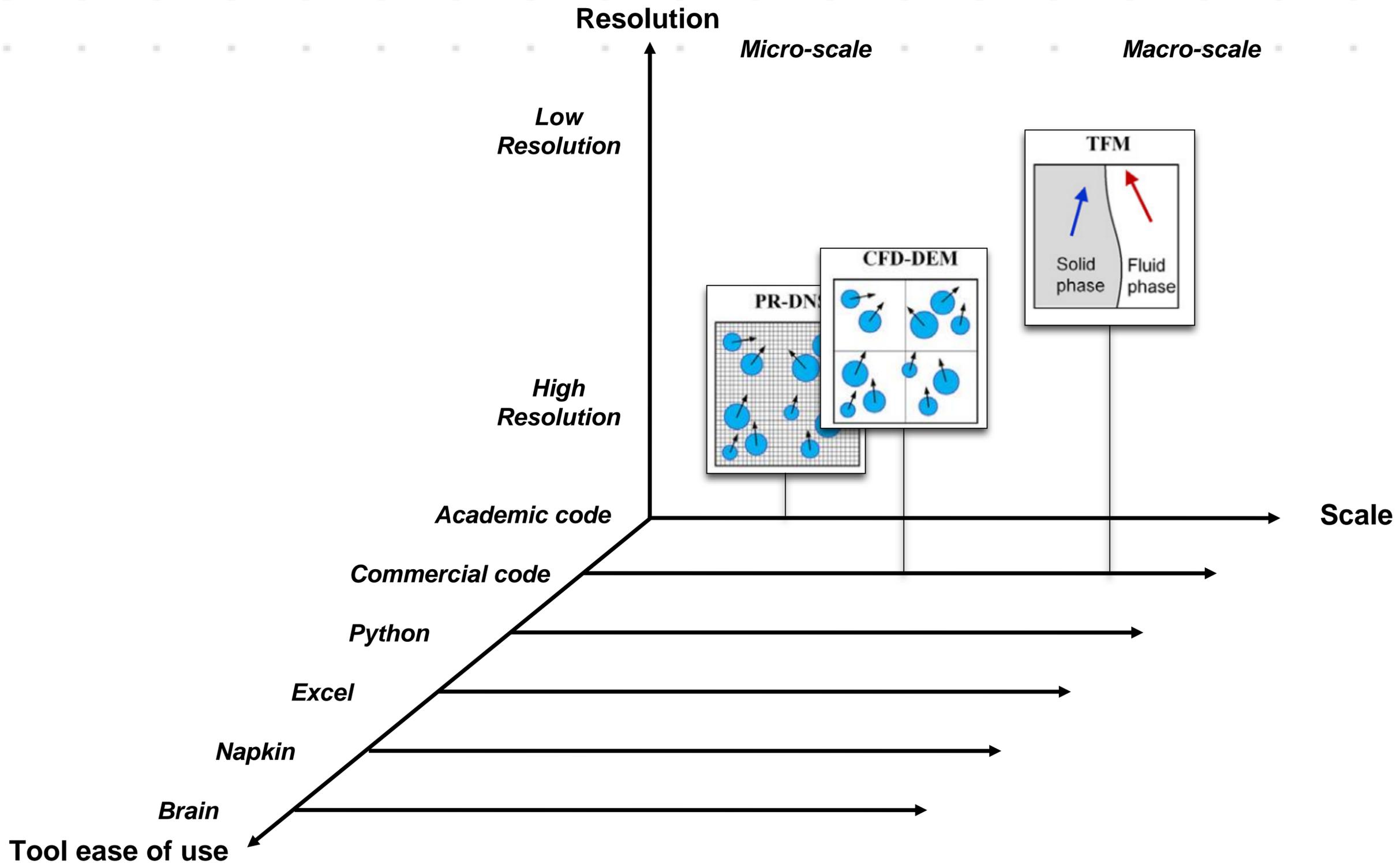

Wang, et al. (2023)

Resolution and Scale

Resolution and Scale

Resolution and Scale

Resolution and Scale

Resolution

Micro-scale   *Macro-scale*

Low Resolution

High Resolution

Academic code

Commercial code

Python

Excel

Napkin

Brain

Tool ease of use

Scale

PR-DNS   CFD-DEM   TFM

Solid phase   Fluid phase
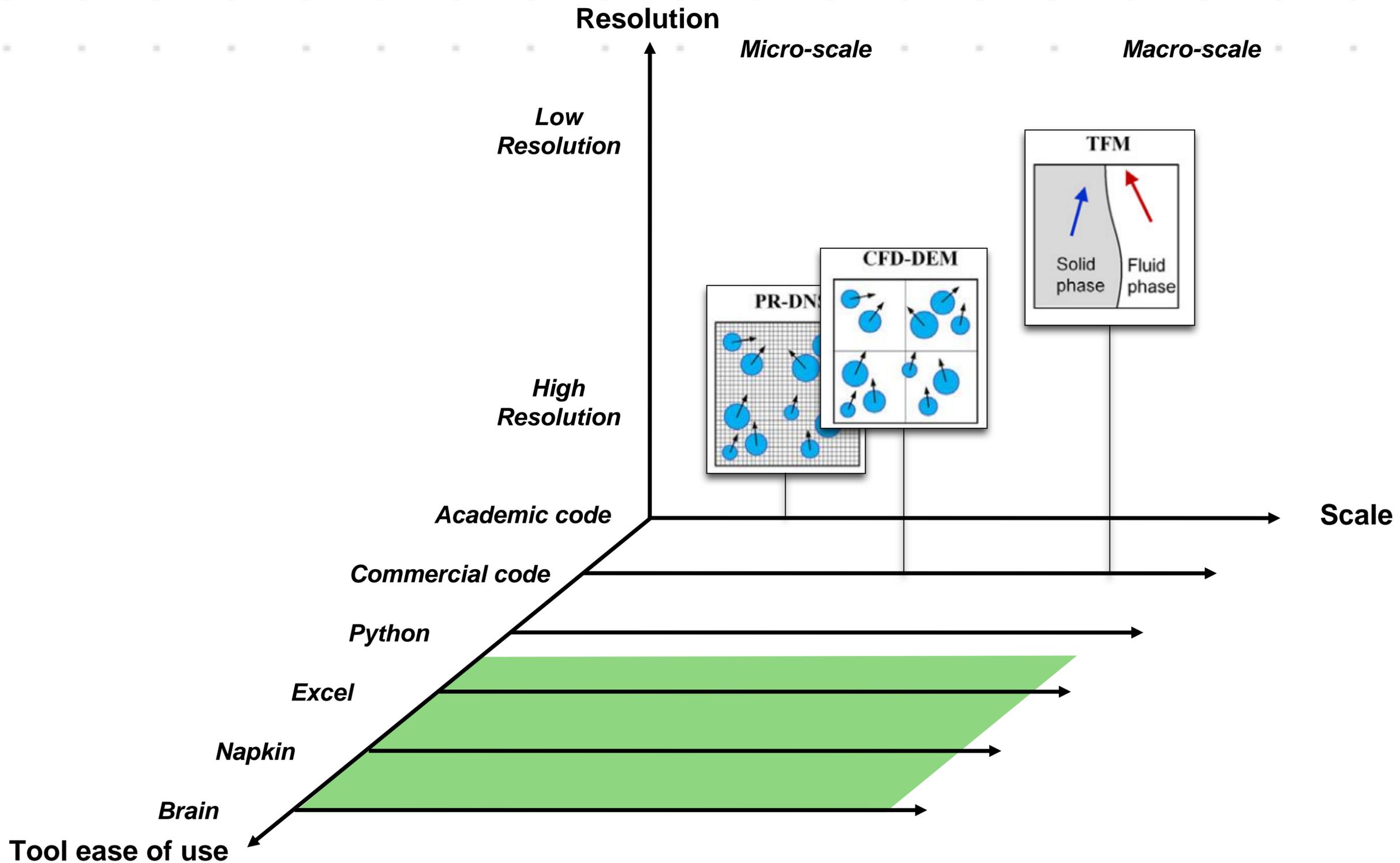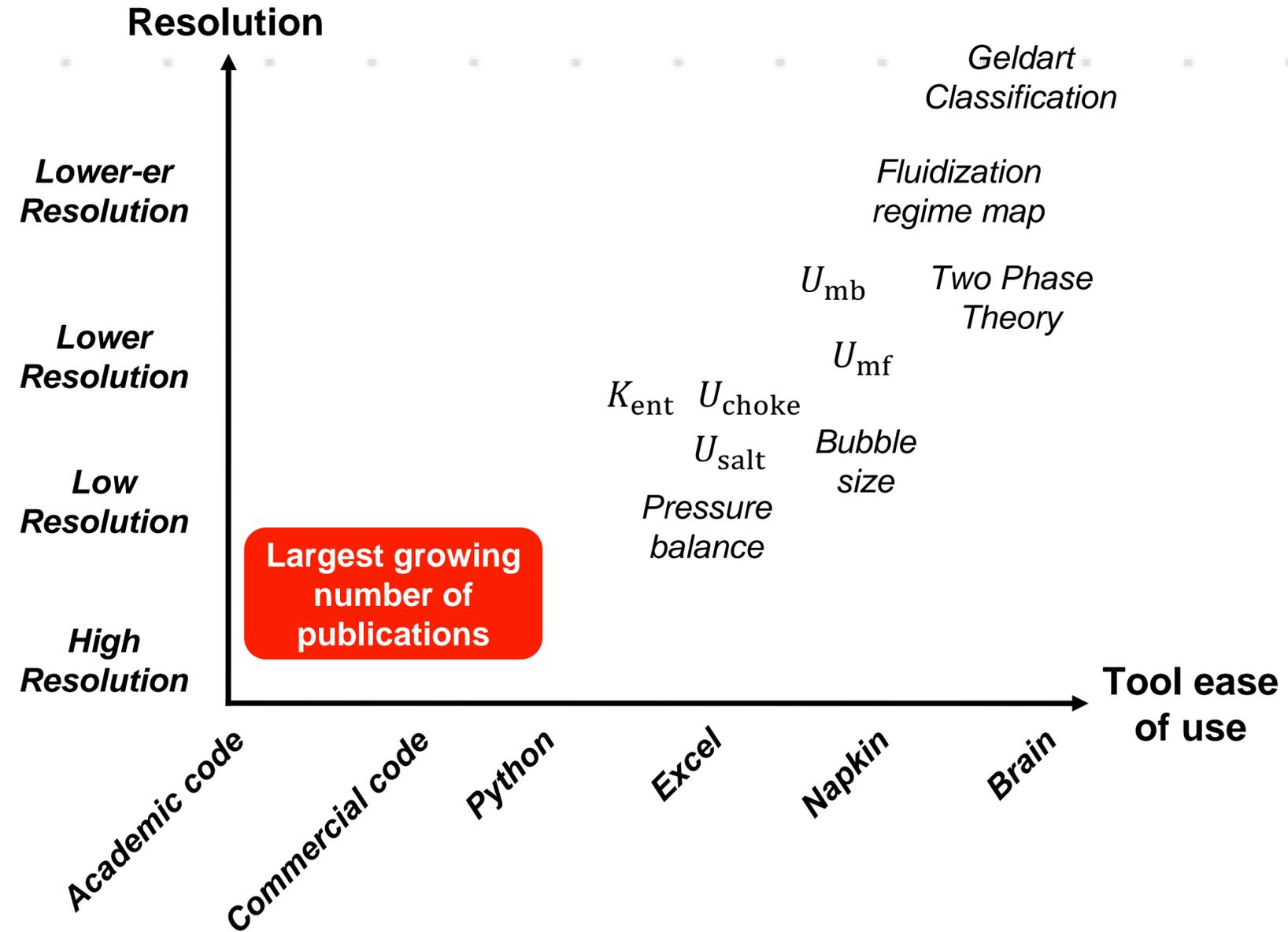
Resolution and Scale
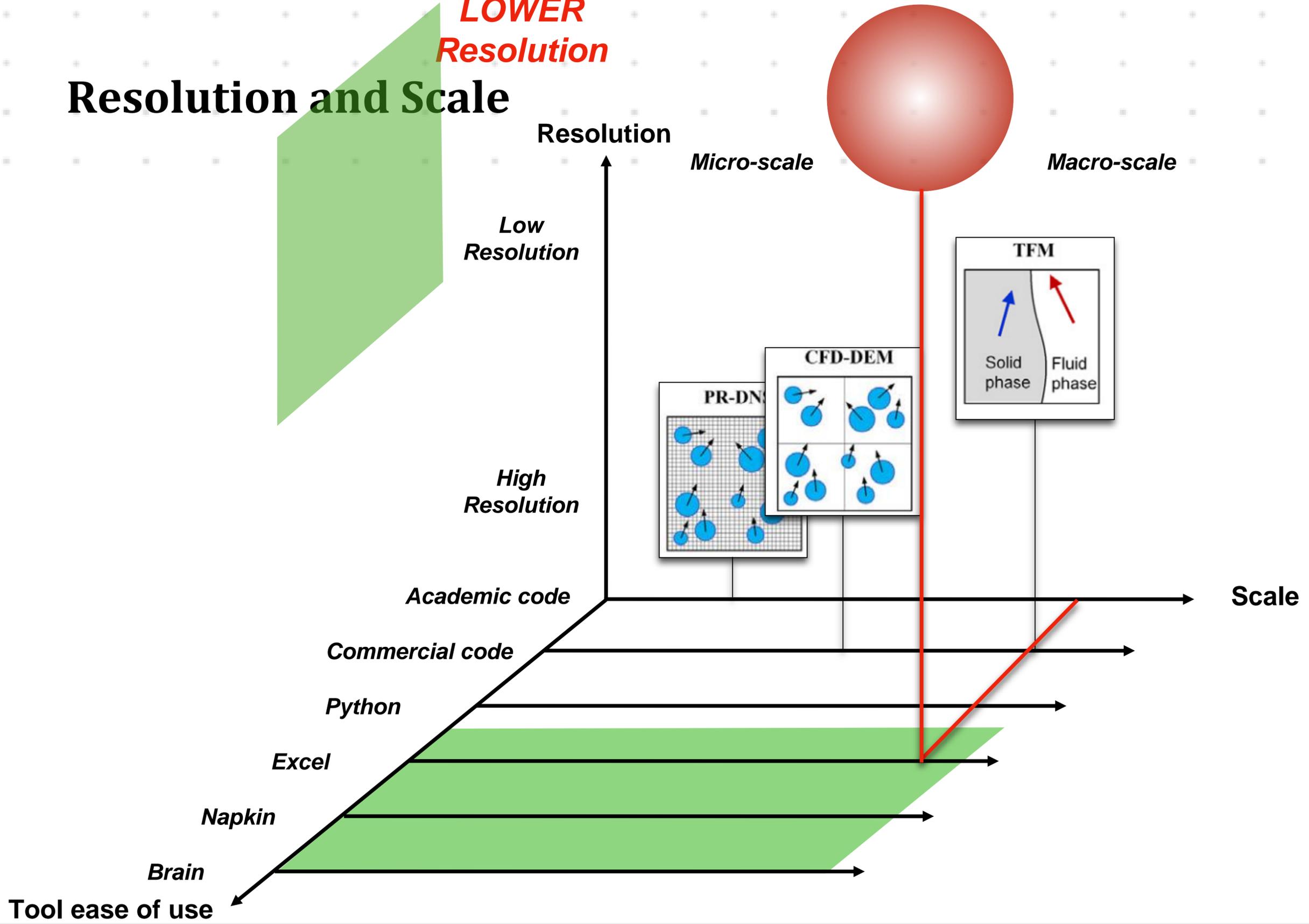
Resolution and Ease of Use

Comments

Challenges with existing tools

- Drag controlled
  - *Clustering, instabilities*
  - *Coarse graining, filtering*

- Intermediate
  - *Always hard*
  - *Especially for cohesive*

- Collision/contact controlled
  - *Continuum models lacking*
  - *Cohesive effects remain a challenge*
  - *De-fluidized transition is an important problem*

Future directions

- Over emphasis on simulation tools
- Dearth of reduced order models
  - *Regime maps*
  - *Lumped parameter models*
  - *1D models*

Out on a limb (for intermediate)

- The discrete is a red herring
  - *We tend to think discrete to continuum*
  - *What about continuum to discrete*
  - *Particle props to continuum props is too hard*
- Continuum is more fleshed out than we claim