INSTITUTE OF MECHANICAL, PROCESS & ENERGY ENGINEERING
Victor Francia Asst. Professor

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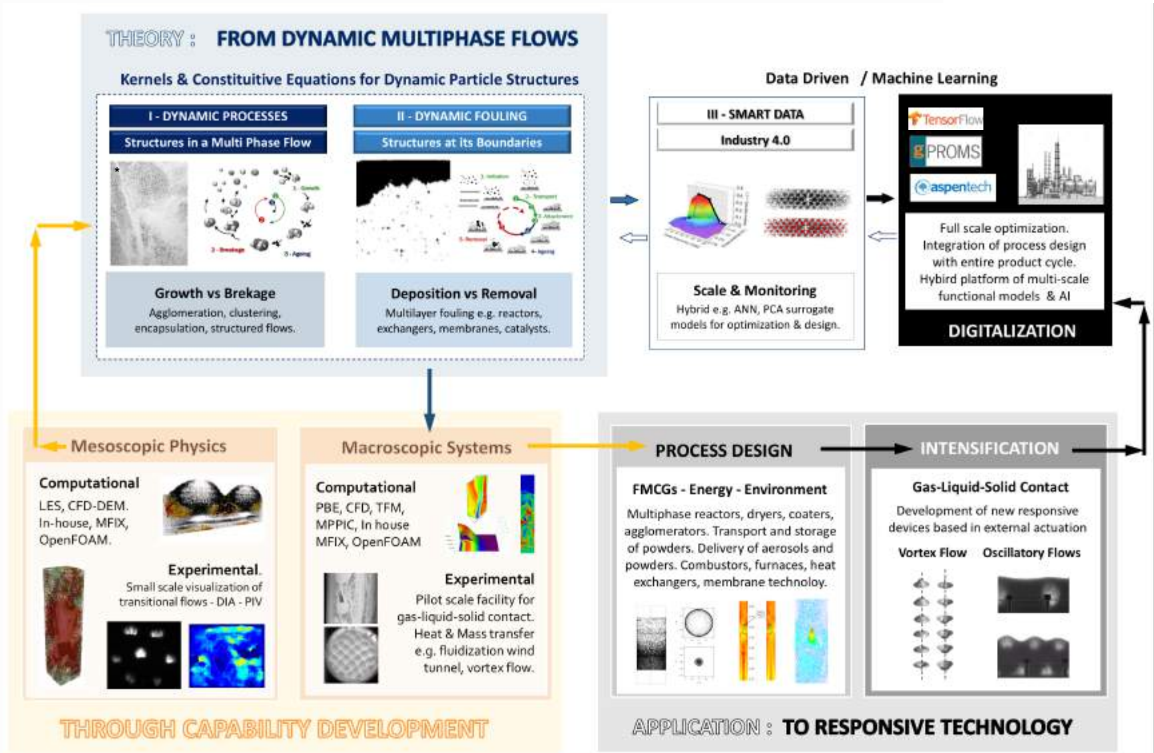
SCALING VORTEX FLOWS

Pitfalls, risks & Challenges

0



* Schaffer et al. 2012. A new method for decomposition of high speed particle image velocimetry data. Powder Technology 220, 164-171

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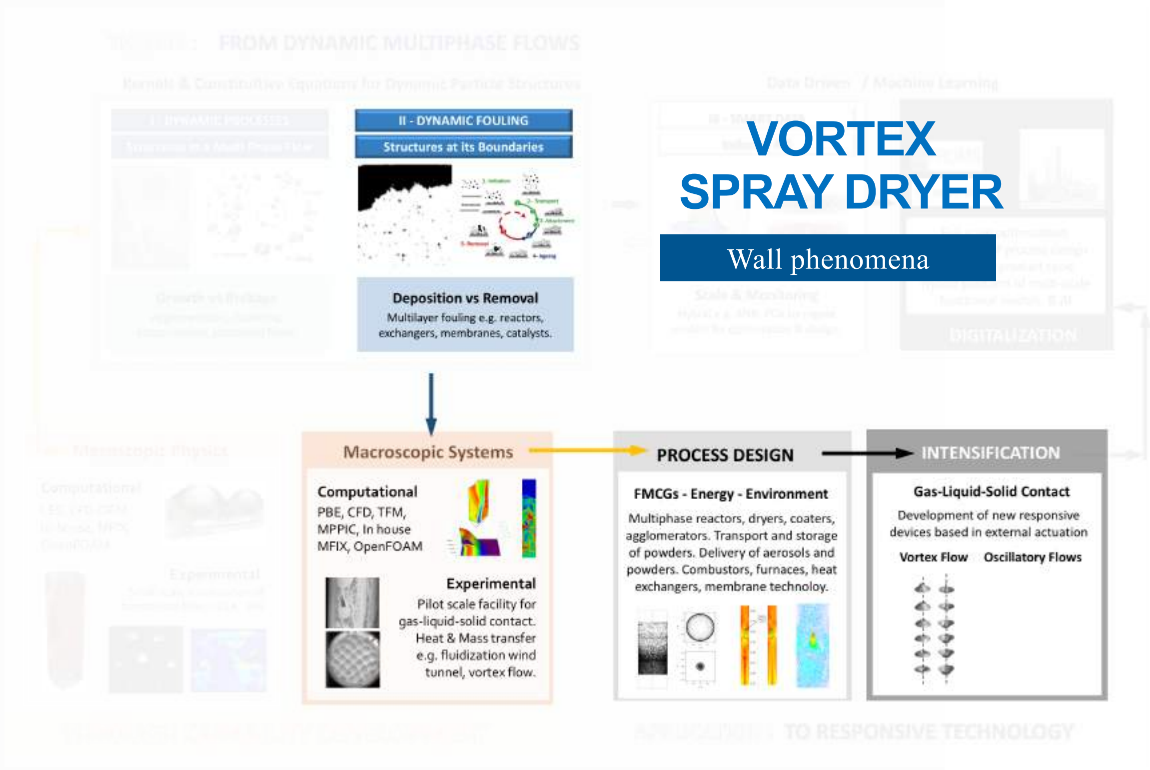


VORTEX SPRAY DRYER

Wall phenomena

GRANULAR DETERGENTS

Swirl tall-form counter current spray dryers

Imperial College London P&G

www.pg.com

Chemical Properties

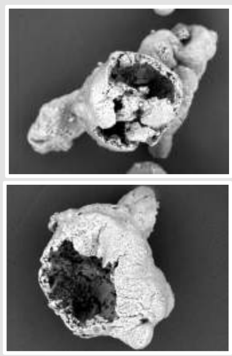
- Formulation: (Surfactant/s , Polymers, Enzymes, Bleach)
- Water content
- Homogeneity

Physical Properties

- Size, Shape
- Density
- Porosity
- Cohesiveness

Spray Dried Powder

- Open Structures
- High Particle Porosity
- Low Bulk Density
- Enhance solution rate
- Consumer perception
- Formula dependent
- Water content
- Droplet drying



COUNTER - CURRENT SPRAY DRYING

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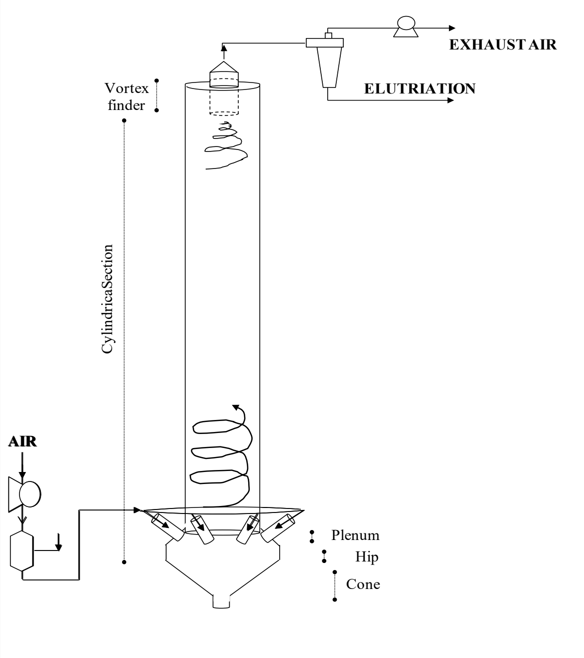
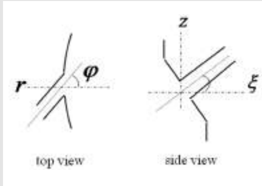


1- Swirling Air Flow

- Counter-current mode
- Swirl Intensity, $\Omega > 2$
- High Turbulence Intensity
- Near Wall concentration



Scale & Design

Ω_i	[5.2]
$\Omega_{Cylinder}$	[1 - 2]
H/D	[10.6]
d/D	[0.3]

Air Operation

Re	[50-120.10^4]
T_{IN}	[300 °C]
T_{EX}	[80-90 °C]

Francia V et al. 2016. Agglomeration in counter-current spray drying towers. Part A: Particle growth and the effect of nozzle height. Powder Tech. 301 : 1330-1343

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COUNTER - CURRENT SPRAY DRYING

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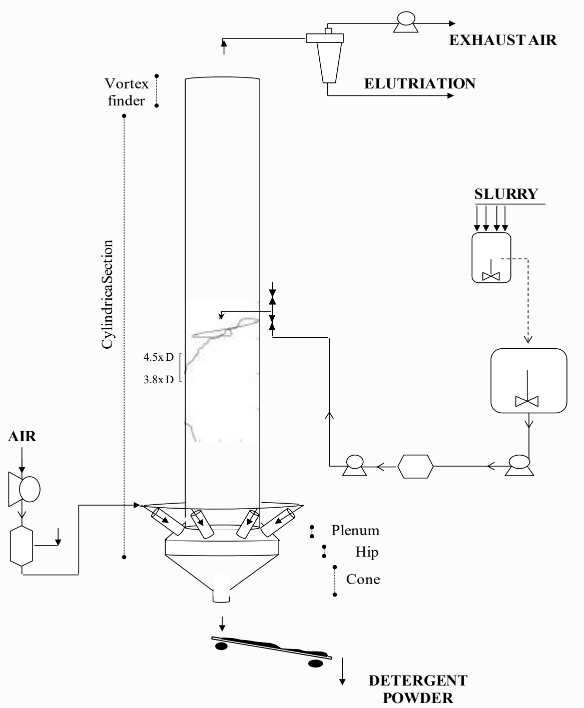


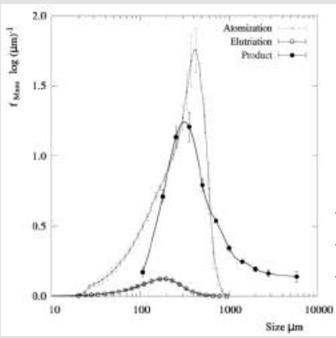
2- Detergent Slurry

Preparation
- Surfactants/s
- Polymers
- Inorganic salts
- Other

Mixing
- Batch to Continuous
- High shear Mill
- High pressure line.

Atomization
- Swirl Pressure Nozzle/s
- Hollow Cone Pattern
- Solid-Liquid Separation

Elutriation ← → **Product**



- x & ρ_{bulk} targets
- ↓ ρ granules
- Open structures
- Aggregation

$r_{Product} > 93$ %

x_{50} [353 ± 20 µm]

x_{90} [933 ± 490 µm]

x_{10} [165 ± 3 µm]

Francia V et al. 2016. Agglomeration in counter-current spray drying towers. Part A: Particle growth and the effect of nozzle height. Powder Tech. 301 : 1330-1343

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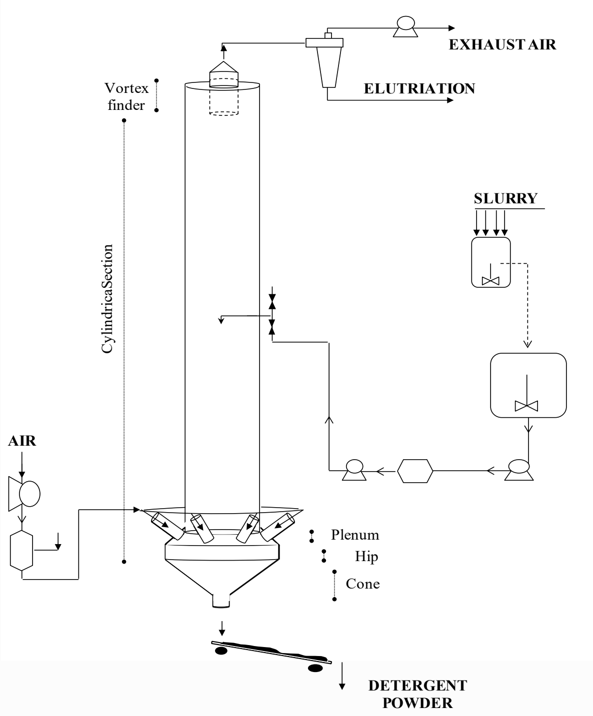
COUNTER - CURRENT SPRAY DRYING



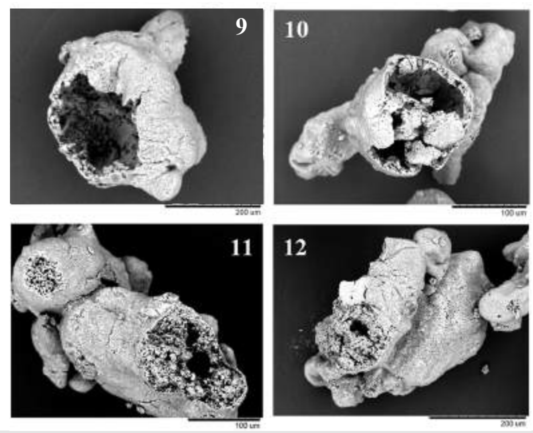
3- Design & Operation

Semi Empirical

- 50 yrs of experience
- Non standardized design
- ↑ Experimental Costs
- Qualitative Modeling

Particle Interactions

- Focus from 00´s
- Size, density, porosity
- Process efficiency



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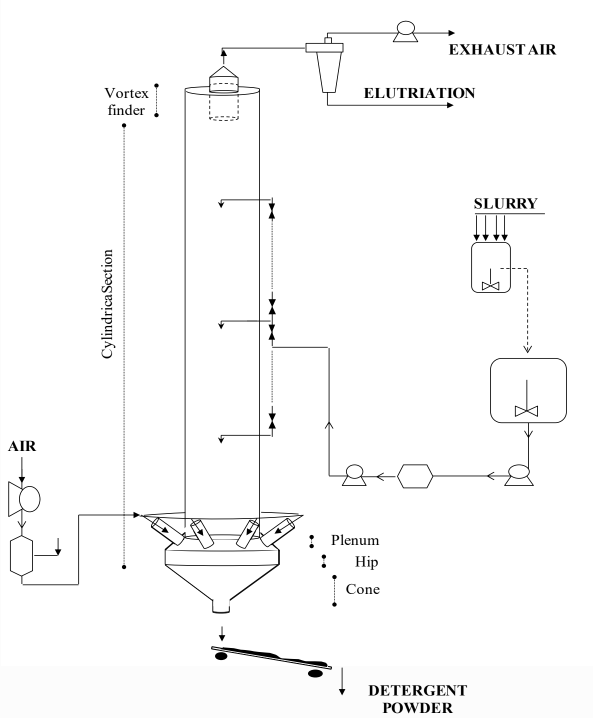

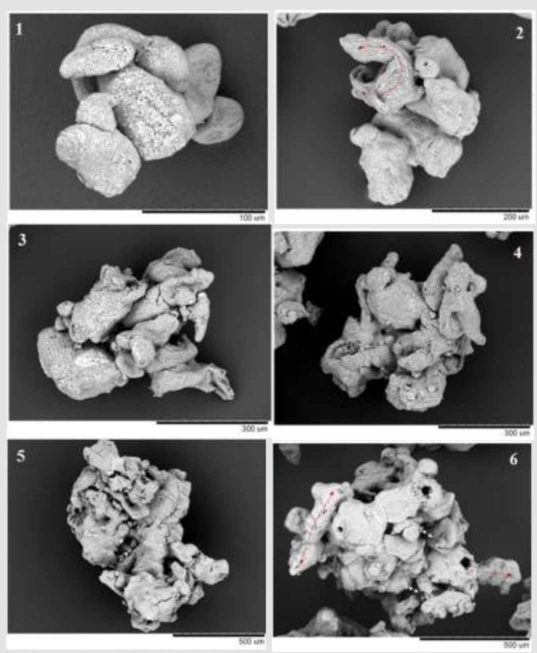

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COUNTER - CURRENT SPRAY DRYING

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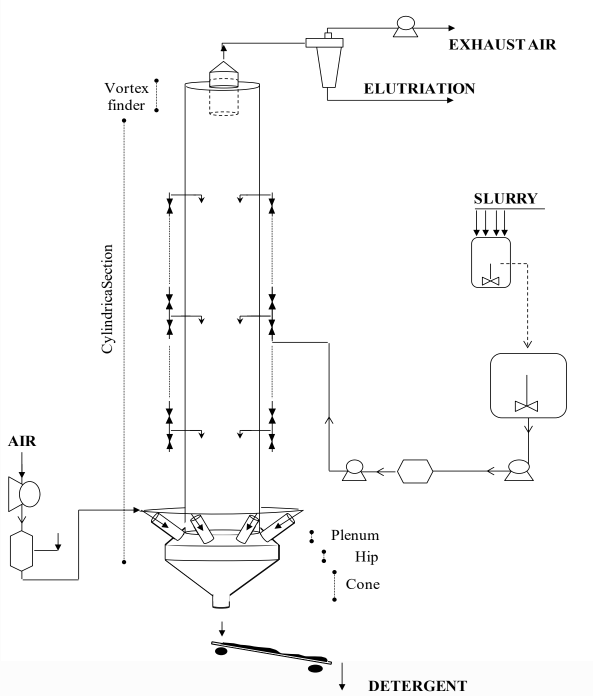

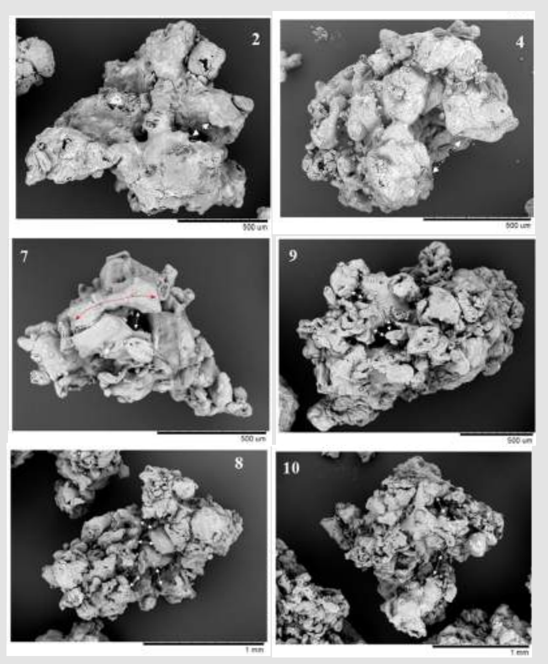

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COUNTER - CURRENT SPRAY DRYING

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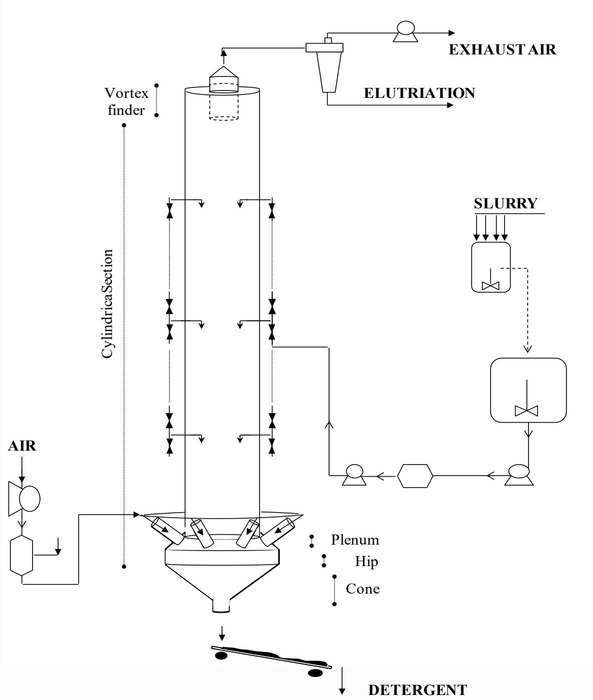
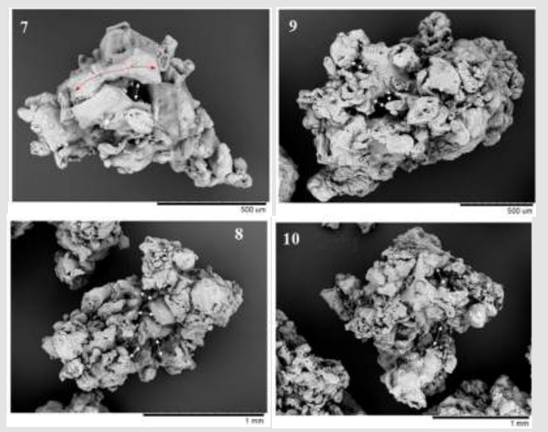


4- Control Agglomeration

CAPACITY	ENERGY
~ 15 % recirculation Discarded product Too (Fine + Coarse) Size, density, porosity	Excess fuel / emissions Residence Time Size & water content Stability (T history)



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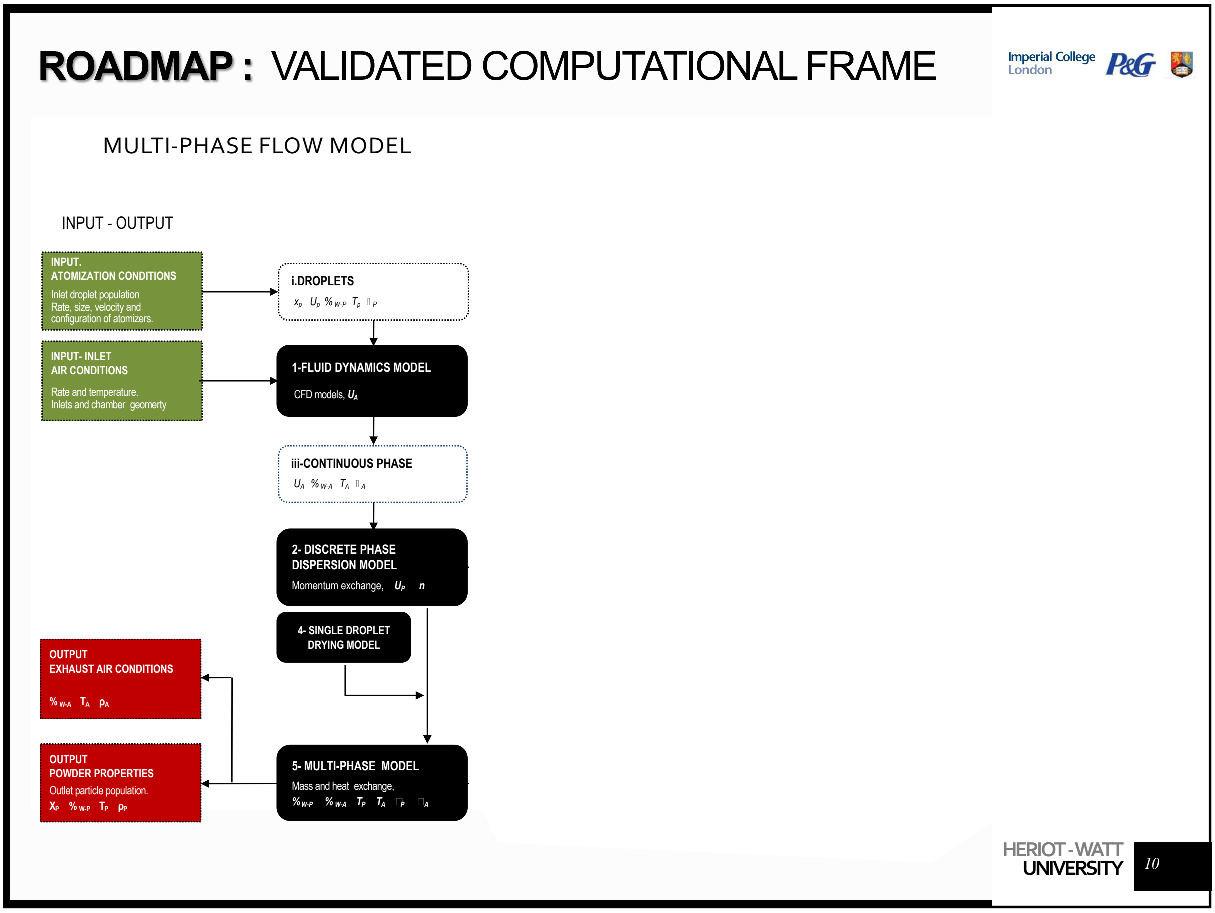
ROADMAP : VALIDATED COMPUTATIONAL FRAME
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P&G
MULTI-PHASE FLOW MODEL
INPUT - OUTPUT
INPUT. ATOMIZATION CONDITIONS
Inlet droplet population
Rate, size, velocity and configuration of atomizers.
INPUT- INLET AIR CONDITIONS
Rate and temperature.
Inlets and chamber geometry
i.DROPLETS
1-FLUID DYNAMICS MODEL
CFD models, U_A
iii-CONTINUOUS PHASE
2- DISCRETE PHASE DISPERSION MODEL
Momentum exchange, U_P n
4- SINGLE DROPLET DRYING MODEL
OUTPUT EXHAUST AIR CONDITIONS
OUTPUT POWDER PROPERTIES
Outlet particle population.
5- MULTI-PHASE MODEL
Mass and heat exchange,
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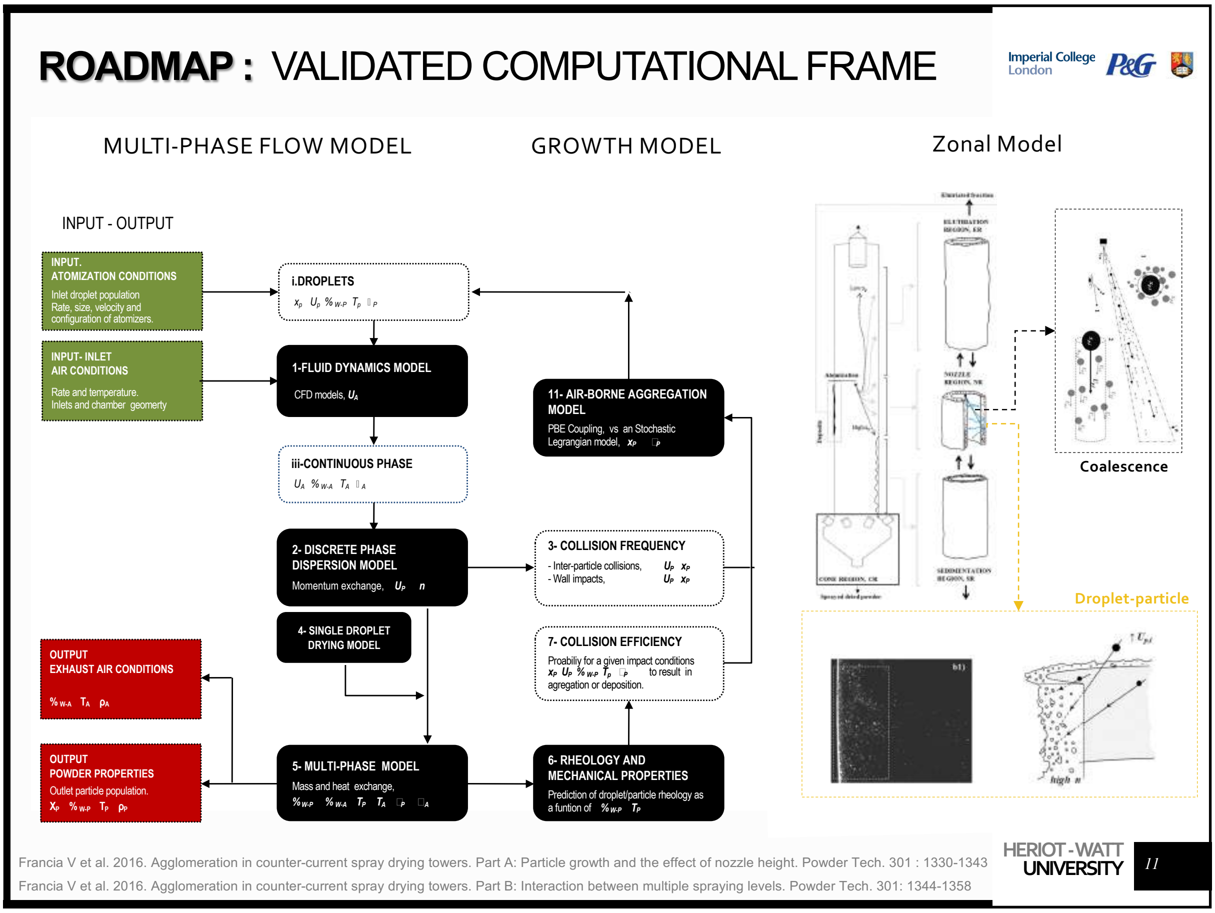
ROADMAP : VALIDATED COMPUTATIONAL FRAME
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P&G
MULTI-PHASE FLOW MODEL
GROWTH MODEL
Zonal Model
INPUT - OUTPUT
INPUT. ATOMIZATION CONDITIONS
Inlet droplet population
Rate, size, velocity and configuration of atomizers.
INPUT- INLET AIR CONDITIONS
Rate and temperature.
Inlets and chamber geometry
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OUTPUT EXHAUST AIR CONDITIONS
OUTPUT POWDER PROPERTIES
Outlet particle population.
5- MULTI-PHASE MODEL
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11- AIR-BORNE AGGREGATION MODEL
PBE Coupling, vs an Stochastic Legrangian model,
3- COLLISION FREQUENCY
- Inter-particle collisions,
- Wall impacts,
7- COLLISION EFFICIENCY
Proability for a given impact conditions to result in agregation or deposition.
6- RHEOLOGY AND MECHANICAL PROPERTIES
Prediction of droplet/particle rheology as a funtion of
Coalescence
Droplet-particle
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Francia V et al. 2016. Agglomeration in counter-current spray drying towers. Part B: Interaction between multiple spraying levels. Powder Tech. 301: 1344-1358
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ROADMAP : VALIDATED COMPUTATIONAL FRAME

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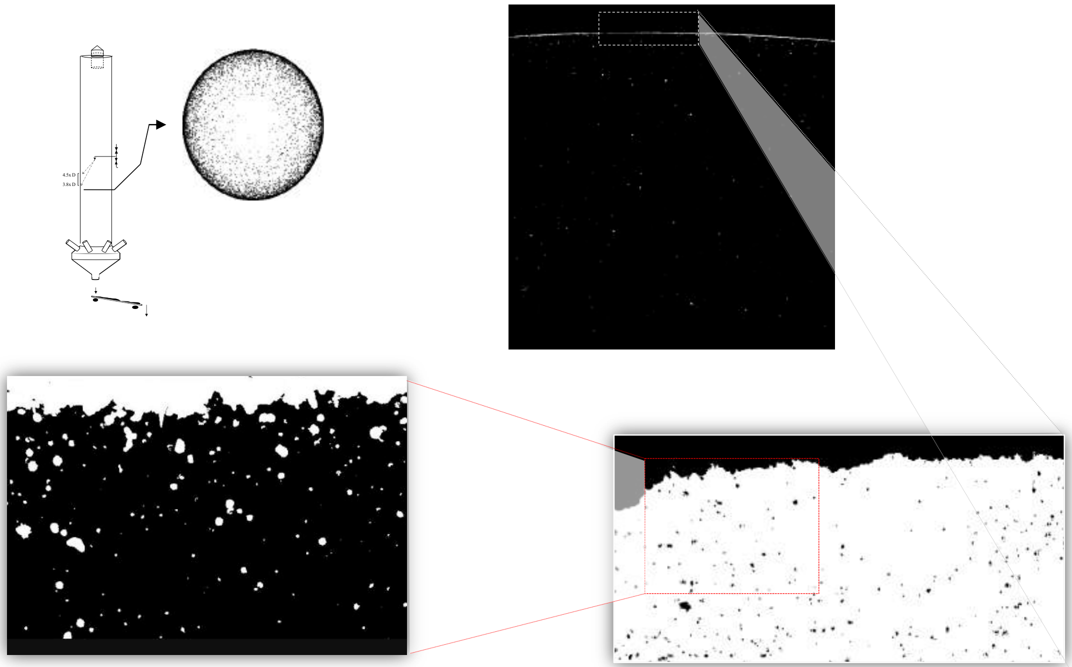

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ROADMAP : VALIDATED COMPUTATIONAL FRAME

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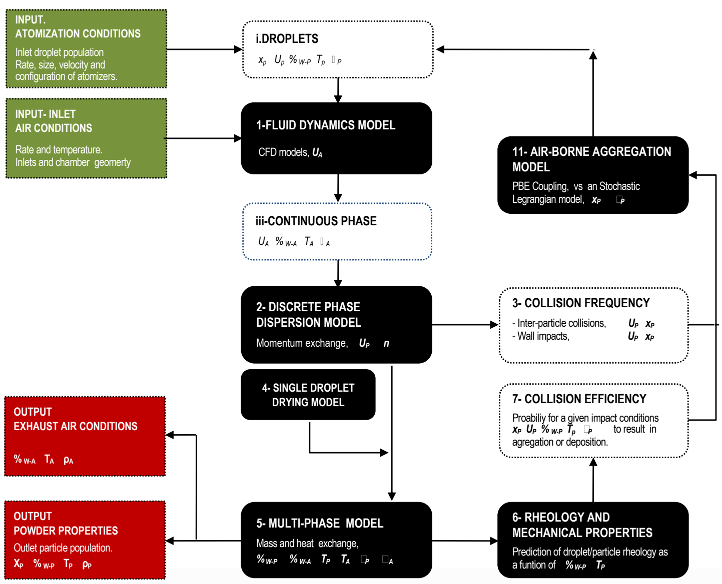
MULTI-PHASE FLOW MODEL GROWTH MODEL

INPUT - OUTPUT



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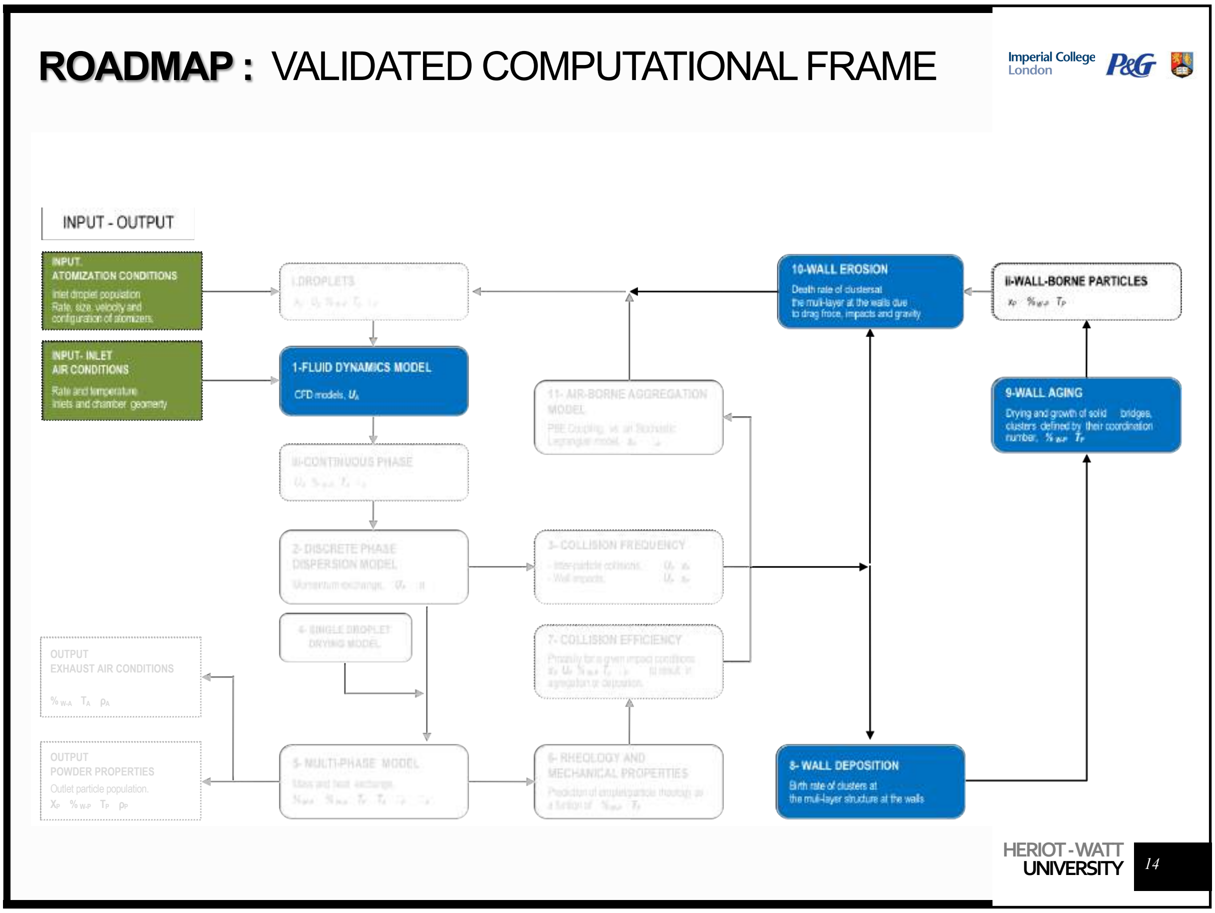
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10-WALL EROSION
Death rate of clusters at the muli-layer at the walls due to drag froce, impacts and gravity
ii-WALL-BORNE PARTICLES
9-WALL AGING
Drying and growth of solid bridges, clusters defined by their coordination number,
8- WALL DEPOSITION
Birth rate of clusters at the muli-layer structure at the walls
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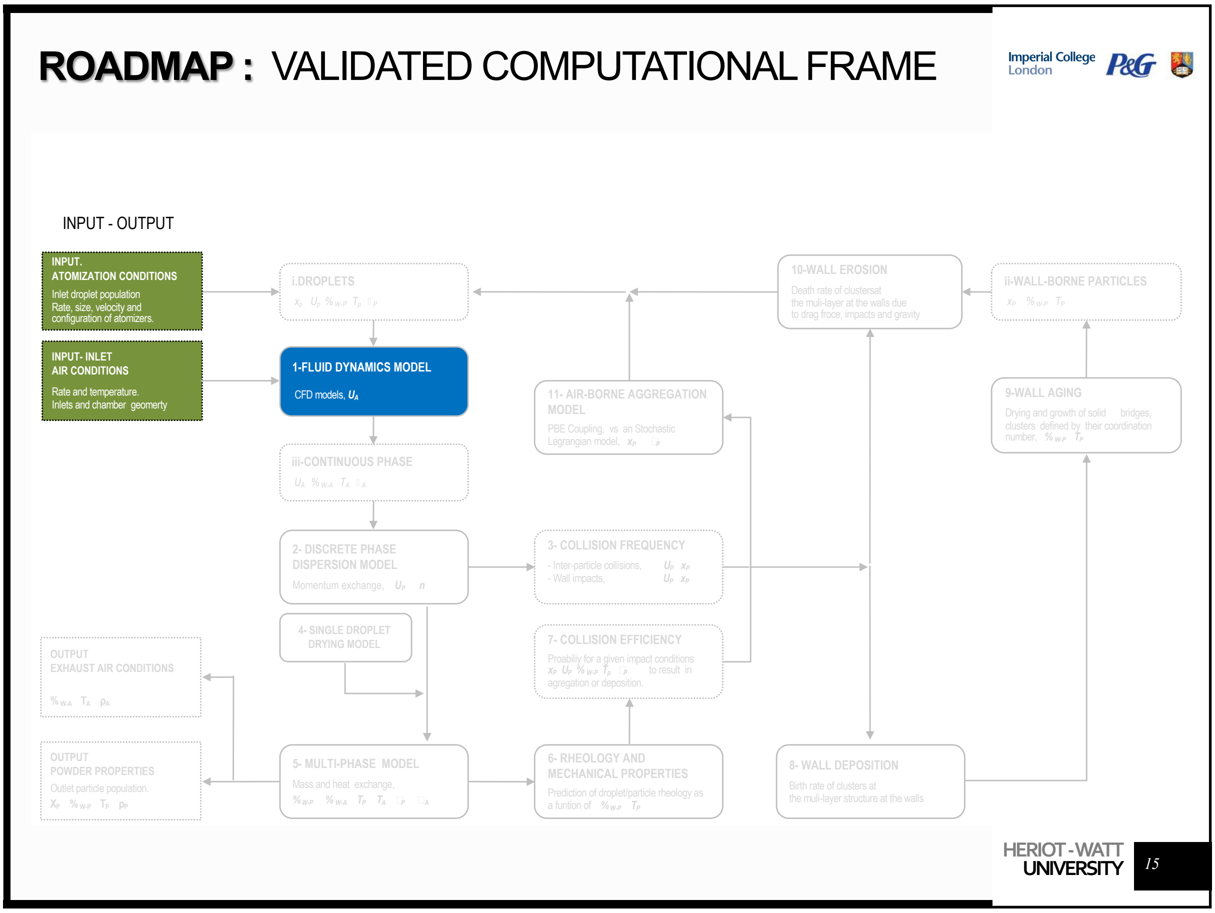
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LARGE CONFINED VORTEX

Laser Based Methods vs Sonic Anemometry

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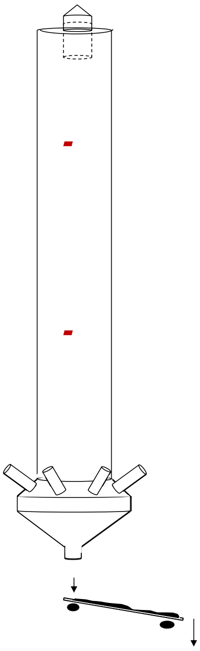
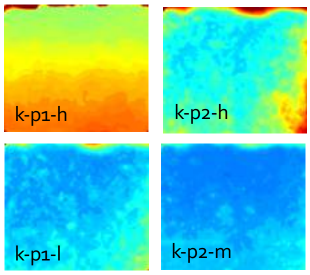


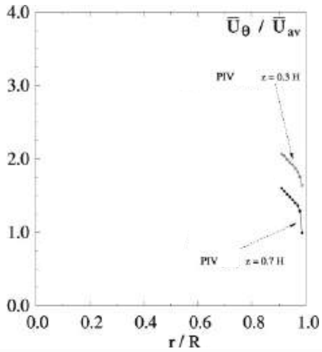
Wall PIV, Hassall 2012



- ✓ Abnormal swirl
- ✓ 30 - 60 % ↓ vs Lab / CFD

Intrusive set up ?
Incomplete profiles ?
Restricted ?

INCONCLUSIVE



1990
- Visualization Pilot, Sharma
- Vanes, Full Fieg
- CFD Full Harvie

2004
- LDA + CFD Lab, Bayly
- LDA + CFD Pilot, Zbicinski
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2012
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- Anemometry Full, Francia

2017

Hassall G. Wall build up in spray driers. EngD Thesis. Birmingham, UK. University of Birmingham, 2011.

Francia V et al 2016. Use of sonic anemometry for the study of turbulent swirling flows in large confined industrial units. Flow Measurement and Instrumentation. 50 : 216-228.

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LARGE CONFINED VORTEX

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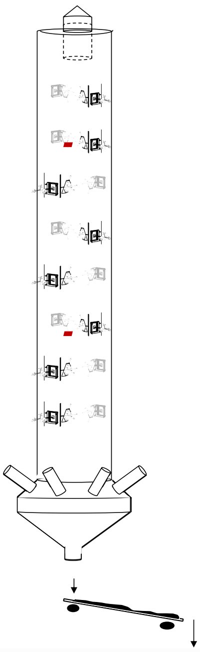

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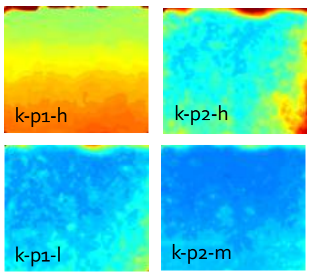
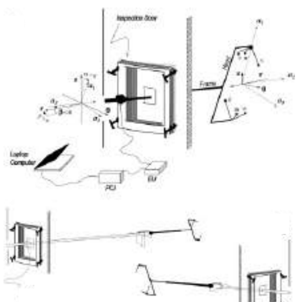


HS50, Francia 2016

- Full Vortex Structure
- Detail Turbulence Data
- Quick & Low cost
- Full Uncertainty Analysis
- 2500 measurements
- Re - ε/D - Ω - scale



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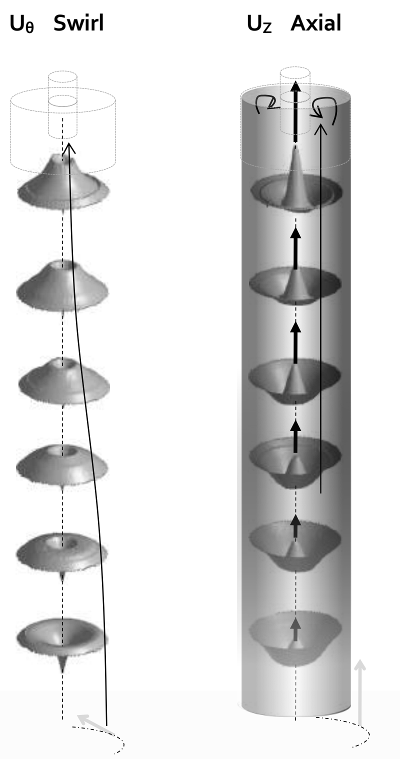
LARGE CONFINED VORTEX



VORTEX STRUCTURE

- ✓ A low-pressure exit drives the vortex inwards reaching the top at swirl intensity $\Omega > 1$.
- ✓ The exit contraction causes back-pressure to build up, and the formation of a central jet.
- ✓ Characteristic anisotropy. Data to assess RANS closures.
- ✓ Instability of the vortex core. Precession at constant St.
- ✓ ↑ Re - Self similar structure. Asymmetries due to inlet design.
- ✓ Friction due to the presence of layers of particulate deposits.

Francia V et al 2015. An experimental investigation of the swirling flow in a tall-form counter-current spray dryer. Exp. Thermal and Fluid Science 65 : 52-64

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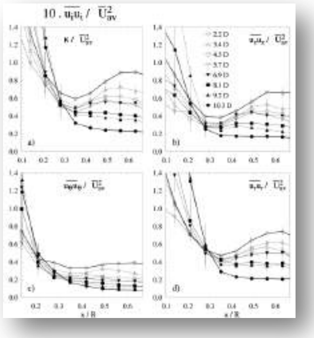
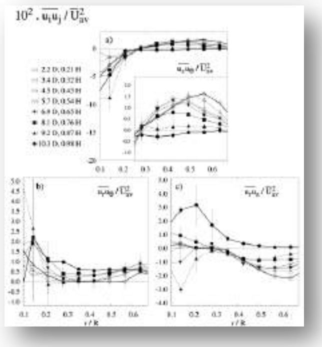
LARGE CONFINED VORTEX

Intensities



Re stresses



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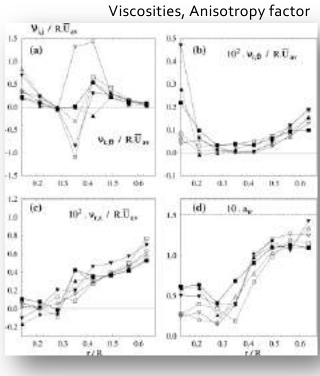
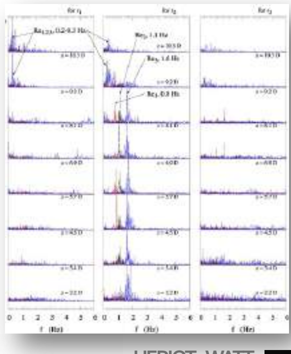
Viscosities, Anisotropy factor



Periodicity, Cross correlation



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LARGE CONFINED VORTEX

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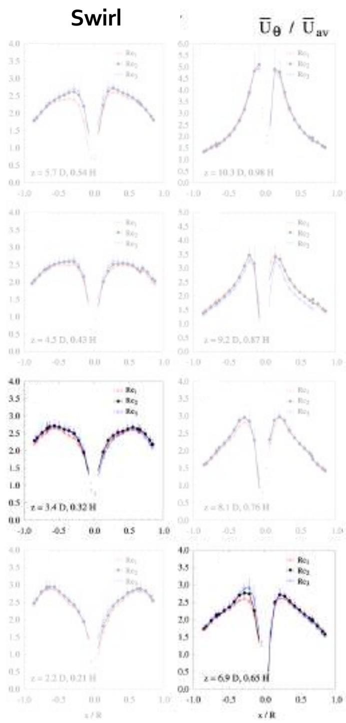

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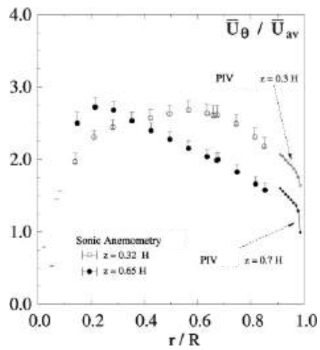

Over-prediction of U_θ by 1 order of magnitude in a full scale unit. The wall roughness causes a much stronger friction than anticipated, ignored in all previous studies.

Decay can be reproduced with scalable wall functions

Not robust in ∇P.

Turbulence produiction.

Francia V et al 2015. An experimental investigation of the swirling flow in a tall-form counter-current spray dryer. Exp. Thermal and Fluid Science 65 : 52-64

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FRICTION: SWIRL DECAY

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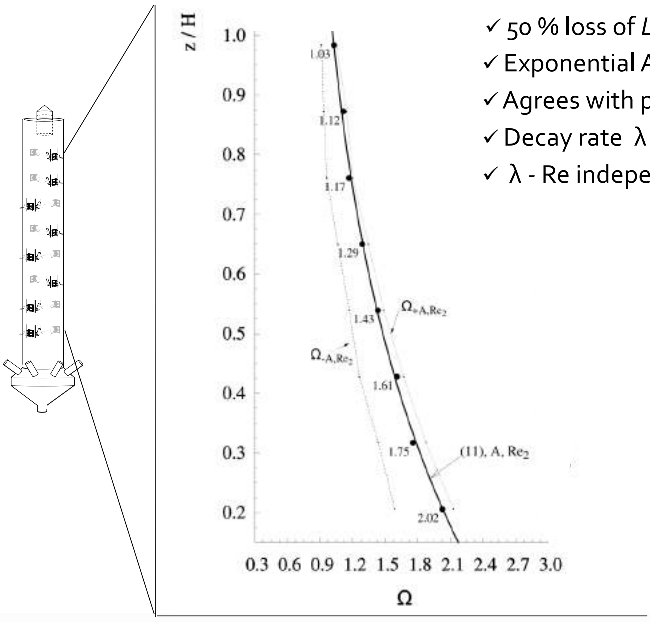
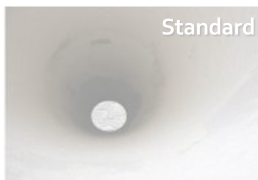
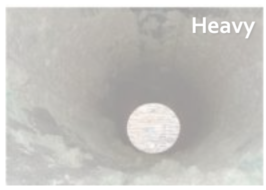
Ω - SWIRL INTENSITY



- ✓ 50 % loss of *L*
- ✓ Exponential Axial decay
- ✓ Agrees with pipe flow
- ✓ Decay rate λ x 10
- ✓ λ - Re independent





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Francia V et al 2015. Influence of wall friction on flow regimes and scale up of swirl spray dryers. Chemical Engineering Science 134: 399-413.

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FRICTION: SWIRL DECAY

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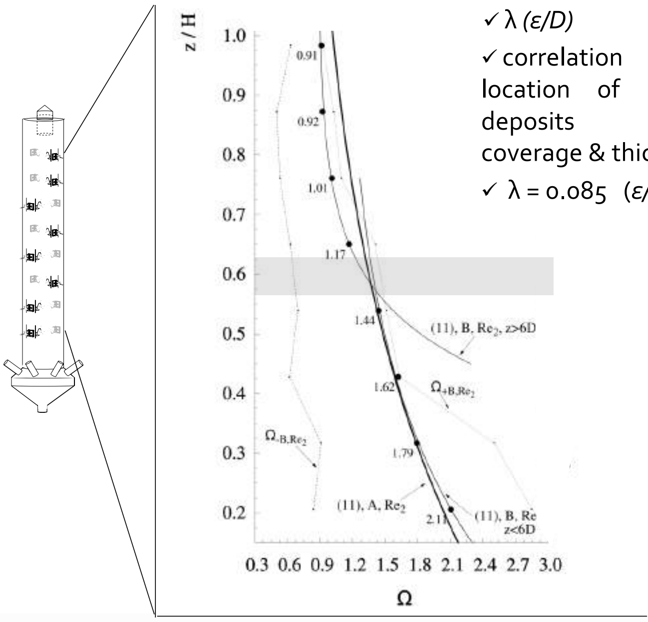
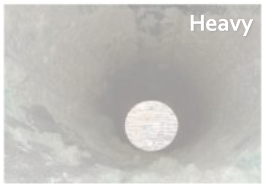
Ω - SWIRL INTENSITY



- ✓ λ *(ε/D)*
- ✓ correlation with location of bands of deposits (spray/s), coverage & thickness.
- ✓ λ = 0.085 *(ε/D ~ 0.006)*



Francia V et al 2015. An experimental investigation of the swirling flow in a tall-form counter-current spray dryer. Exp. Thermal and Fluid Science 65 : 52-64

Francia V et al 2015. Influence of wall friction on flow regimes and scale up of swirl spray dryers. Chemical Engineering Science 134: 399-413.

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FRICTION: SWIRL DECAY

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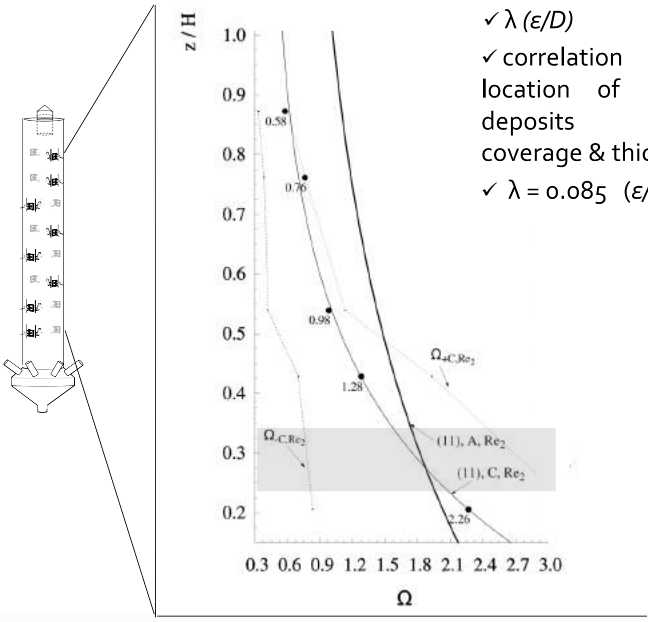
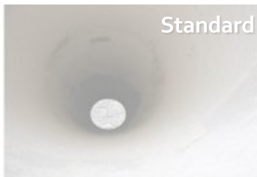
Ω - SWIRL INTENSITY



- ✓ λ *(ε/D)*
- ✓ correlation with location of bands of deposits (spray/s), coverage & thickness.
- ✓ λ = 0.085 *(ε/D ~ 0.006)*



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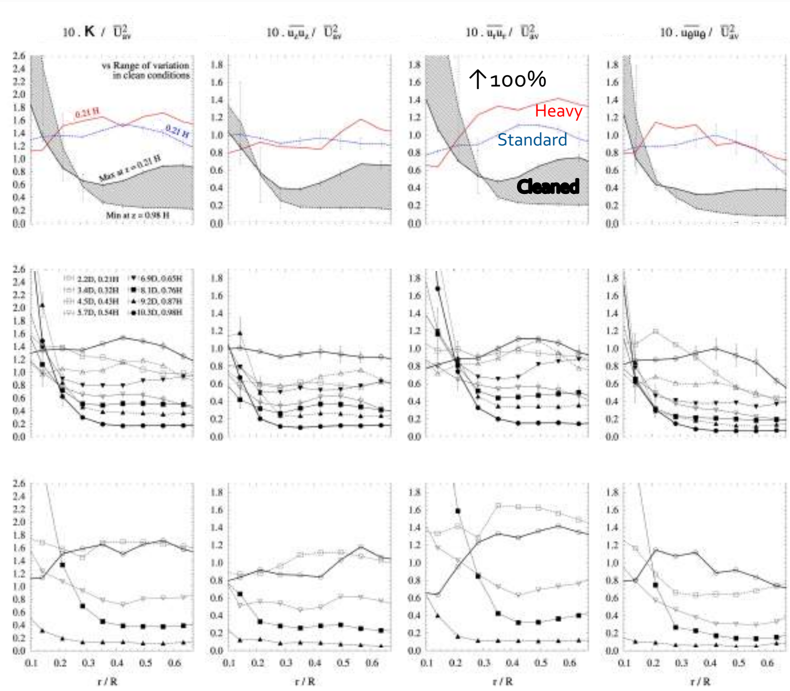
FRICTION: SOURCE OF TURBULENCE

Imperial College London P&G



Francia V et al 2015. Influence of wall friction on flow regimes and scale up of swirl spray dryers. Chemical Engineering Science 134: 399-413.

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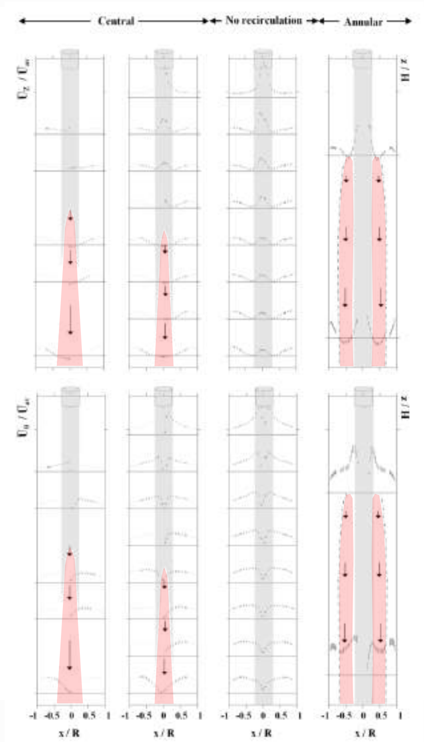
FRICTION: VORTEX BREAKDOWN

Imperial College London P&G



NO RECIRCULATION

- ✓ The expected reversal at Ω > 0.6 is suppressed by the influence of a downstream contraction that extends to the bottom of the chamber.
- ✓ A central jet is formed.
- ✓ 50% decay of *G* is lost in a tower with cleaned walls.

Ω_e

- ✓ The chamber design can lead to **a stronger operating swirl.**
- ✓ The reversal extends beyond the radius of the exit duct.
- ✓ An annular recirculation zone forms enveloping the jet.
- ✓ Operation at higher velocity

ANNULAR $\Omega_e > 2$

CENTRAL $\Omega_e < 1$

- ✓ Design & friction can lead to operate at **a weaker swirl**.
- ✓ A jet cannot form at the bottom. The vortex breaks into a conical recirculation zone.
- ✓ Faster & wider recirculation areas as the swirl weakens.
- ✓ Errors up to 70 - 200 %

Francia V et al 2015. Influence of wall friction on flow regimes and scale up of swirl spray dryers. Chemical Engineering Science 134: 399-413.

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FRICTION: SCALE UP

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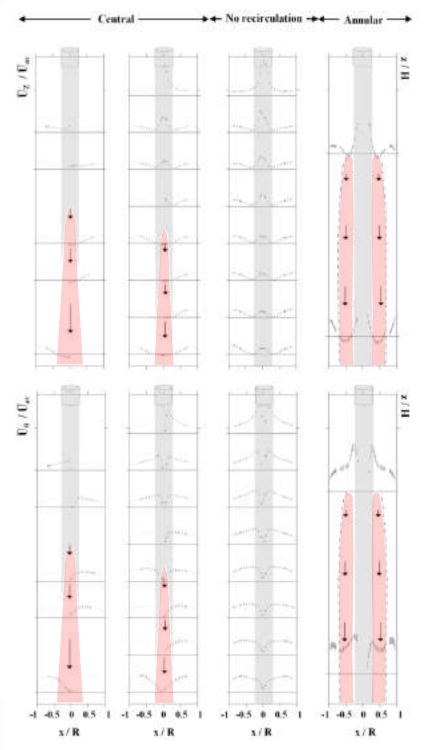


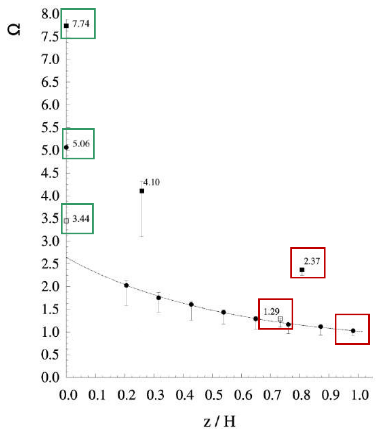
Adjust Initial Intensity

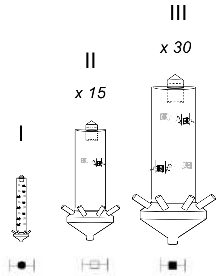
$$\Omega_i = \frac{\overline{M}_i^2}{\overline{M}_C^2}\frac{A_c}{A_i}\frac{R_i}{R_c}\sin\varphi\cos\xi$$

Predict Decay

$$\Omega_e = \left(\Omega_o + \frac{B}{A}\right)e^{2Aa} - \frac{B}{A}$$

$A \sim f(Re, \varepsilon/D)$ $(\Omega_o, B) \sim f(\Omega_i)$ Tabulated





Scale I	$\Omega_i \sim 5$	$a \sim 10$
Scale II	$\Omega_i \sim 3$	$a \sim 3$
Scale II	$\Omega_i \sim 8$	$a \sim 3$

Francia V et al 2015. Influence of wall friction on flow regimes and scale up of swirl spray dryers. Chemical Engineering Science 134: 399-413.

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FRICTION: SCALE UP

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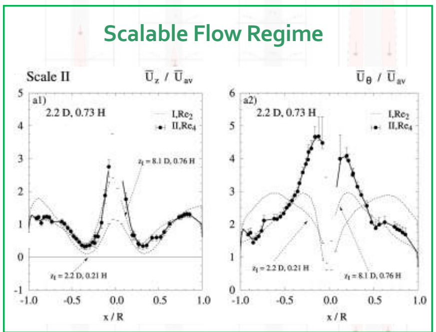

Adjust Initial Intensity

$$\Omega_i = \frac{\overline{M}_i^2}{\overline{M}_C^2}\frac{A_c}{A_i}\frac{R_i}{R_c}\sin\varphi\cos\xi$$

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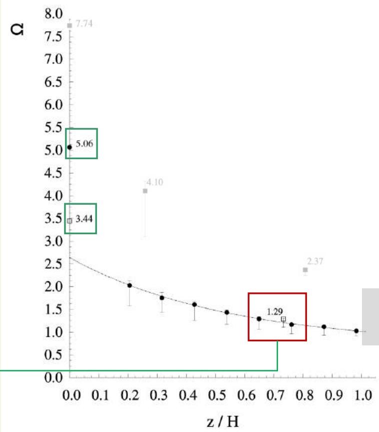

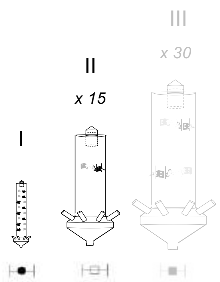

Scale I	$\Omega_i \sim 5$	$a \sim 10$
Scale II	$\Omega_i \sim 3$	$a \sim 3$
Scale III	$\Omega_i \sim 8$	$a \sim 3$

Francia V et al 2015. Influence of wall friction on flow regimes and scale up of swirl spray dryers. Chemical Engineering Science 134: 399-413.

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ROADMAP : VALIDATED COMPUTATIONAL FRAME

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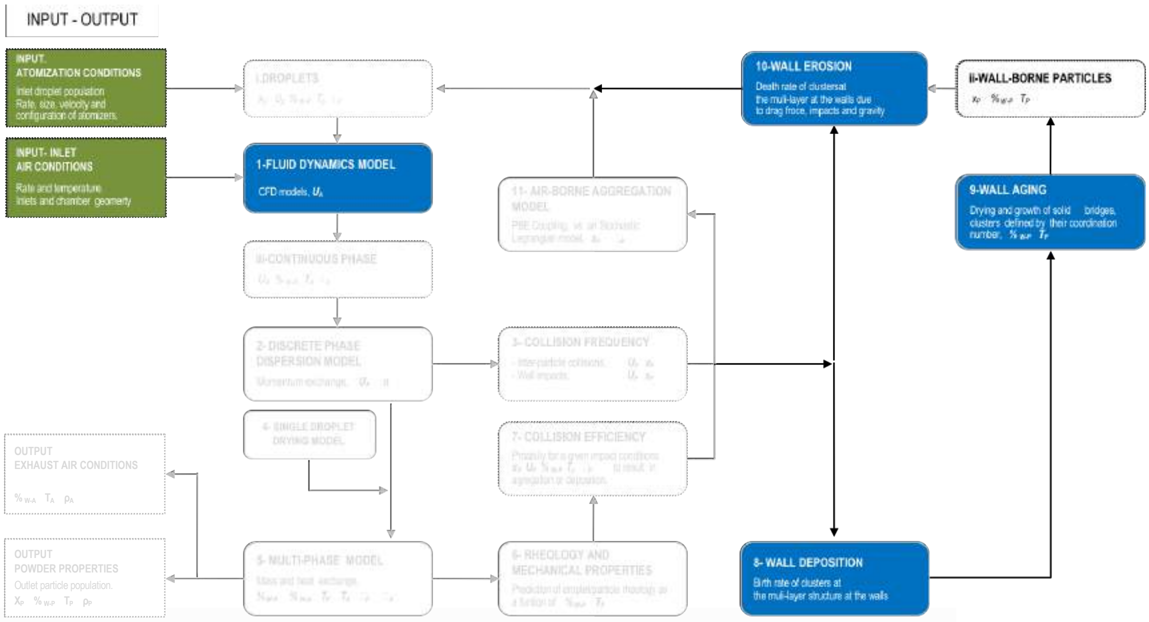

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FOULING DYNAMICS: TRACER EXPERIMENT

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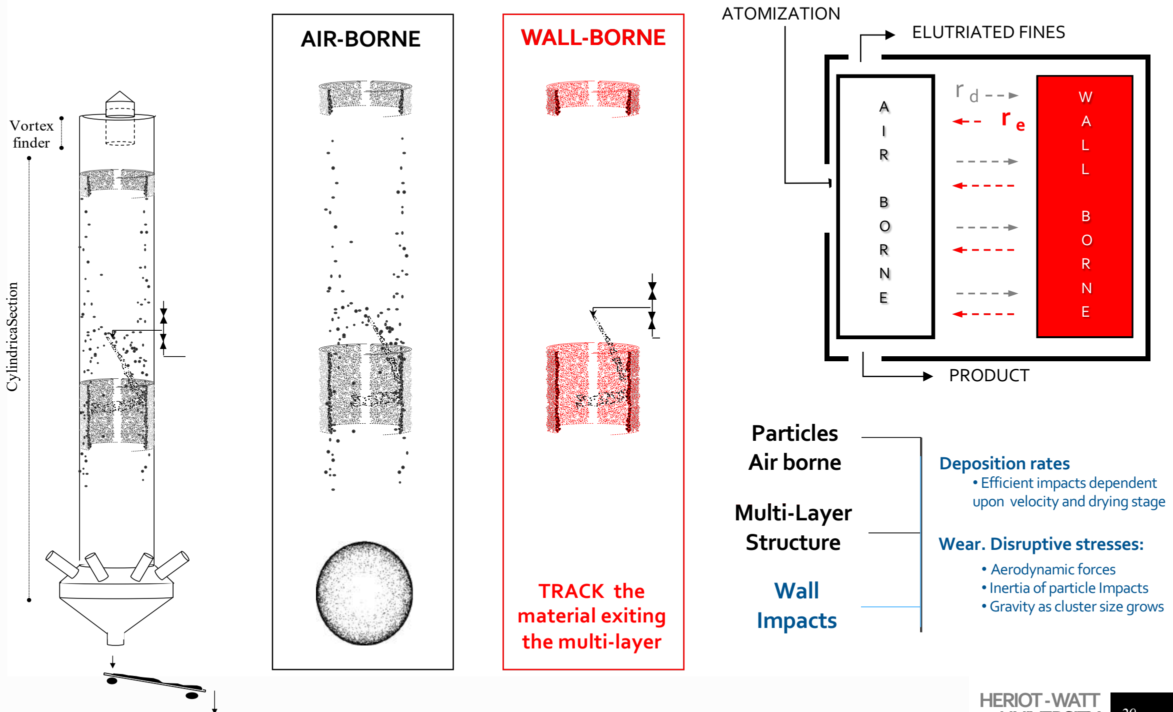

Francia V et al. 2015. The role of wall deposition and re-entrainment in swirl spray dryers. AIChE Journal 61, 6:1804-1821

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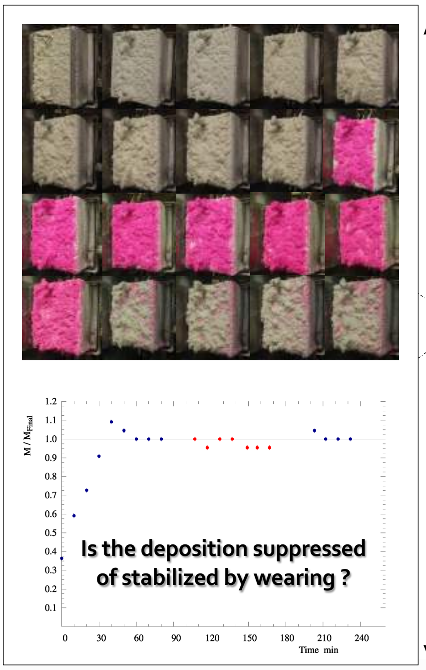
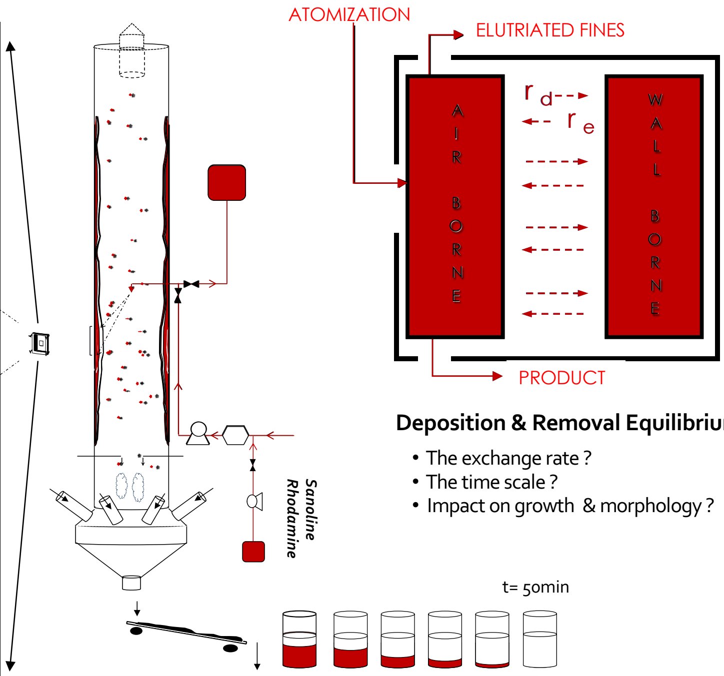
FOULING DYNAMICS: TRACER EXPERIMENT





Deposition & Removal Equilibrium

- The exchange rate ?
- The time scale ?
- Impact on growth & morphology ?

UV / Vis Spectrophotometer $C_{Ref,s,t} \approx 100\ ppm$

Francia V et al. 2015. The role of wall deposition and re-entrainment in swirl spray dryers. AIChE Journal 61, 6:1804-1821

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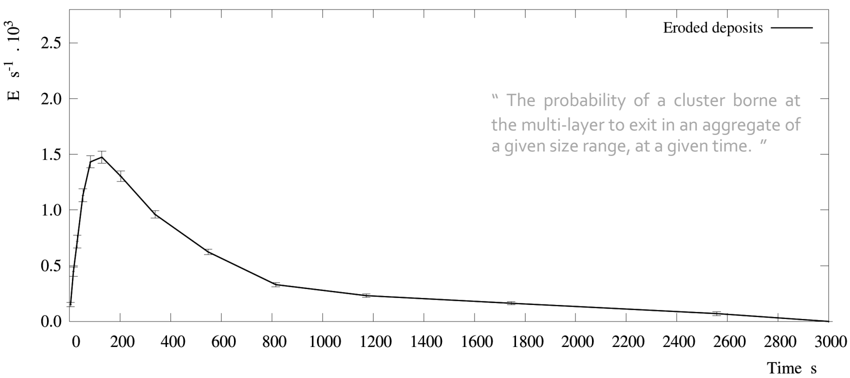
30

30

FOULING DYNAMICS: DEPOSITION vs REMOVAL

Time scale, *E* : Age distribution of the wall-borne material



1- The exchange rate

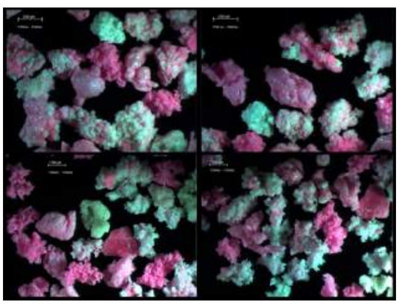
$r_{Exchange}$

$X_{t=0}$ 0.20 r_{Prd}

2- The time scale

Statistics

E_{50}	470 ± 30 s
E_{1m}	780 ± 30 s
E_{16}	140 ± 10 s
E_{84}	1510 ± 130 s



1. DRYING KINETICS

MAJOR HANDICAP TO PREDICT OVERALL DRYING RATES

Francia V et al. 2015. The role of wall deposition and re-entrainment in swirl spray dryers. AIChE Journal 61, 6:1804-1821

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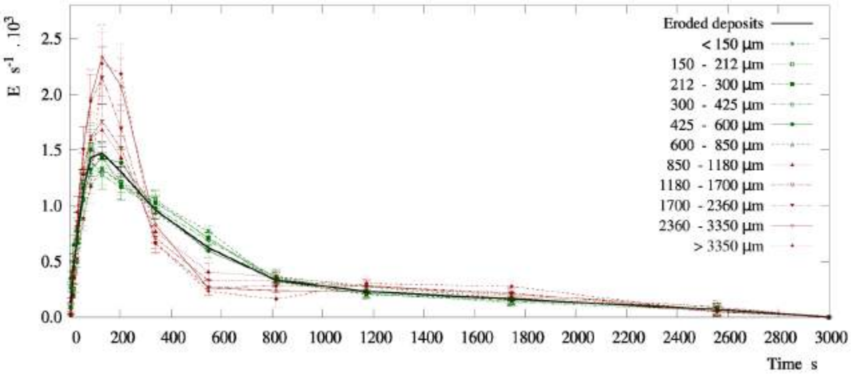
FOULING DYNAMICS: NET AGGLOMERATION

Deposition, consolidation & resuspension of a particle multilayer



1- The exchange rate

$r_{Exchange}$

$X_{t=0}$ 0.21/0.46 r_{Prd}

2- The time scale

Statistics

E_{50}	310/510 s
E_{1m}	710/870 s
E_{16}	110/150 s
E_{84}	1450/1720 s

2. GROWTH KINETICS

- ~10-20% of aggregates comes from Dry Erosion.
- ~100% of granules >850 µm come from Dry or Wet Erosion.
- No different structure to the rest. Is it all deposits ??

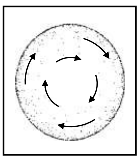
FUNDAMENTAL IN PARTICLE FORMATION

Francia V et al. 2015. The role of wall deposition and re-entrainment in swirl spray dryers. AIChE Journal 61, 6:1804-1821

OPTIMIZATION: AGGLOMERATION CONTROL

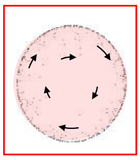
Reference $T_{Air\ IN}$ $M_{Air\ IN}$

Residence time (↓↓ $n_{(x)}$)
Drying rate (↓ 40 °C)
Velocity U_{air}
Momentum $G_{k\ \&}\ G$
Impact / s & velocity



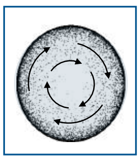
High Temperature ↑ $T_{Air\ IN}$ ↓ $M_{Air\ IN}$

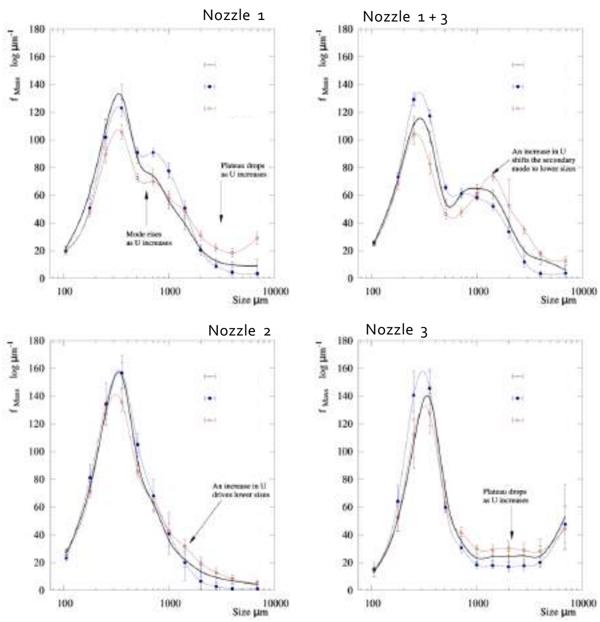
MIN residence time (↓↓ $n_{(x)}$)
MAX drying rate (↓ 40 °C)
↓ 20 % U_{air}
↓↓ 80 % in $G_{k\ \&}\ G$
↓↓↓ Impact / s & velocity



High Velocity ↓ $T_{Air\ IN}$ ↑ $M_{Air\ IN}$

MAX residence time (↑↑ $n_{(x)}$)
MIN drying rate (↓ 40 °C)
↑ 20 % U_{air}
↑↑ 80 % in $G_{k\ \&}\ G$
↑↑↑ Impact / s & velocity





Francia V et al - 2017. Agglomeration during spray drying: Airborne clusters or breakage at the walls? Chemical Engineering Science 162: 284-299

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OPTIMIZATION: AGGLOMERATION CONTROL

Imperial College London

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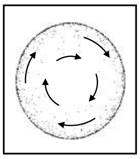
Velocity U_{air}
Momentum $G_{k\ \&}\ G$

Impact / s & velocity



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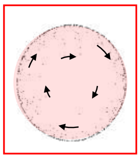

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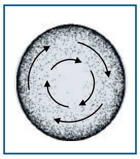

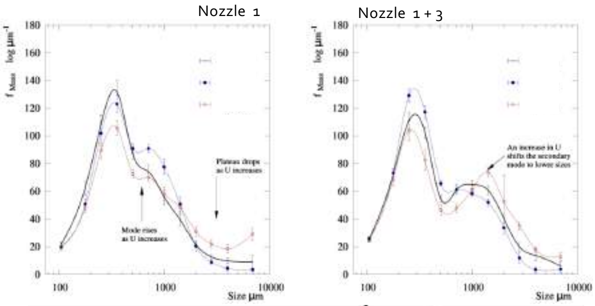

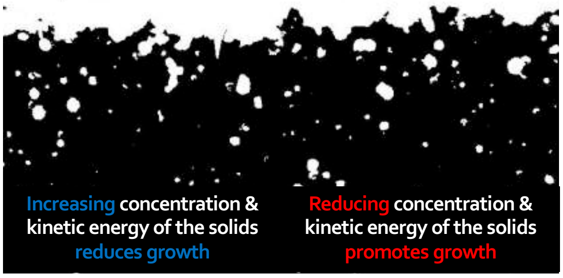

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OPTIMIZATION: AGGLOMERATION CONTROL

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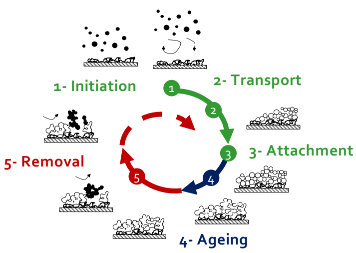
DYNAMIC FOULING
NEW PARADIGM IN SWIRL SPRAY DRYERS

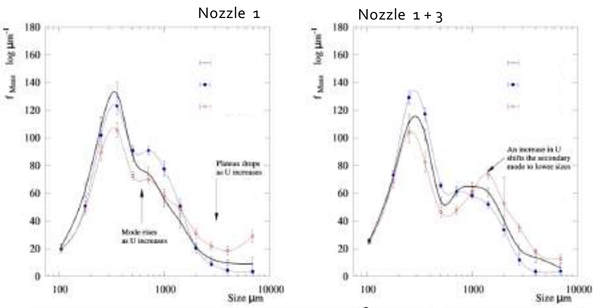
Direct 2 – 5 % increase in overall capacity.

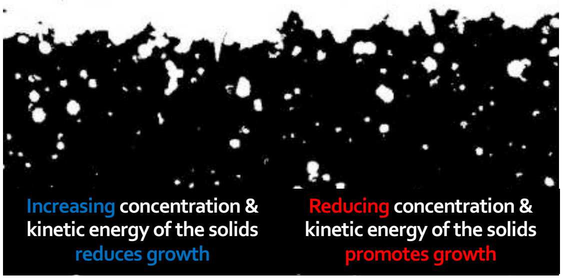
Similar overall drying efficiency, but the operation at low T allows energy integration leading to **20 % drop in energy consumption**

Drying, process efficiency, energy consumption and product quality driven by the interactions of the solid phase with and at the walls.

Deposition - Consolidation - Breakage







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INSTITUTE OF MECHANICAL, PROCESS & ENERGY ENGINEERING
Victor Francia Asst. Professor

BEWARE OF "STANDARD" PRACTISE VALIDATION

•

SCALE MATTERS:

LIMITATIONS OF RANS IN PRODUCTION SCALES

FRICTION UNDERPINS VORTEX STRUCTURE, TURBULENCE & STABILITY

•

DYNAMIC NATURE OF FOULING

WALL-BORNE AGGLOMERATION

MODULATION WITH THE VORTEX MOMENTUM

•

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03/20 - PhD - Computational - CFD-DEM modelling
07/20 - PhD - Experimental - Structure of cohesive powders

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THANK YOU

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