A new predictive tool for design and operational optimisation of spray dryers

Advanced Process Modelling Forum
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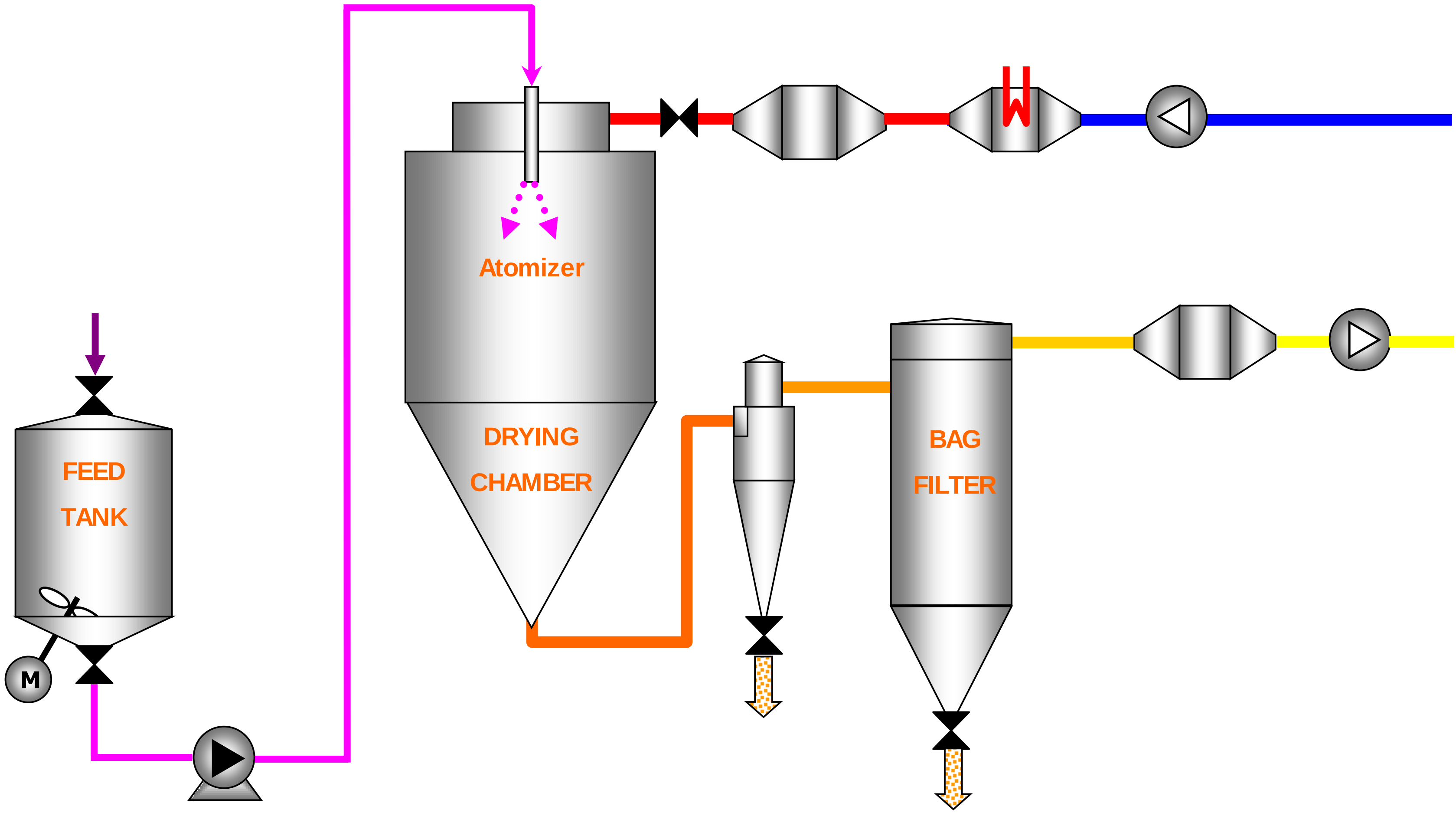
Typical Co-current Spray Drying Process



Co-current tower

Product particle size range: 5-200 microns

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Spray Drying Process Flow Diagram for Detergent Powder Manufacture

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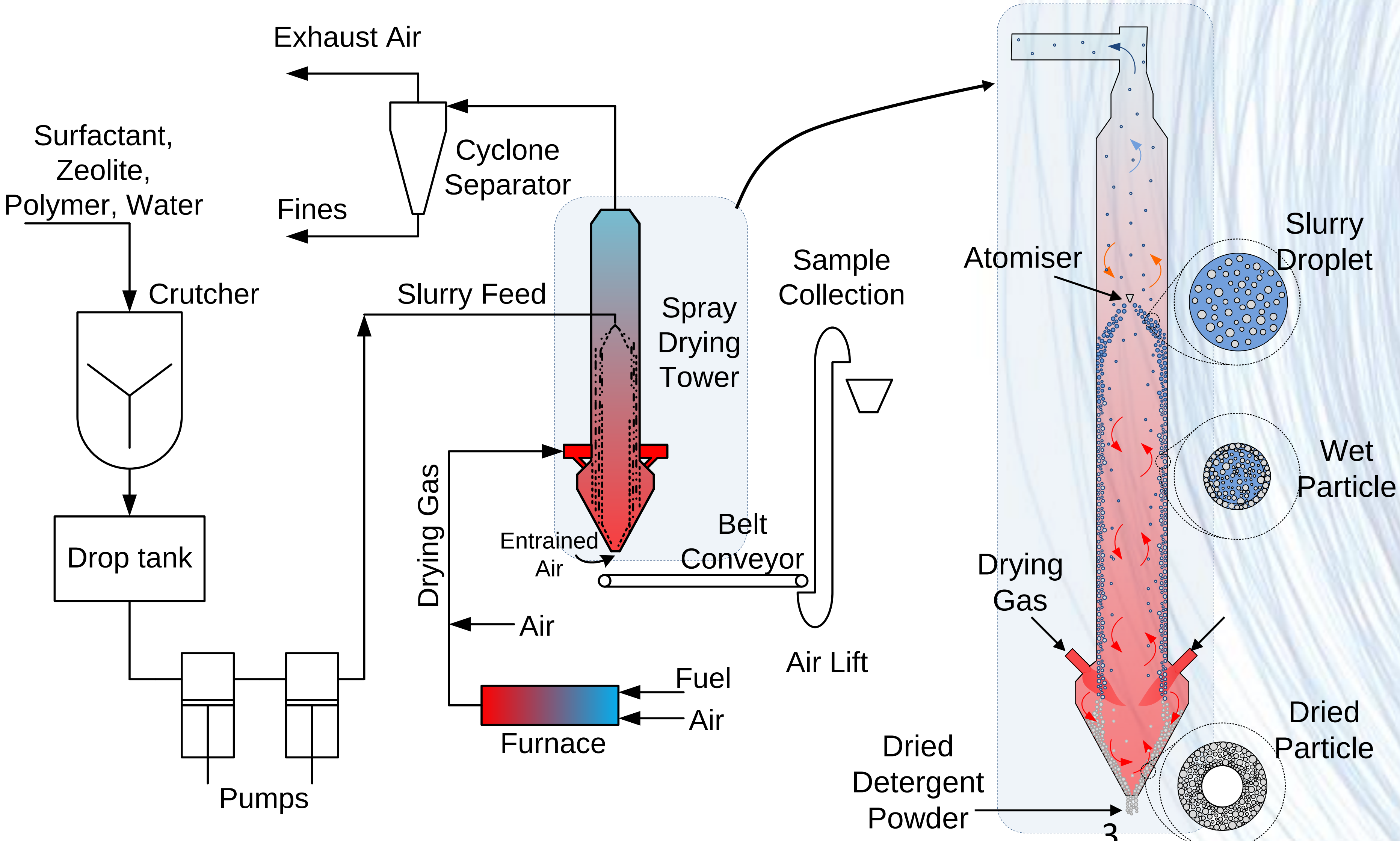

Introduction

- **Spray drying is commonly used in many different industries**
  - pharmaceuticals, foods, detergents, enzymes

- **Complex interacting phenomena determine critical quality attributes of product**

- **Desire to understand process to optimise and control**
  - product quality i.e. particle properties
  - production rate
  - production reliability, e.g build-up

- **Important to understand droplet drying history in a spray dryer particularly for thermally sensitive ingredients**

- **Current modelling mainly concentrated at two extremes**
  - **Mass and energy balance models**
  - **Computationally demanding and inefficient CFD calculations**

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Business Need

A high fidelity, efficient and user-friendly modelling tool that can be used to increase understanding, optimise existing processes and explore operation space

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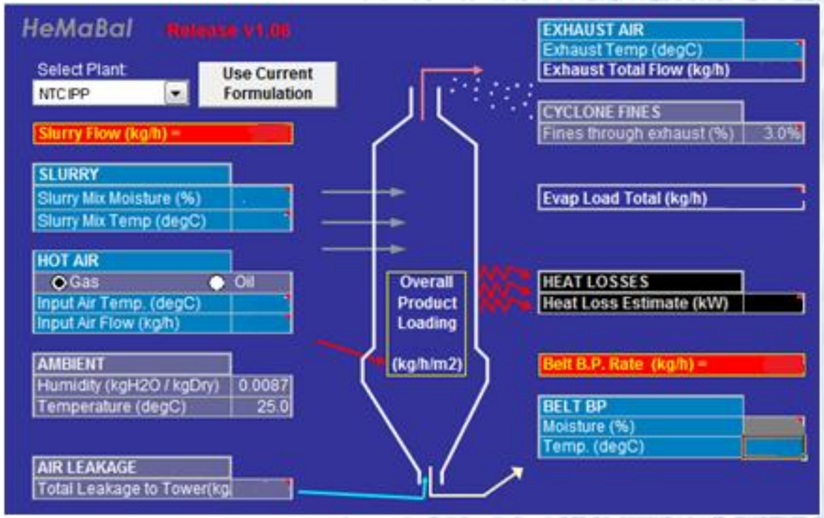
The Overall Challenge

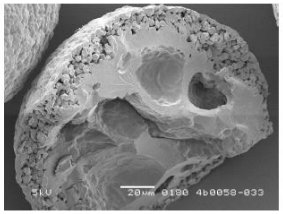
Predictability: Process results and product properties:

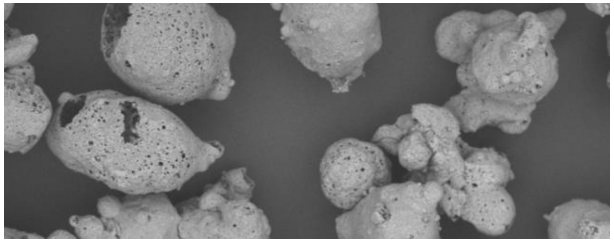
- Currently can predict rate or moisture content (overall)
- Cannot predict PSD and moisture, porosity and chemistry per size range.
- Cannot be used to scale-up from mini -> macro -> manufacture or across scales.



Innovation: influencing the cycle:

- How do cut innovation cycle?
- Can we use the model as a source of innovation? Design novel morphologies.
- Understand product-process interplay!





Simplicity: Not CFD:

- Available to typical process engineer without training/expertise on using complex tools such as CFD.
- Ensure we do not need to re-run a CFD model for each scenario.
- Need to solve population balance equations efficiently.

Innovate UK (formerly TSB) funded consortium

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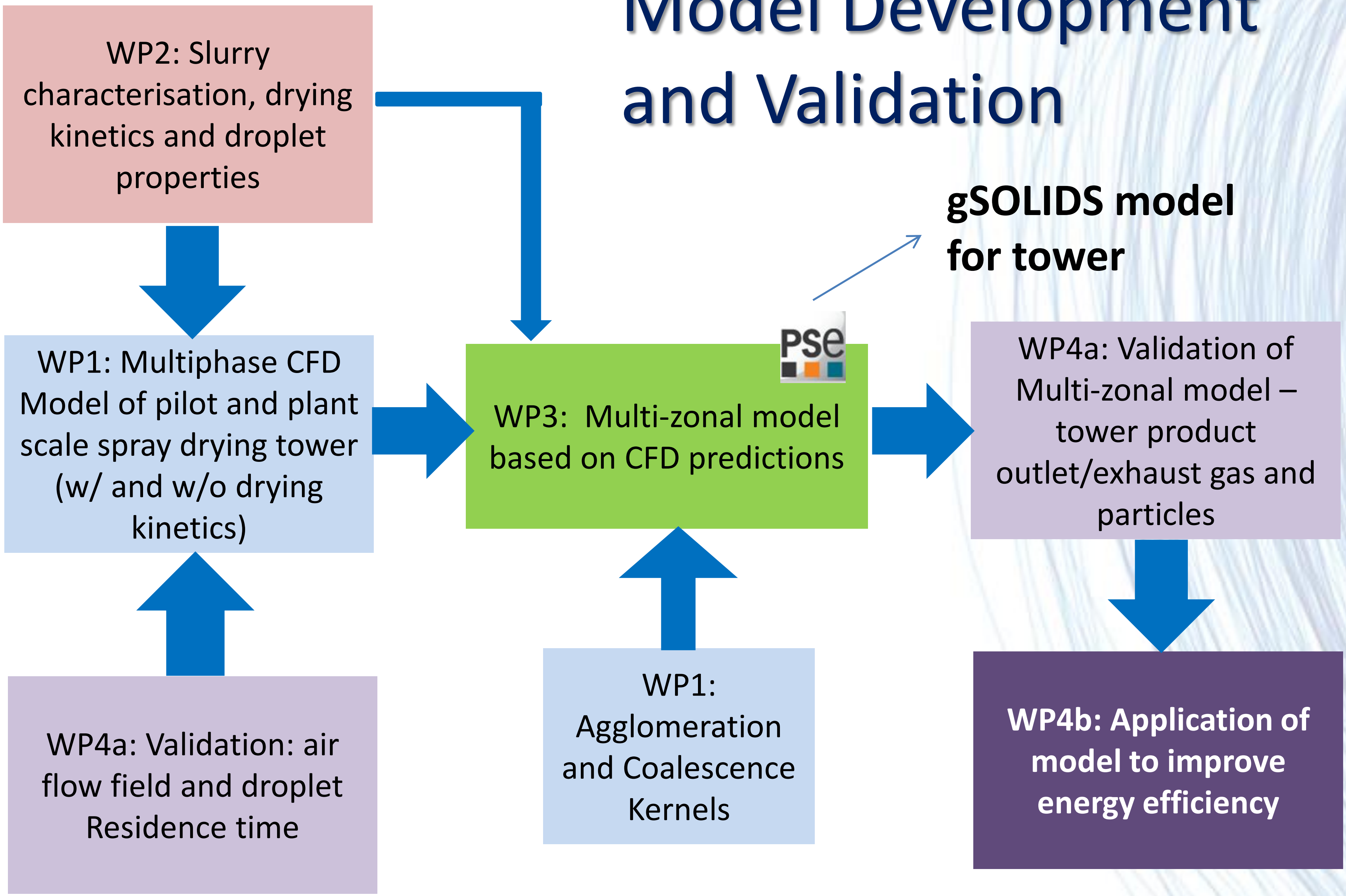
Technology Strategy Board
Driving Innovation

novozymes
Rethink Tomorrow

P&G

PSE

Model Development and Validation



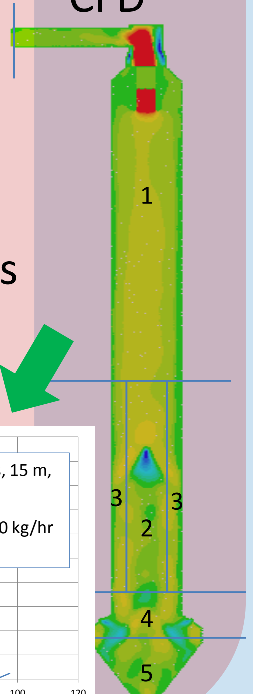
Phase 1

Input PSD

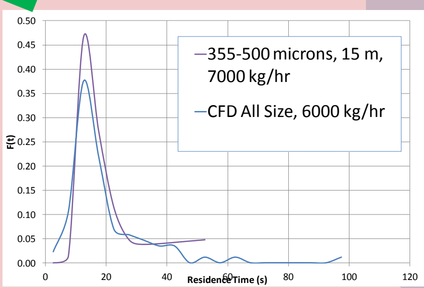
WP1, WP2 and WP4

P&G/Novo Pilot Plant and 1 Plant

VS



Validate RTD – vary **drag** to get best representation



TM: UoL, P&G, Novo

Phase 2

WP1 and WP3

Export:

-Fluxes between boundaries

-Volumes of zones and areas of interfaces

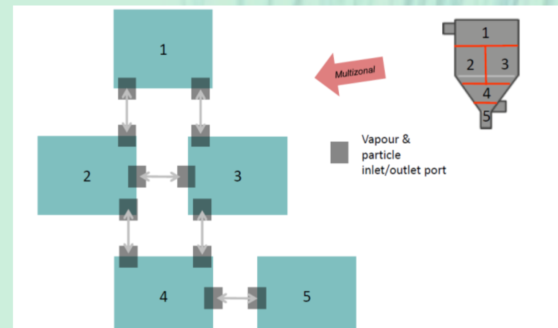
TM: PSE, UoL

Phase 3

WP1 and WP3

TM: PSE, UoL

gSOLIDS Compartment Model

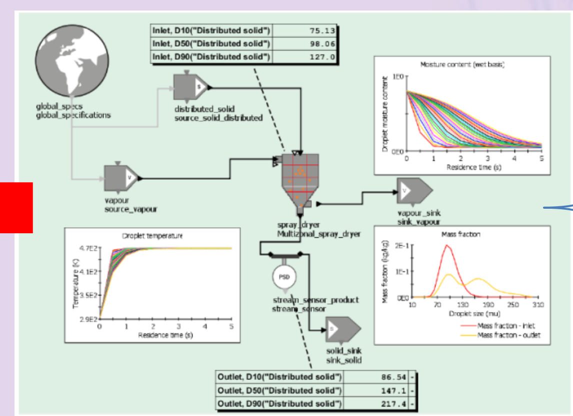


Check RTD vs CFD

Understand impact of zonal strategy on RTD

Phase4

WP1, WP2 and WP3



Droplet Drying (Hecht and Sloth)

Coalescence (literature from UoL)

Wall Agglomeration and make-up (literature from Uol)

Heat losses (measured)

TM: PSE, UoL, P&G, Novo

Phase 5

WP3 and WP4

Understand scaling between zones as function of conditions:

- Air flow rate,
- Air temperature,
- Nozzle positions,
- Multiple nozzles,
- Droplet size and density et...
- Etc...

TM: PSE, UoL, P&G, Novo

Phase 6

WP3 and WP4

Validate PSD, powder moisture, powder temperature, exhaust temperature vs pilot plant and plant setups.

TM: PSE, P&G, Novo

What do we need from CFD?

- How good are multi-phase CFD models at predicting the tower performance?
  - Issues input data, quality validation data
- What do the air and particle flow patterns tell us about how to create zones?
- Understand if it possible to ‘scale’ air and particle flows.

Air velocities in co-current tower

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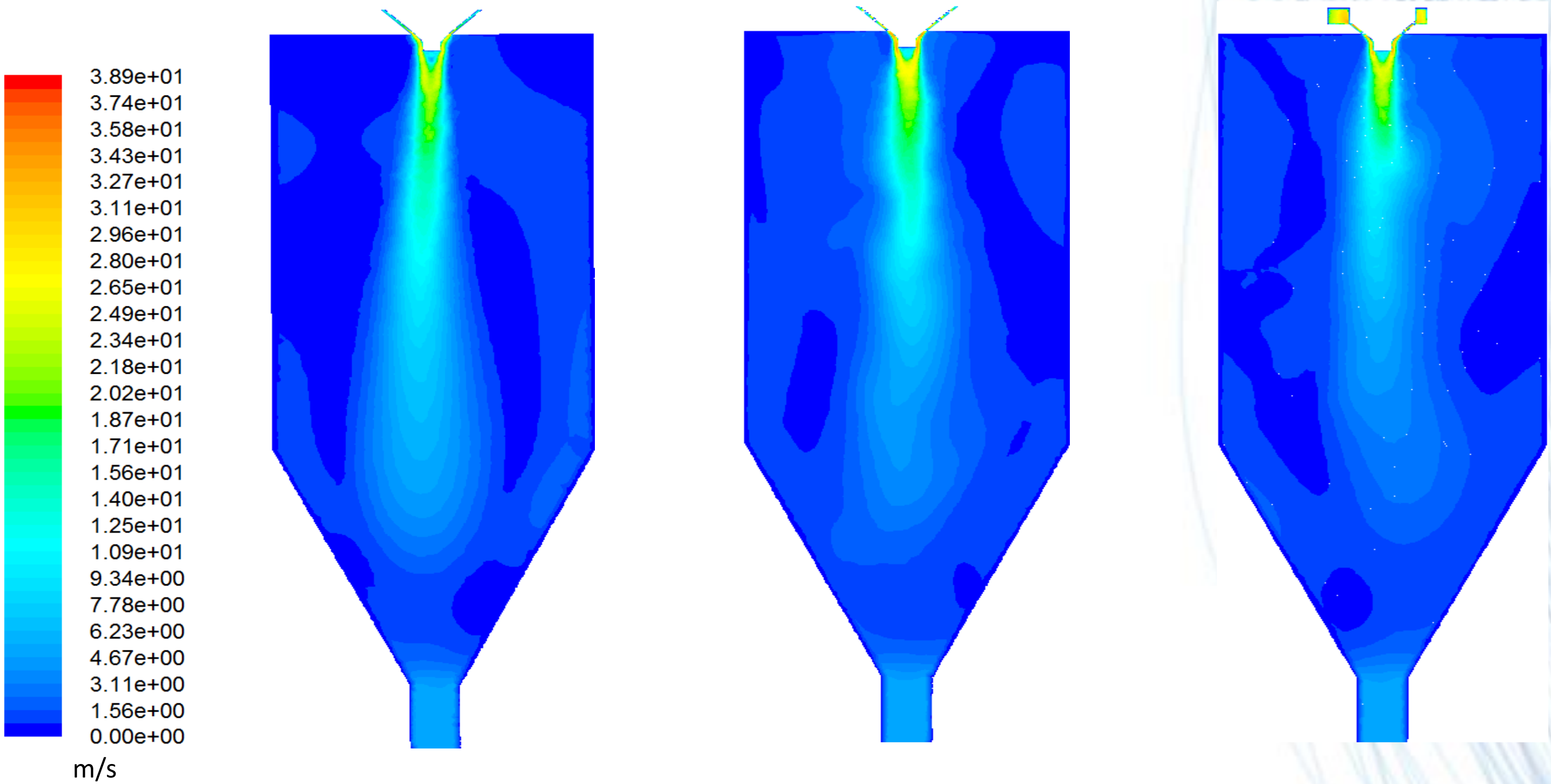

Without vanes With swirl vanes With distributor and vanes

Single Phase Simulations Velocity Magnitude Contours

CFD Modelling Results (cont.)

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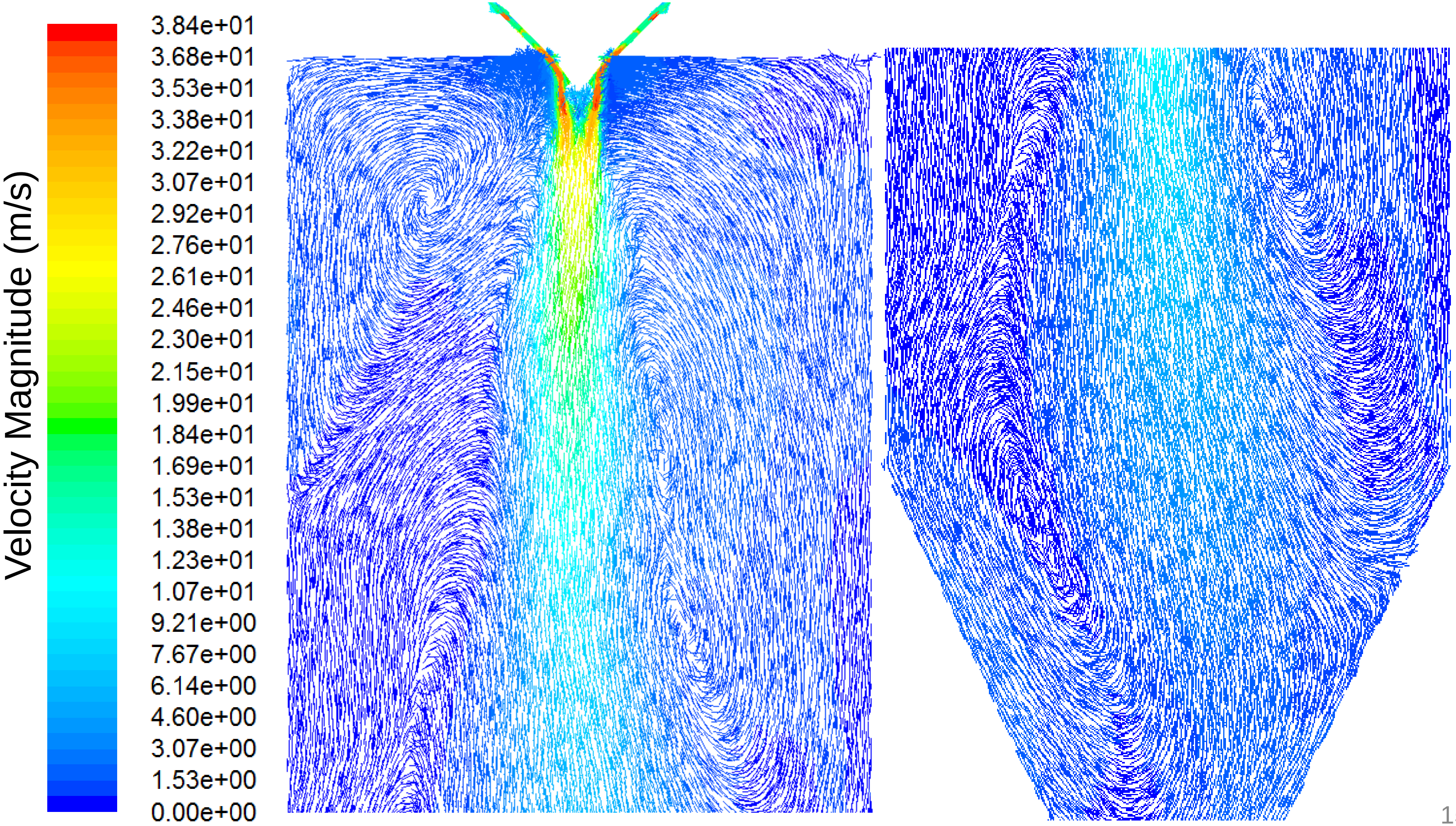
- Vector plot coloured by velocity magnitude:



Modelling of Spray Drying Process

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Sub-Models

Droplet Drying Model
Heat/Mass Transfer, Size and Morphological Changes

Particle-Wall Interaction Model
Deposition, Re-entrainment, **Rebound** and Breakage

Heat Loss Through the Insulation

Particle-Particle Interaction Model
Coalescence, Agglomeration, Rebound and Breakage

→ **Multiphase CFD Modelling of Spray Drying Process**

Trajectories coloured by Moisture Fraction

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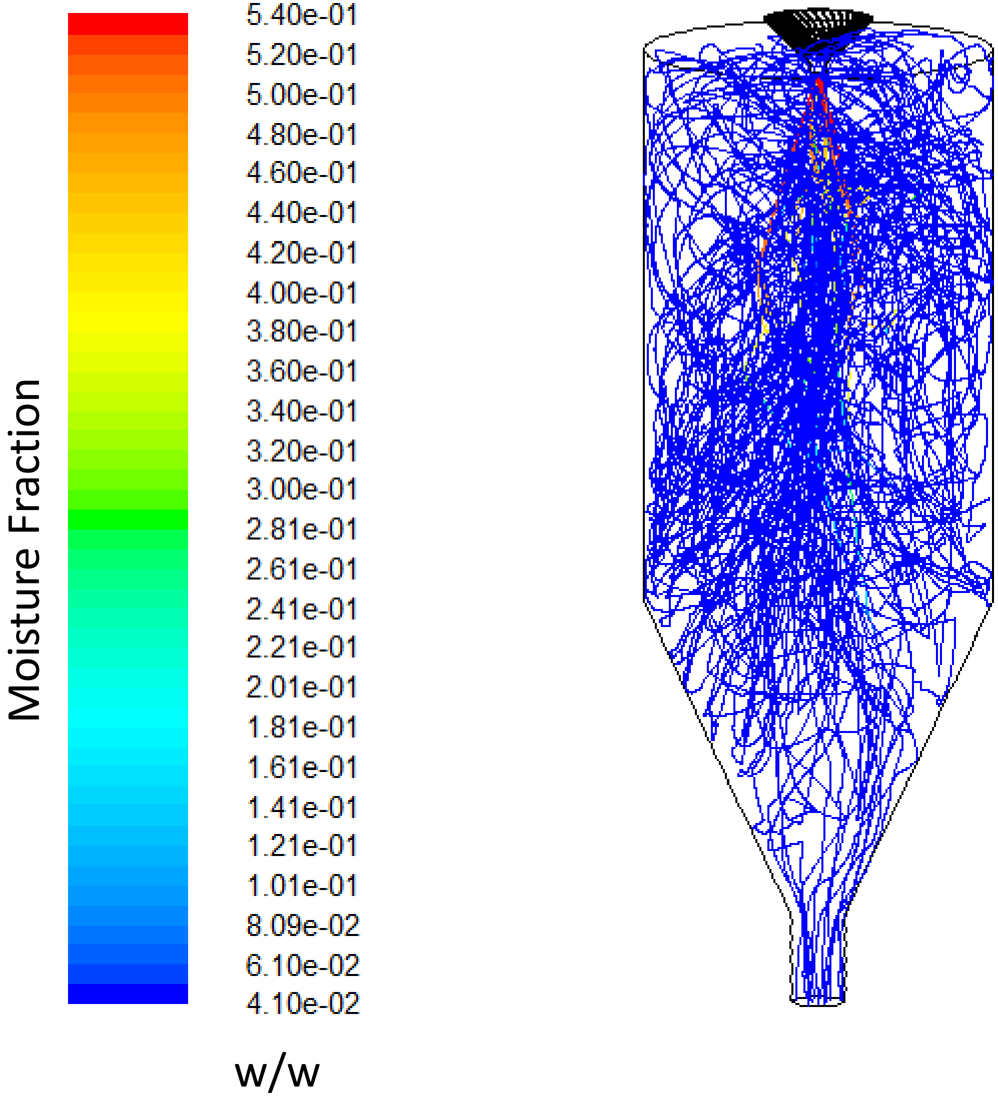

Trajectories coloured by Moisture Fraction

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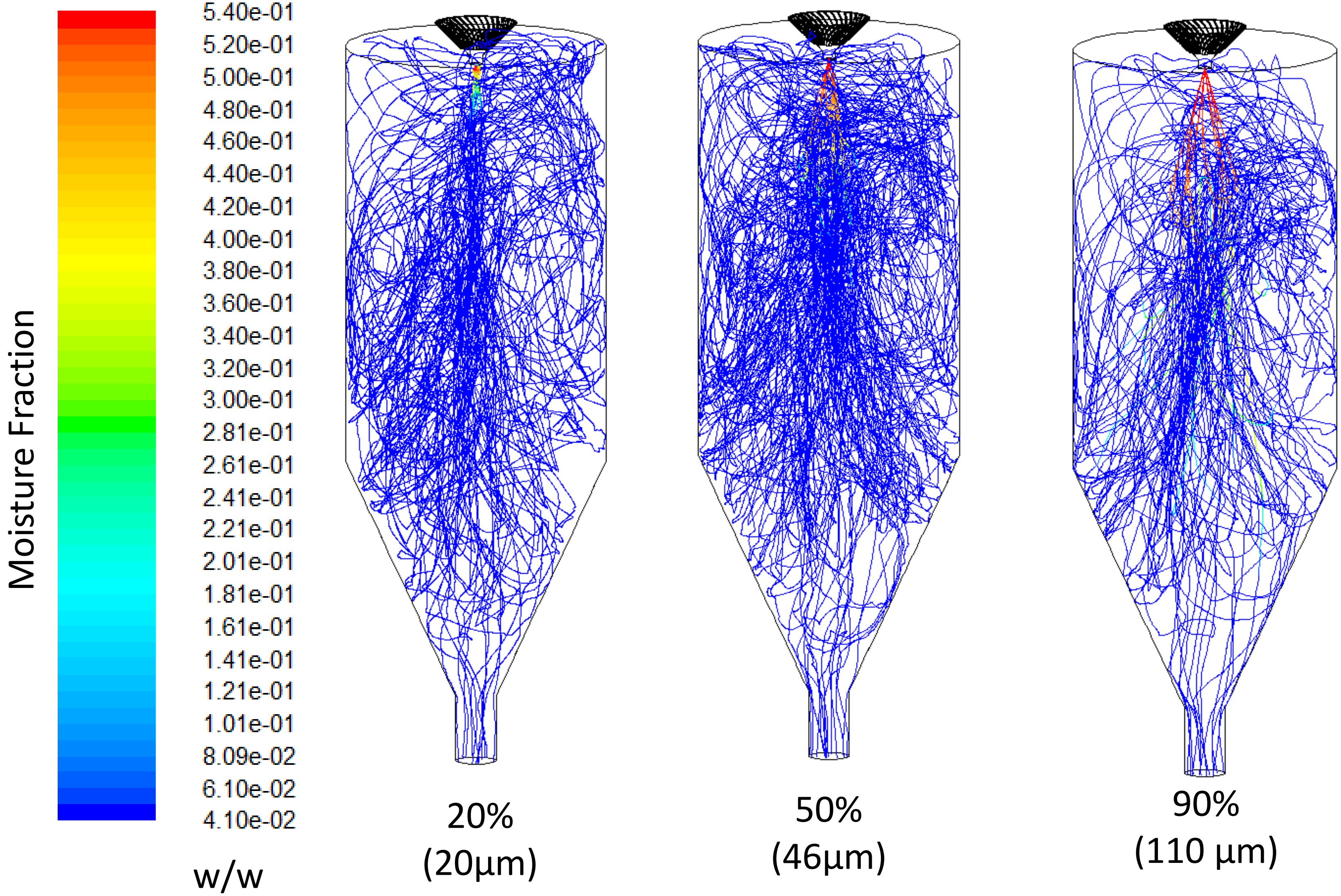

Trajectories coloured by Particle Temperature

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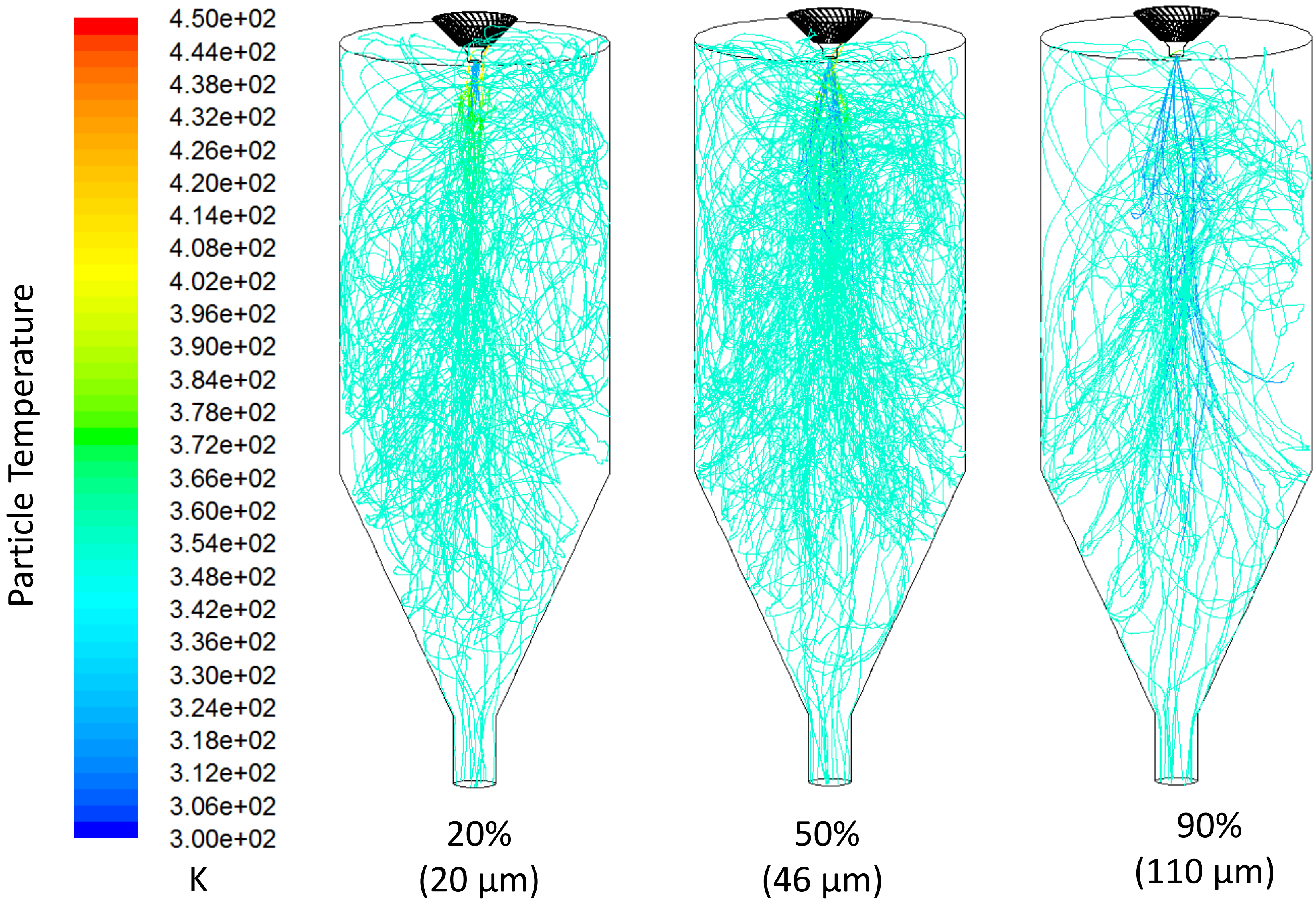

Air Velocities with Particles

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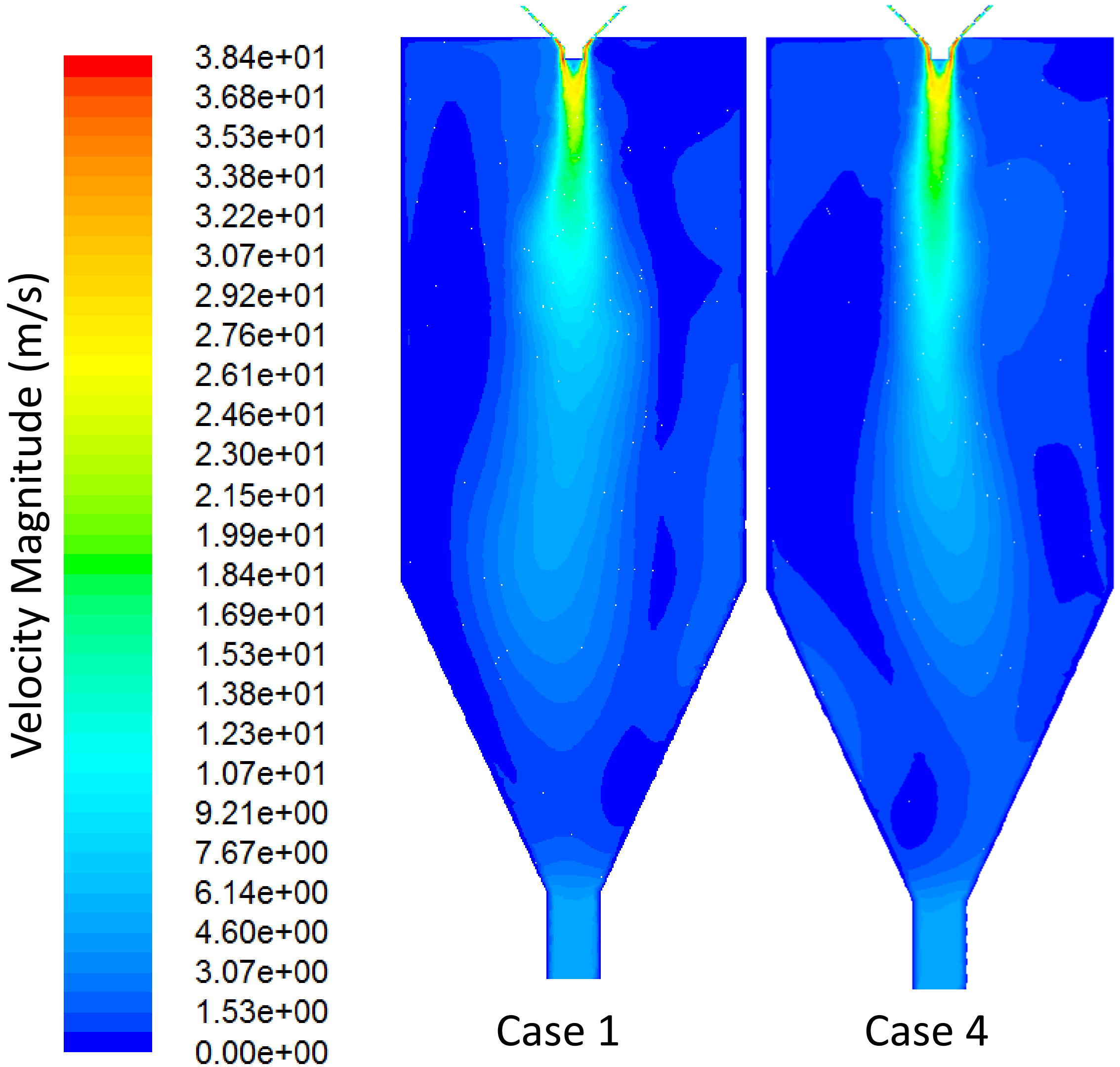

No significant change versus simulation without particles

Air Temperature

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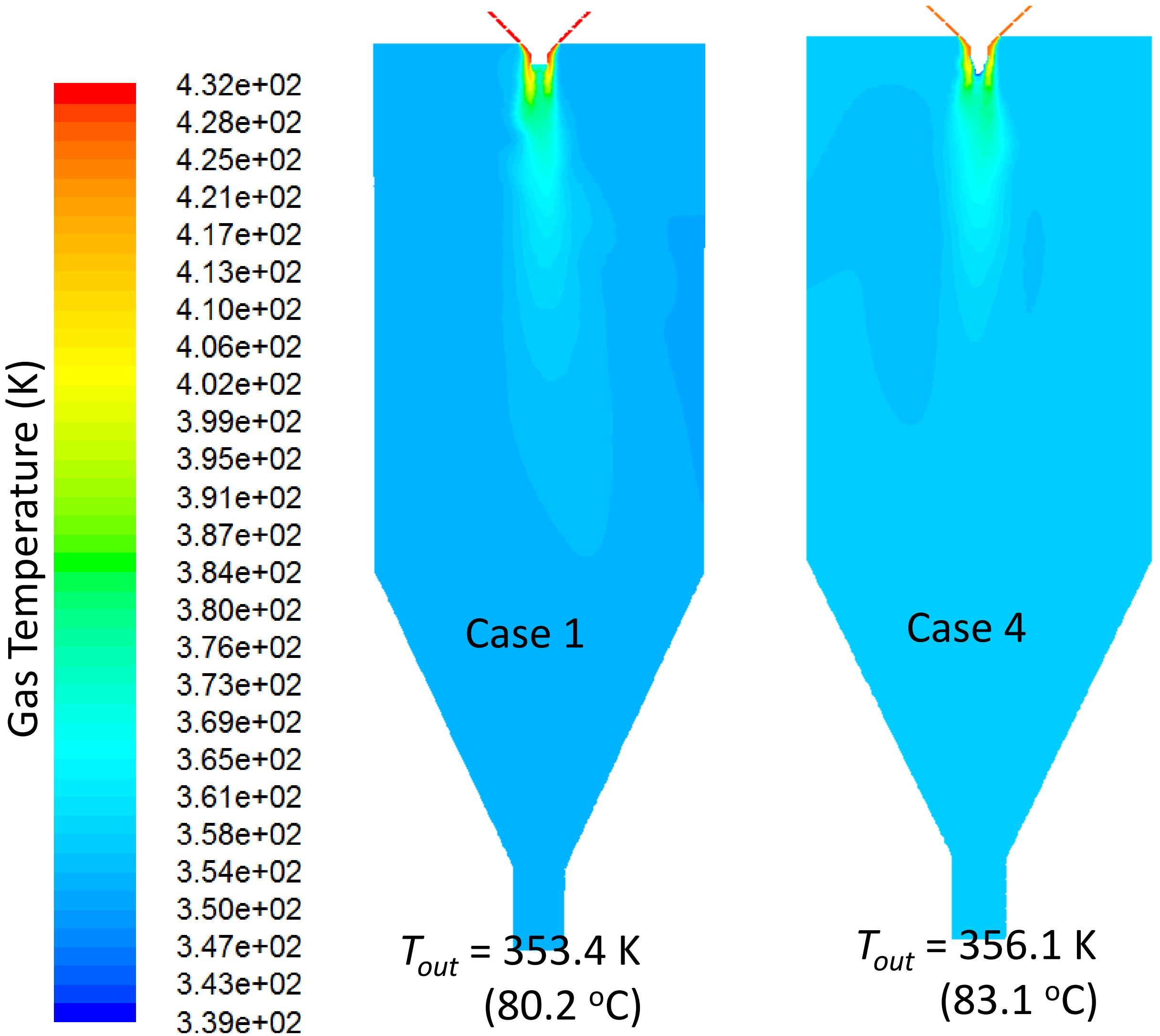
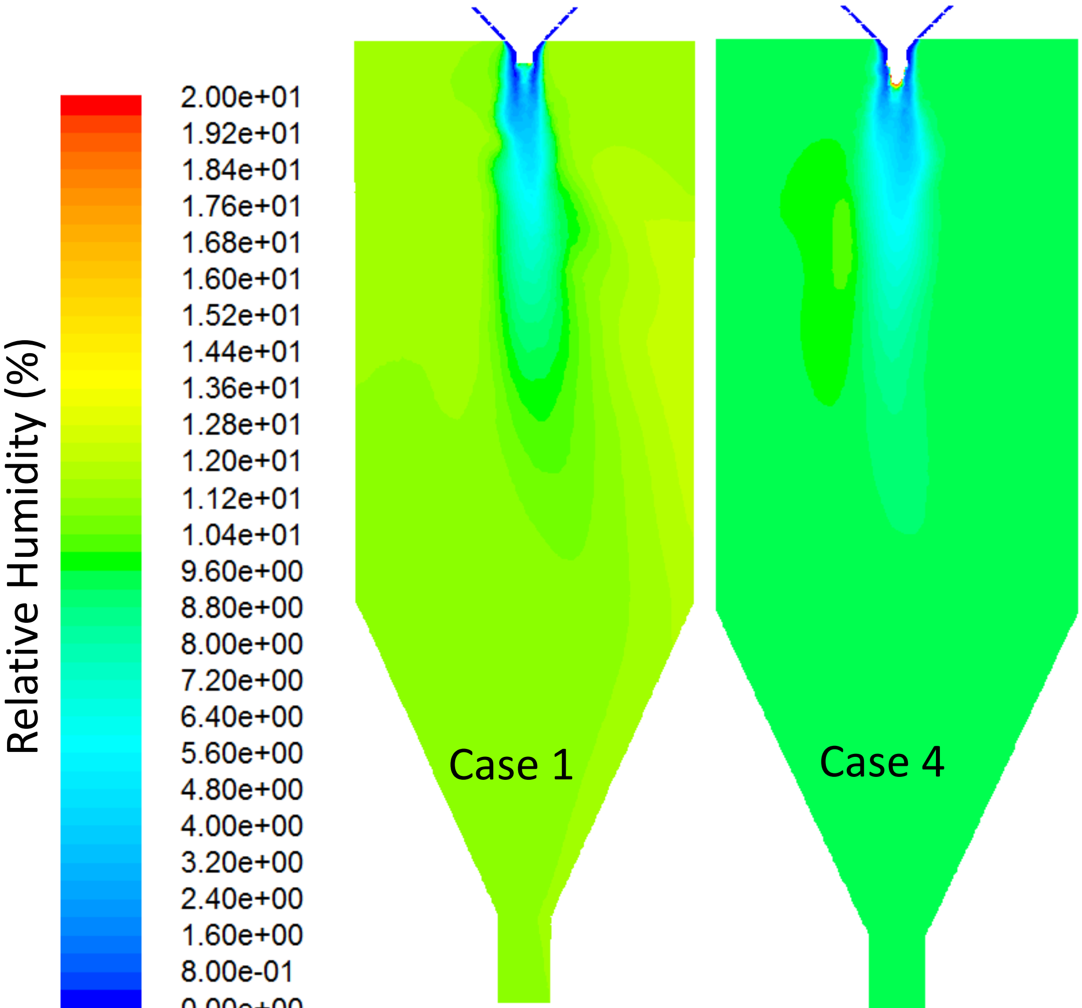


Small hot jet surrounded by large cool region

Measured T_{out} = 348 K (75 °C)

Air Moisture



RH_{out} = 11.2% RH_{out} = 9.2%

Small dry jet surrounded by large humid region

CFD Modelling Results (cont.)

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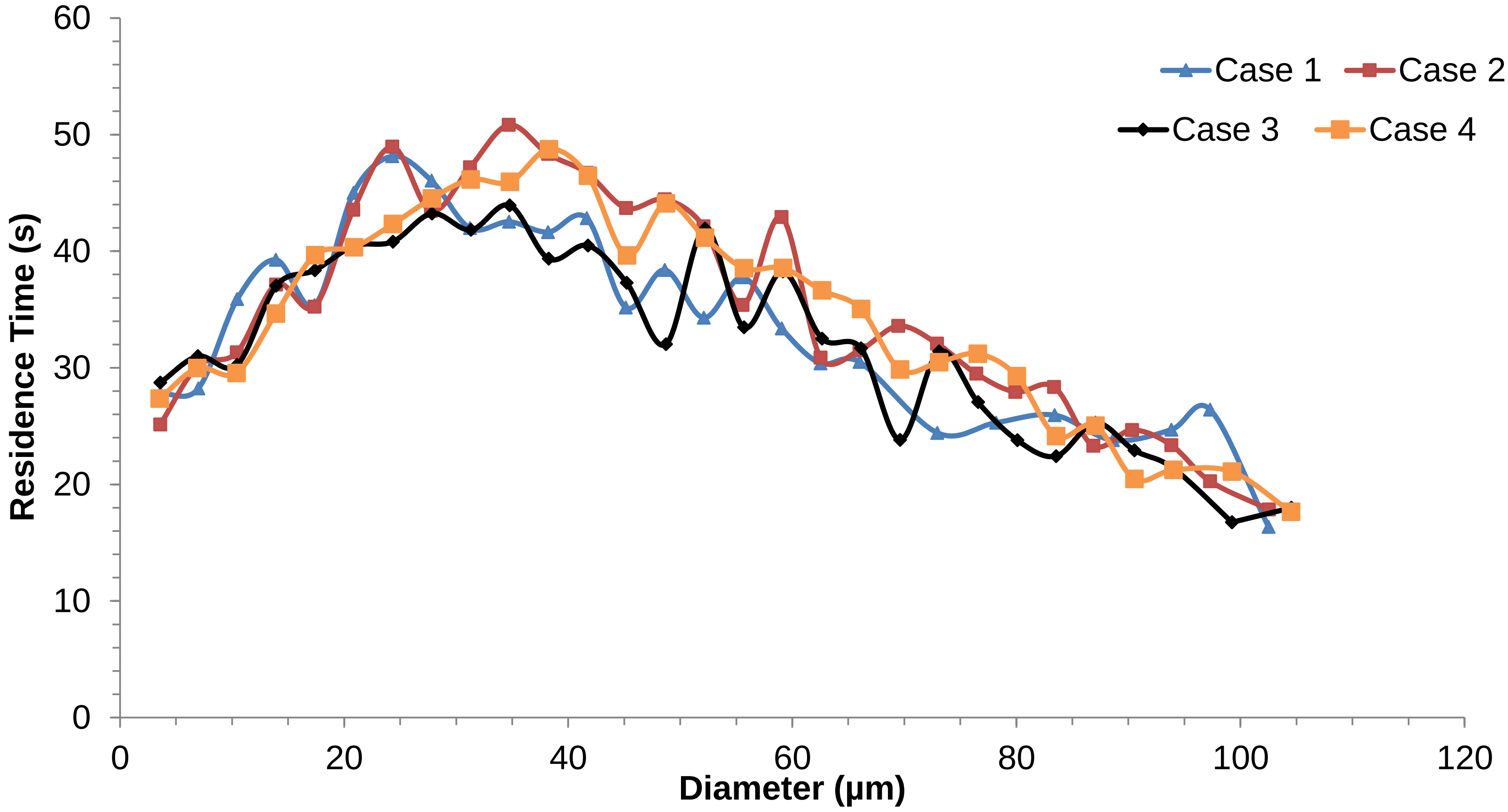
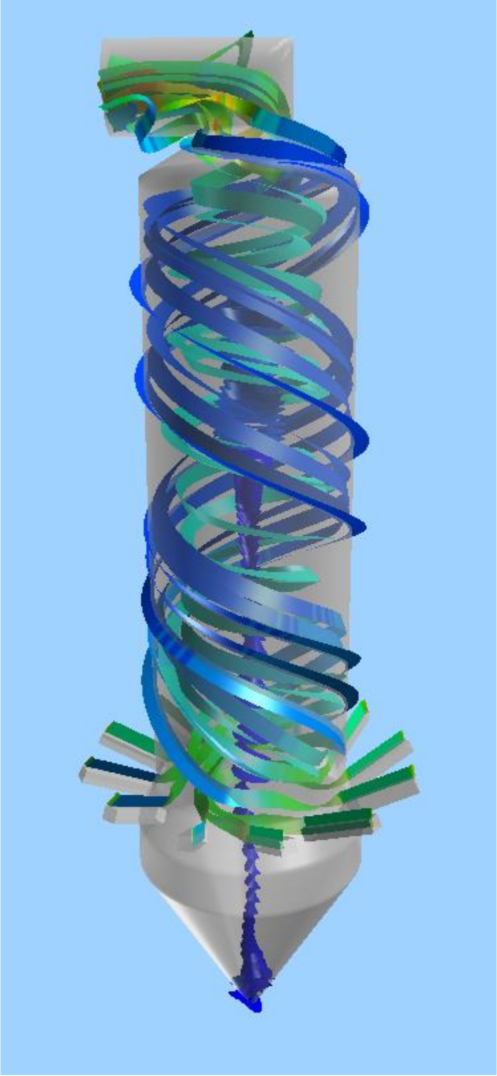
Average residence times of particles of various sizes.



Co-current Summary

- Drying all occurring near nozzle
  -> Particle moisture in equilibrium with exhaust air
- You don’t need CFD to predict moisture (in this case), …… however to model deactivation of enzyme you need particle histories
- A given particle size’s residence time is independent of the overall initial particle size

Counter-Current Tower



Counter-current

- Inlet Temp. 300C
- Swirling component to inlet air

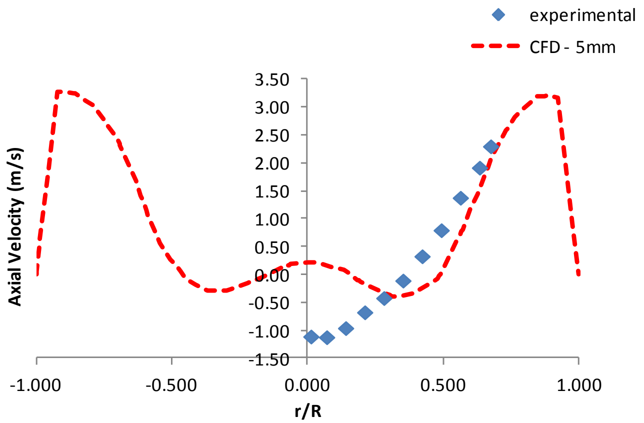
Multiple nozzles and nozzle levels

Some granules collide and stick together – agglomeration

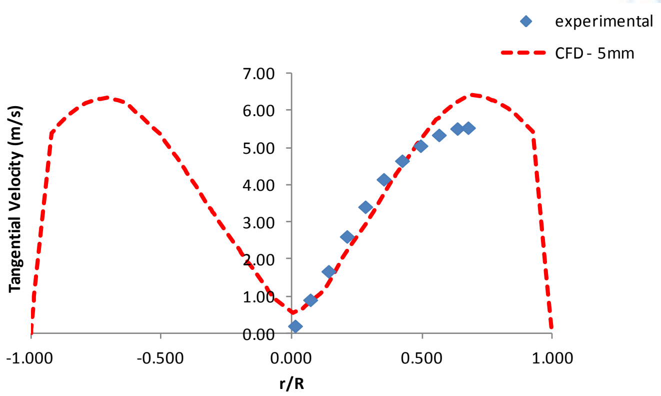
Puffing occurs creating internal porosity

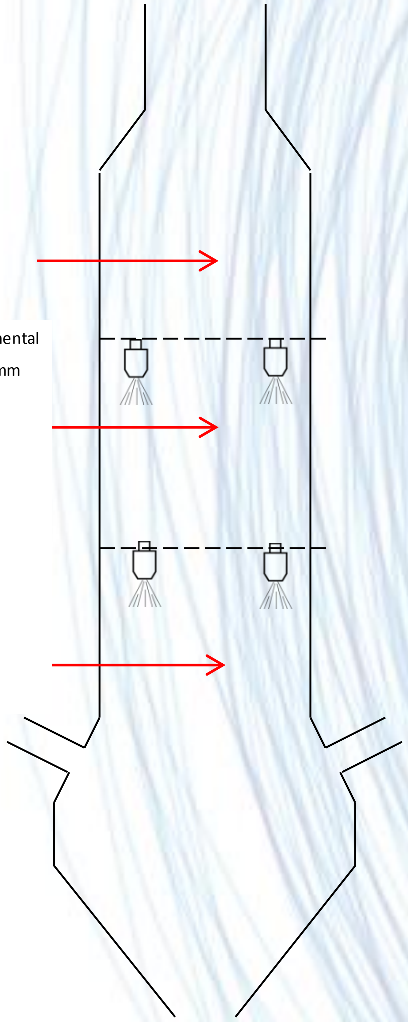
Experimental Air Flows vs CFD

Axial



Tangential





Critical to calibrate the level of wall friction in CFD to give correct tangential velocity

Measurements by V. Francia Garcia
CFD by M. Ali

CFD Modelling Results - Trajectories

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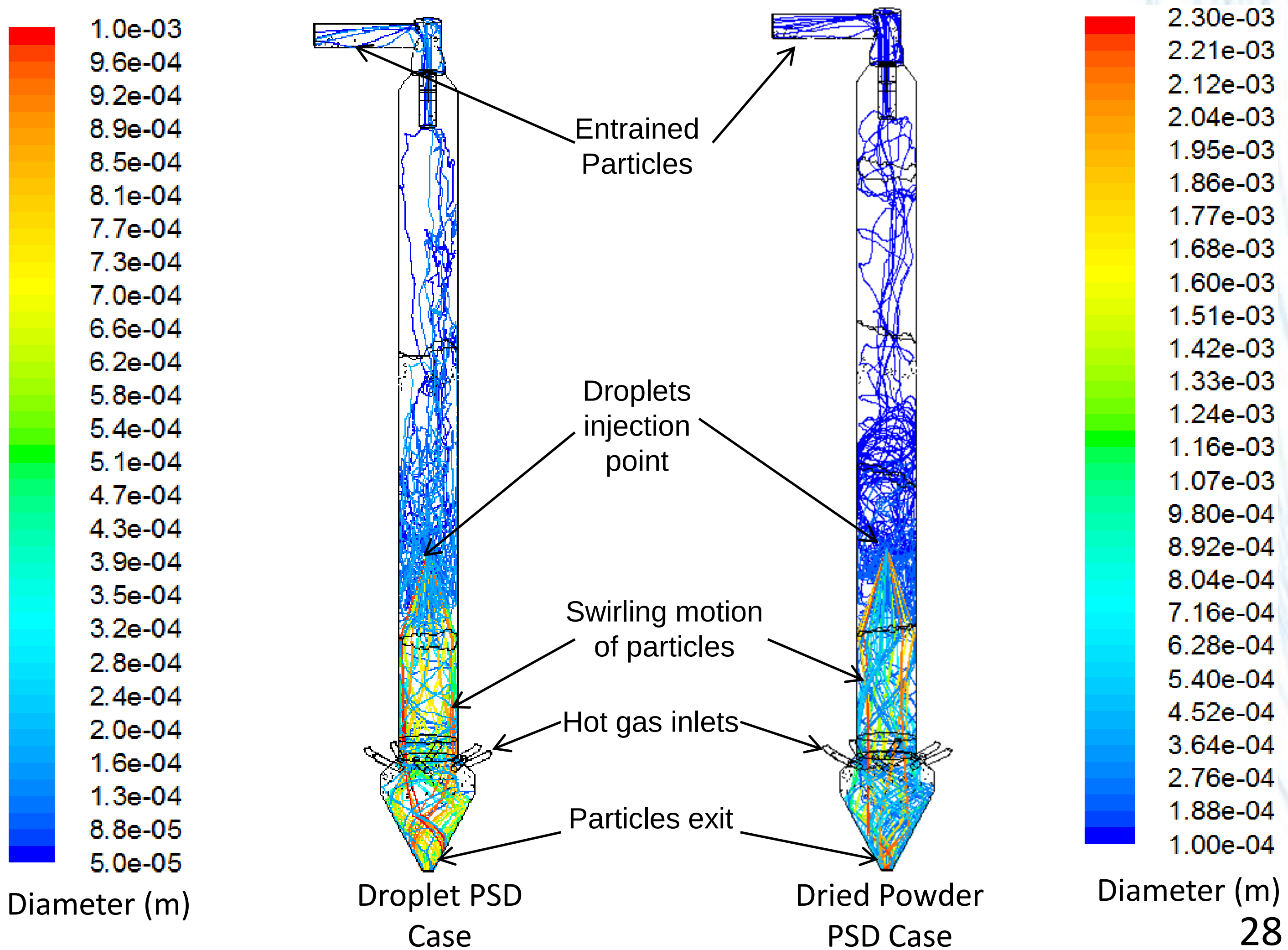
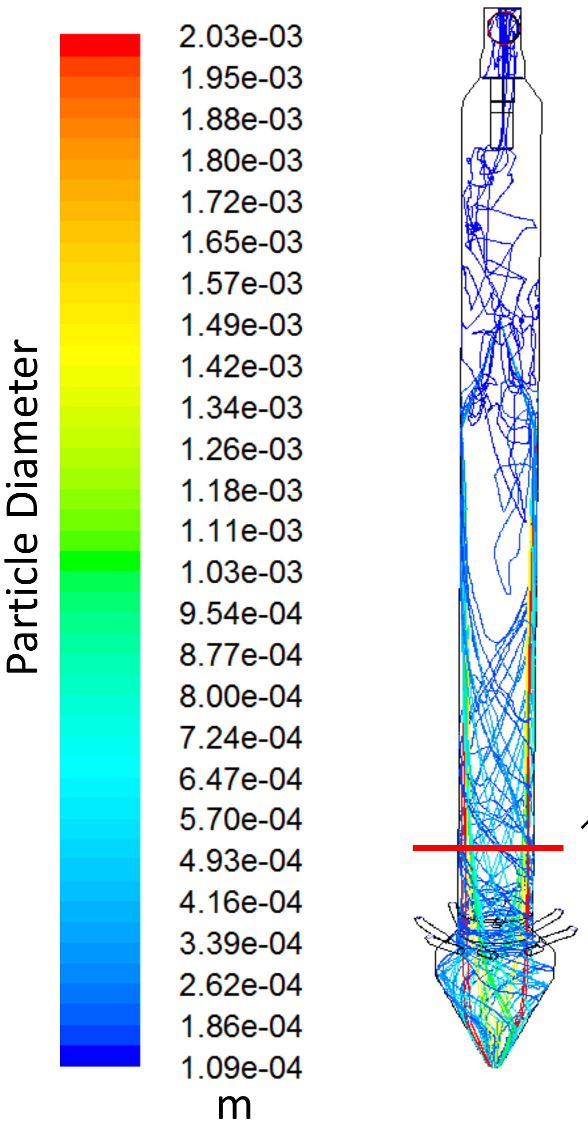
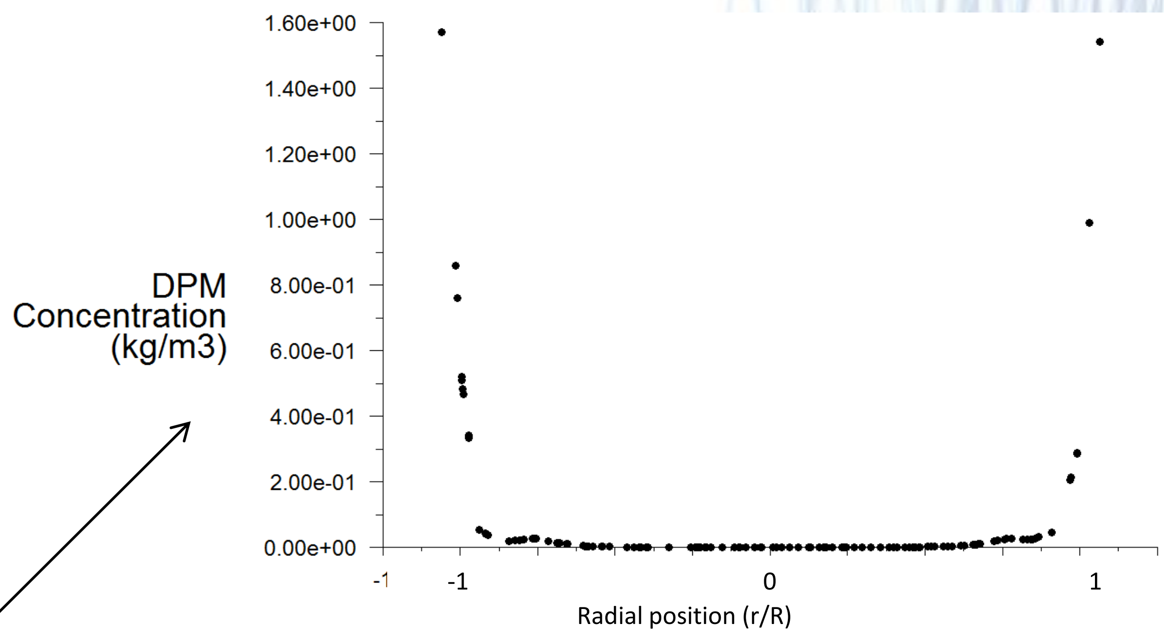
Predicted Droplets/Particle Trajectories



Trajectories and concentration



<u>Concentration of particles along the radius in the cylindrical region (*z/Z*=0.2)</u>



RTD measurements glass beads discharge

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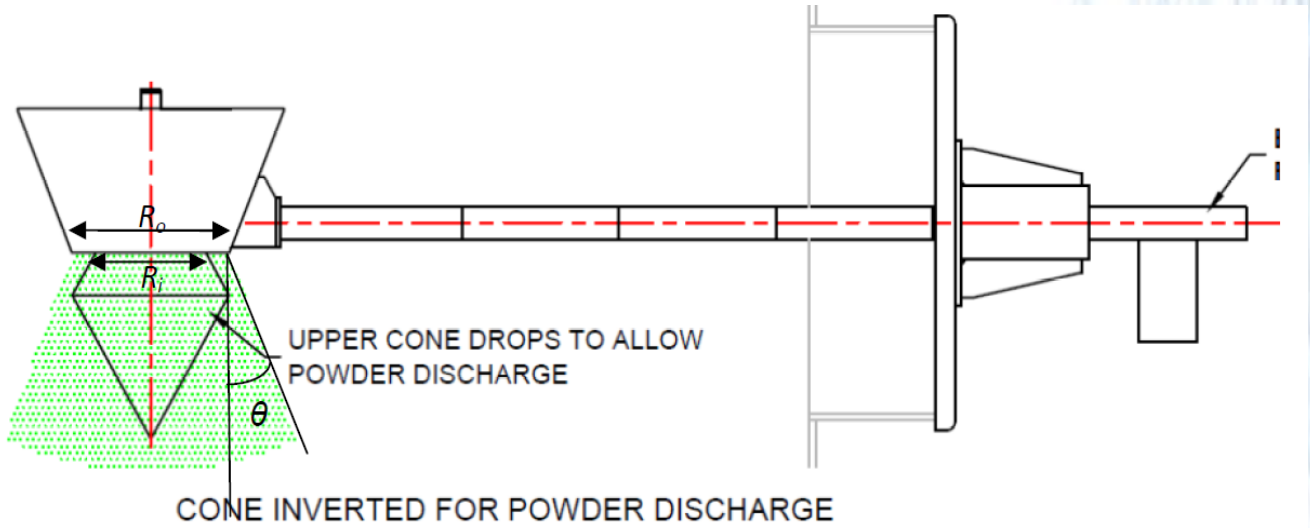

Pulse of glass beads added, time to exit measured

Glass Beads

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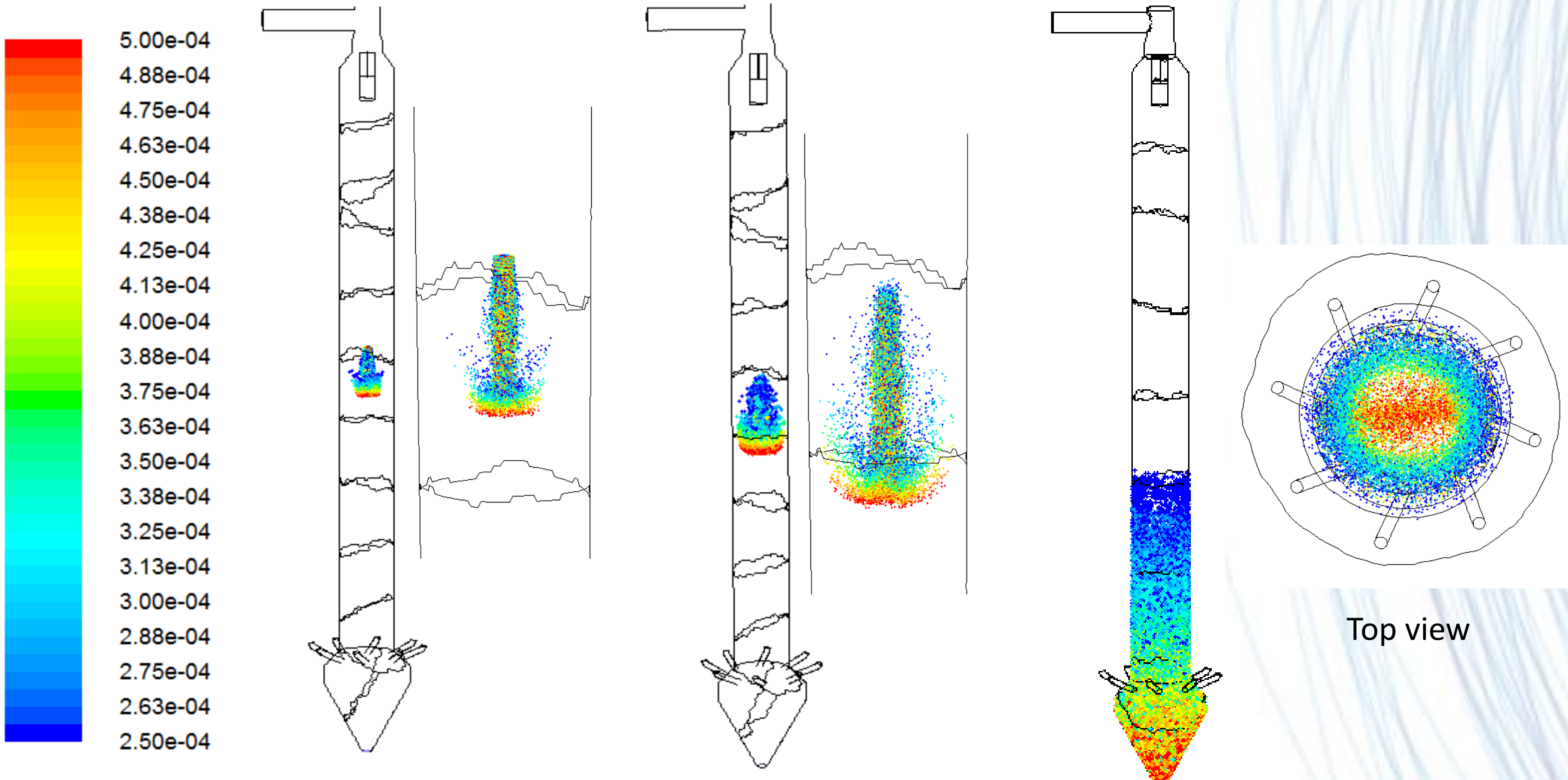

0.7s

1.02 s

5.7 s

Diameter (m)

Predicting Residence Time

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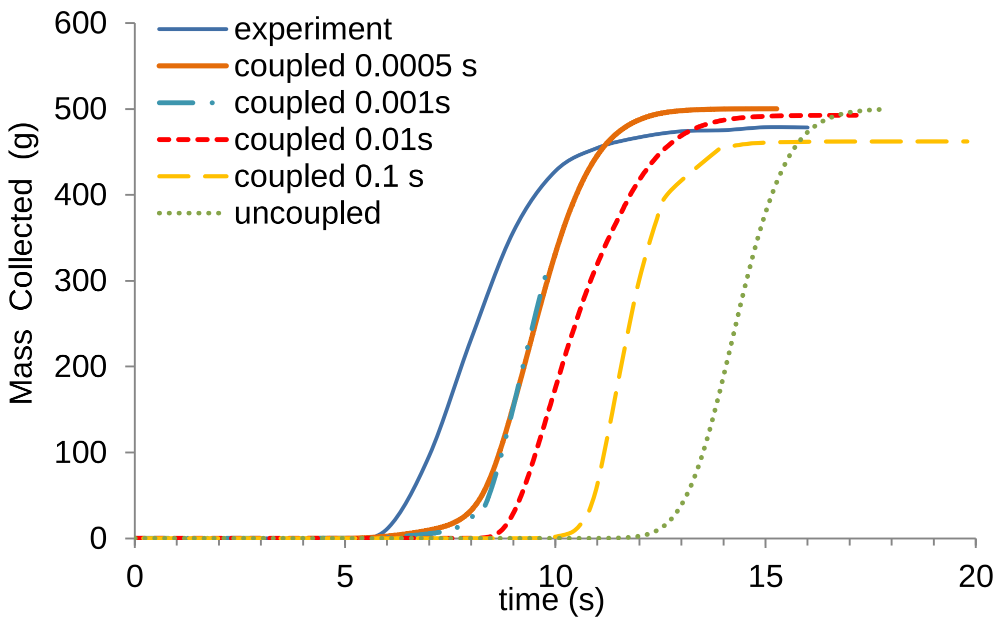

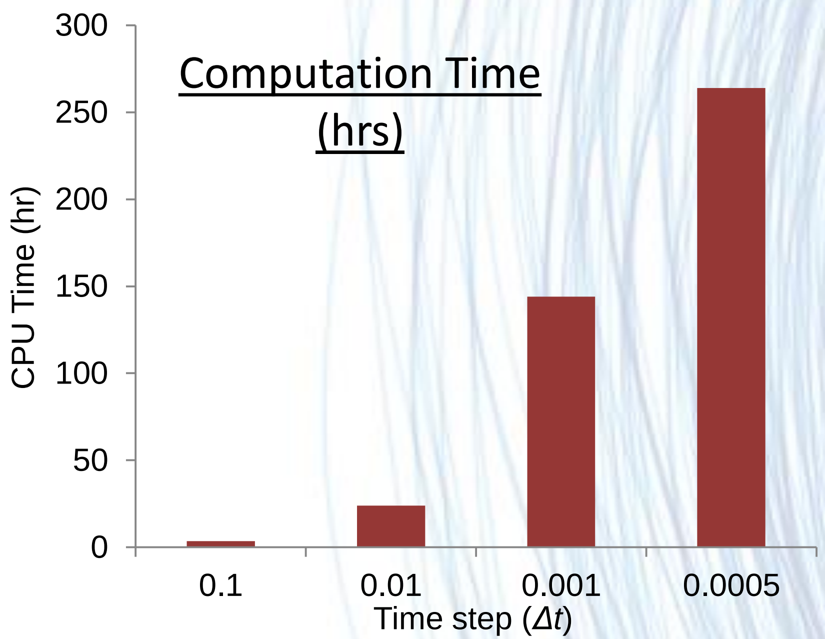

Effect of time step on predicted residence times

- Unsteady simulation
- Momentum coupling is important and must be included
- Wall collision model important

CFD Modelling Results
Comparison of Exit Moisture

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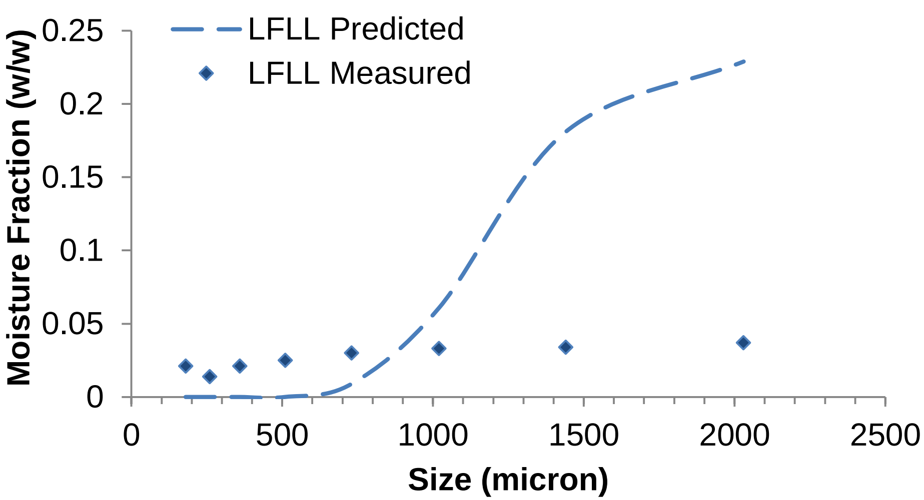

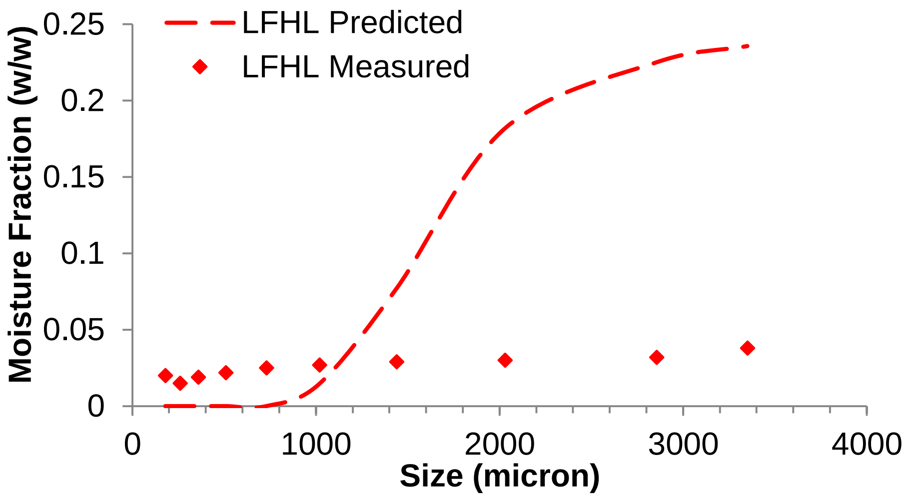

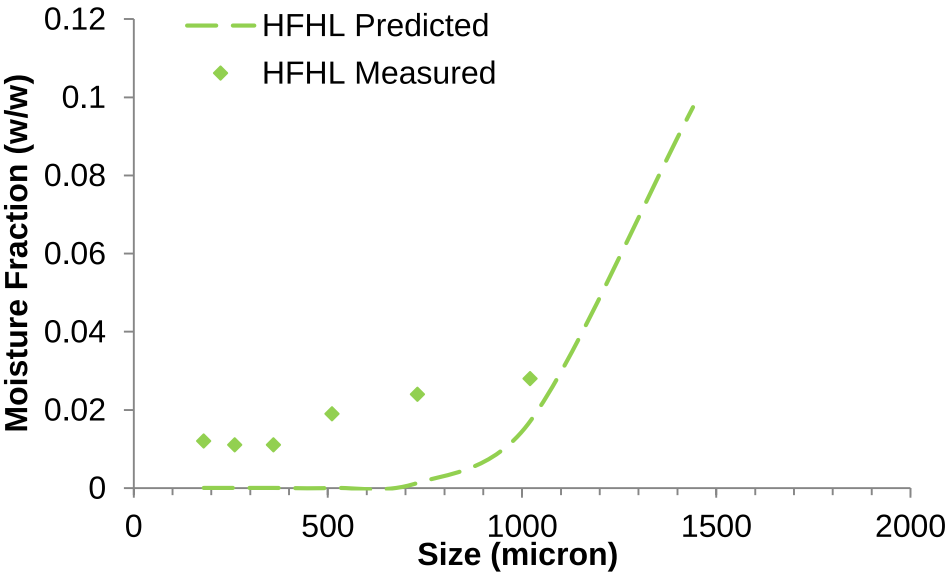

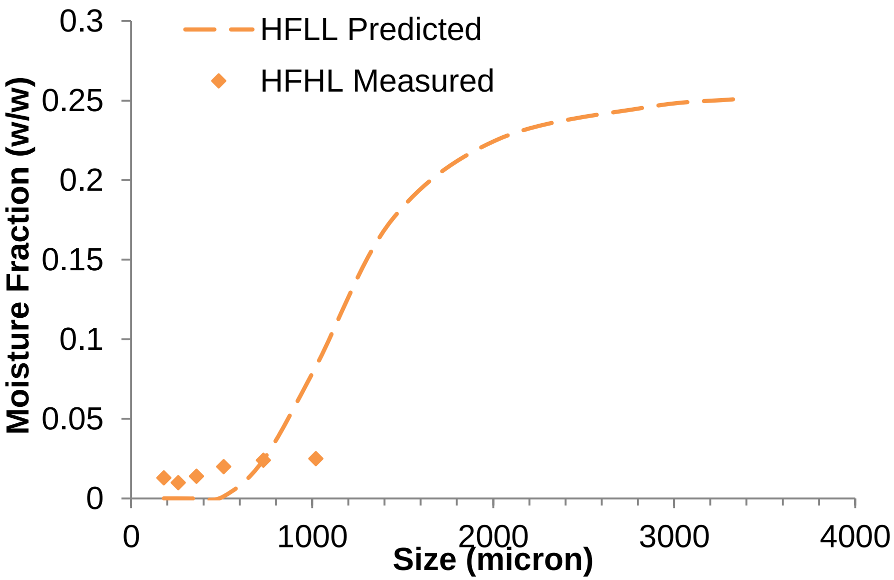

Size Distributions – Droplet and Product

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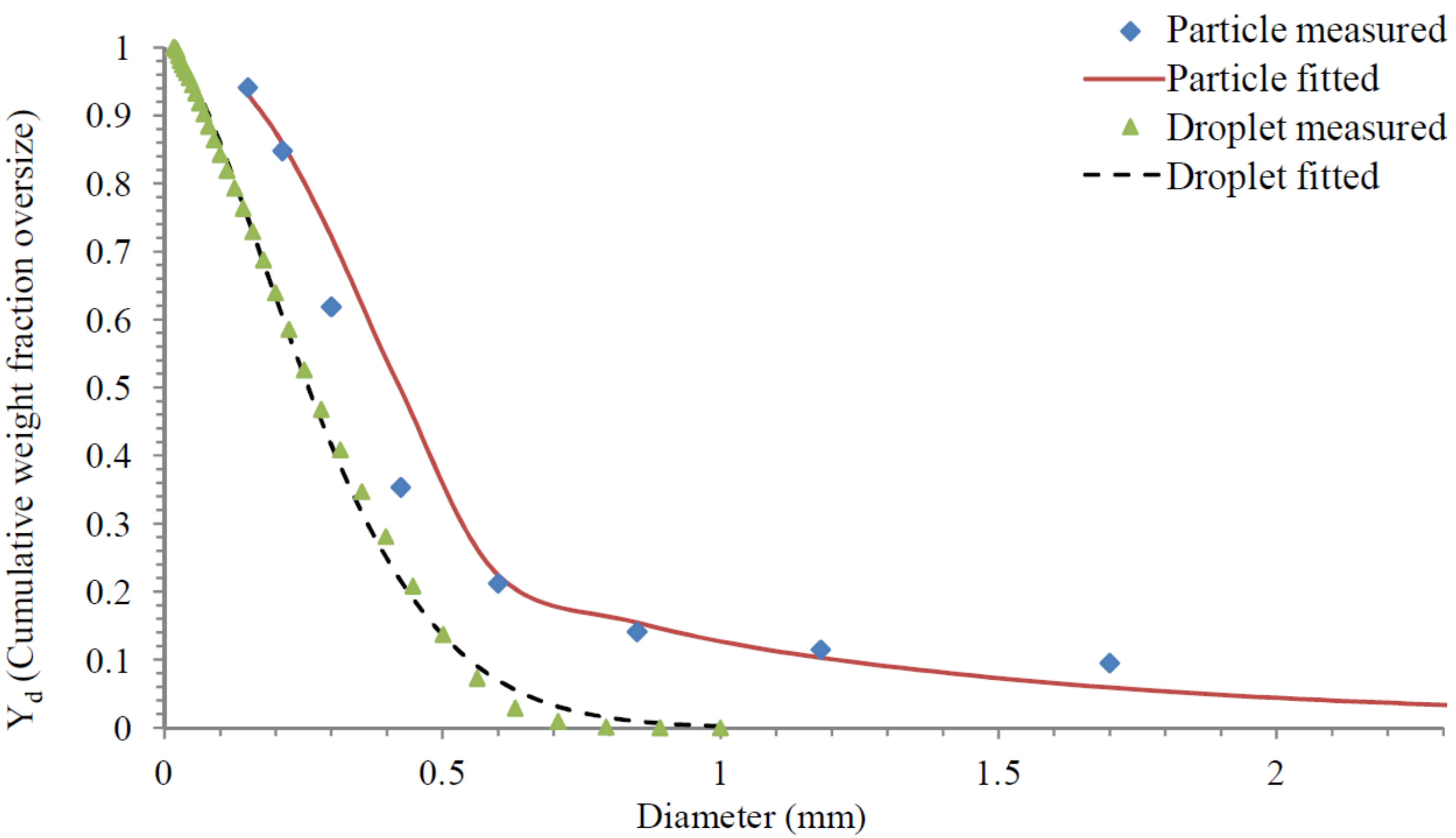


Measured data and Rossin-Ramler fits

Counter Current Summary

- Complex air flow dominated by swirl.
- Residence time agrees (in some cases)
- Agglomeration
- We definitely do need compartment model, however wall collisions are likely to be key

What do we need from CFD?

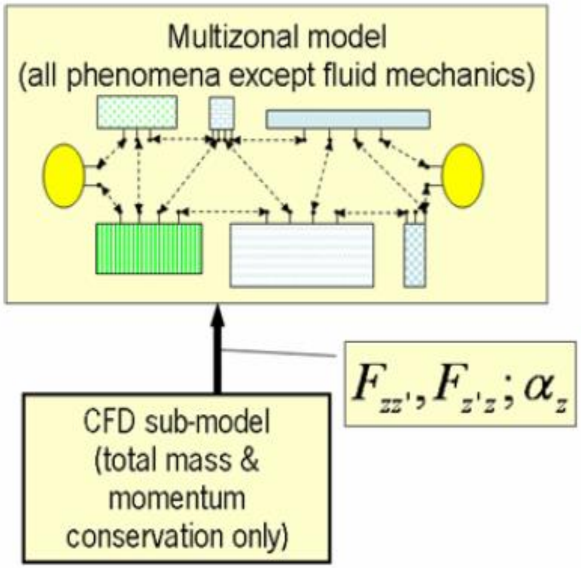
- How good are multi-phase CFD models at predicting the tower performance?
  - OK, need agglomeration, drying models, accurate BCs
- What do the air and particle flow patterns tell us about how to simplify?
  - Insights gained, especially for the co-current tower.
- Is it possible to scale the behaviour so we don’t have to run a CFD model for every condition
  - work in progress, some simplifications possible

Multizonal framework

- Well-established concept
  - separation of intrinsic phenomena (e.g. drying kinetics, agglomeration modelled in gPROMS) and macroscopic hydrodynamics (from CFD)
  - also referred to as **compartmental modelling**

- Divide the CFD solution domain into a network of zones
  - Each of these ‘internal’ zones represents a subset of cells in the CFD model

- The Multizonal model comprises a network of internal and environment zone models
  - Environment zones represent boundary conditions from CFD (e.g. inlet of hot air, outlet of particles)
  - Flow between zones defined by CFD data



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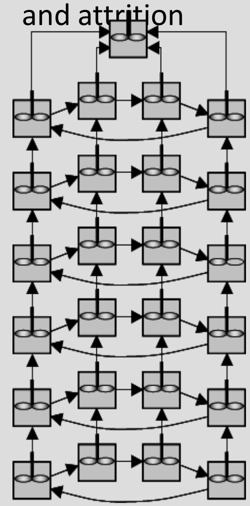
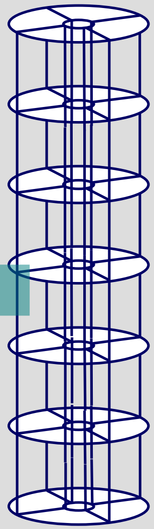
Extension to Eulerian-Lagrangian simulations

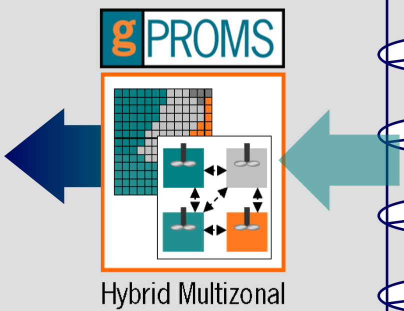
- Multizonal concept previously for continuous phase only
- CFD
  - Fluid dynamics (Eulerian)
  - Particle dynamics (Lagrangian)
- gSOLIDS
  - Well-mixed zone model
  - Detailed droplet drying model
  - Population balance model to account for droplet coalescence, agglomeration and heat losses
- Flow between Multizonal internal zones extracted from CFD for both particles and vapour

gSOLIDS network of well-mixed zone models of droplet drying, coalescence and attrition



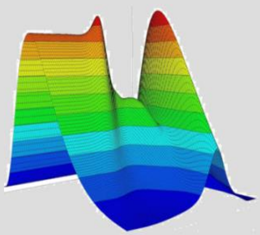
CFD model of gas flow dynamics and particle trajectory tracking





Zone model developed in gSOLIDS accounting for detailed droplet drying kinetics, particle coalescence and attrition

Results
Evolution of particle size distribution as a function of time, product moisture content



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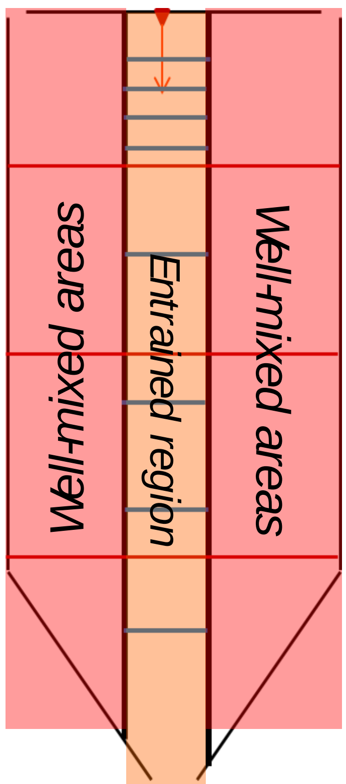
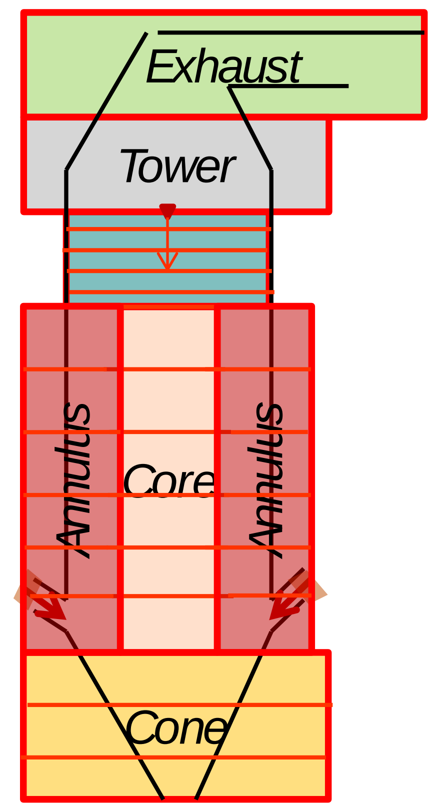
Zoning strategy

- The zoning strategy is key to extracting informative and appropriate data to configure the particle and vapour flow between zones
  - Use previous studies and knowledge, as well as CFD results, to compartmentalise areas of similar characteristics such as concentration, temperature and flow pattern.





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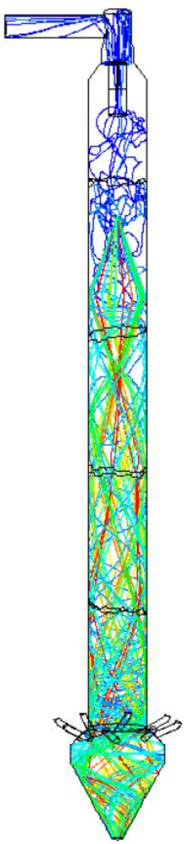
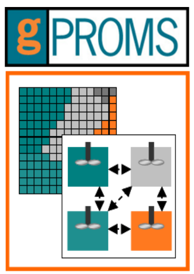
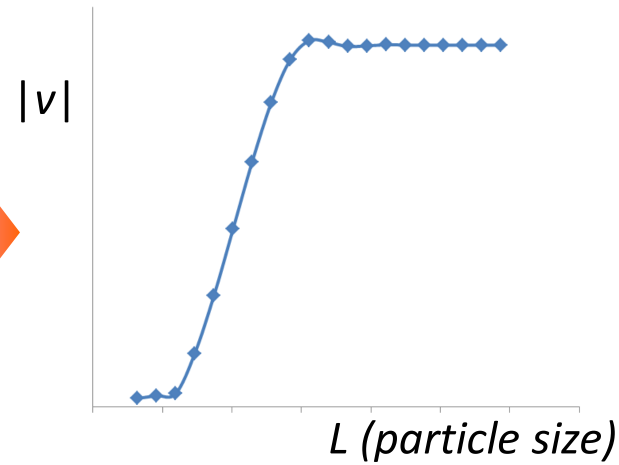
Coupling CFD and gSOLIDS

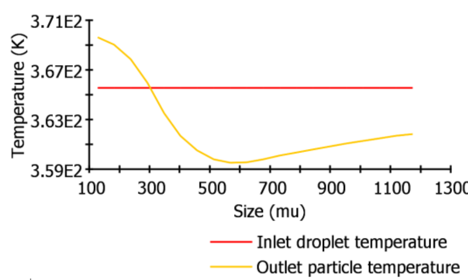
- Particle velocities sampled at each zone interface
  - Multizonal UDF extracts and writes data
  - Multizonal FO processes data to create velocity distribution at each interface of an internal zone to pass to compartmental model

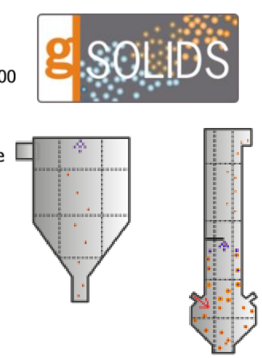


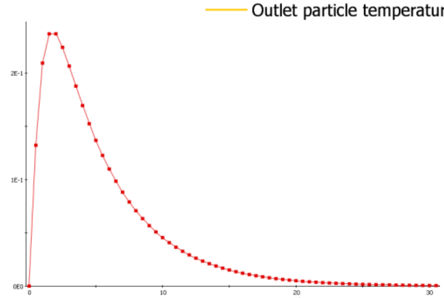


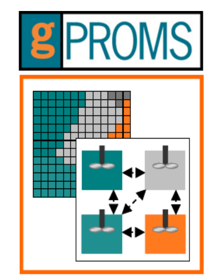
Hybrid Multizonal
UDF











Hybrid Multizonal

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Modelling of key phenomena

In the Multizonal model

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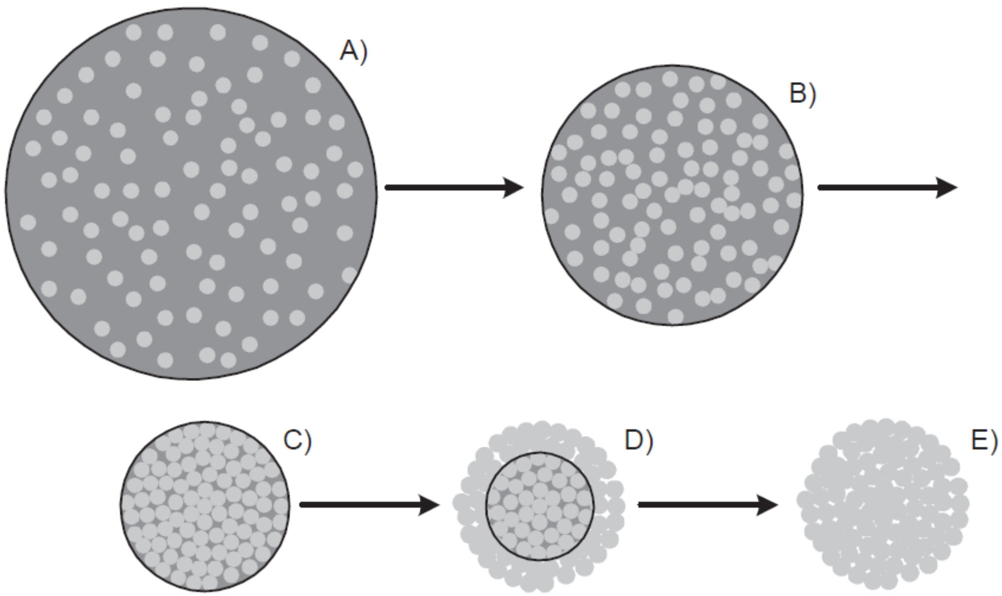
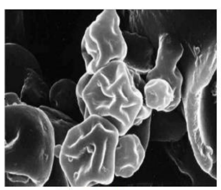
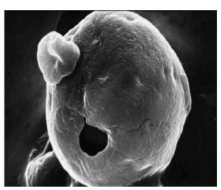
Droplet drying model

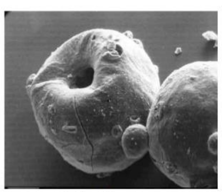


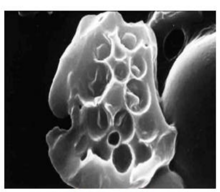
Constant rate drying*: Heat transfer to surface from bulk and diffusion into vapour are rate limiting*

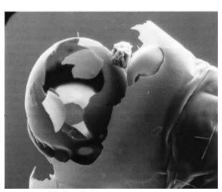
Falling rate drying*: Moisture transport to particle surface is rate limiting*

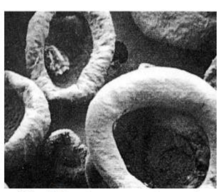

(a) Collapse.

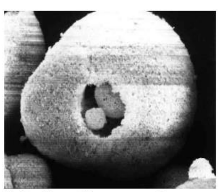

(b) Blow hole.


(c) Crater.


(d) Cavities.


(e) Fractures.


(f) Mushroom-head.


(g) Small particles inside larger.

[1] J. Sloth (2007) Formation of enzyme containing particles by spray drying. Ph.D. thesis, Technical University of Denmark and Novozymes A/S

[2] Jakob Sloth, Poul Bach, Anker D. Jensen, Soren Kiil, Evaluation method for the drying performance of enzyme containing formulations, Biochemical Engineering Journal, Volume 40, Issue 1, 15 May 2008, Pages 121-129

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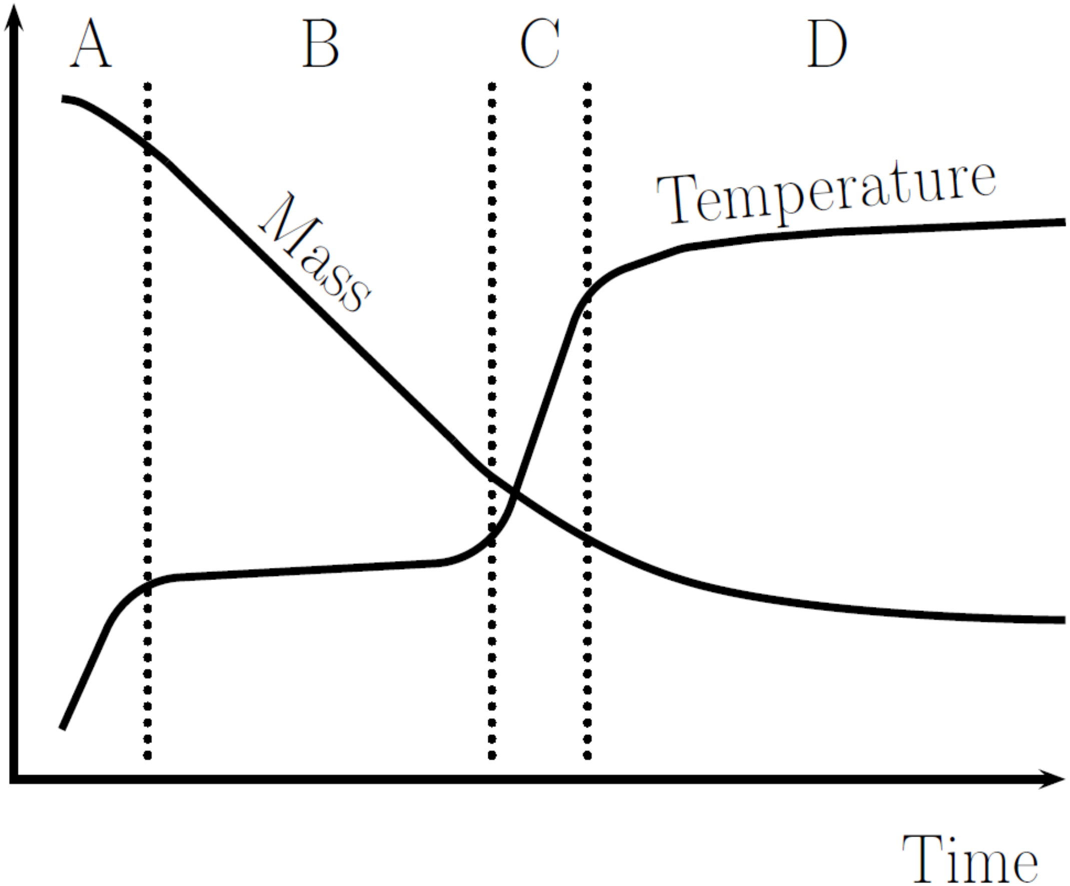
Droplet drying model: four stages of drying



A. *Induction: Heating droplet to wet bulb temperature*

B. *Constant rate drying period*

C. *Falling rate drying period*

D. *Further heating of dry particle*

[1] J. Sloth (2007) Formation of enzyme containing particles by spray drying. Ph.D. thesis, Technical University of Denmark and Novozymes A/S

[2] Jakob Sloth, Poul Bach, Anker D. Jensen, Soren Kiil, Evaluation method for the drying performance of enzyme containing formulations, Biochemical Engineering Journal, Volume 40, Issue 1, 15 May 2008, Pages 121-129

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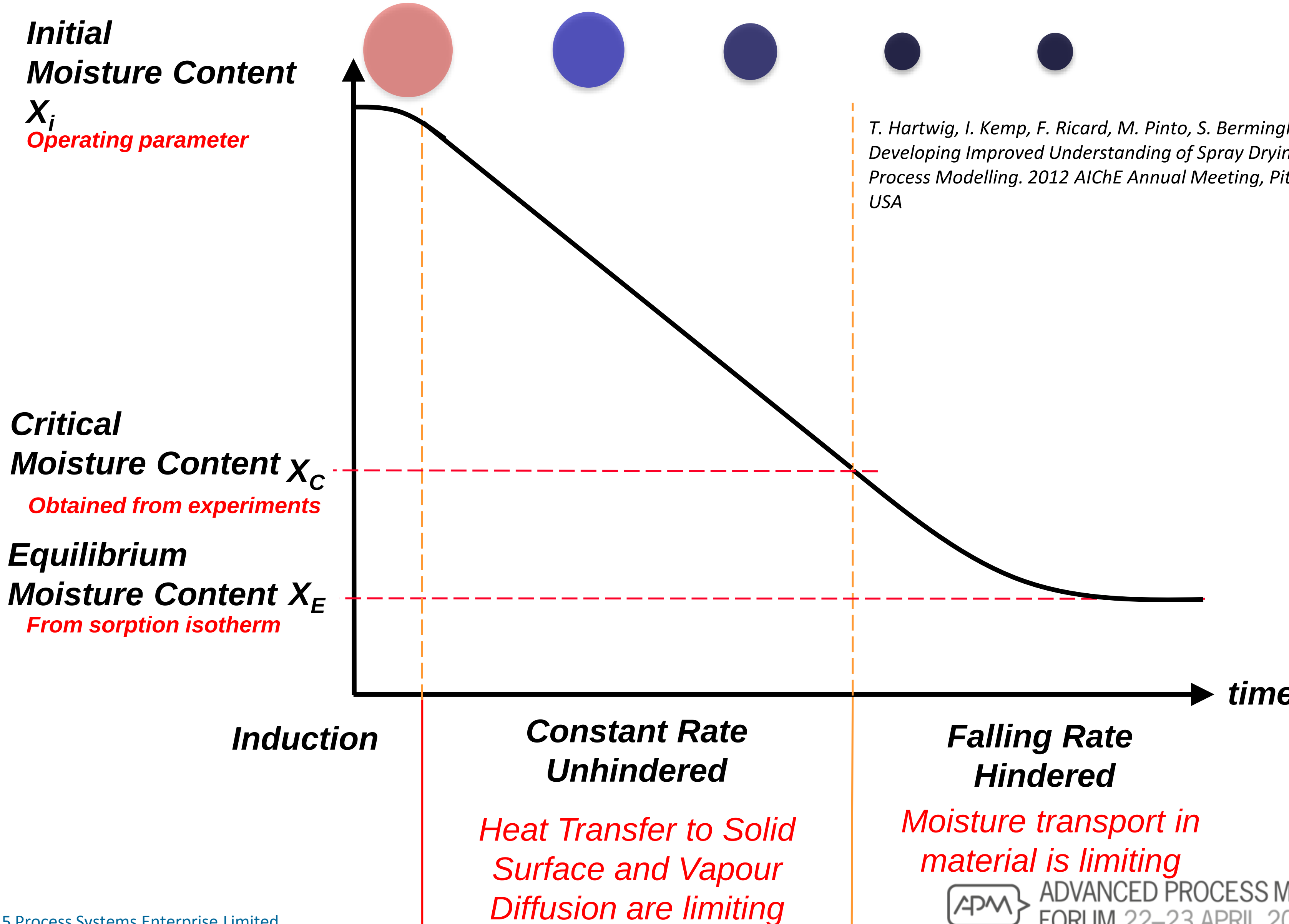
Droplet drying model: size change



T. Hartwig, I. Kemp, F. Ricard, M. Pinto, S. Bermingham. Developing Improved Understanding of Spray Drying Through Process Modelling. 2012 AIChE Annual Meeting, Pittsburgh, PA, USA

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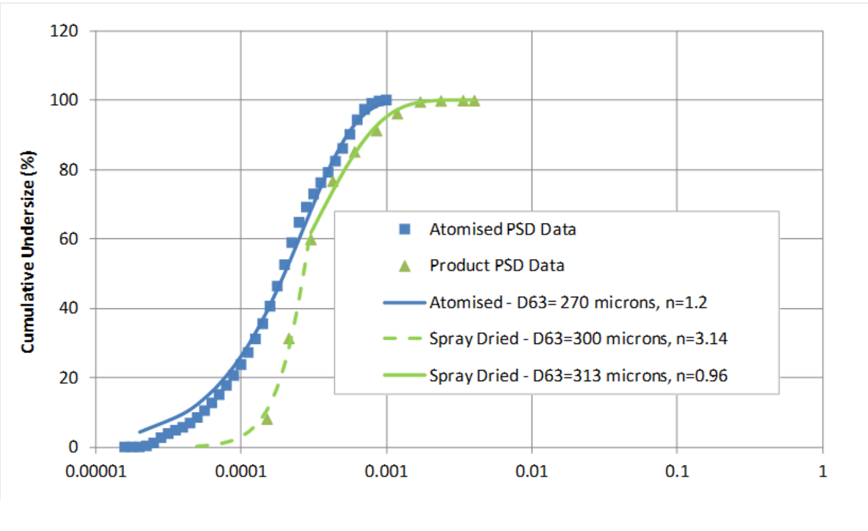
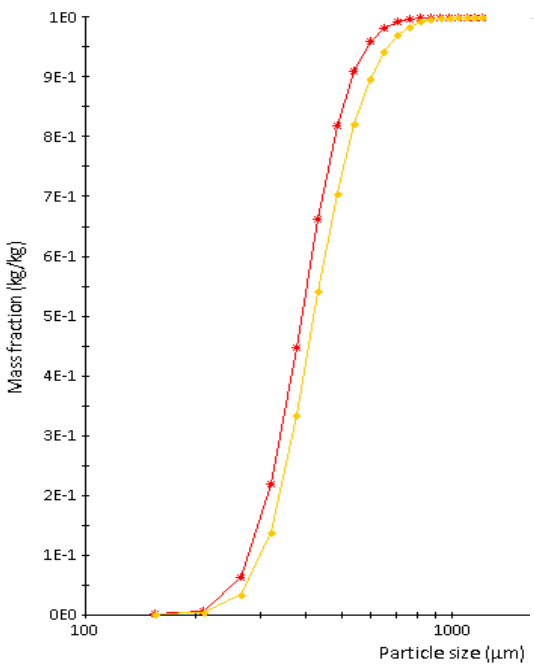
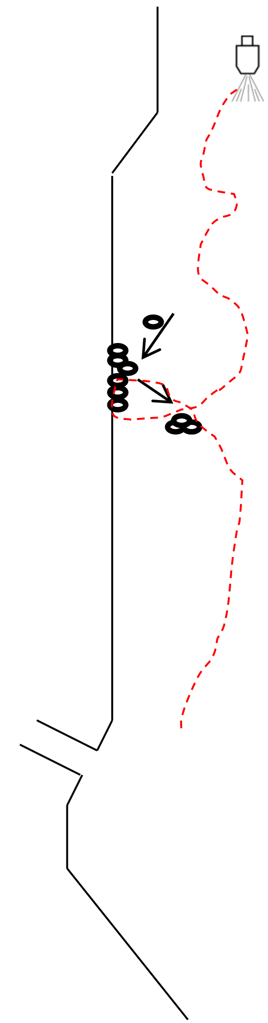
Agglomeration & coalescence





- Coalescence of droplets is incorporated where appropriate and prevalent
- Wall agglomeration and drying to be implemented to capture wet particles sticking to chamber walls
- Ability to capture shift in PSD from atomised droplet size



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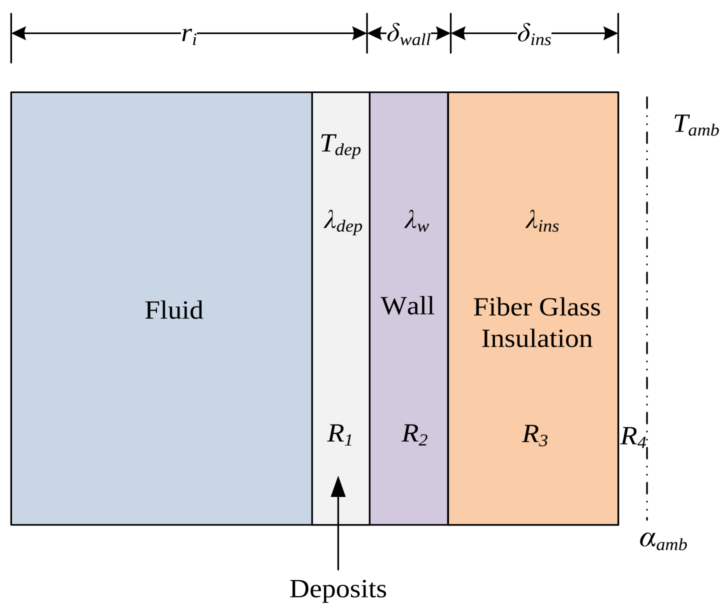
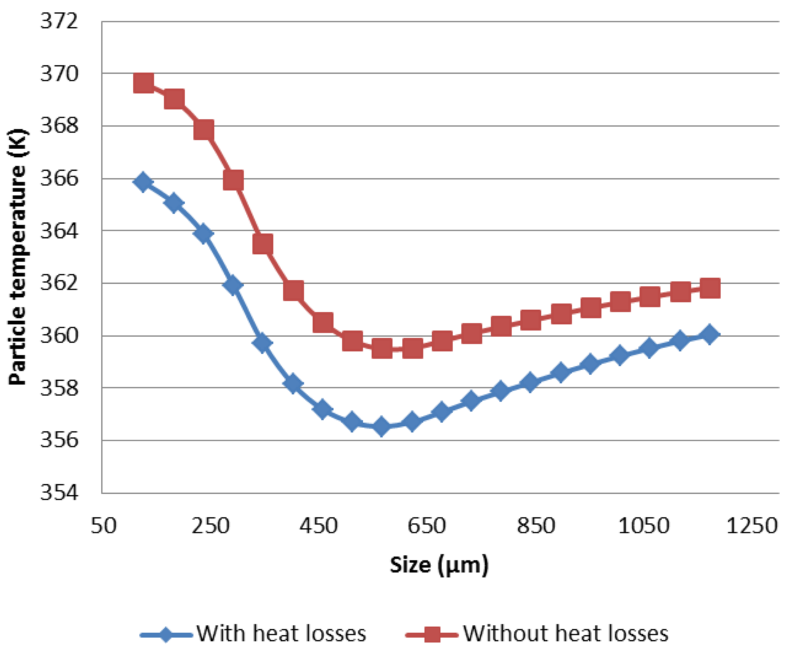
Heat losses

- Heat losses in tower can impact heavily the drying rate and temperature in the tower

$$\frac{1}{U}=\frac{r_i\ln\left(\frac{r_i}{r_i-\delta_d}\right)}{\lambda_{dep}}+\frac{r_i\ln\left(\frac{r_i+\delta_w}{r_i}\right)}{\lambda_w}+\frac{r_i\ln\left(\frac{r_i+\delta_w+\delta_{ins}}{r_i+\delta_w}\right)}{\lambda_{ins}}+\frac{r_i}{\alpha_{amb}(r_i+\delta_w+\delta_{ins})}$$





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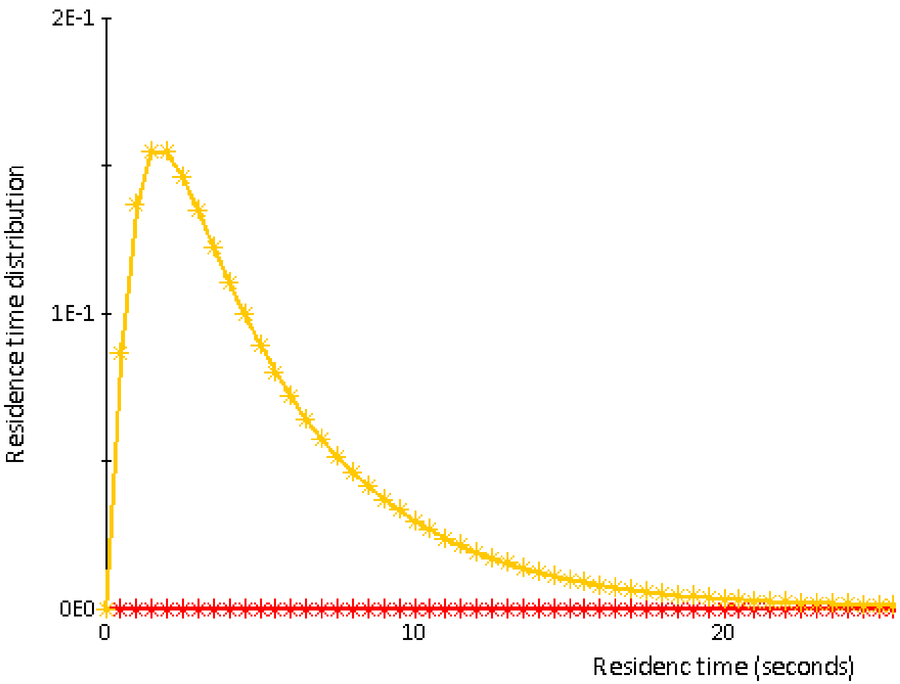
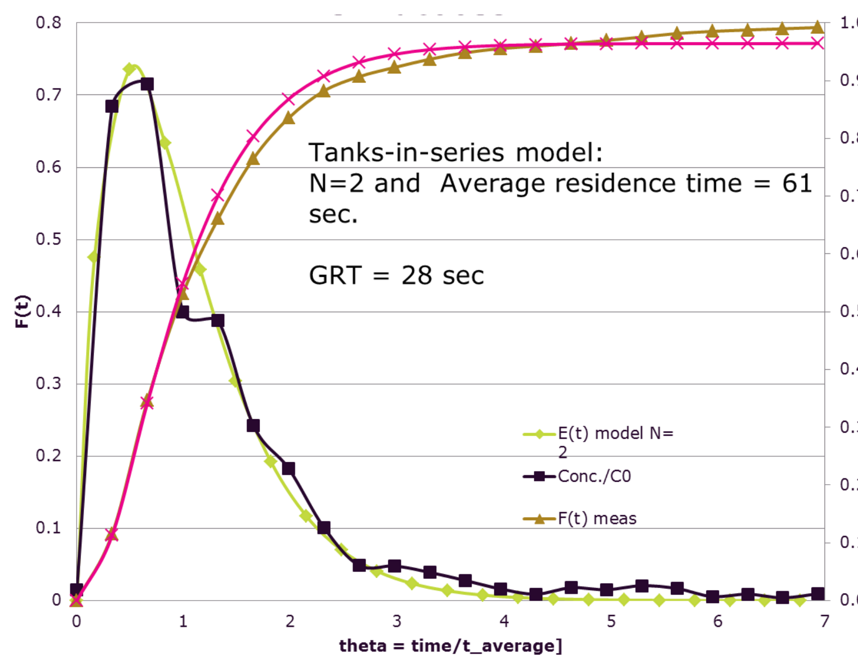
Residence time distribution

- Residence time is determined by the fluxes extracted from CFD
  - Informs mass flow between the zones of the particles
- Important to develop understanding of input process parameters on fluxes between compartments
  - Develop scaling relationships based on process conditions -> reduces number of CFD simulations





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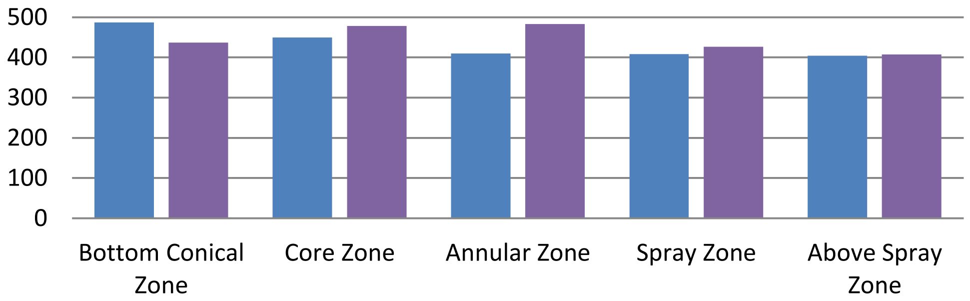
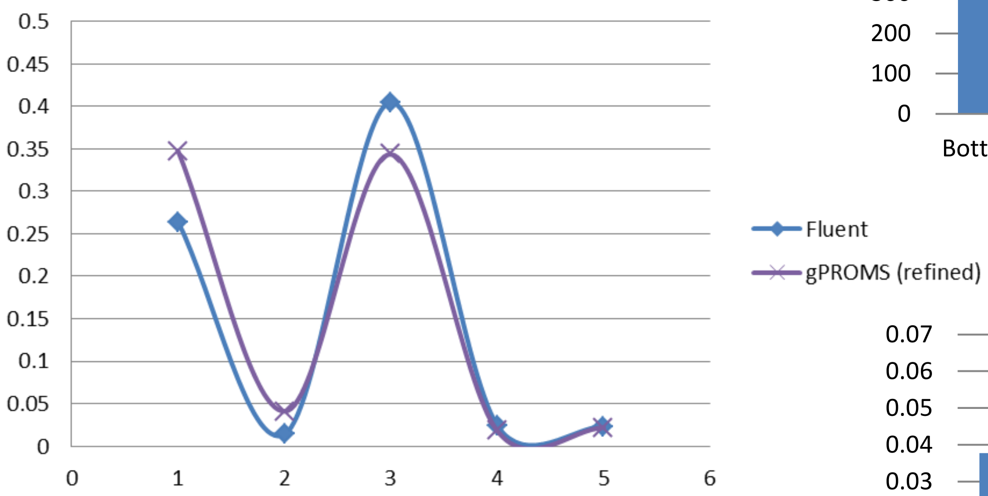
Comparison to CFD

- Capturing the dynamics and gradients within the spray dryer from CFD is vital to successfully creating compartmental model
  - Key variables include concentration of particles, temperature and vapour humidity as well as residence time
  - Zoning strategy is key to success!

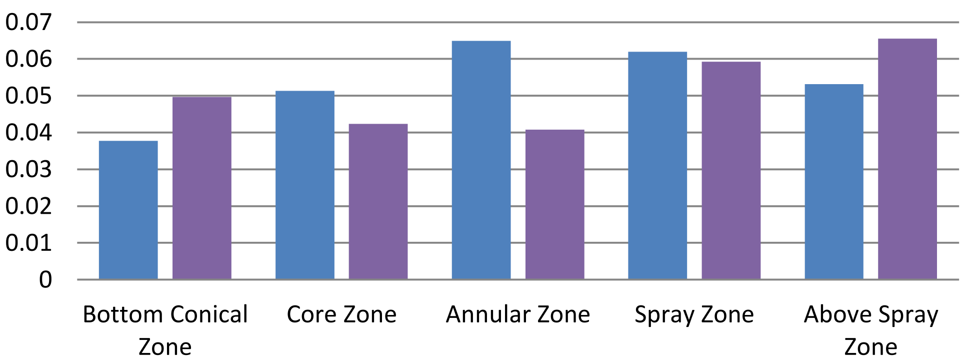
Vapour temperature (K)



Particle concentration (kg/m3)



Mass fraction h20 in vapour



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Implementation in gSOLIDS

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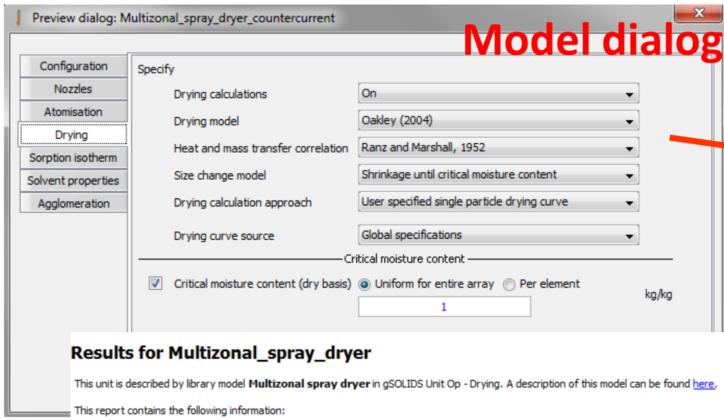
User interface and reports

- Key requirement of the compartmental model is to be user-friendly and not expert dependent like CFD

Model dialogs



Model report summaries

Results for Multizonal_spray_dryer

This unit is described by library model **Multizonal spray dryer** in gSOLIDS Unit Op - Drying. A description of this model can be found here.

This report contains the following information:

1. Inlet and outlet vapour properties (table).
2. Inlet and outlet distributed phase properties (table).
3. Mass fraction - inlet and outlet (graph).
4. Particle temperature (graph).
5. Wet basis moisture content (graph).

For further results, please see the trajectories in the case.

1. Inlet and outlet vapour properties

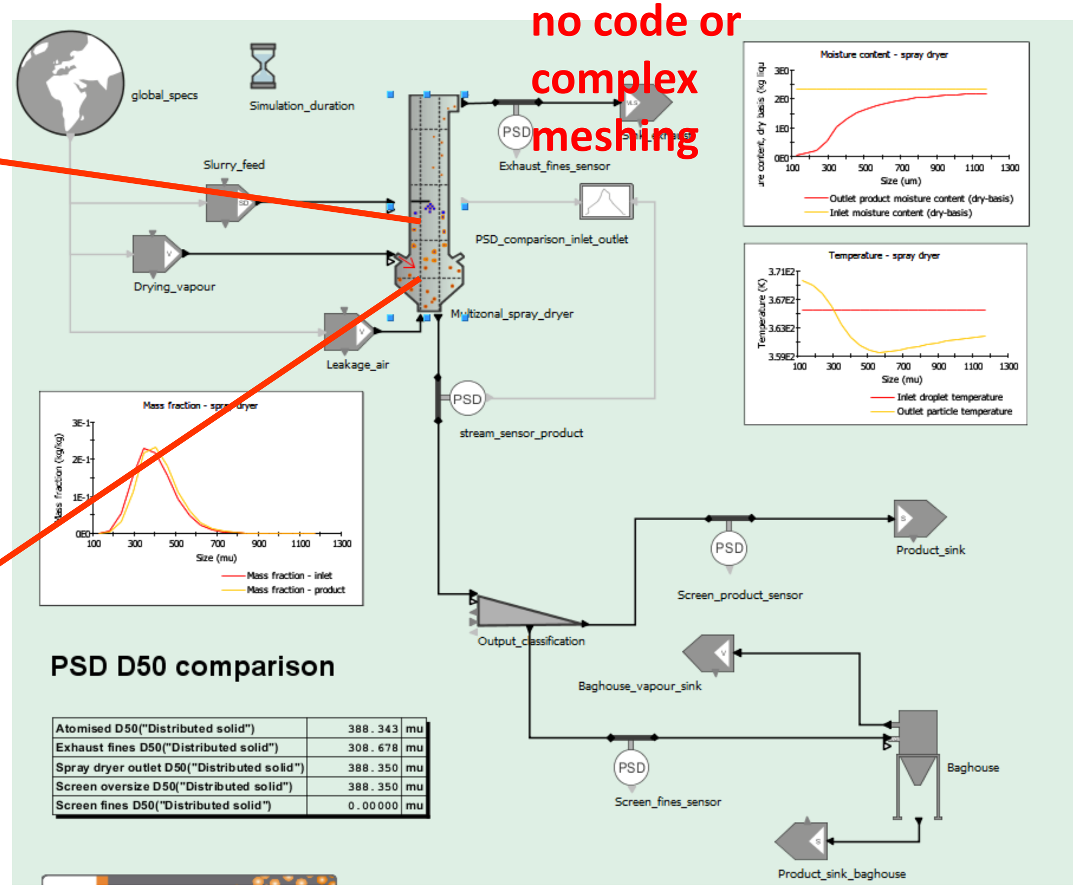
Property	Value at time 360.000	Units
Drying gas temperature	559.800	K
Exhaust vapour temperature(1)	357.574	K
Humidity drying gas (wet basis)("Water")	0.000429002	kg/kg
Humidity exhaust gas (wet basis)(1,"Water")	0.0452575	kg/kg

2. Inlet and outlet distributed phase properties

Property	Value at time 360.000	Units
Inlet solid mass flowrate("Distributed solid")	0.400000	kg/s
Fines mass flowrate(1,"Distributed solid")	2.49179E-05	kg/s
Product mass flowrate("Distributed solid")	0.315174	kg/s
Inlet solid temperature("Distributed solid")	365.550	K
Fines temperature(1,"Distributed solid")	360.795	K
Product temperature("Distributed solid")	420.621	K
Average moisture content at inlet (wet basis)("Distributed solid","Water")	0.300000	kg/kg
Average moisture content of fines (wet basis)(1,"Distributed solid","Water")	0.225712	kg/kg
Average moisture content of product (wet basis)("Distributed solid","Water")	0.111247	kg/kg

3. Mass fraction - atomised droplet, product and fines

Flowsheeting - no code or complex meshing



PSD D50 comparison

Atomised D50("Distributed solid")	388.343	mu
Exhaust fines D50("Distributed solid")	308.678	mu
Spray dryer outlet D50("Distributed solid")	388.350	mu
Screen oversize D50("Distributed solid")	388.350	mu
Screen fines D50("Distributed solid")	0.00000	mu

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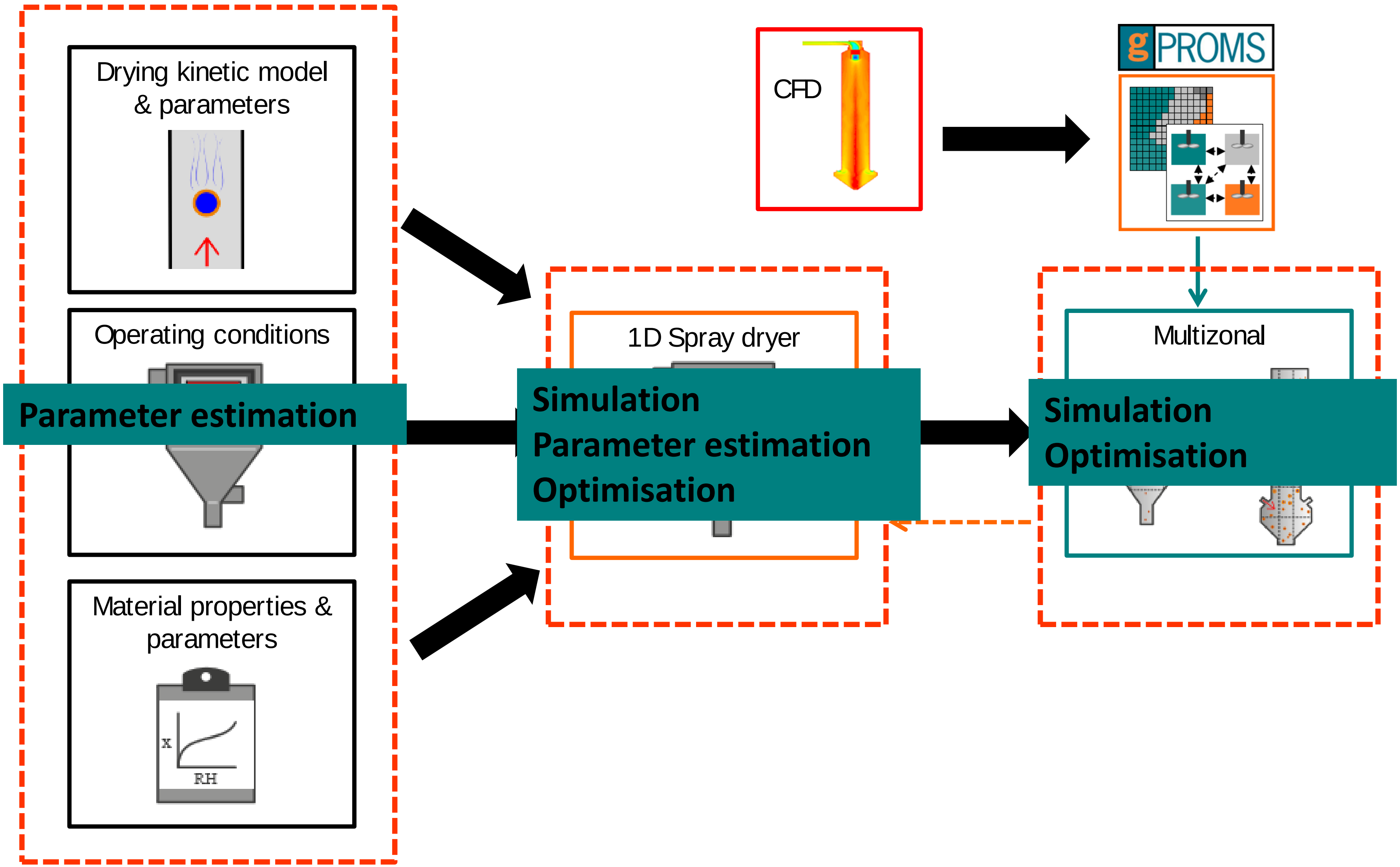
Workflow of modelling spray drying process



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Summary and conclusions

- Multizonal concept extended to Eulerian-Lagrangian CFD simulations
  - Compartmental model captures key phenomena of spray drying
  - Coupled to CFD for flow of particles and vapour between compartments (for co- and counter-current towers)

- A new predictive spray drying tool has been developed, it can be incorporated into an easy to use, flowsheeting setting which can be rolled out to non-expert modellers
  - Optimise process and explore design space

- Multizonal approach can be easily adopted for other unit operations
  - For example: fluid bed dryers and granulators

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Acknowledgements & contributions

- Project partners
  - P&G: Luis Martin de Juan, Zayeed Alam, Mark Crosby, Hossein Ahmadian
  - University of Leeds: Muzammil Ali, Mojtaba Ghadiri, Tariq Mahmud, Peter Heggs, Mazaher Molaei
  - PSE: Sean Bermingham
  - Novozymes: Poul Bach

- Innovate UK funded project
  - Spray Drying Process Efficiency Step Change - 101332

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Thank you

Tower Modelling Capability Development – C+D Projects

Spray Drying gPROMS Model

P&G PSE UNIVERSITY OF LEEDS

TSB: 2013-2015

Atomisation

The University Of Sheffield.

Post-doc: 2012-2013

UNIVERSITY OF BIRMINGHAM

Agglomeration

EngD: 2010-2013

Droplet Coalescence Experimentation

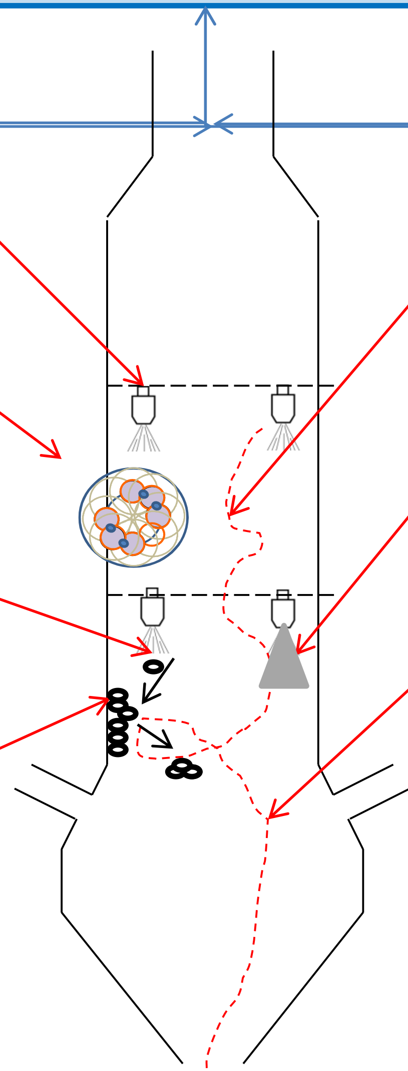
Imperial College London

Post-doc: 2013-2016

Wall Make-up Mechanisms

Imperial College London

Post-doc: 2014-2016



CFD RTD

UNIVERSITY OF LEEDS

PhD: 2011-2014

Droplet Coalescence PBM

PhD: 2012-2015

University of Strathclyde Glasgow

Experimental in Air

Imperial College London

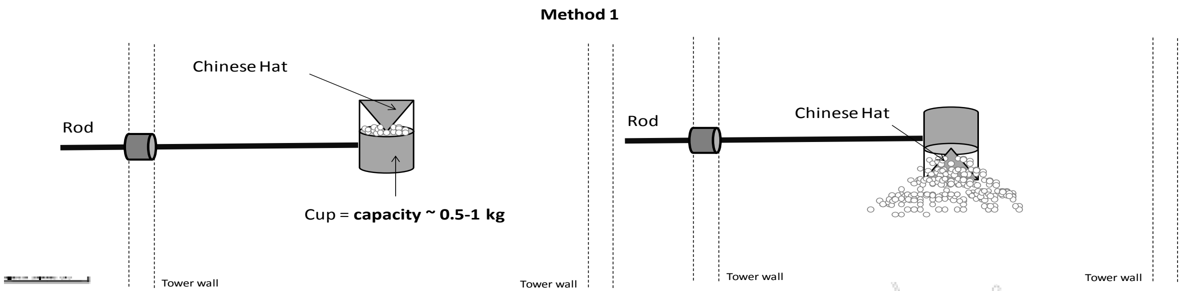
PhD: 2014-2017

Long term capability projects in key areas leading to better understanding and predictability.

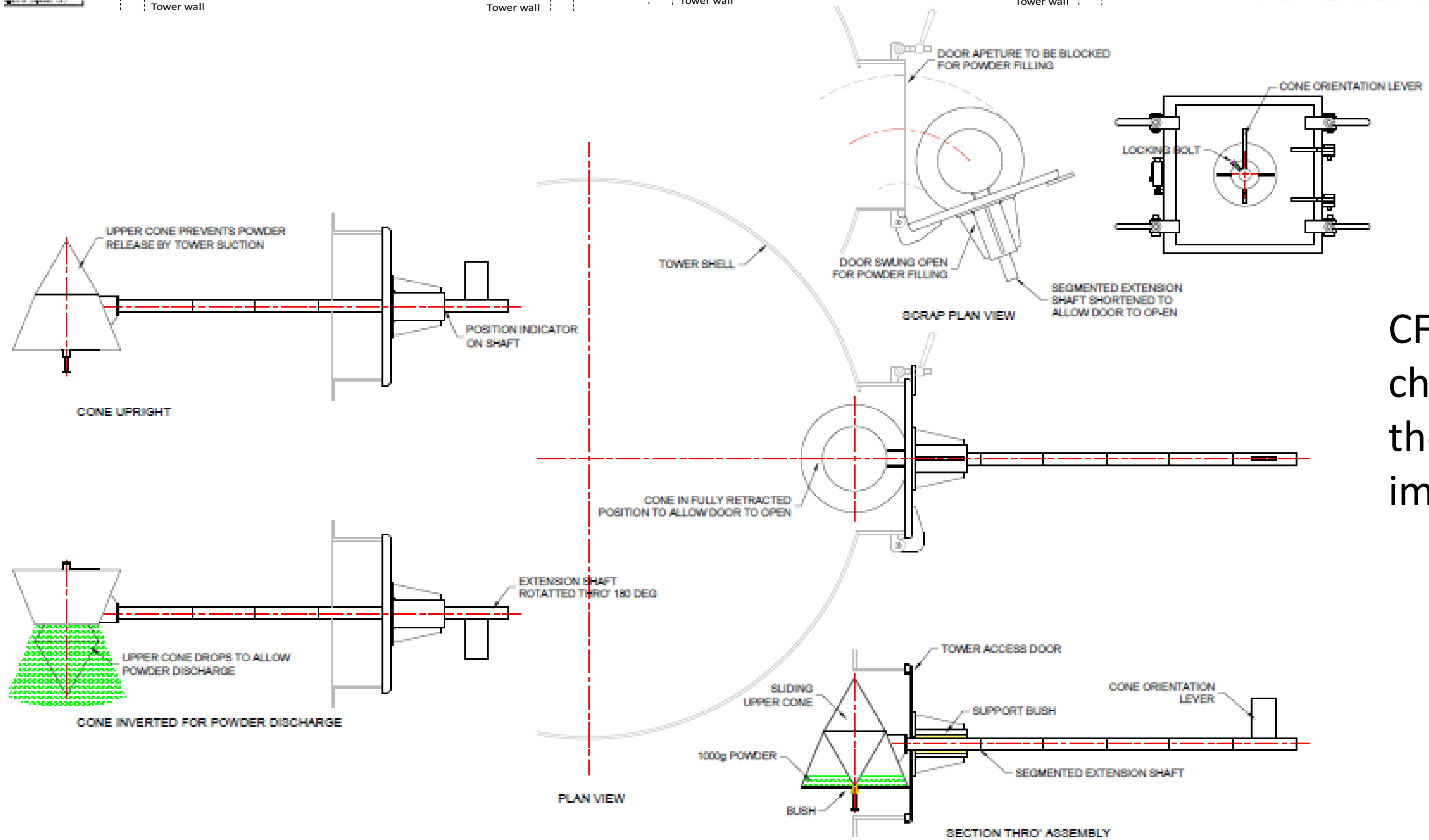
Work Packages

Work Package	Leader	Description	Team members
WP1	University of Leeds	**Developmental of compartmental modelling approach using CFD simulations for various tower systems:** • Model the range of operational scenarios in P&G/Novozymes 1 pilot plant and 1 manufacturing plant using CFD simulations. • Validate the CFD model using pilot plant data/measurements. • Construct approach to compartmentalise towers (both co-current and counter-current).	Mazaher Molaei, Mojtaba Ghadiri Peter Heggs, Andrew Bayly and Tariq Mahmud (Poul Bach and Hossein Ahmadian,
WP2	Novozymes A/S (as sub-contractor)	**Characterisation of slurries and single droplet drying. Analysis of slurry thermo-physical properties, atomisation and selection of correct drying model:** • P&G slurry characterisation done in NIC. • Novozymes slurry characterisation done in Bargsvaerd, Denmark.	Poul Bach (and Hossein Ahmadian/Luis Martin De Juan). Possibly other members of MSUC and Process Design.
WP3	Process Systems Enterprise	**Development of robust spray drying unit operation model based on air flow and droplet motion:** • Develop first compartment model block with selection of single droplet drying models (Hecht and Sloth). • Develop multi-compartment model to represent spray drying unit operation. • Implement a selection of models for population balancing (agglomeration) and heat losses. • Integrate model into a flowsheet.	David Slade, Sean Bermingham and Mark Pinto (Mazaher Molaei)
WP4	P&G	**a) Verification and validation of model on various spray drying tower scales.** • Check fidelity of drying model as well as parameter estimate coalescence and agglomeration in towers. • Validate model on plant scale. **b) Application of validated model for energy minimisation per unit product.** • Demonstrate usage of model (for energy saving) by changing nozzle configuration, air flowrates and temperature, loading, reduction in coarse material and changes in ancillary equipment.	David Slade, Hossein Ahmadian, Poul Bach, Luis Martin De Juan (others in M&S/MSUC)

WP4: Tower in process measurement (Particles)



Function size, axial and radial position (1kg of material).

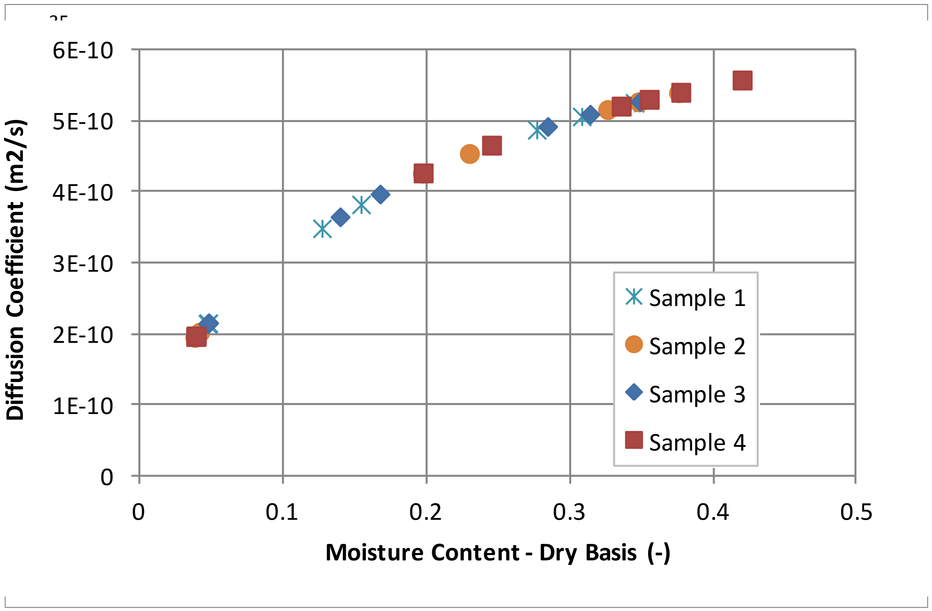


CFD underway to check how badly the assembly impact air flow

WP2: Diffusion Coefficient – P4

Diffusion coefficients is measured using the drying slab method. The procedure involves:

- using slurry or granules which have been mixed with water back to the target slurry moisture.
- placing them in petri dish (8.5 cm in diameter) with different heights (8 and 12 mm). This equates to around 60-100g of slurry depending on size.
- drying them mix in an above (top of petri dish open) at 75 ^{o}C whilst monitoring the weight of the sample for 3-4 days.



- This plot is then fitted to find a diffusion coefficient as a function of moisture content for a slab (using gPROMS).

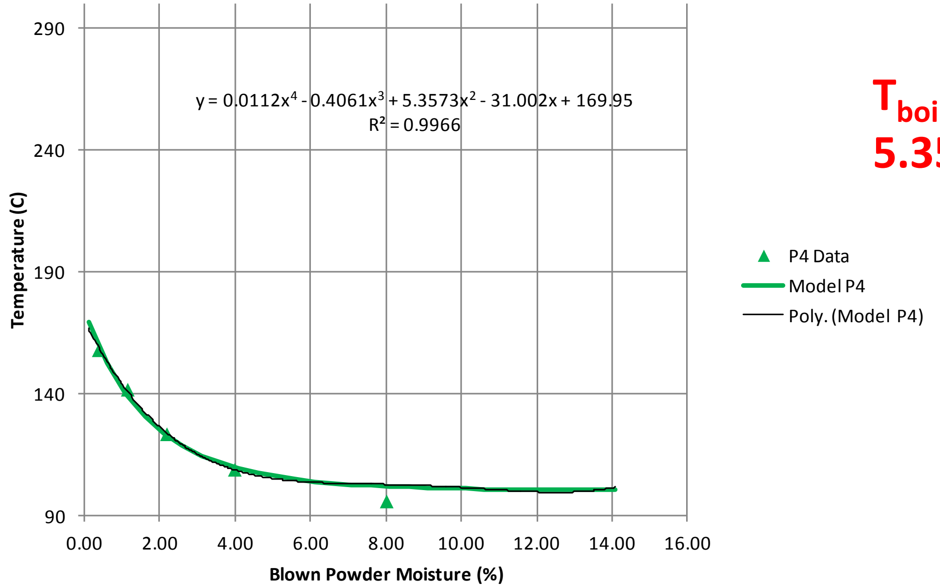
- The coefficients for diffusion, density, specific heat capacity etc.. are then used to run the full Hecht and King (2002) drying model in gPROMS to extract coefficients A, B and C.

- For this formulation, these are A = 40, B=0.29 and C=16.5.

WP2: Boiling Point – P4

Boiling point rig involves placing around 10-13g of pre-sieved powder (300-425 microns) in vials and pre-conditioning the samples to various moistures (e.g. 8%, 4%, 2%, 1%).

The vial is then place in the boiling point rig (pressure vessel) where the temperature is set at 100 ^oC then increased every 2 hrs to 115, 130, 140 and finally 150 ^oC. The vapour pressure inside the vial is monitored allowing to calculate the boiling point – this is then plotted for all case as shown below:



$$T_{boil} = 0.0112\, w_i^4 - 0.4061 w_i^3 + 5.3573 w_i^2 - 31.002 w_i + 169.95$$

Particle motion only

- Motion (transfer between zones) and accumulation of particles in a zone under well mixed assumption – mass flux in calculated in adjacent zones:

$$\frac{dM(z)}{dt} = \sum_{j=1}^{NI}\left(\phi_{in}^{j}(z) - \phi_{out}^{j}(z)\right)$$

$$\text{At } t = 0,\ M(z) = m_0$$

$$M(z) = V\ C(z)$$

$$\phi_{out}^{j}(z) = SA(j)\ v_j(z)\ C(z)$$

$$C(z) = N(z)\ \frac{\pi}{6} z^3\ \rho(z)$$

$$\tau_{avg} = \frac{M(z)}{\sum_j \phi_{out}^{j}(z)}$$

$M(z)$: mass holdup of particles of diameter z (kg),

NI : number of interfaces with adjacent zones,

$\phi_{in}^{j}(z)$: mass flux in of particles of diameter z through interface j (kg/s),

$\phi_{out}^{j}(z)$: mass flux out of particles of diameter z through interface j (kg/s),

m_0 : initial mass of particles in zone (kg),

V : volume of zone (m^3),

$C(z)$: mass concentration of particles of diameter z (kg/m^3),

$SA(j)$: surface area of interface j (m^2),

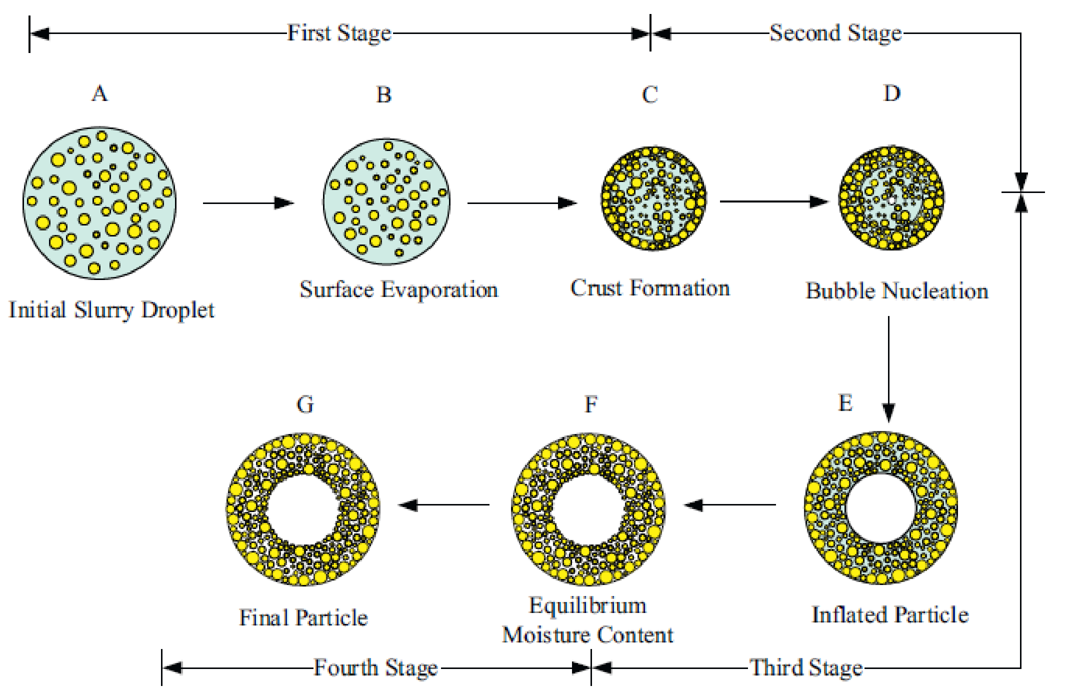
$v_j(z)$: velocity of particles of diameter z at interface j (m/s),

$N(z)$: number concentration of particles of diameter z ($\#/m^3$),

$\tau_{avg}(z)$: average residence time of particles of diameter z (s).

- NB: Surface area, velocities, volume of zone are the quantities to be extracted from CFD simulation via Multizonal interface.

Drying Model



- Using Hecht dryi
- 1st stage -Initi

$$D_R = 4 \cdot \pi$$

efficient.

Heat and mass t

- 2nd stage - Part an exponential curve fit equatio

constants for the ed in gPROMS or Excel.

$$D_R = r_p \times \exp\left[-A\left(\frac{\cdots}{r_p}\right) - C\right]$$

- 3rd stage - Particle drying rate after the boiling point is given by an energy balance about the particle:

$$D_R = \frac{\alpha 4\pi \left(\frac{d_p}{2}\right)^2 (T_g - T_p)}{h_{fg} - \left(w_s c_{p,s} + w_l c_{p,l}\right) w_s \frac{dT_{boil}}{dw_l}}$$

T_{boil} = f(moist)

Coalescence/Agglomeration

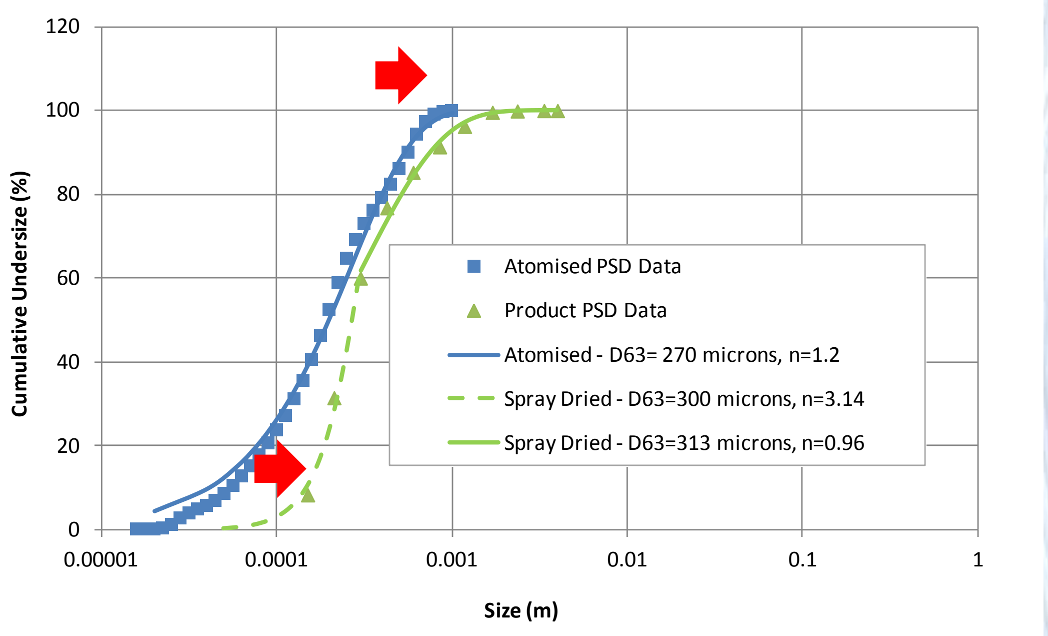
Currently not accounted in CFD.

Population balances (e.g. Liu and Litster, 2002) already in gSOLIDS.

Multitude of models available for collisions kernels (6 in gSOLIDS) and plan to include 1-2 of:

- O'Rouke (parcels)
- Abrahamson

Droplet/particle size enlargement



For collision efficiency, reapply work on Blei and Sommerfeld (2007) including different types of collisions based on Ohnesorge number:

ST-droplet	vs	ST – droplet
ST-droplet	vs	Dry/Viscous droplet
Viscous droplet	vs	Viscous/Dry particle
Dry particle	vs	Dry particle

$$Oh^2 = \frac{\mu^2_{droplet}}{d_{droplet}\rho_{droplet}\sigma_{Droplet}}$$

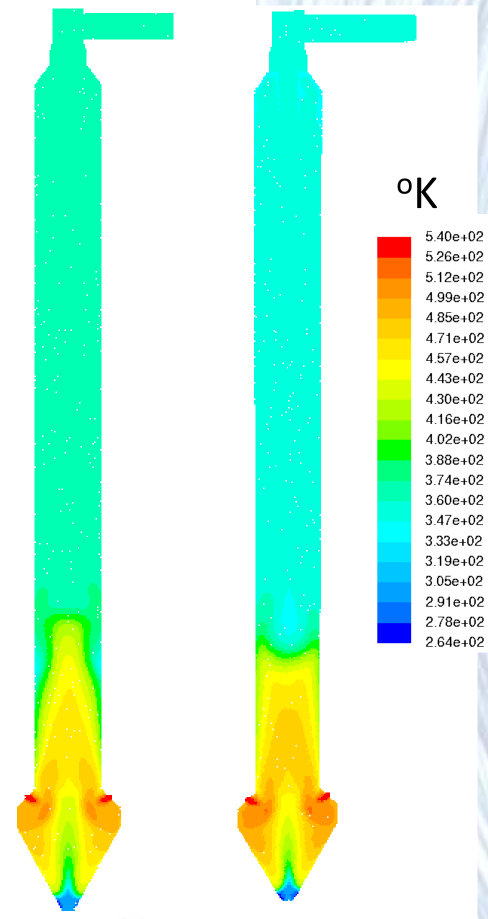
CFD vs Experiments (no agglomeration – full size)

Single nozzle tower

	Exp	CFD (spherical)	CFD (Rough)
Hot Air Inlet Temperature (°C)	268		
Hot Air Rate (kg/hr)	Confidential		
Slurry Rate (kg/hr)	Confidential		
Nozzle Position (m)	Confidential		
Exhaust temp (°C)	91.1	90.68	74.85
Powder Temperature (°C)*	71.6	168.5	170.59
Powder Rate (kg/hr)	1185	1181.1	1148
Yield (%)	~95%	94%	90%
Moisture content of particle (wt/wt%)	1.93	7.6	5

* Should be similar to boiling point ~125 °C

- Whilst for the smooth case, the exhaust gas temperature and rate can be predicted, the final product moisture is incorrect (due to lack of drying of larger particles).
- Lack of coalescence or agglomeration models in CFD may also cause issues given that atomised droplets are smaller and dry more prior to size enlargement.
- There is also significant heating of the dried droplets to much higher temperatures than boiling point (energy inefficient).



Smooth **Rough**