DENSE GAS-PARTICLE FLOWS WITH WET PARTICLE-PARTICLE INTERACTION

CURRENT STATUS AND FUTURE CHALLENGES

IFPRI WORKSHOP
PARTICLE PROCESSING - MODELING OF POWDER FLOW
JUNE 9-10, 2023, LAFAYETTE, IN USA

J.A.M. KUIPERS

GROUP MULTIPHASE REACTORS
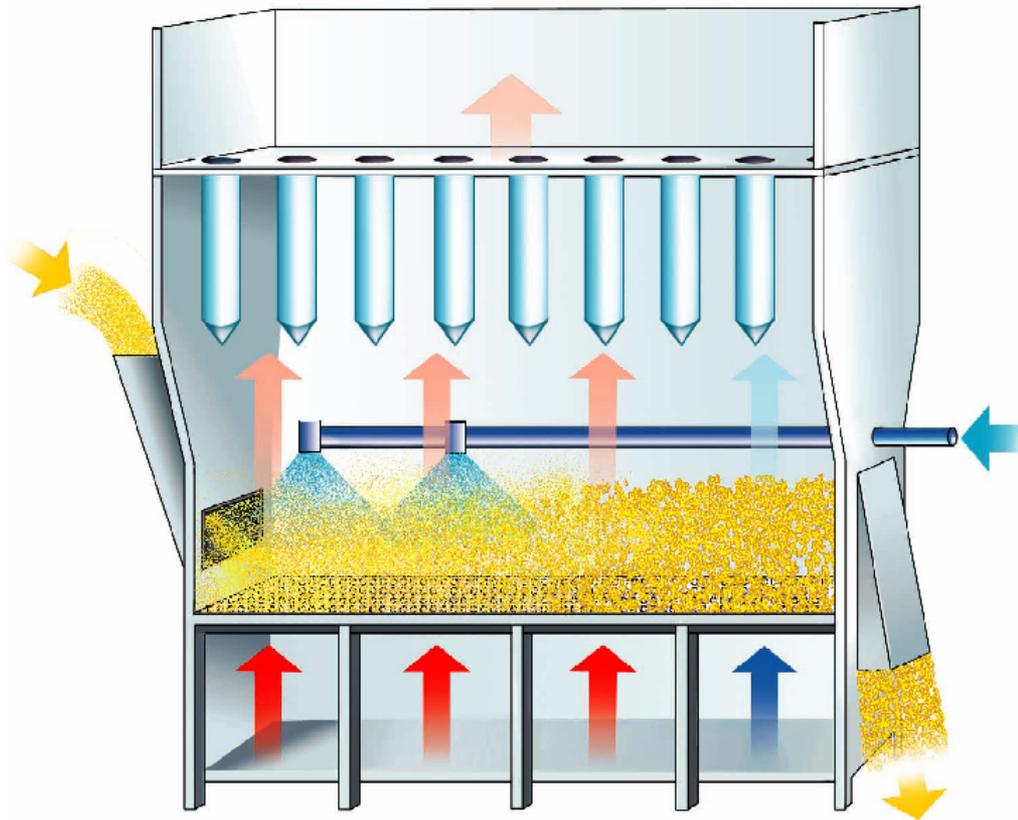
EINDHOVEN UNIVERSITY OF TECHNOLOGY

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Technische Universiteit
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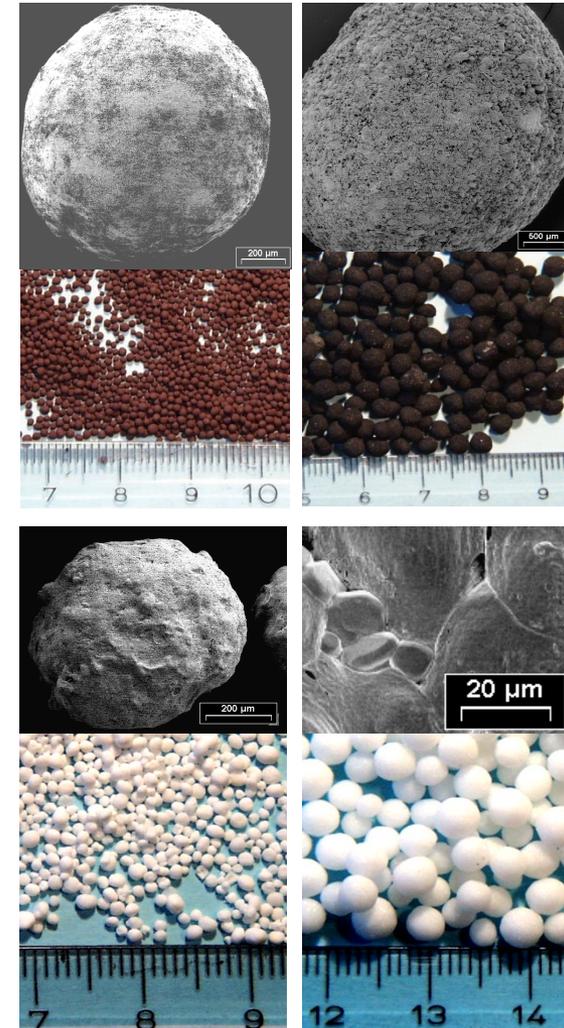**Where innovation starts**

Prof. Stefan Heinrich (TUHH)

TU/e Technische Universiteit Eindhoven University of Technology

DNS DEM TFM

larger geometry, lower detail
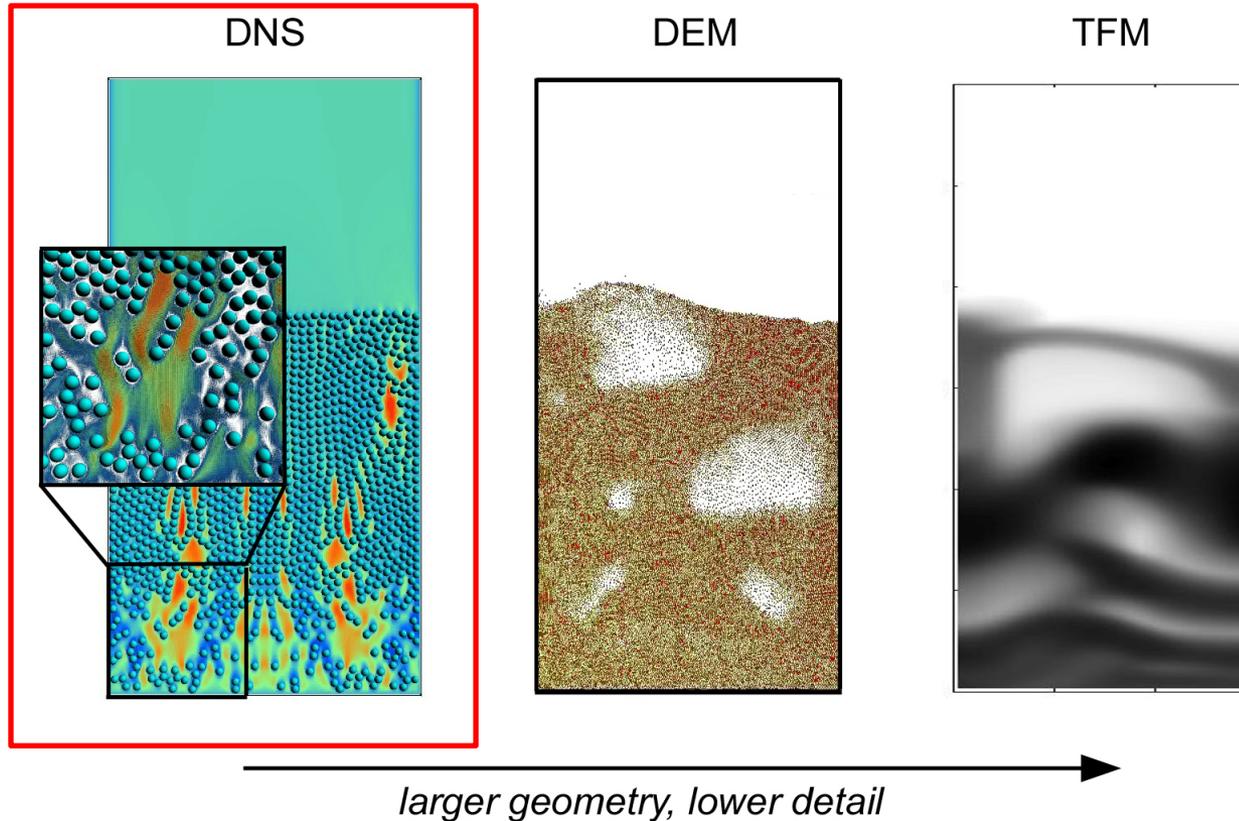
mass, momentum and heat transport in polydisperse particulate systems

droplet-droplet interaction + droplet-particle interaction

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IB-VOF-DP (DNS) MODEL

- FEATURES

  + Eulerian grid + implicit boundary condition treatment at IB
 + VOF module for free surface tracking and wetting behavior

- ADVANTAGES

  + details of continuous phase flow field and interface dynamics captured
  + arbitrary shape of solid particles can be accounted for

- DISADVANTAGES

  + IB-VOF-DP simulations are CPU-demanding (especially in 3D)
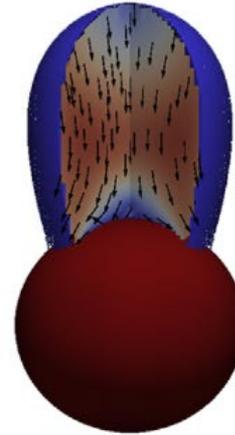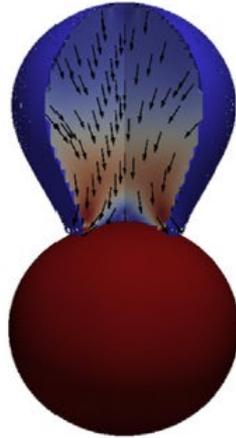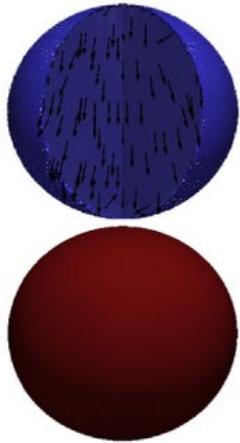 + limited to relatively small number of solid bodies (typically 10^3)

solid line: analytical
dashed line: simulated
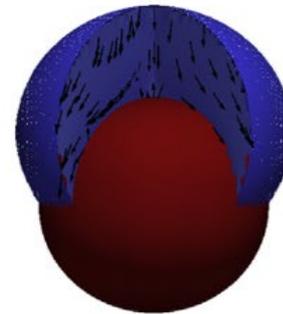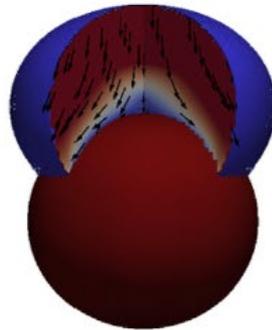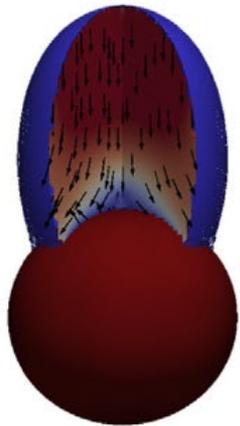

Patel et al., 2019, CES
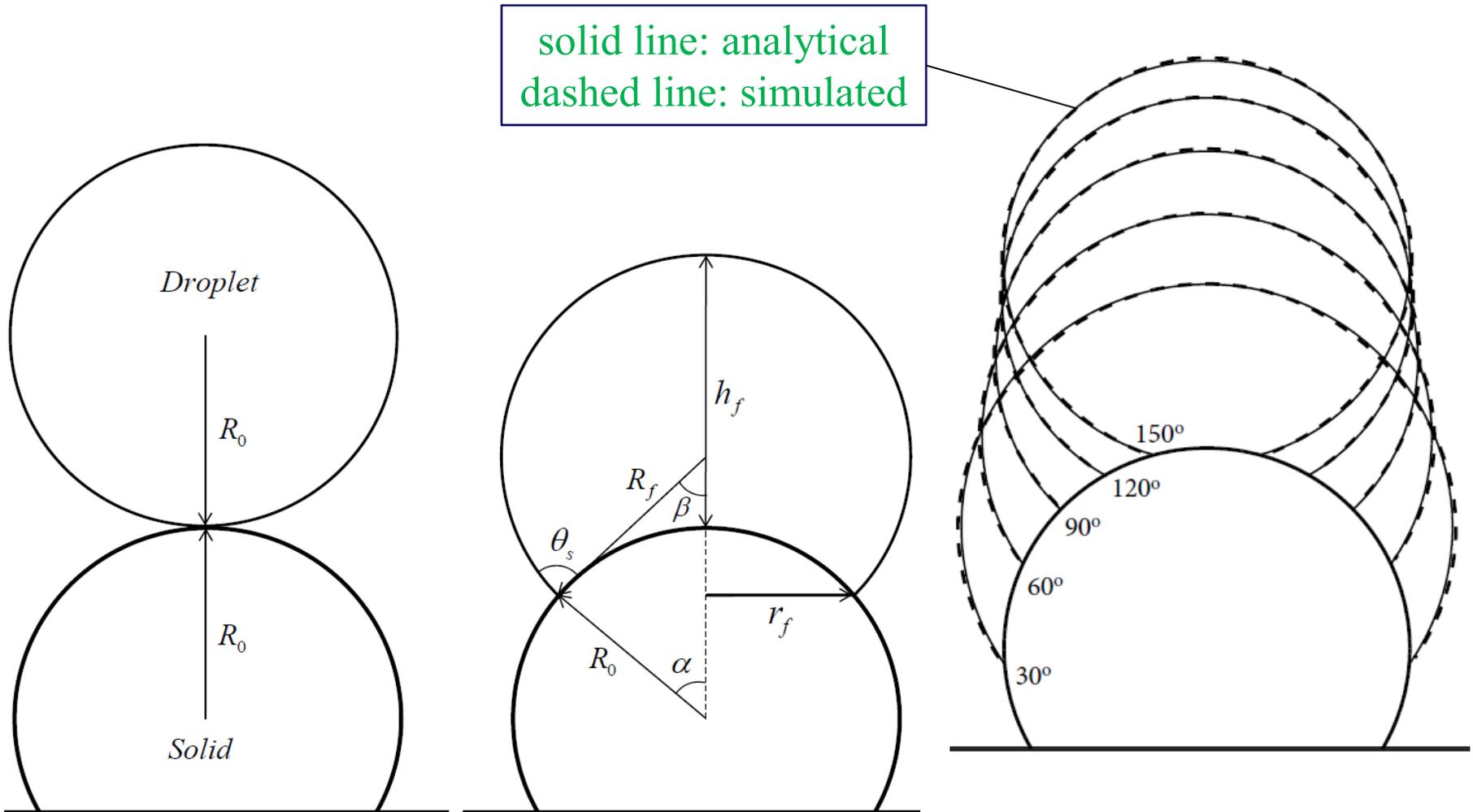
DROPLET-PARTICLE INTERACTION
contact and droplet spreading regimes

initial state
and kinematic
spreading phase

inertial and (slow)
viscous
spreading phase

Milacic et al., 2019, PT

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R_s obtained from calculated wetted area

R_s

R_p

α
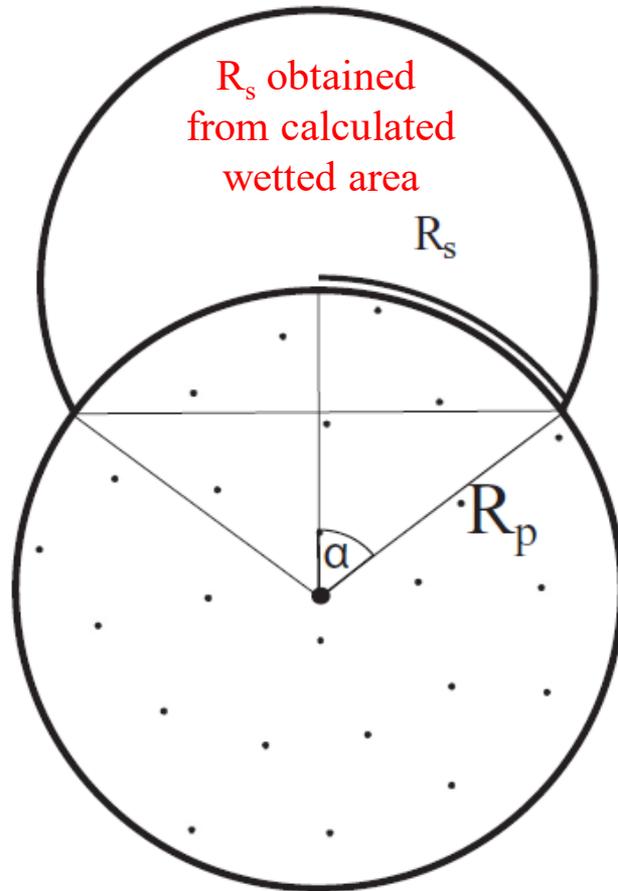
surface area ratio F

$$F = \left(\frac{R_d}{R_p} \right)^2$$

dimensionless time
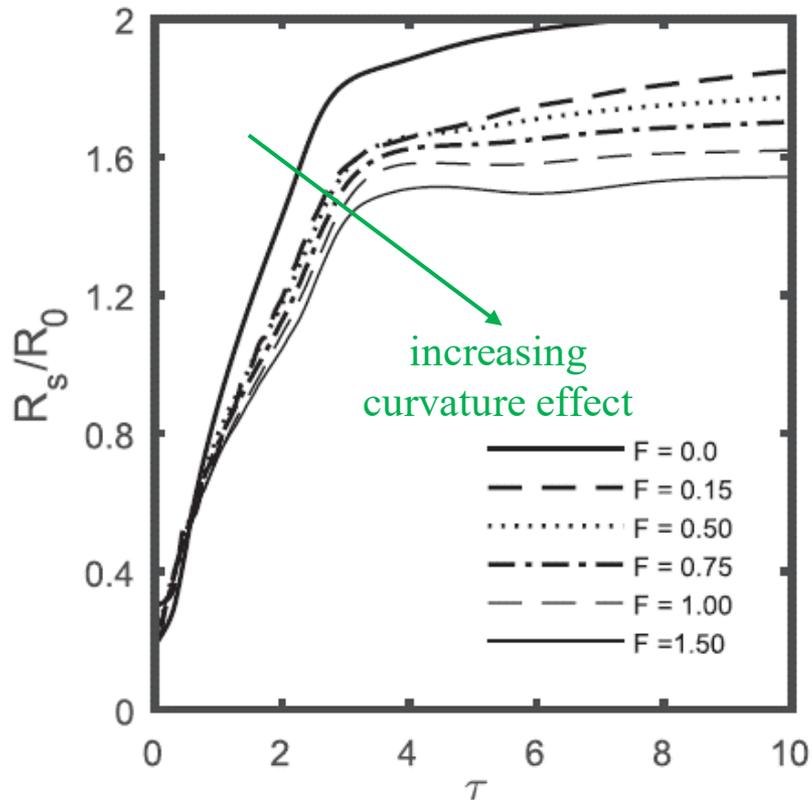
$$\tau = \frac{t}{\sqrt{\dfrac{\rho R_0^3}{\sigma}}}$$
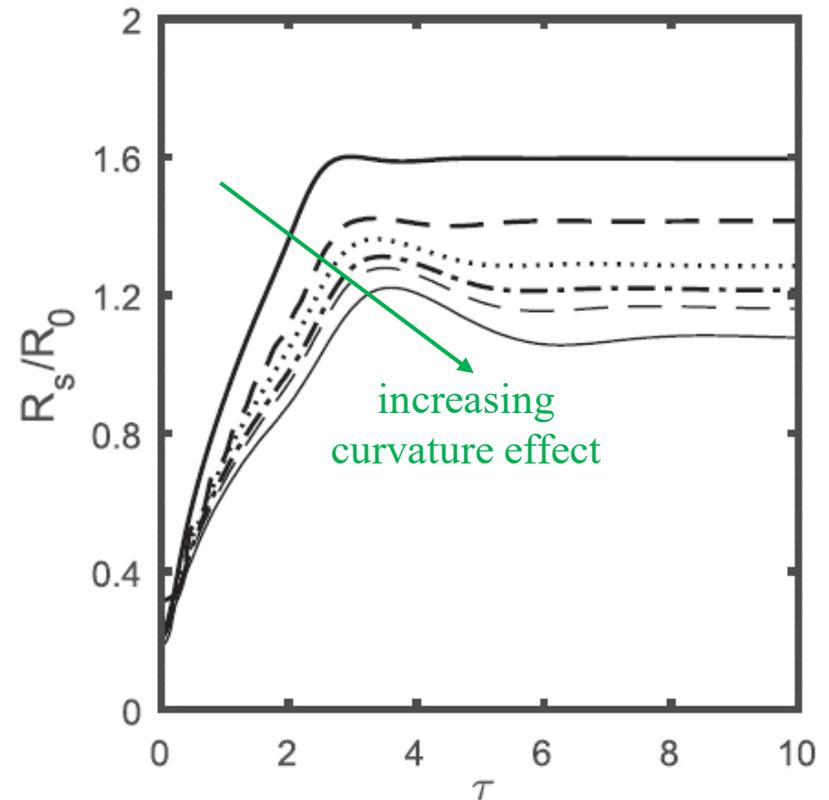
dimensionless spreading parameter

$$\frac{R_s}{R_0}$$

Milacic et al., 2019, PT   TU/e   Technische Universiteit **Eindhoven** University of Technology

$$D_0 = 0.1 \ mm \quad \theta = 30^o$$

$$D_0 = 0.1 \ mm \quad \theta = 60^o$$

I spreading   *II* capillary wave   *III* imbibition

porosity is defined by the diameter d of the cylinders and pitch p

Das et al., 2018, PoF

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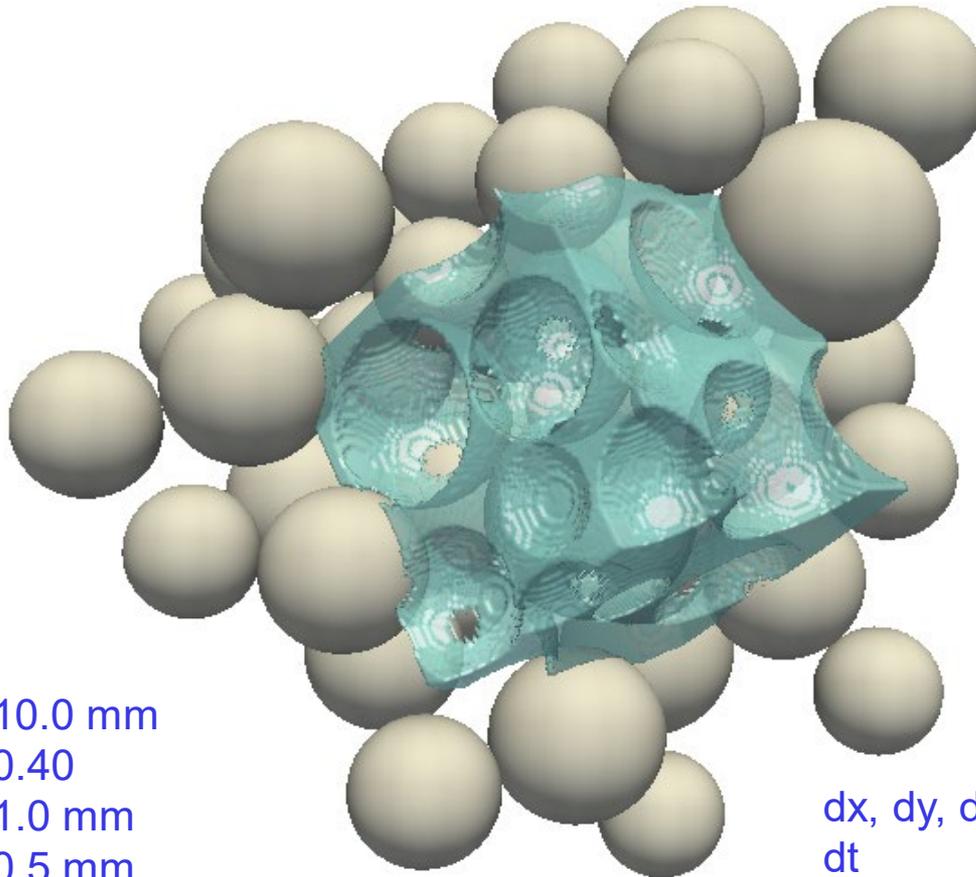# DROPLET-POROUS-MEDIUM INTERACTION
IB-VOF-DP simulation
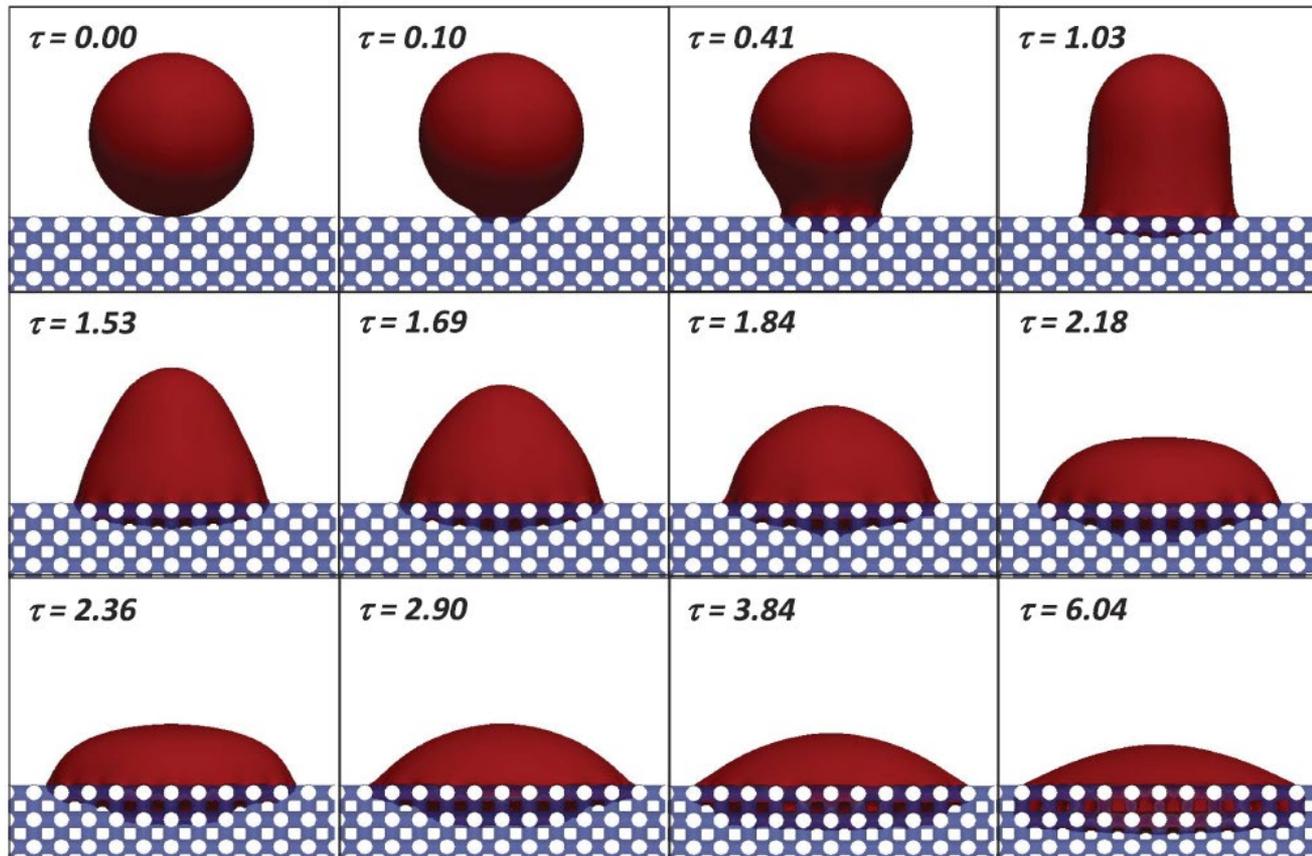
d_d = 0.2 mm

ε_{void} = 0.5

Gas = air

Liquid = squalane

Θ = 30°

$$La = \frac{\rho_l \sigma R_d}{\mu_l^2} = 45$$

dx, dy, dz = 3 μm

dt = 10^{-7} s

Fluid-interface = VOF

Solid-interface = IBM

Das et al., 2018, PoF
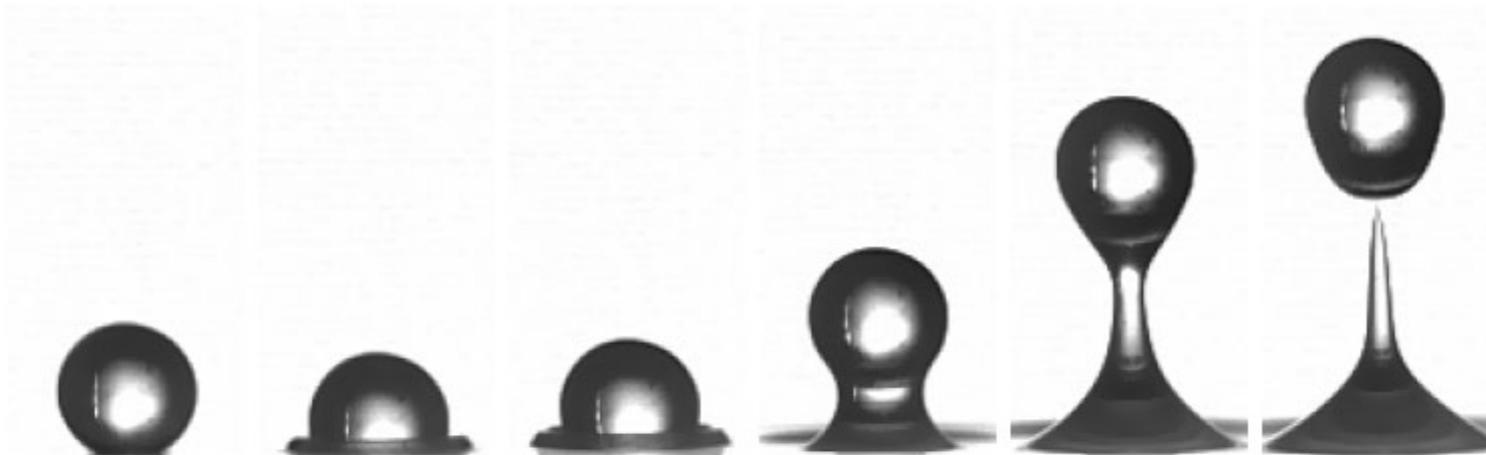
d_{cub} = 10.0 mm
ε_{void} = 0.40
$<d_p>$ = 1.0 mm
σ = 0.5 mm
Gas = air
Liquid = squalane
Θ = 30°

dx, dy, dz = 0.1 mm
dt = 10^{-7} s
Fluid-interface = VOF
Solid-interface = IBM

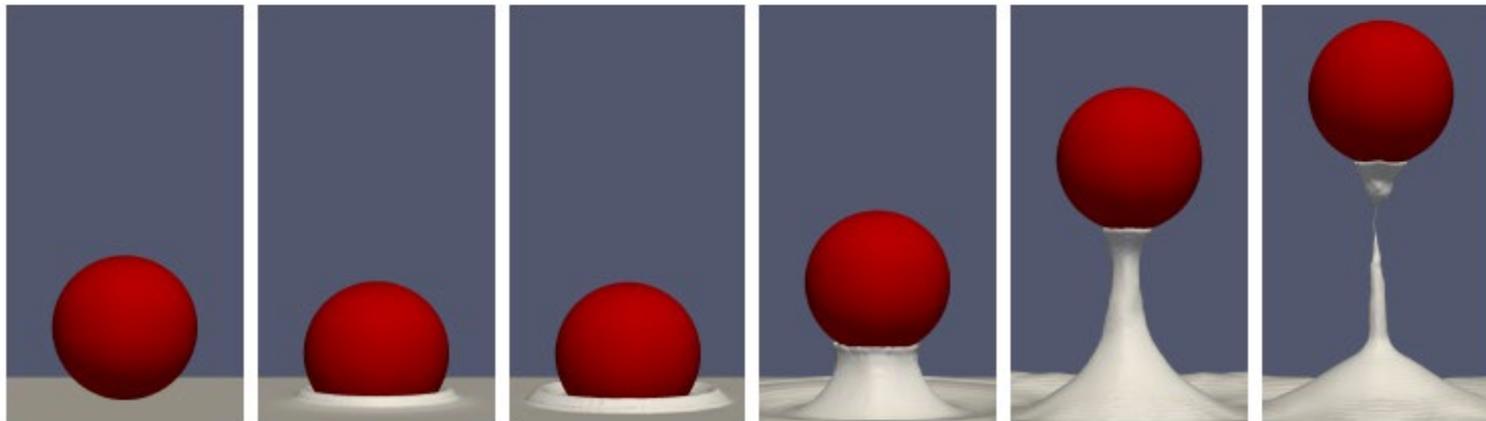**TU/e** Technische Universiteit
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PARTICLE COLLISION WITH A FLAT PLATE COVERED WITH A VISCOUS LIQUID
particle impact with liquid bridge formation and rupture

Particle:

d_p=1.74 mm
v_p=1.13 m/s

Liquid layer:

water
δ=400 μm

Tang et al., 2017, AIChEJ TU/e Technische Universiteit Eindhoven University of Technology

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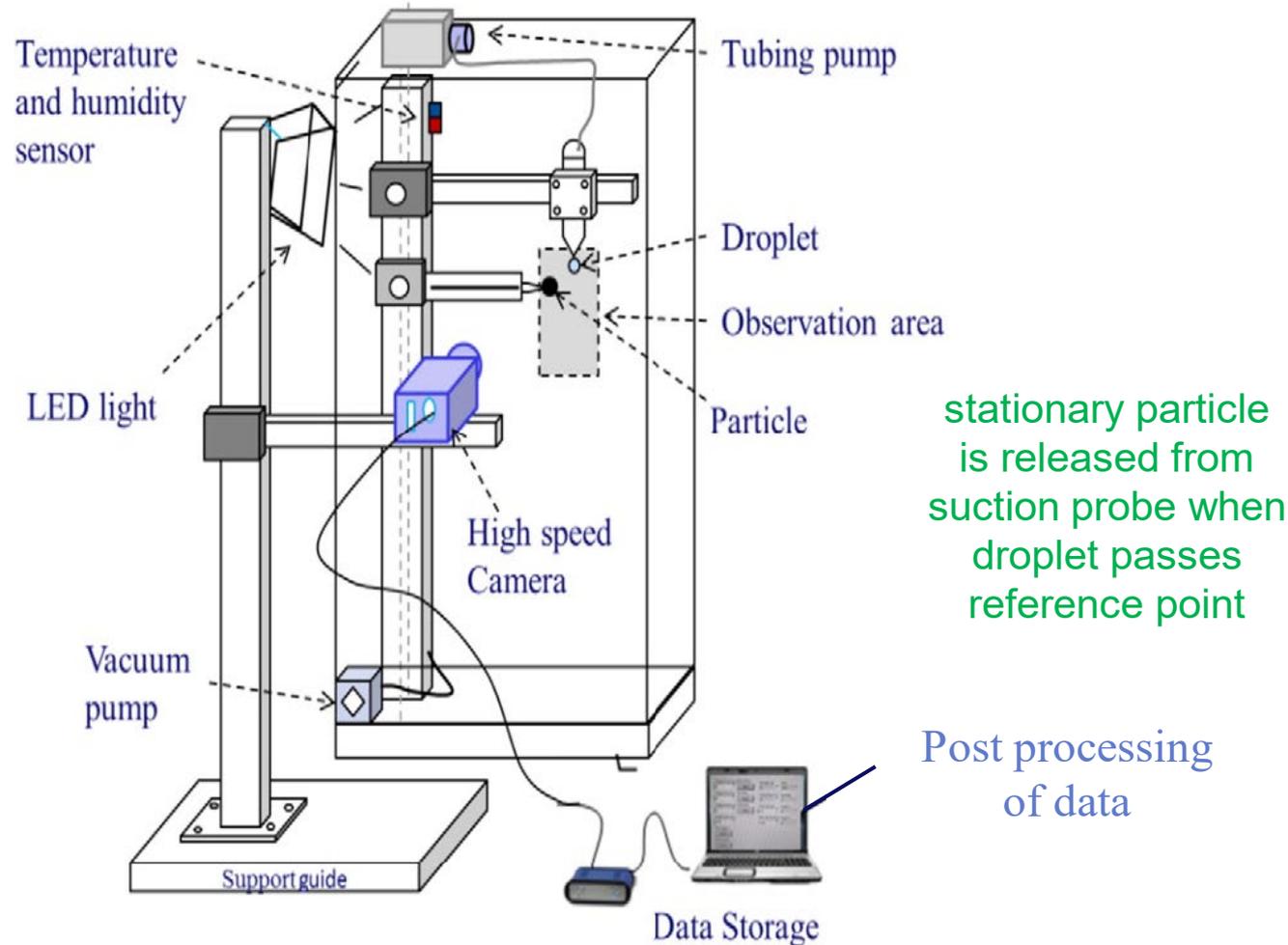
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Tang et al., 2017, AIChEJ

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Temperature and humidity sensor

Tubing pump

LED light

Droplet

Observation area

Particle

High speed Camera

Vacuum pump

Support guide

Data Storage

stationary particle is released from suction probe when droplet passes reference point

Post processing of data

Pawar et al., 2016, PETC

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A
AGLOMERATE

SS
STRETCHING SEPARATION

SD
STRETCHING SEPARATION
WITH SATELLITE DROPS

Pawar et al., 2016, PETC

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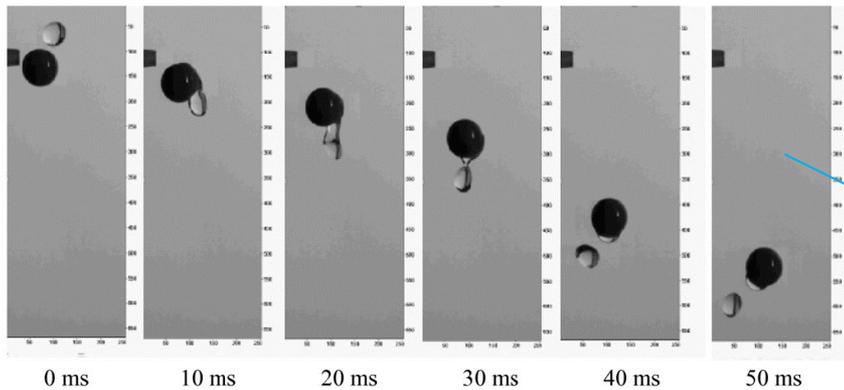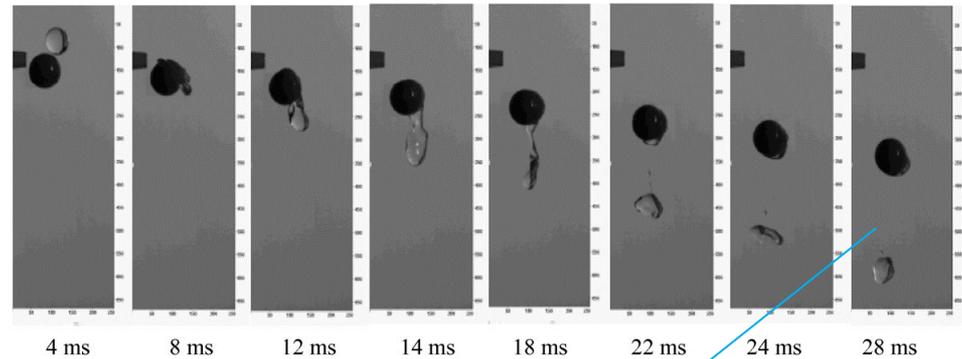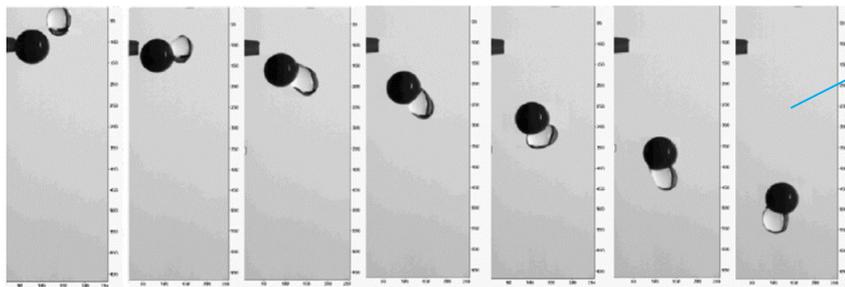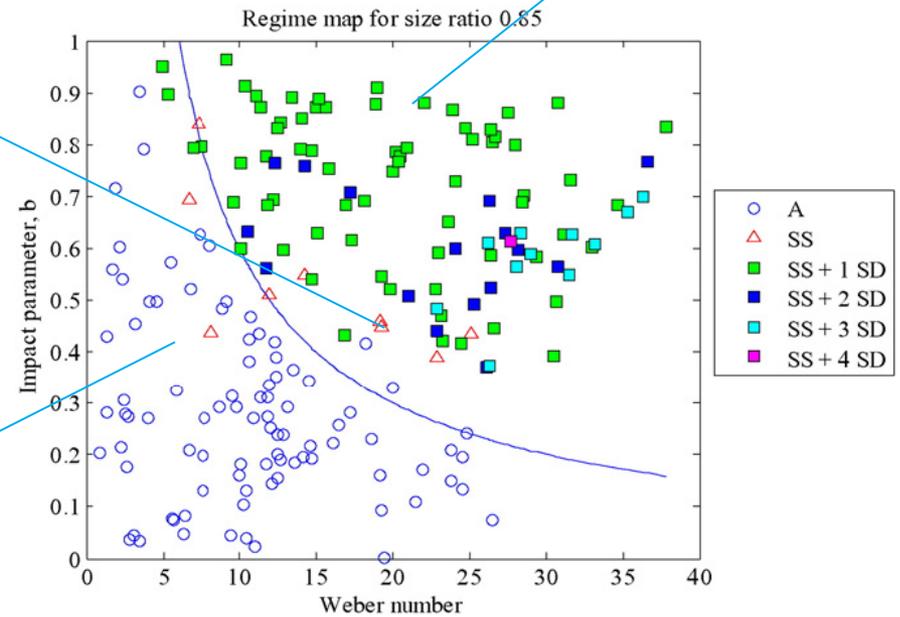
MULTI-SCALE MODELLING

DNS

DEM

TFM

larger geometry, lower detail
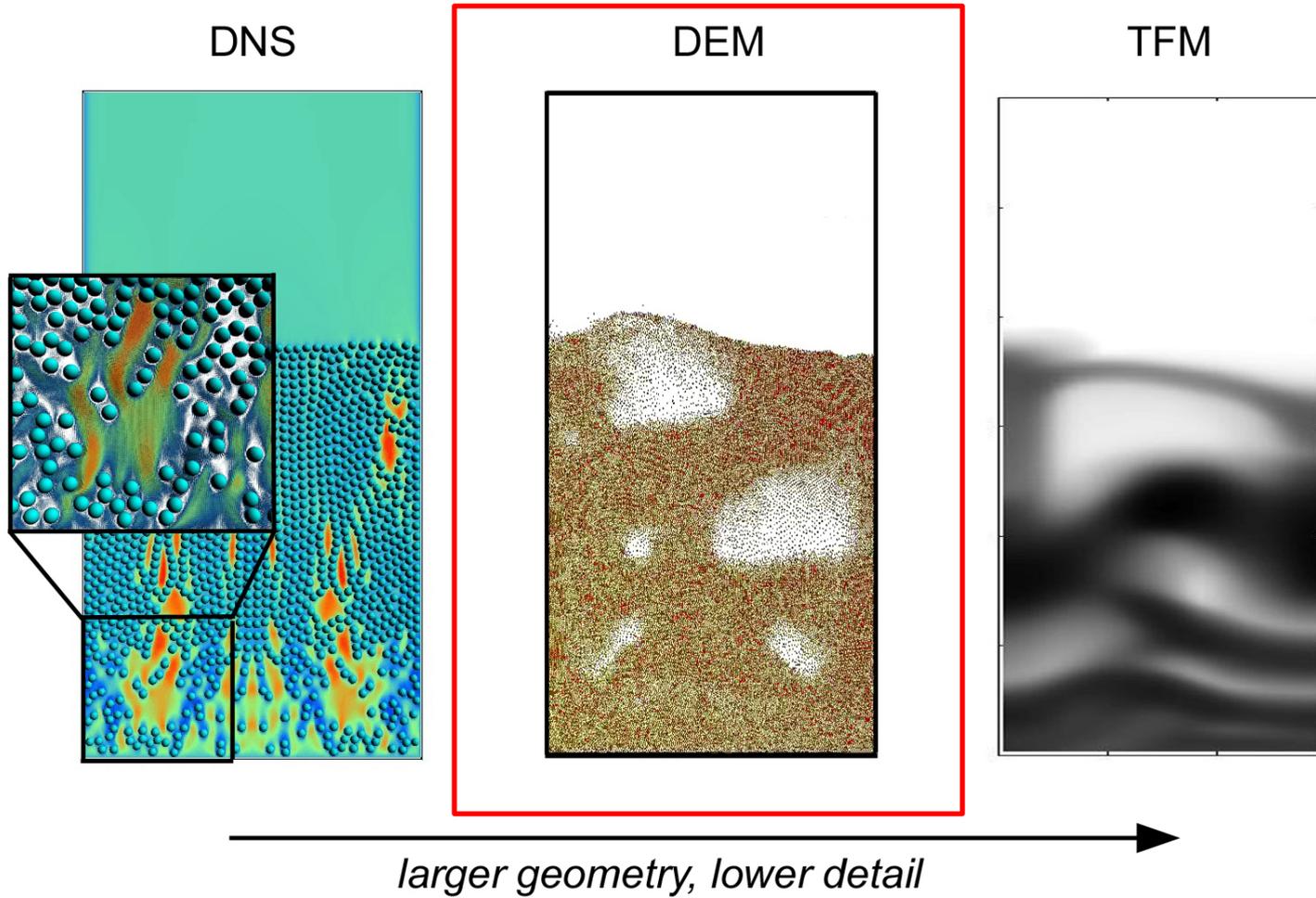
KEY STEPS IN DISCRETE "PARTICLE" MODELS

Eulerian cell

gravity

drag

"particle" (solid particle or droplet) moves due to external forces while encounters with other "particles" and/or confining walls may occur
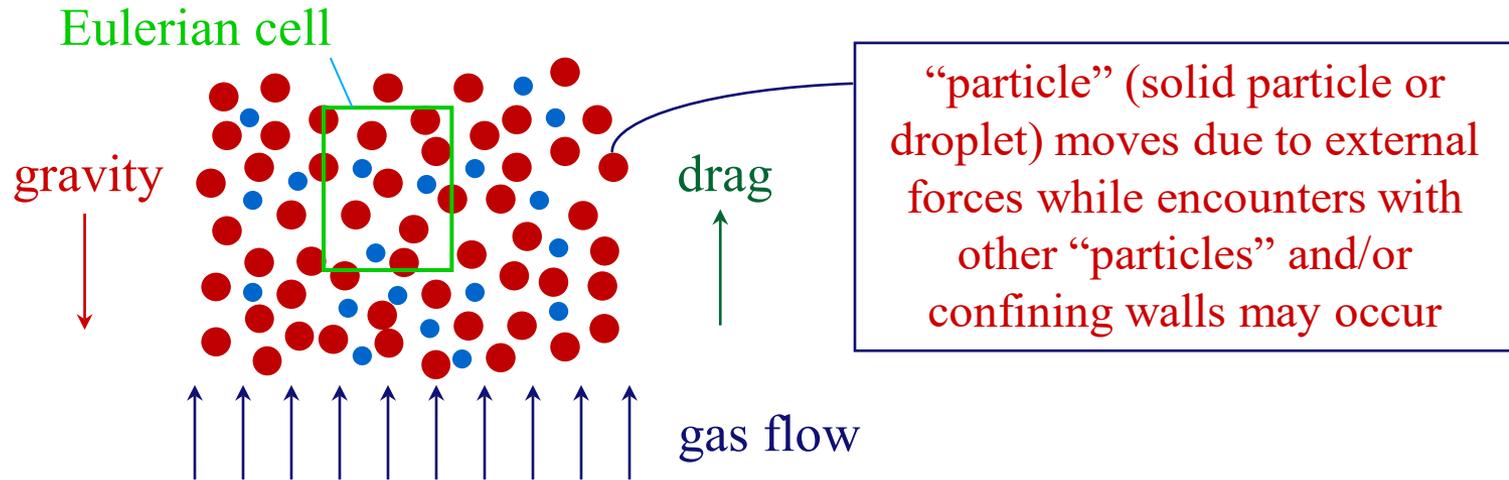
gas flow

+ gas phase flow field

+ encounter times and associated partners (efficiency)

+ encounter dynamics

+ bed voidage and source terms in momentum equation gas phase

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droplet-particle encounter

Droplet — Droplet particle impact — Wet particle

δ_l — d_p

coupled mass and heat transport

Gas-liquid film — Particle — Liquid film

$T_p = T^*_p$ — T_g

w^*_g — w_g

Nozzle top view

1 mm

6 mm

8 cm

18 cm

Back plate

Filler

Heating coils

Background gas

Spout gas

Nozzle liquid

Nozzle gas

1.8

Sutkar et al., 2016, CEJ

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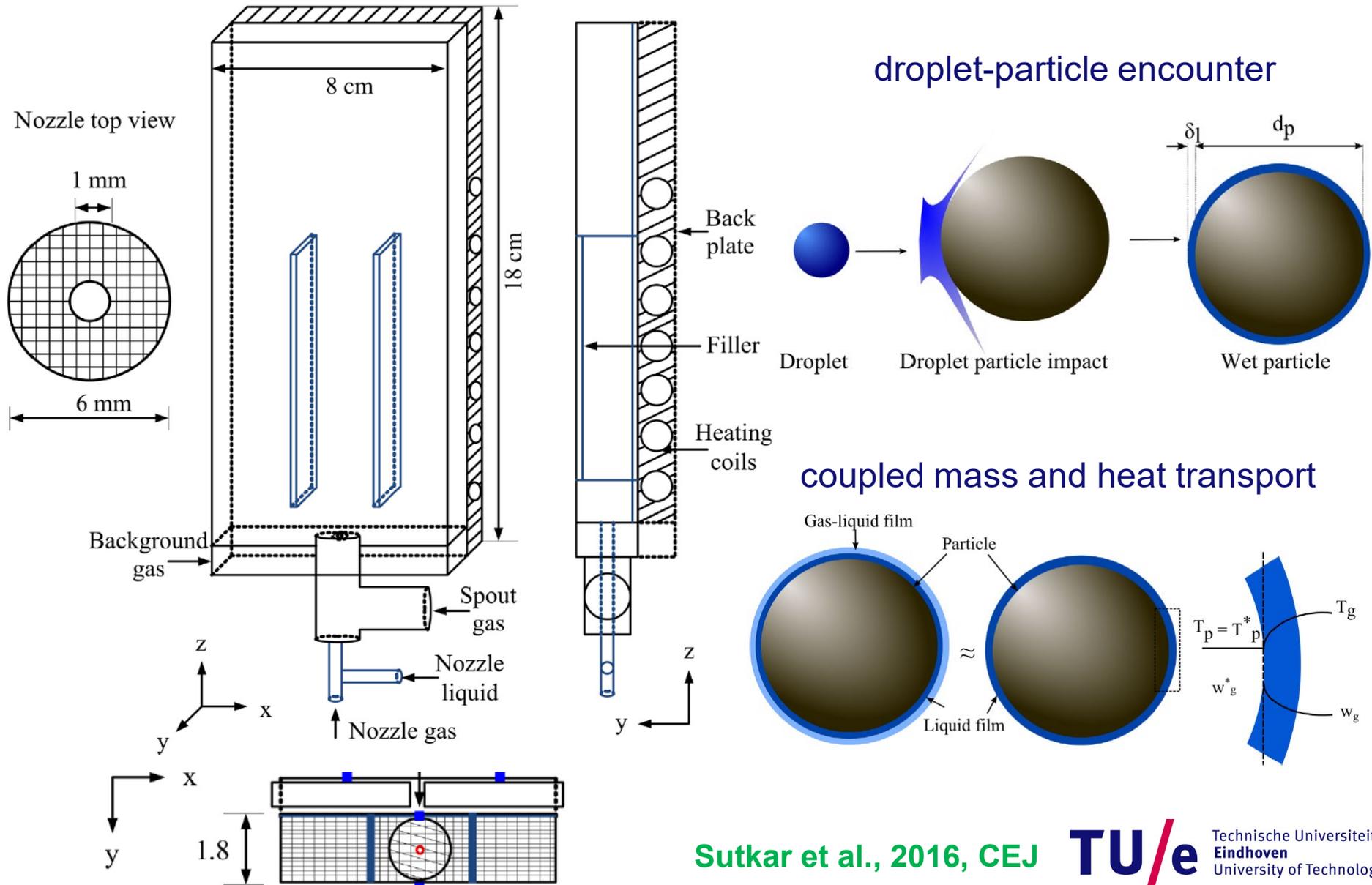
droplet-particle encounter
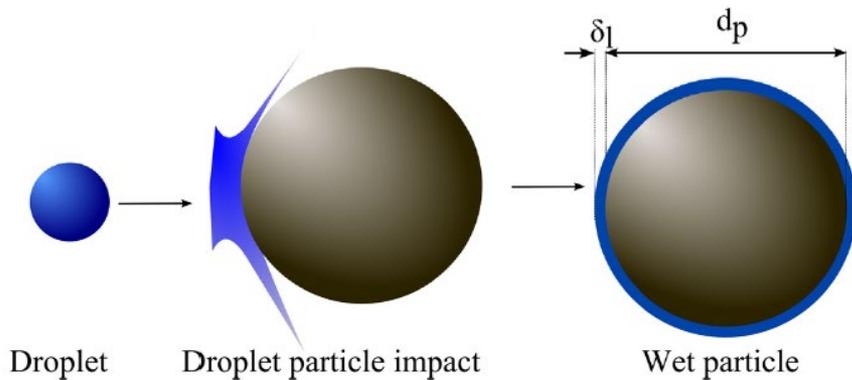
coupled mass and heat transport
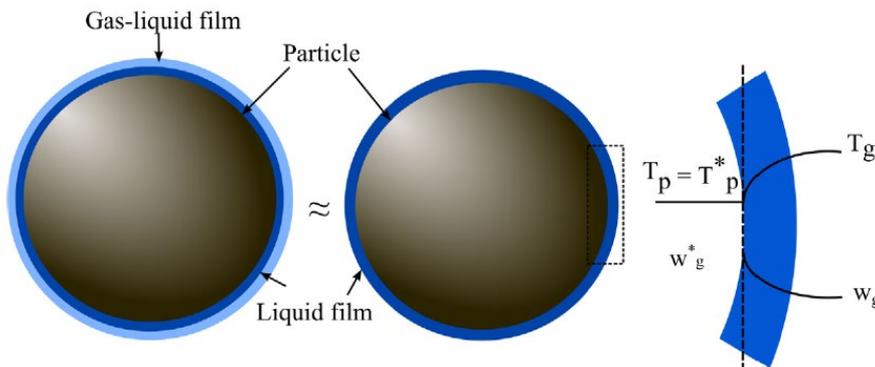
main assumptions in CFD-DEM

no droplet fragmentation upon impact on particle ($We_d < 1$)

uniform wetting after droplet-particle encounter

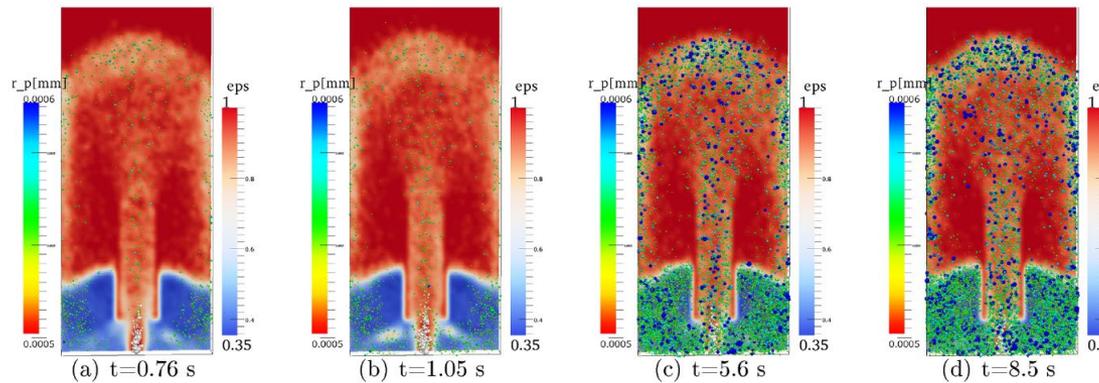wet restitution follows simplified model of Davis et al. (2002):

$$e_{wet} = \begin{cases} e_{dry}\left(1 - \frac{St_c}{St}\right) & \text{if } St > St_c \\ 0 & \text{if } St < St_c \end{cases}$$

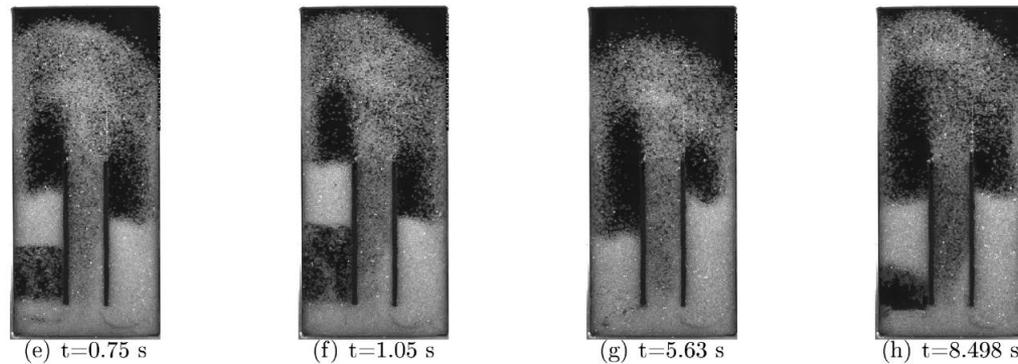negligible intra-particle temperature gradients ($Bi \ll 1$)

external mass and heat transfer follows Gunn (1978) correlation

Sutkar et al., 2016, CEJ

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particle size (CFD-DEM)

(a) t=0.76 s   (b) t=1.05 s   (c) t=5.6 s   (d) t=8.5 s

bed behavior (visual)

(e) t=0.75 s   (f) t=1.05 s   (g) t=5.63 s   (h) t=8.498 s
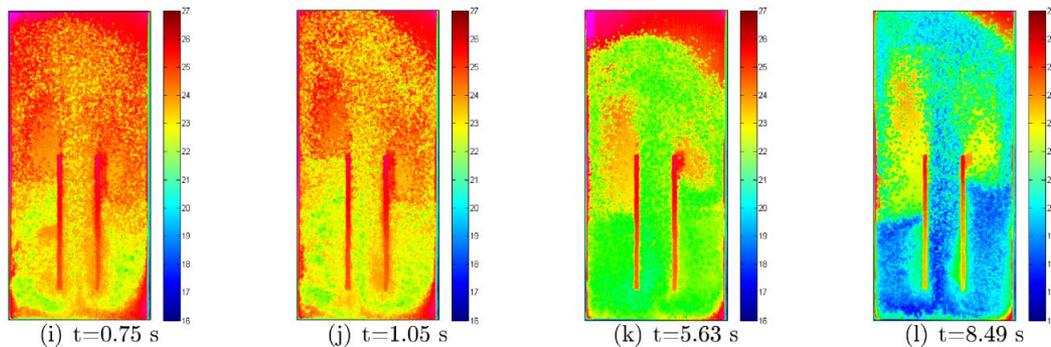
bed behavior (IR-thermography)

(i) t=0.75 s   (j) t=1.05 s   (k) t=5.63 s   (l) t=8.49 s

Sutkar et al., 2016, CEJ

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with draft plates

without draft plates

Sutkar et al., 2016, CEJ
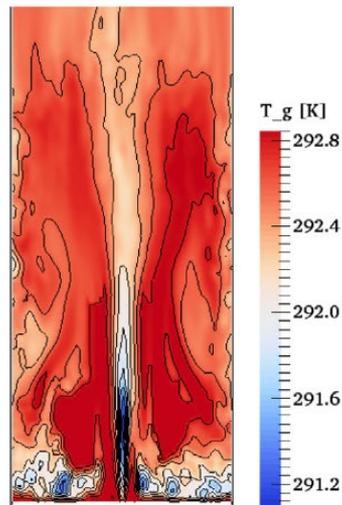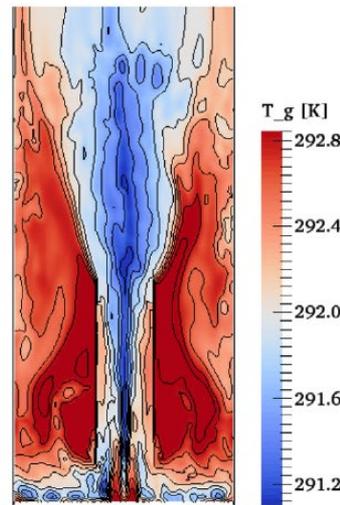
with draft plates

without draft plates

(a) t=0.76 s   (b) t=1.06 s   (c) t=5.6 s
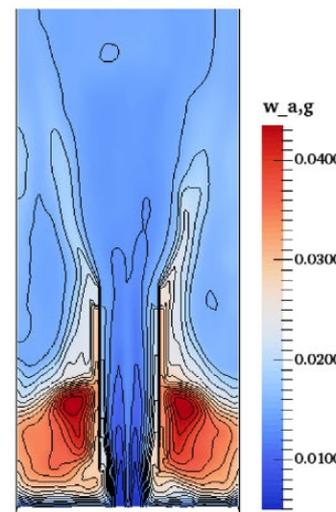
(d) t=0.76 s   (e) t=1.06 s   (f) t=5.6 s

Sutkar et al., 2016, CEJ
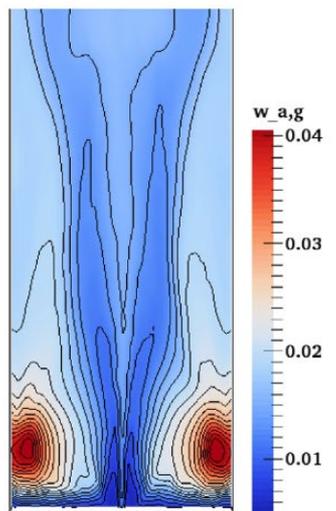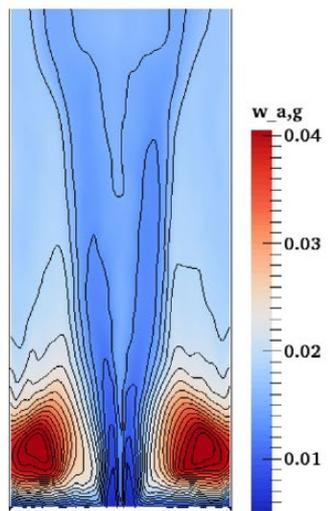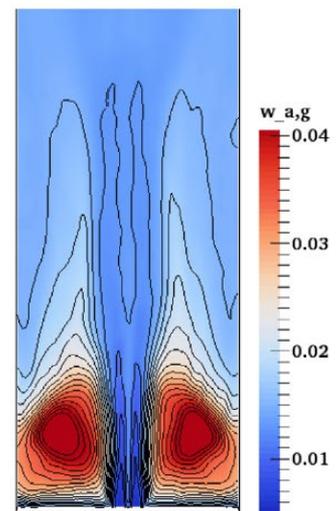
- DENSE PARTICULATE FLOWS WITH LIQUID INJECTION

  + very complex interactions at micro-scale with strong impact on macro-scale
  + important role for multi-scale approach (experiments & simulations)

- WET PARTICLE-PARTICLE INTERACTION

  + DNS approach promising but much more work required (complex fluids)
  + moving + non-spherical (porous) particles + thermal aspects

- MAJOR CHALLENGES

  + development and incorporation of reliable closures for CFD-DEM (ML ?)
  + acceleration of CFD-DEM (scaled particles, DSMC, R-CFD)

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Harshil Patel	Shell
Sandip Pawar	STW
Amit Patil	Tetra Pak
Vinayak Sutkar	Unilever
Yali Tang	Yara

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