Cyclone science and improving product recovery in spray drying (SD) processes

Romualdo Salcedo
CTO, Advanced Cyclone Systems
Professor, ChemEngDep, University of Porto

April 13th, 2016
University of Leeds

Why are cyclones important in SD?

Because they are the best collectors for first-grade product recovery

DISADVANTAGES OF LEGACY SOLUTIONS:

HE Cyclones:

Low efficiency for fine particles

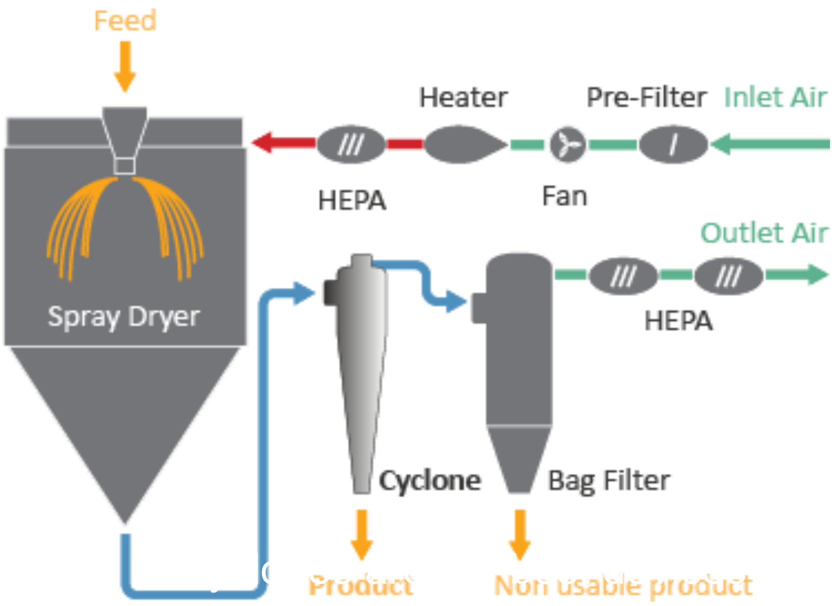
Bag Filters:

Product degradation

Product contamination

Production downtime

Cleaning costs



Several constraints are imposed on design

- Wide range of operating conditions:

…- 85ºC < T < 120ºC (negative T for cryogenic micronizers)

…mg/Nm^3 < C_in < …kg/Nm^3 (highest values occur with jet mill micronizers)

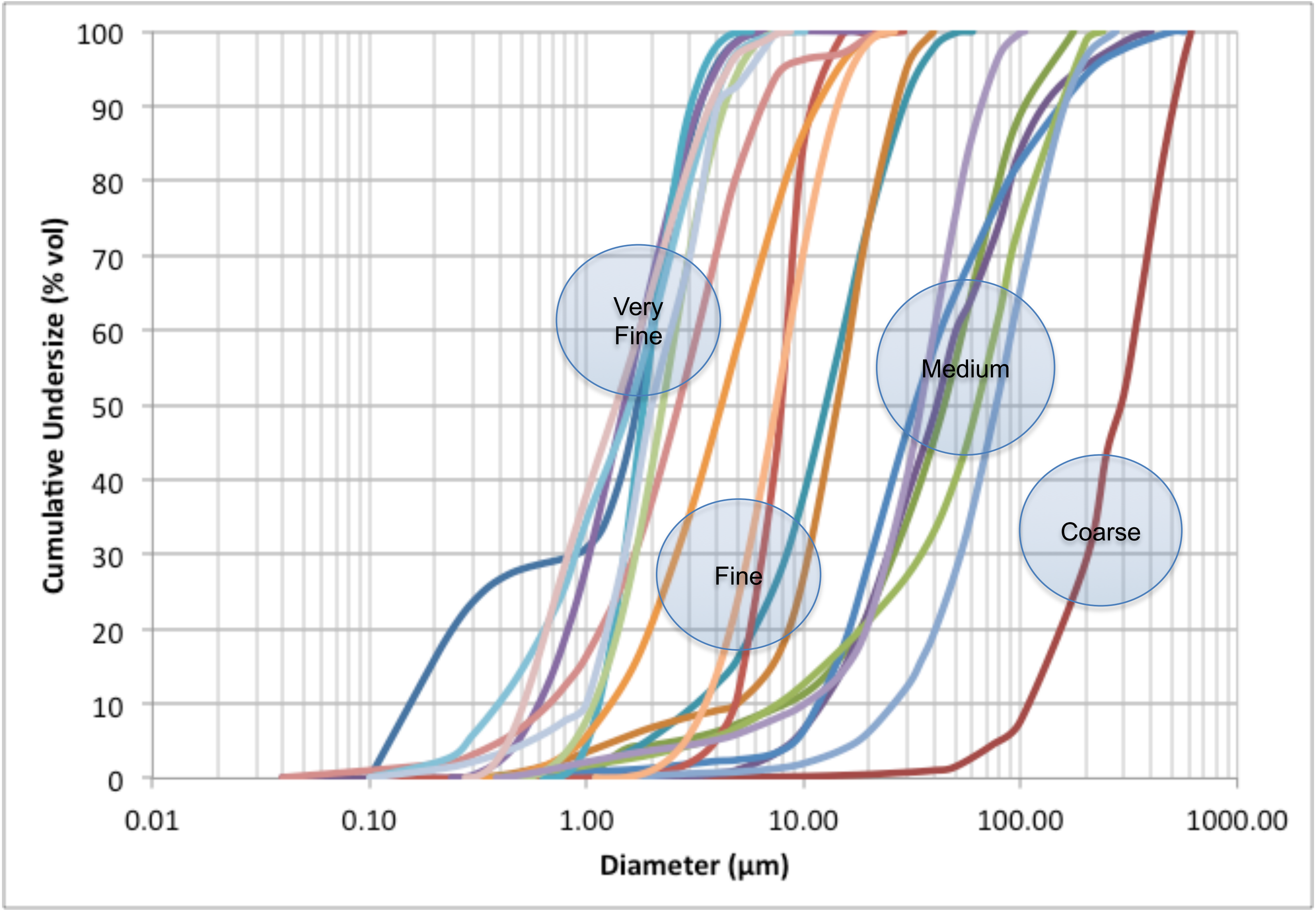
…25 Nm^3/h < Q < …150,000 Nm^3/h (highest flowrates occur with quasi-pharma applications, e.g., food ingredients)

- Type of product:

…solid dispersions, inhalable, injectable, microcapsules, tablets' waste recovery, …
…wide range of densities (non-porous, porous)

This makes it very difficult to have a single cyclone geometry to effectively deal with all cases

Particle size distributions in SD

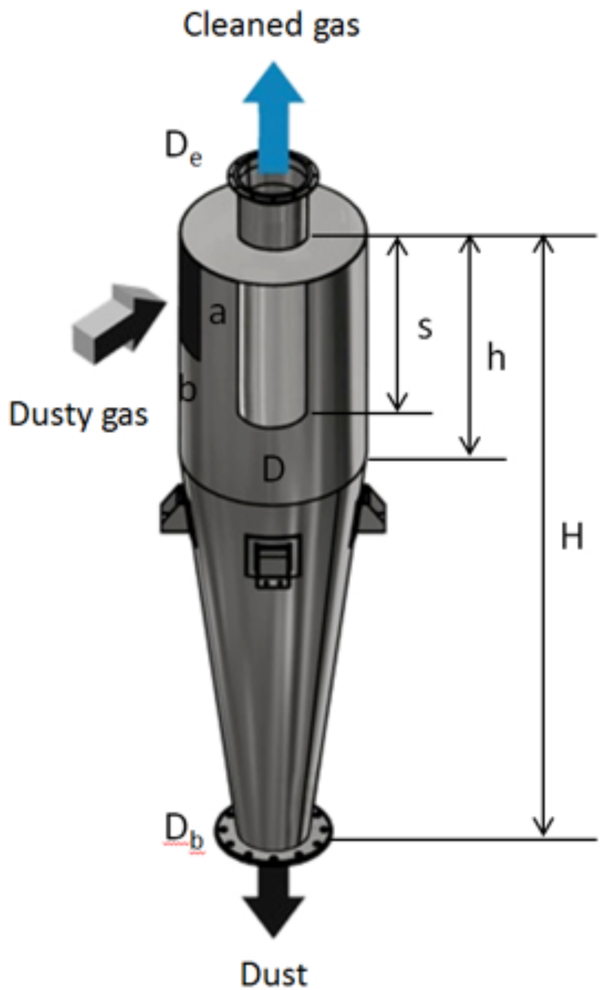


How can we design better cyclones?

- The cyclone geometry is defined by 7 dimensionless ratios of its 8 independent dimensions to the cyclone D

- To optimize the geometry becomes a problem with 7 degrees of freedom, usually non-linear and non-convex

- A 2-level factorial design would require building 128 prototypes and a 4-level, 16384……



Setting up a mathematic problem

Maximize efficiency, conditioned to:

Equality constrains

- Relevant design équations (cyclone modeling)
- Particle size distribution and density
- Gas flow rate and dust load
- Gas temperature, density and viscosity

Inequality constrains

- Maximum pressure loss
- Saltation velocity
- Geometric constraints

Solution:

Numerically optimized cyclones → hurricane

The solution

- We have abandoned pure empiricism and resorted to mathematical programming

- Use empiricism only to test and possibly improve the numerical solution, found among thousands of virtual prototypes

- But first, one has to understand how cyclones work…cyclones are deceptively simple

Cyclone dynamics

- Effect of operating conditions
  (P, T, PSD)

- Effect of multiphase flow
  (inlet concentration, particle density and porosity, …)

- Possible clustering and strand formation (Muschelknautz)

- Highly vorticial asymmetric turbulent flow field

- CFD only in 2015 used for global optimization

How to proceed?

1. Find an appropriate collection model - neglect particle-particle interaction

2. Superimpose particle-particle interaction

1. Optimize using a global optimizer - stochastic is slower but much better at obtaining the global optimum (Salcedo, 1992)

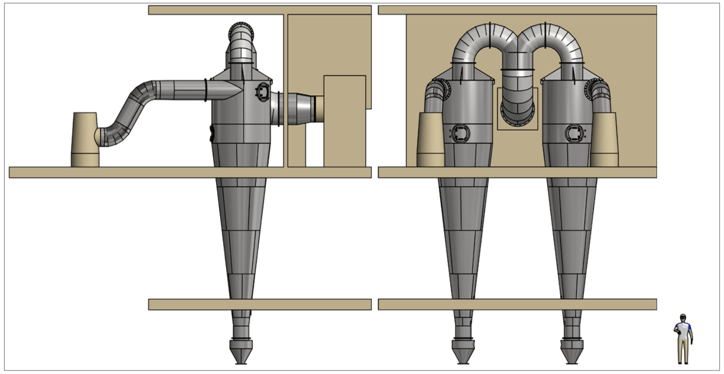
1. Build and test the numerical solution

1. Find an appropriate collection model

- The Mothes and Loffler model (1988) seems to best describe the collection of particles by cyclones, neglecting particle-particle interaction (Clift et al., 1991)
- Problem: this model depends on the ***particle turbulent diffusivity***, that depends on cyclone operating conditions, particle size distribution and cyclone geometry (Salcedo and Coelho, 1999)
- With the above approach, the line of Hurricane (HR) cyclones has been developed and patented (EP0972572A2)

HR performance in SD applications

- Technology: Hurricane
- Application: Caseinate/Hydrolisate recovery
- **Dimension**: 92,140 am^3/h
- **Client**: Arla Foods
- **Location**: Denmark
- **Load into Cyclone**: 17 g/Nm^3
- **Hurricane Efficiency**: 98.9-99.3 %
- **Alternative technology**: Competitor HE cyclone
- **Alternative Cyclone Efficiency**: 96 %
- **Increased Recovered Powder**: 320 ton/year
- **Reduction in losses**: 77%



Some Pharma results on HR performance from leader API manufacturer

Project 1:
1,500 kg/h (N_2) @ 85ºC
Measured on HR: 96%
Competing cyclone: 83%. Reduction in losses: 76%

Project 2:
80 kg/h (N_2) @ 65ºC
Measured on HR: 85-95%
Competing cyclone: 80-90%. Reduction in losses: 25-50%

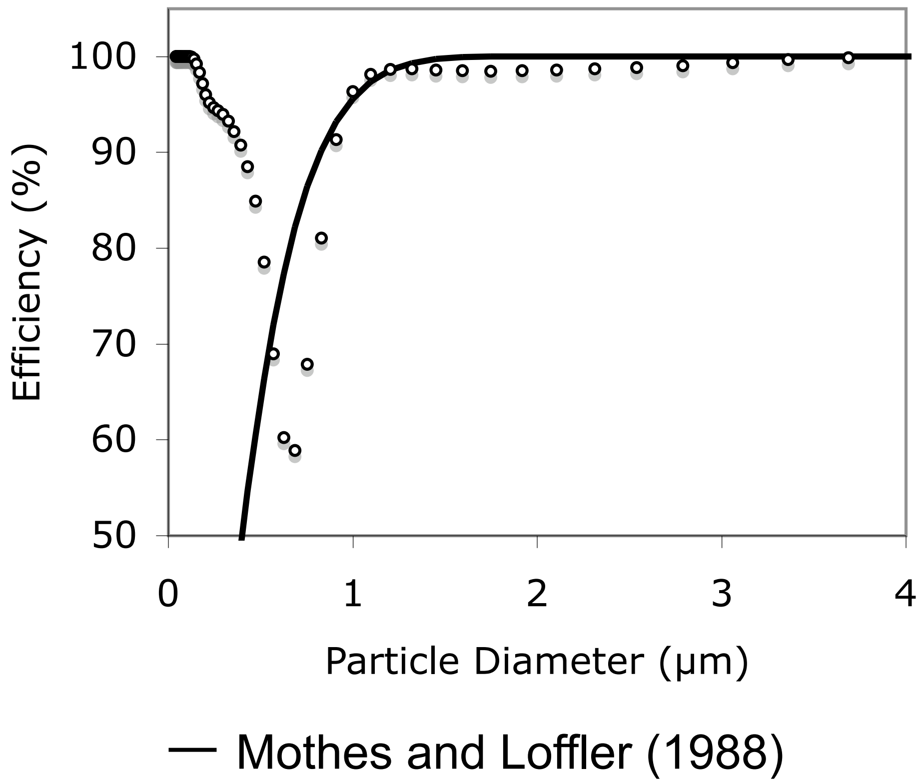
Project 3:
112 kg/h (N_2) @ 65ºC
Measured on HR: 84%
Competing cyclone: 60%. Reduction in losses: 60%

Project 4:
1250 kg/h (N_2) @ 85ºC
Measured on HR: 99.7%
Competing cyclone: 97%. Reduction in losses: 90%

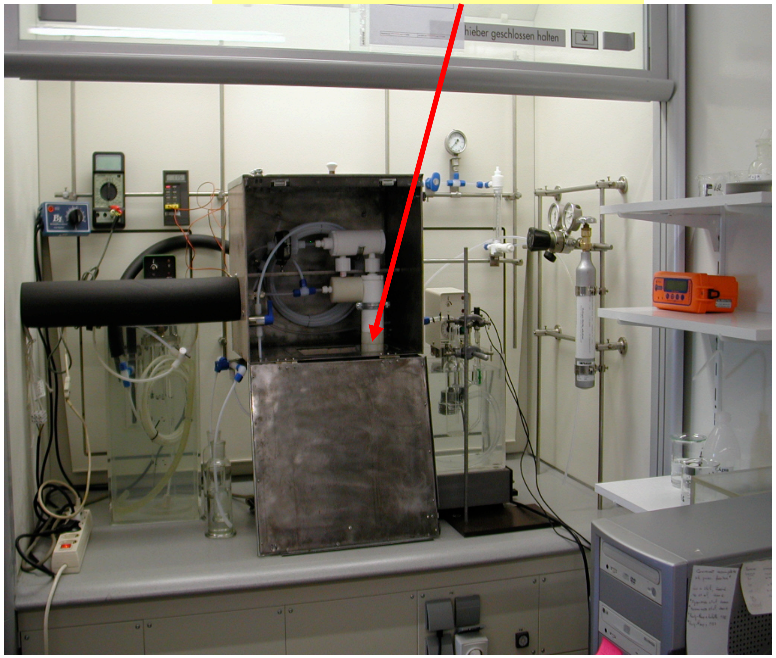
2. Superimpose particle-particle interaction

Grade-Efficiency at Lab Scale

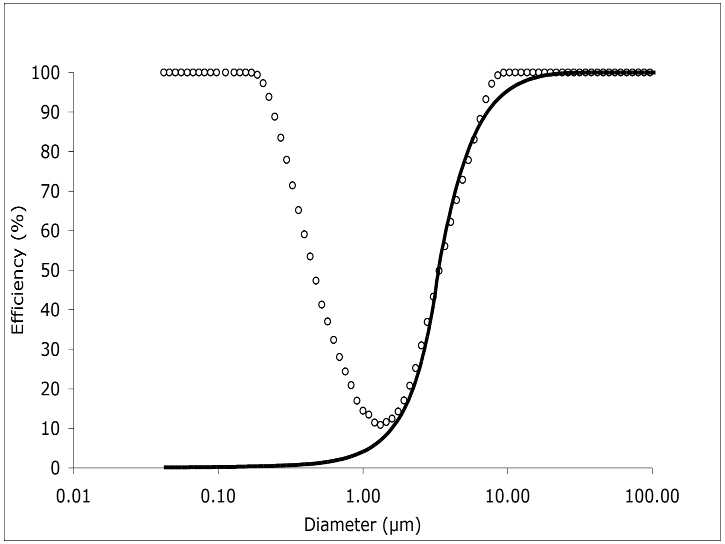
Abnormal capture of fine particles - Why?



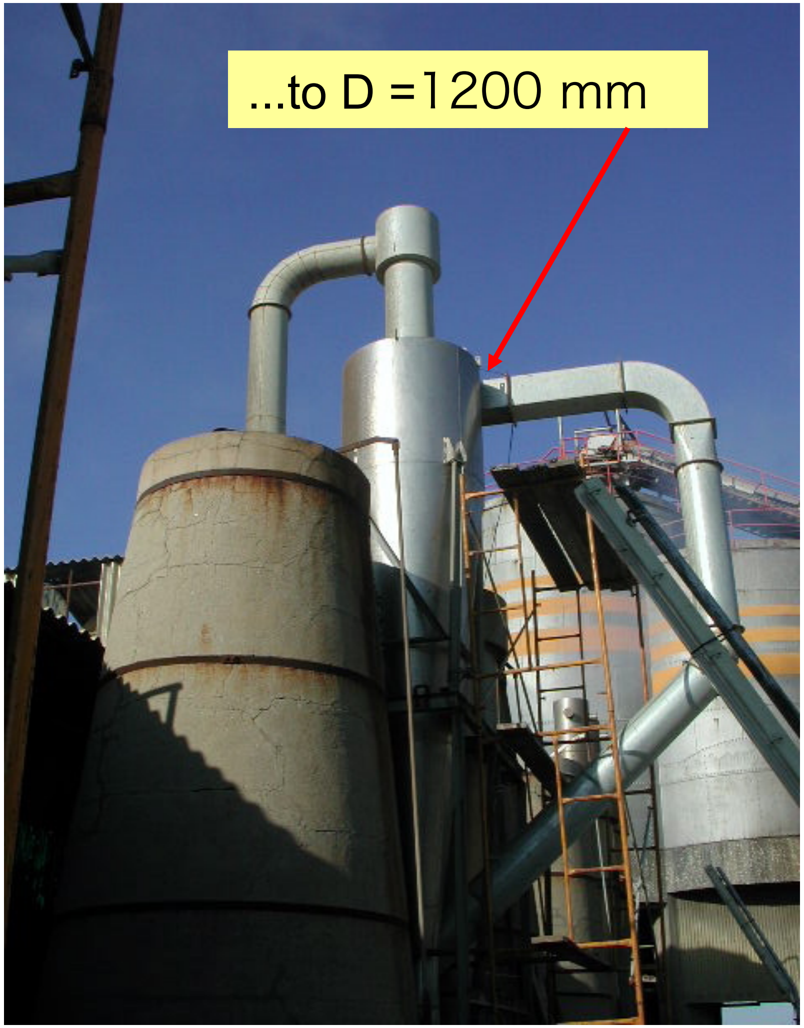
From D =20 mm



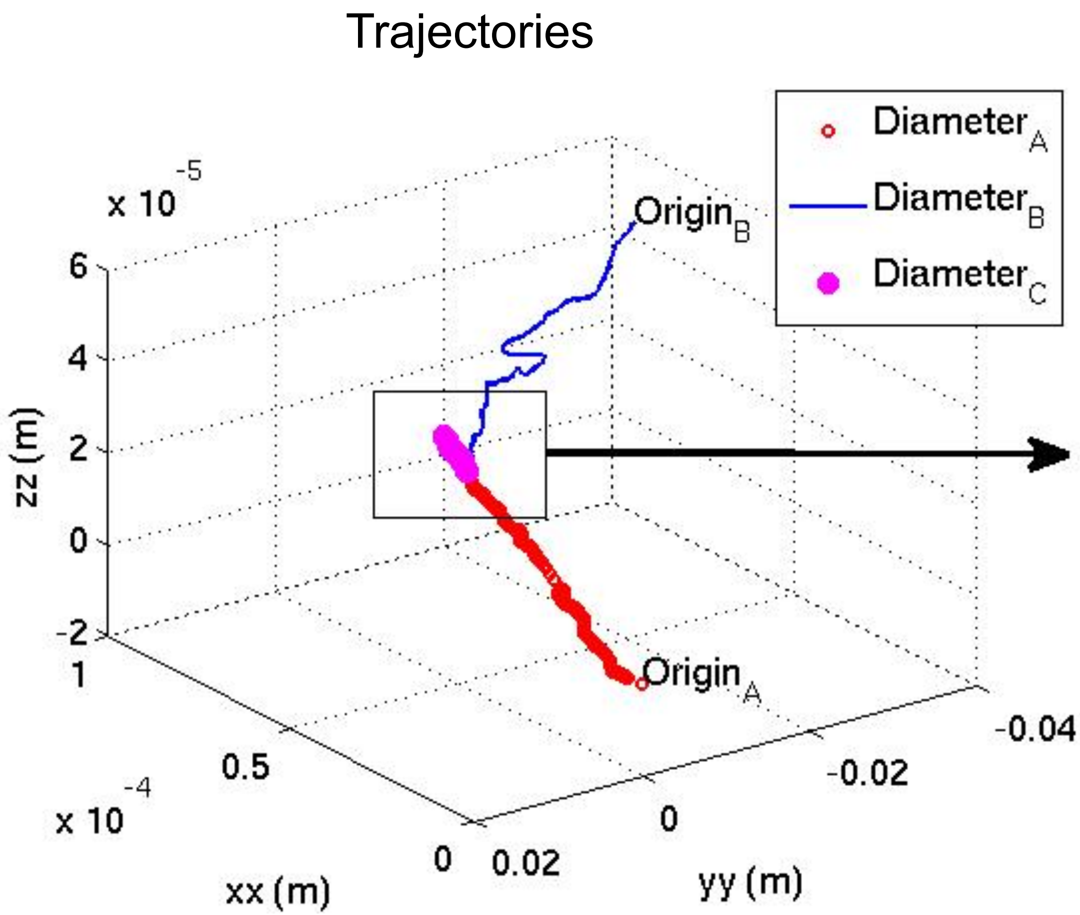
Grade-Efficiency at Industrial Scale

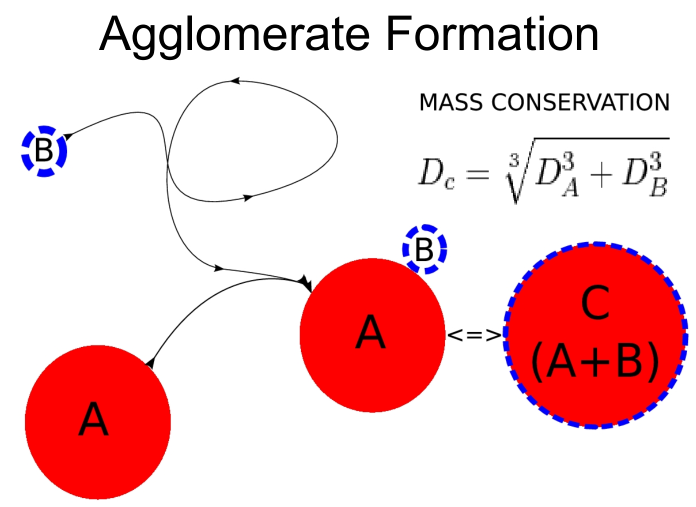


— ML (1988)

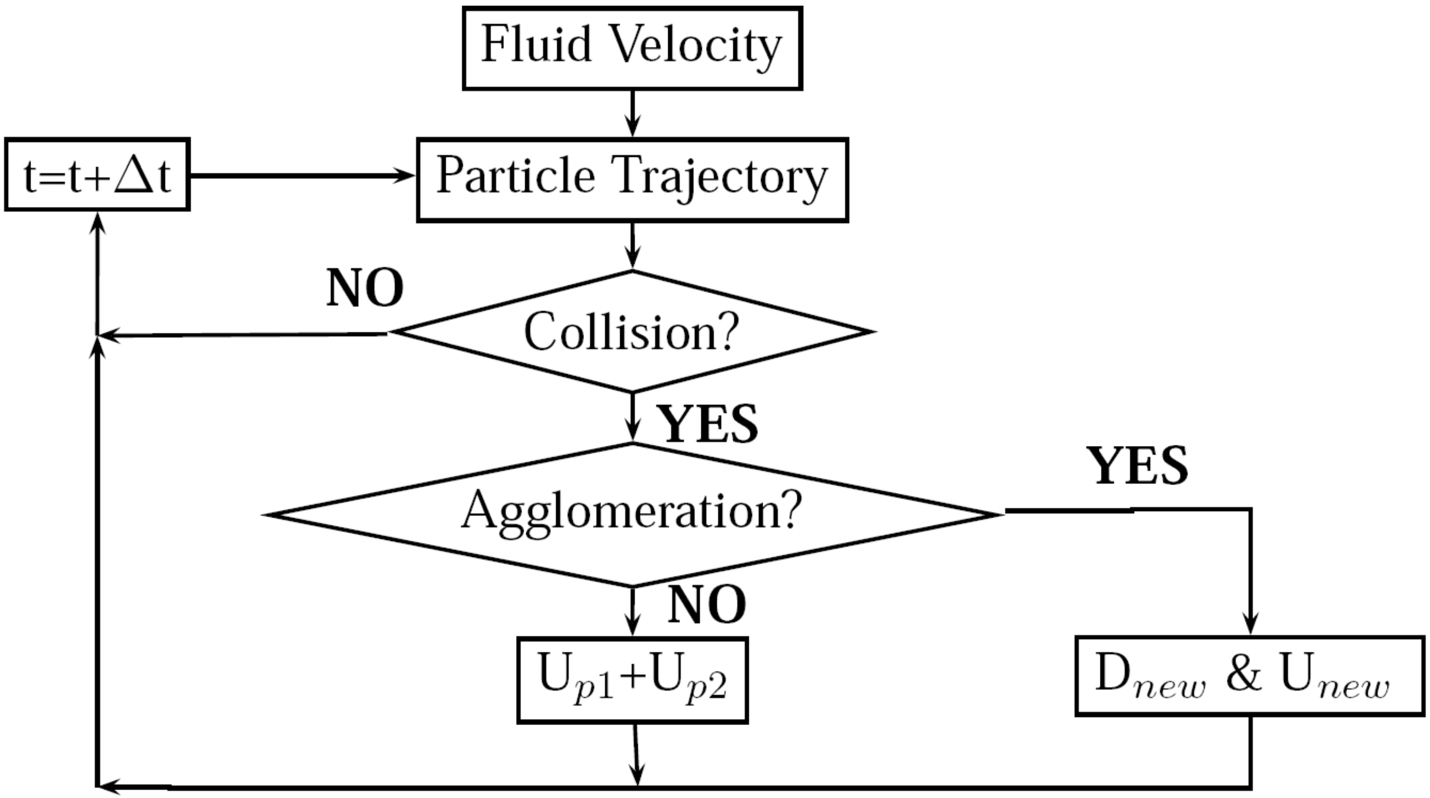


Schematics of particle-particle collisions





Clustering (based on Ho and Sommerfeld, 2002)



Main Model Equations (PACyc)

Particle Trajectory

$$\left.\begin{aligned} \frac{dx_{p,i}^{N}}{dt} &= u_{p,i}^{N} \\ \frac{du_{p,i}^{N}}{dt} &= \frac{3}{4}\frac{\rho_F c_D}{\rho_p D_p^N}\left(u_{F,i} - u_{p,i}^{N}\right)\left|\vec{u}_F - \vec{u}_p^{\,N}\right| + g_i \end{aligned}\right\} \qquad i = 1\ldots 3 \wedge N = 1\ldots N_{particles}$$

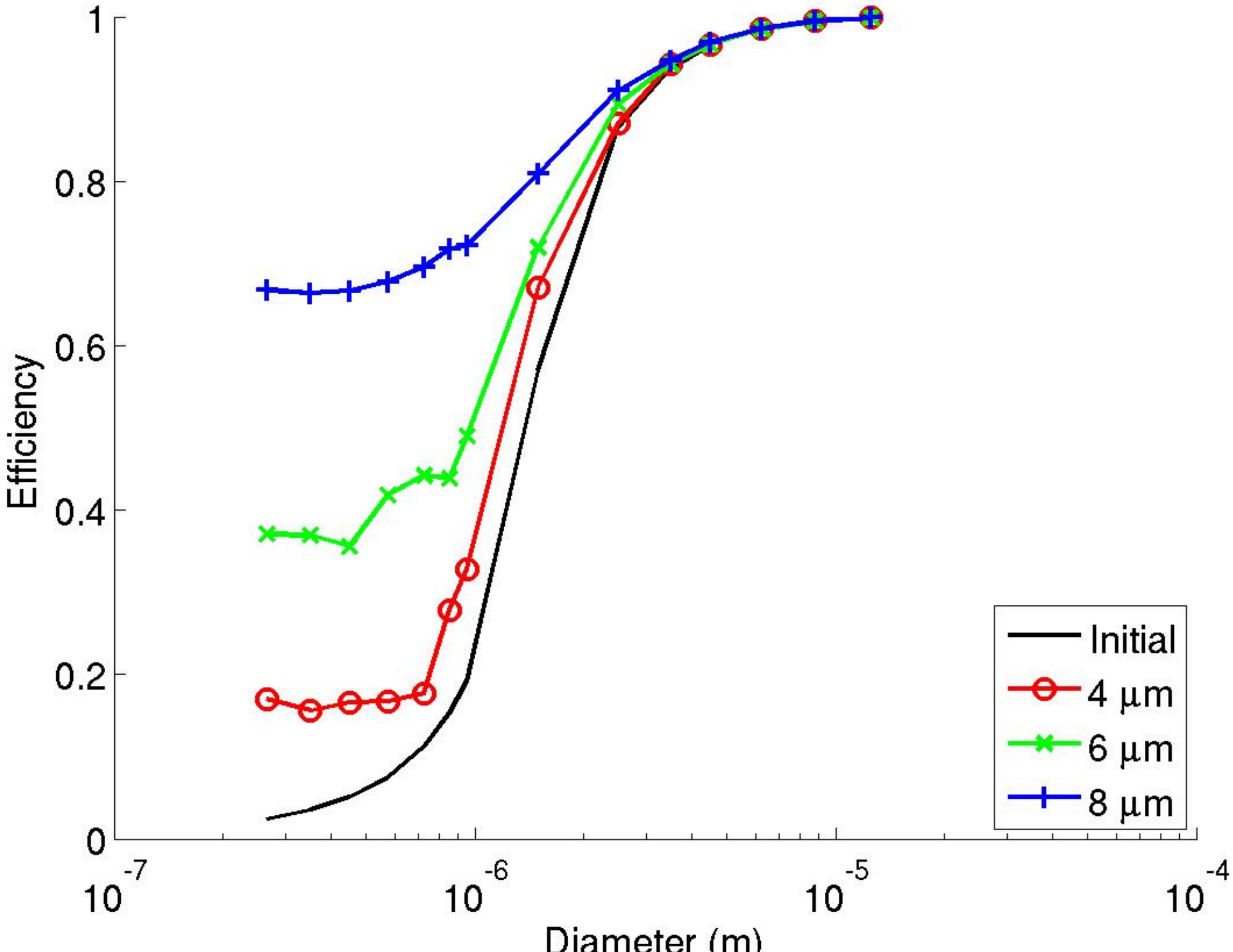
Introducing Turbulence in the Fluid

$$u_{F,i}^{n+1} = u_{F,i}^{n} R_p + \left|u_{F,i}^{n}\right|\sqrt{1 - R_P^2} \times N(0,1)$$

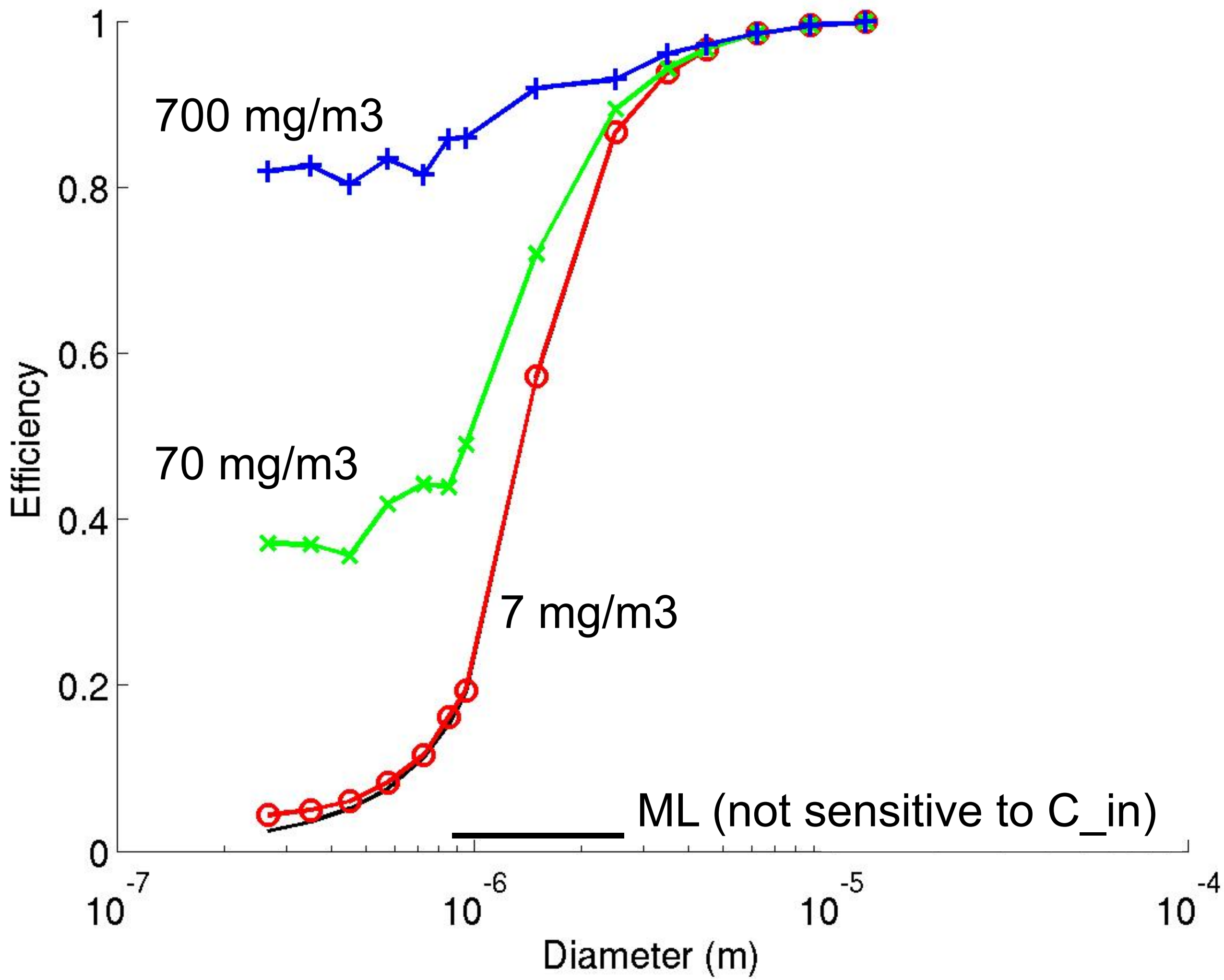
New Class-Efficiency (after History Rebuild)

$$\eta_i^{new} = \frac{\sum_j INFO_{i,j} \times \eta_j}{\sum_j n_{i,j}} \qquad i = 1\ldots N_{classes} \wedge j = 1\ldots N_{diameters}$$

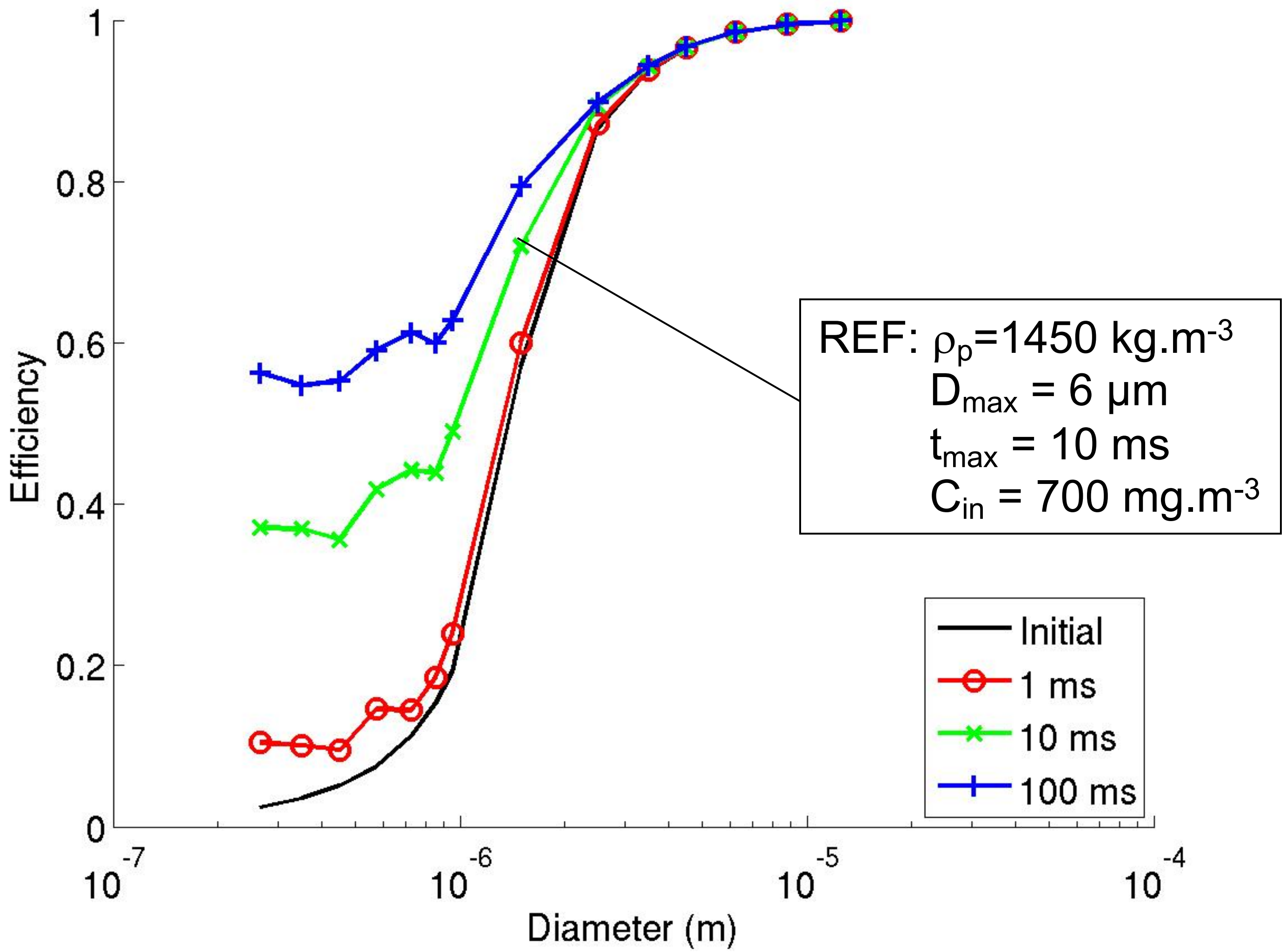
Effect of maximum collision (target) diameter



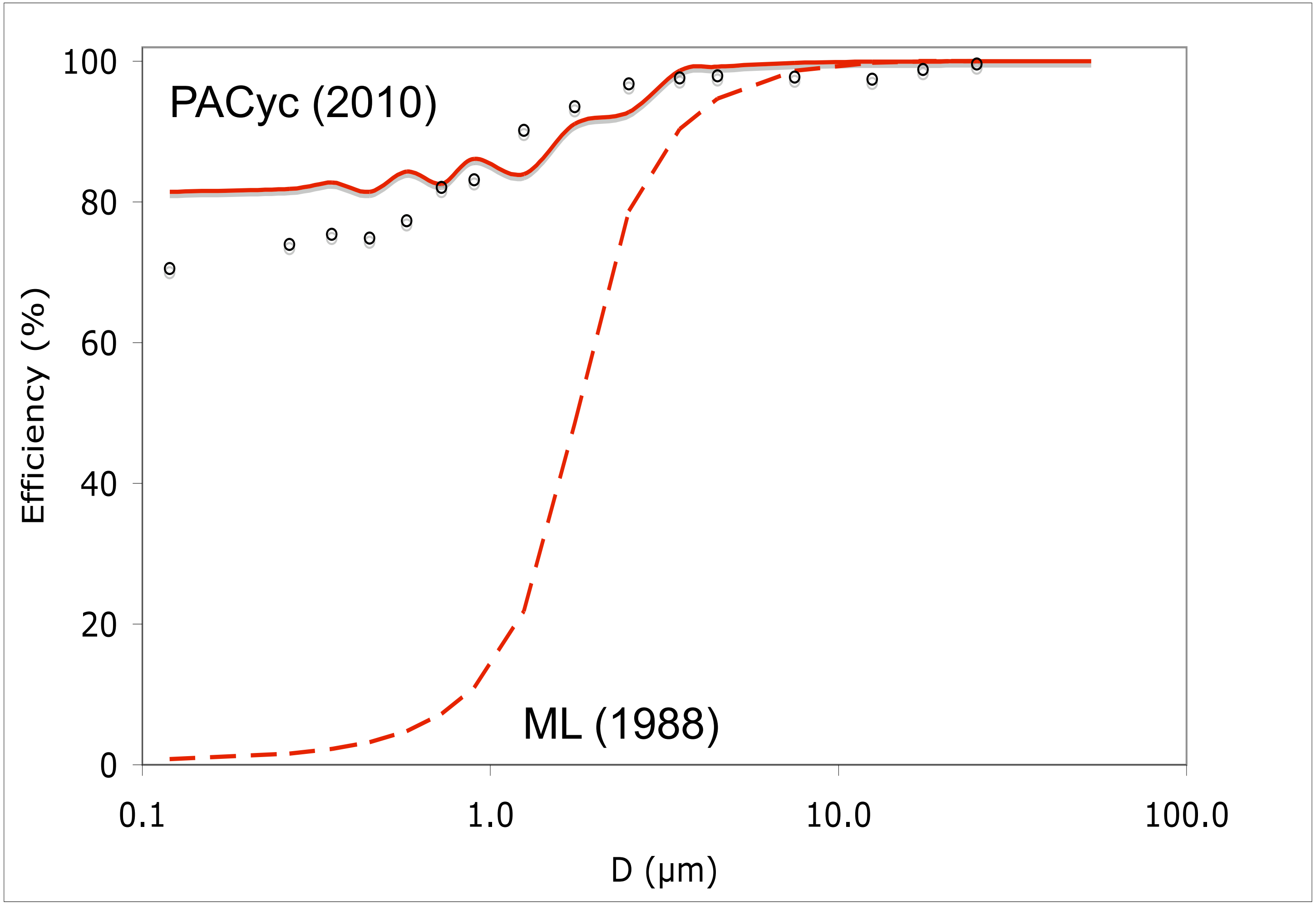
Effect of inlet concentration



Effect of residence time



Very good agreement with experimental data



PACyc conclusions

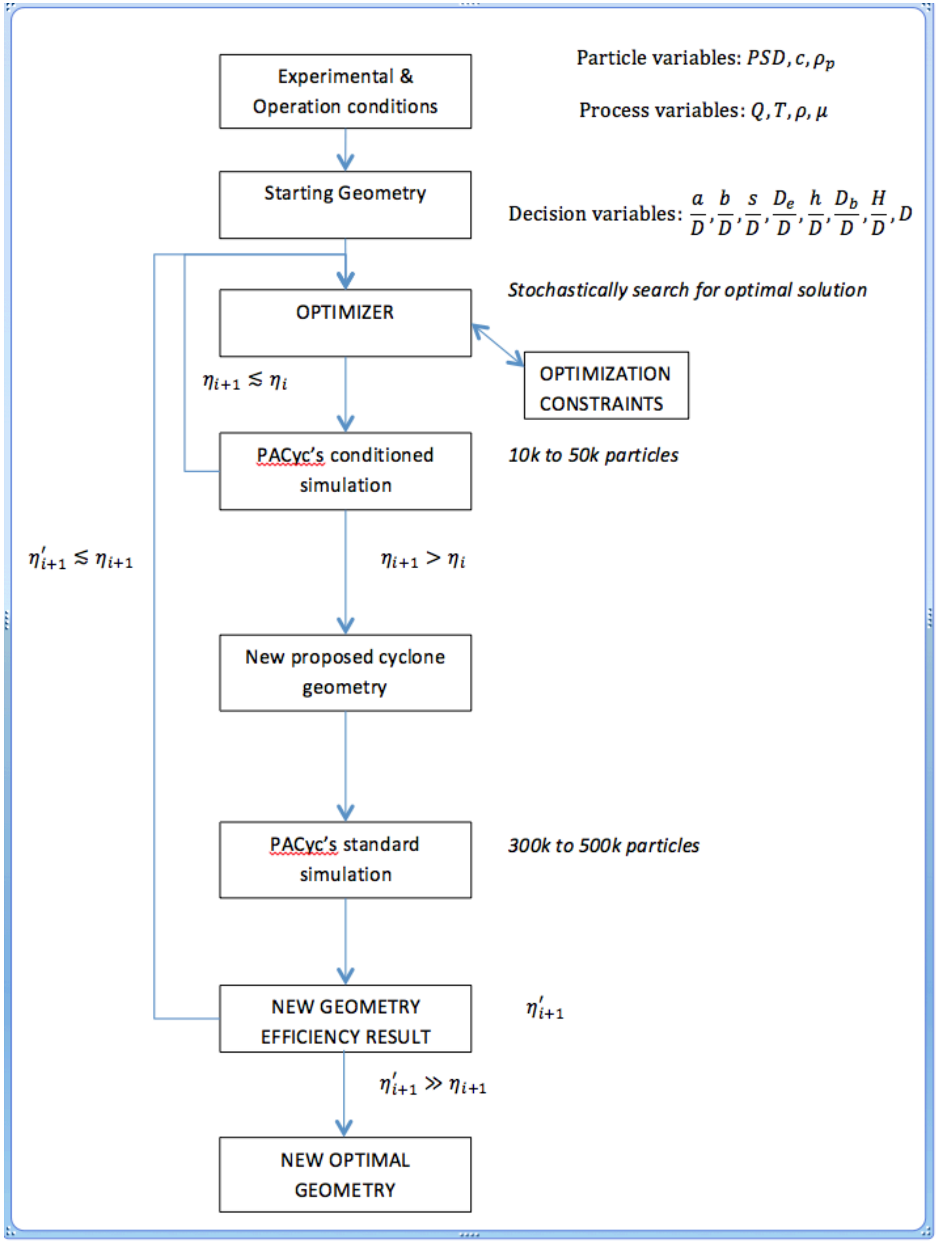
•We have extended the ML (1988) and Ho and Sommerfeld (2002) models to predict fine particle clustering in turbulent cyclone flows

•Fair agreement between experimentally observed grade-efficiency curves and those from our model

•Excellent agreement between predicted and experimental global collection efficiency

•There is now a theoretical framework on which to base our hyphothesis, viz. that clustering inside the cyclone may be responsible for the very high collection of fine particles

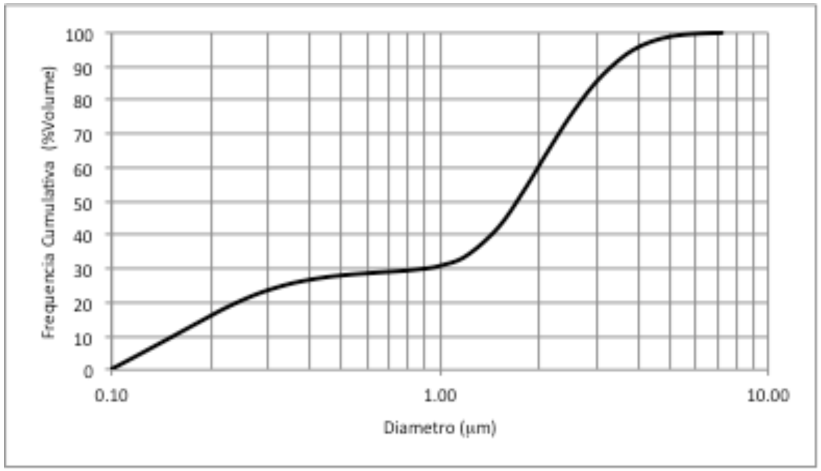
3. Optimize with the PACyc model

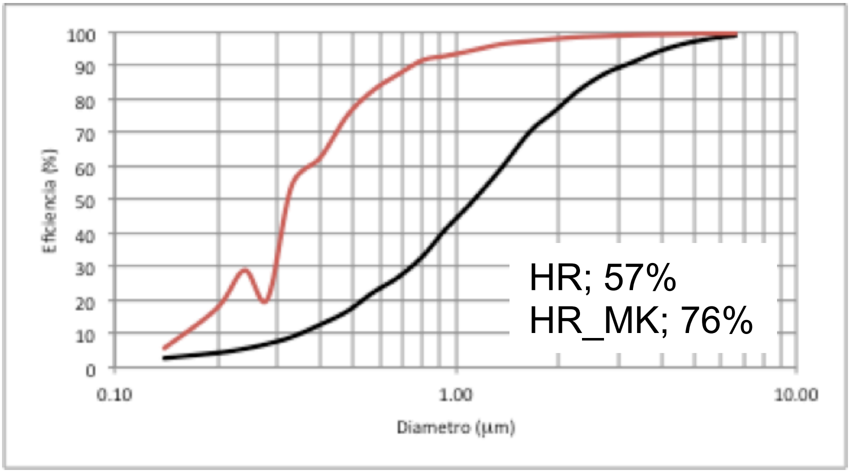


The outcome: the Hurricane_MK

Under patent pending (PTC 107312), it shares no more than 2 ratios with ≈ 190 geometries available in the scientific literature or in the marketplace

Projections for difficult API (ρ_p=450 kg/m^3):





Projections confirmed by client: Reduction in losses 44%

Grade-efficiencies including clustering

HR130; MK250

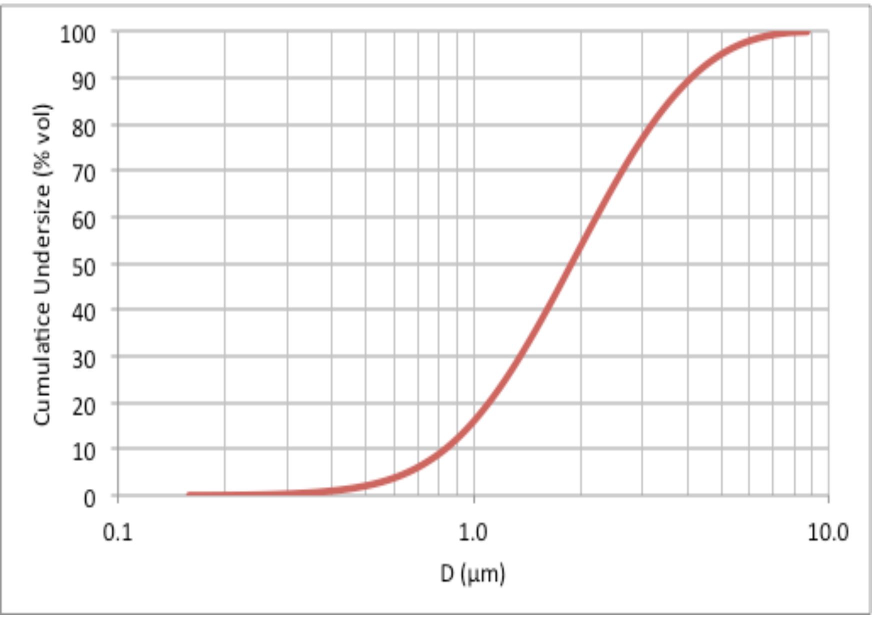


Fig. 1 - Particle size distribution reconstructed from cyclone (42%), filter (53%) and losses (5%).

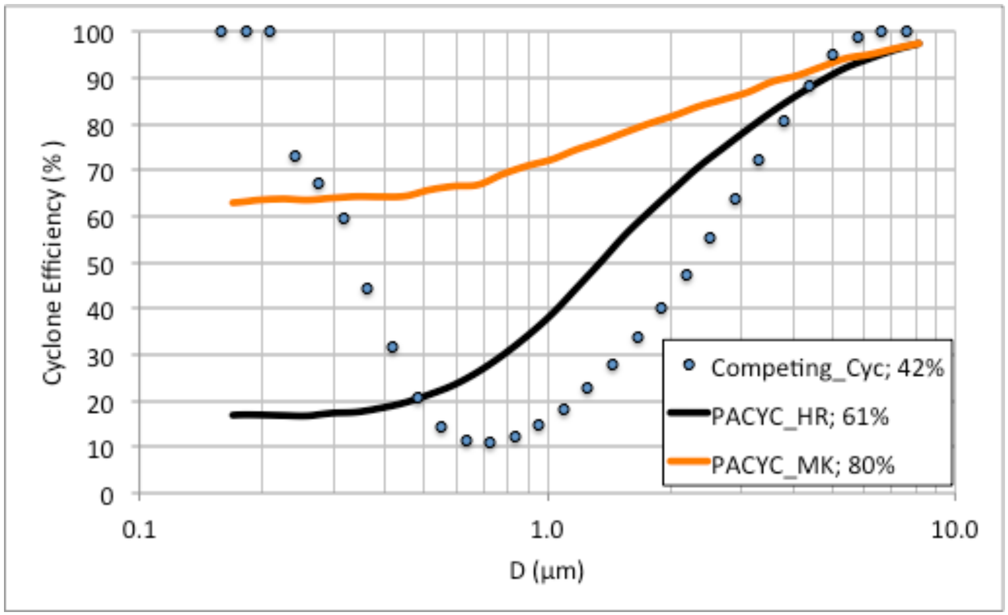
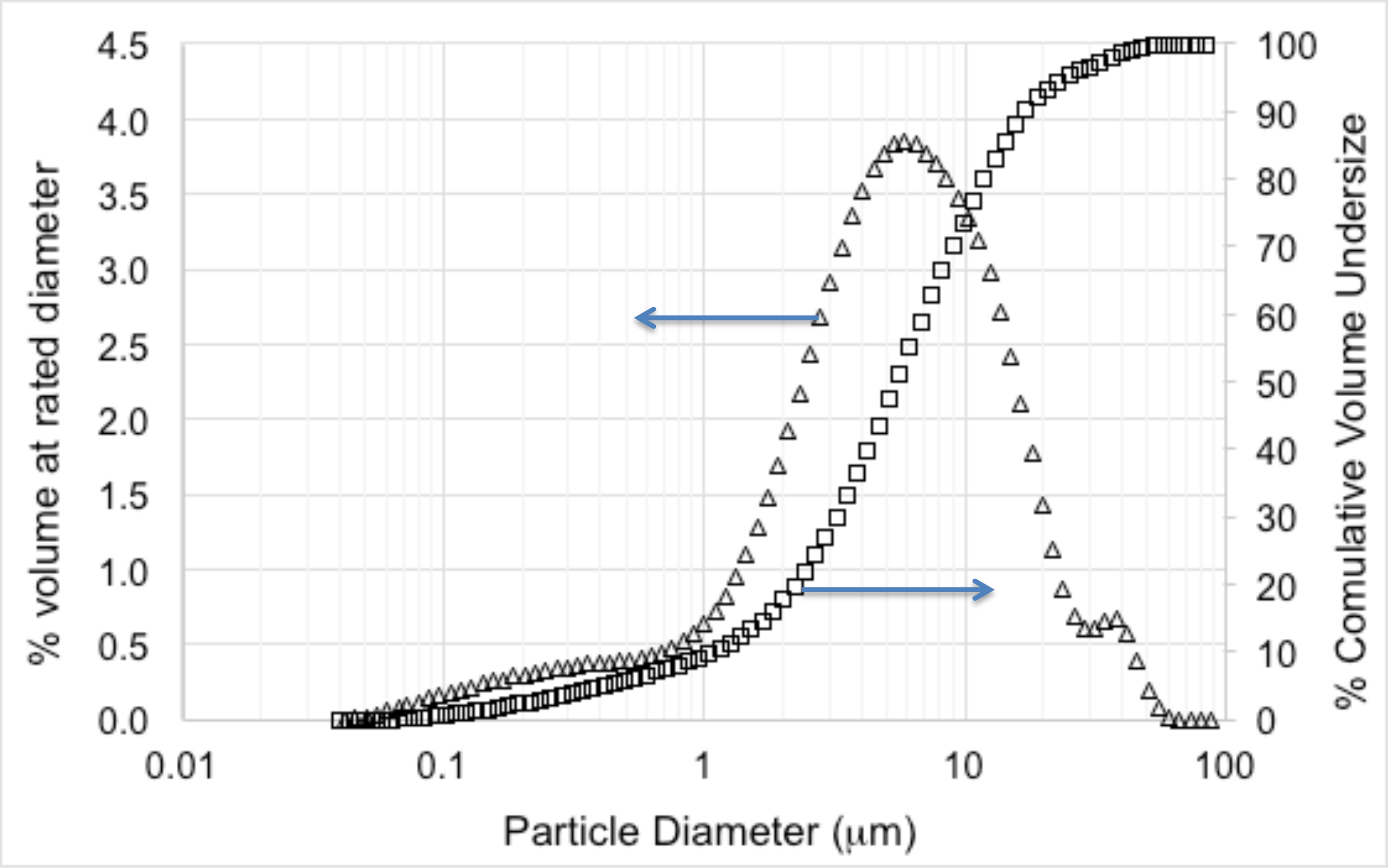


Fig. 2 - Grade and global efficiencies from competing cyclone (experimental) and predicted by PACYC for HR and HR_MK cyclones (particle density; 711 kg/m^3)

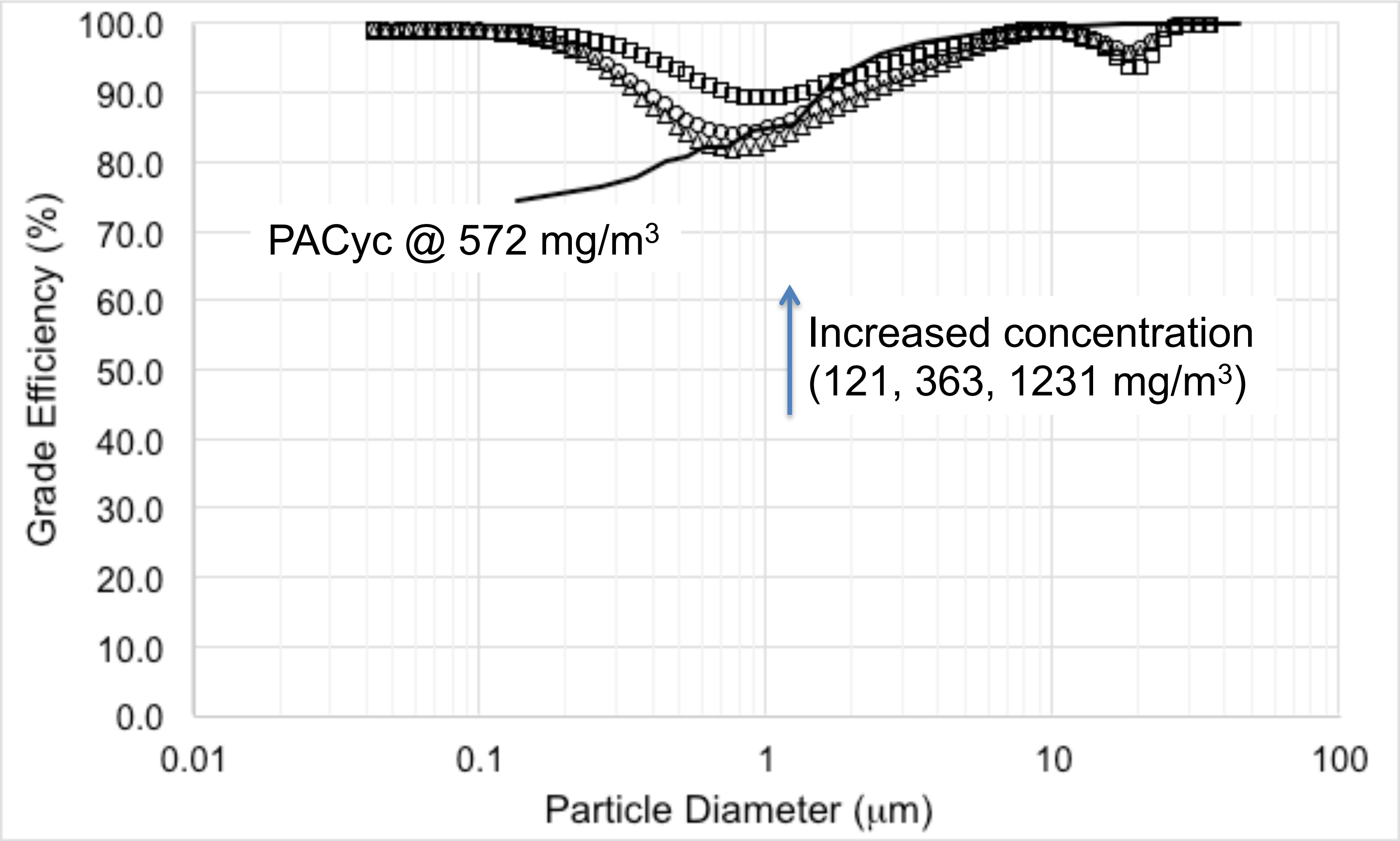
Pilot-scale test conditions

Sample	ρ_p (kg/m^3)	ρ_{ap} (kg/m^3)	ε
A	2379	906	0.62
B	2443	1014	0.59

Sample – fine fly ash inlet PSD



Sample – grade efficiencies

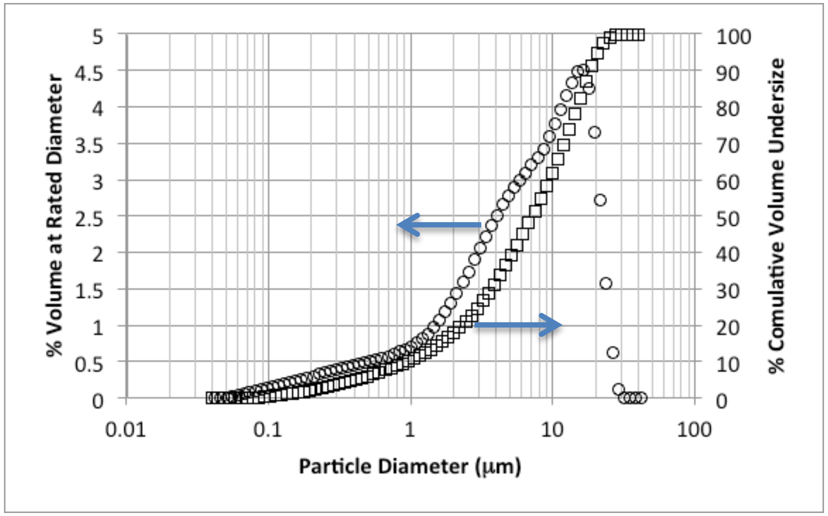


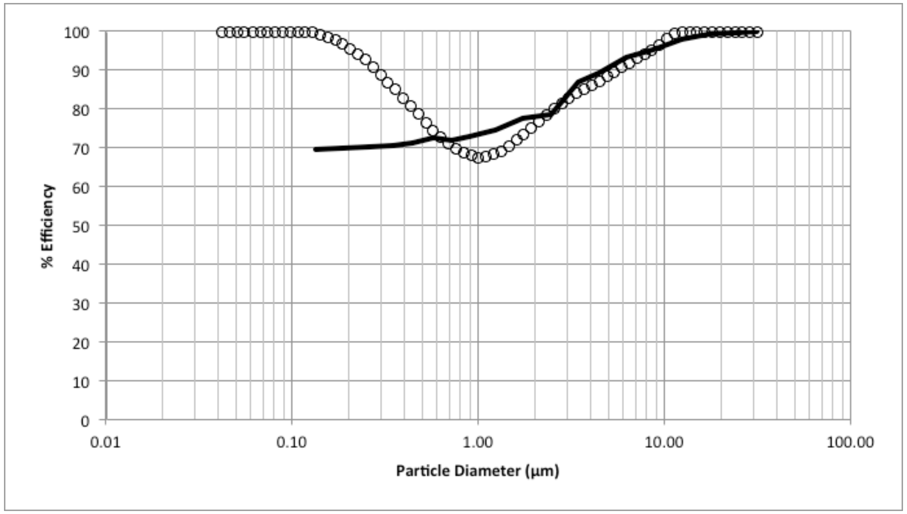
Sample – global efficiencies

Run	C_{in} (mg/m³)	C_{out} (mg/m³)	$\eta_{experimental}$ (%)	$\eta_{theoretical}$ (%)
1	121	6	95.1	-
2	363	15	95.8	-
3	1231	43	96.5	-
PACyc_MK	572	-	-	96.3
PACyc_HR	121	-	-	81.1

Industrial-scale test conditions
(24x1050mm HR_MK)

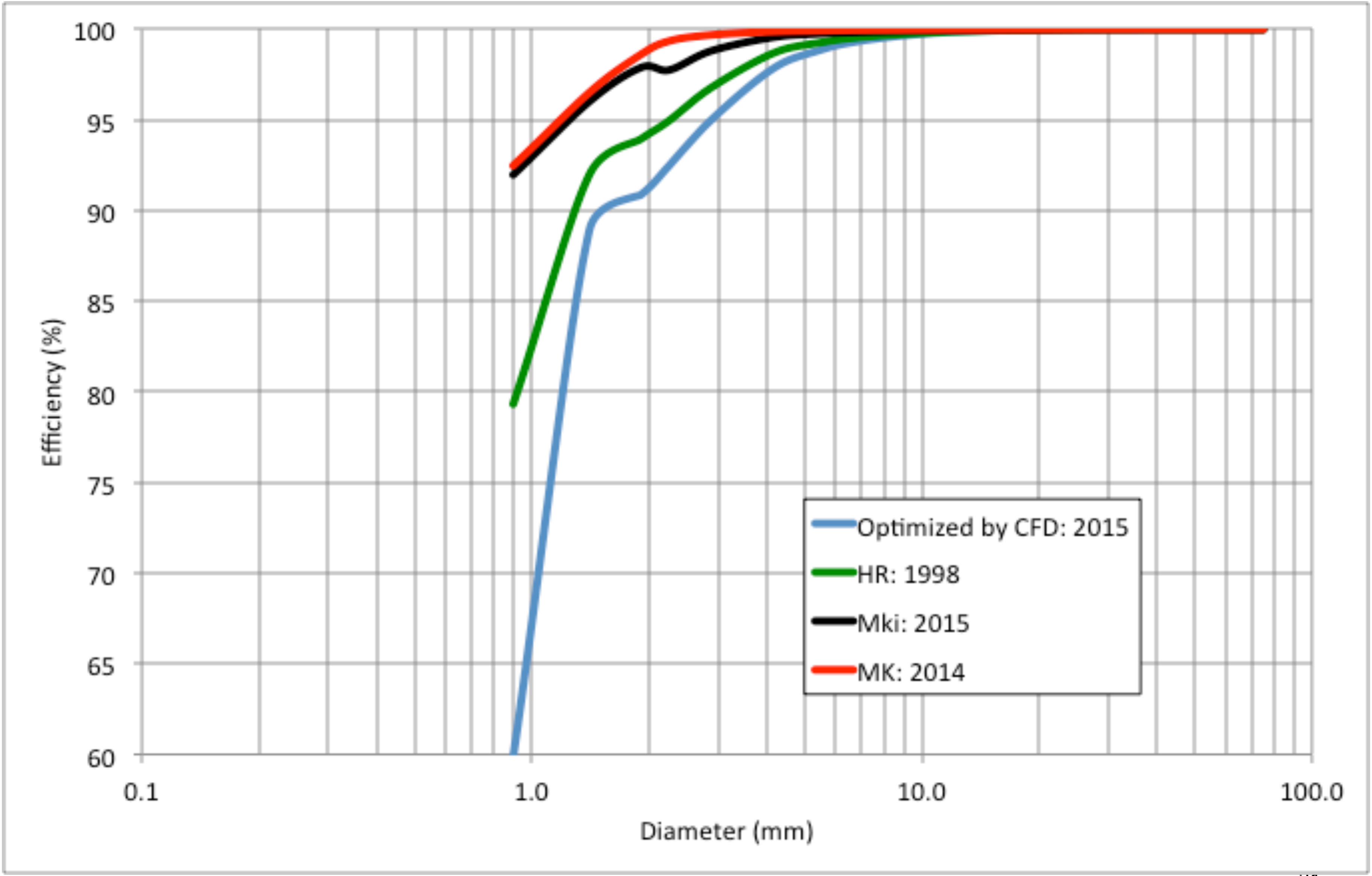
Q (m^3/h)	*T* (ºC)	% O_2	% H_2O	ε
36523 ± 4625	163.8	12.9	6.4	0.66





Run	C_{in} (mg/Nm^3@11%O_2)	C_{out} (mg/Nm^3@11%O_2)	$\eta_{experimental}$ (%)	$\eta_{theoretical}$ (%)
Exp	1048	94	91.0	-
PACyc	1048	-	-	90.0

What about CFD? (Sgrott et al., 2015)



Scaling is no problem

1x10mm hydrocyclone for mamalian cell separation

4x3750mm cyclones for ferrous industry (600,000 m^3/h)

Conclusions

- Global optimization with a good simulation (PACyc) is a powerfull weapon to design better cyclones
- Taylor-made cyclones can be designed to meet specific demands
- Different simulation packages will obtain different ‘optimum’ solutions
- The numerical solutions have to be throughly tested before implementation
- ACS has gained a good confidence on its cyclone design methodology
- Which is the better cyclone will depend partly on the operating conditions and mostly on particle properties (density, porosity and particle size distribution).

References

Alves, A., J. Paiva and R. Salcedo, *Cyclone optimization including particle clustering*, *Powder Technology vol. 272*, 14-22, 2015.

Ho, C. A. and M. Sommerfeld, Modelling of micro-particle agglomeration in turbulent flows, *Chemical Engineering Science*, vol. 57, 3073-3084, 2002.

Clift, R., M. Ghadiri and A. C. Hoffman, A critique of two models for cyclone performance, *AIChE J.*, vol. 37 (2), 1991.

Sgrott, O.L., Noriler D., Wiggers, V.R. and Meier, H.F., 'Cyclone optimization by COMPLEX method and CFD simulation', *Powder Technology*, vol. 277, 11-21, 2015.

Paiva,J., R. Salcedo and P. Araujo, Impact of particle agglomeration in cyclones, *Chem. Eng. J.*, vol. 162, 861-876, 2010.

Mothes, H. and F. Loffler, 'Prediction of particle removal in cyclone separators', *International Chemical Engineering*, vol. 28, 231-240, 1989.

Salcedo, R. L., 'Solving Non-Convex NLP and MINLP Problems with Adaptive Random-Search', *Ind. Eng. Chem. Res.*, vol. 31, no.1, 262-273, 1992.

Salcedo, R. and Coelho, M., 'Turbulent dispersion coefficients in cyclone flow – an empirical approach', *Can. J. Chem. Eng.*, vol. 77, 609-617, 1999.

Salcedo, R. L., High efficiency cyclones, EP0972572A2, European Patent Application 99670006.8, Bulletin 2000103, January 19, 2000 (granted).

Salcedo, R. and J. Paiva, Reverse flow agglomerating cyclone and process thereof, PTC 107312, INPI, November 25, 2013 (pending).

Thank you

contacts:

technical@acsystems.pt