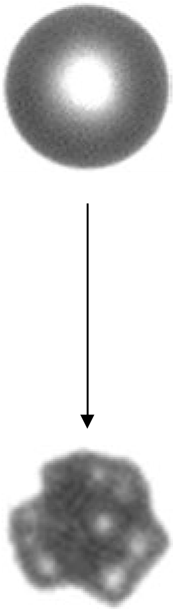
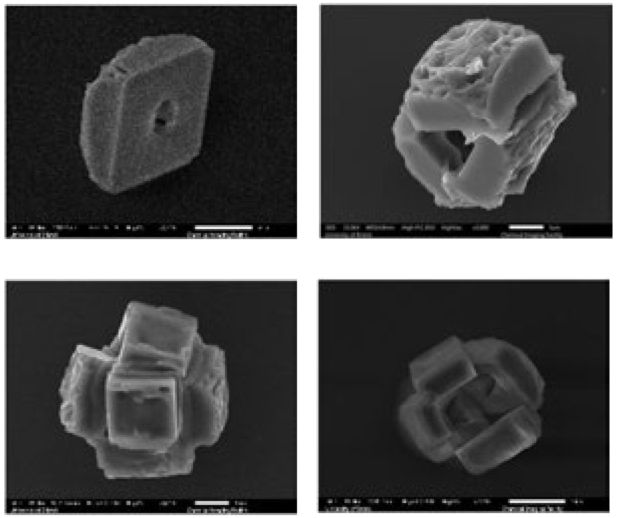
High Time Resolution Measurements of Droplet Evaporation Kinetics and Particle Crystallization



Dan Hardy

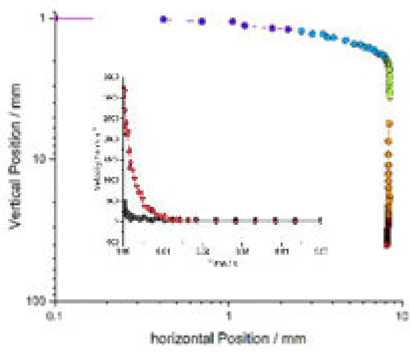


A bit about me

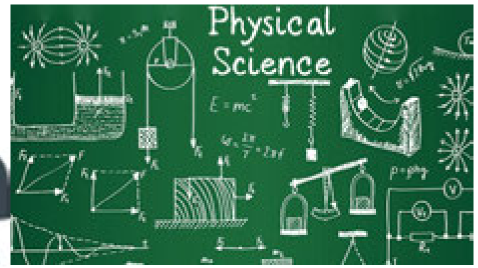
- My history and journey to present day

Some science

- Introduction to my project
- Some results



How did I end up where I am?



Profile

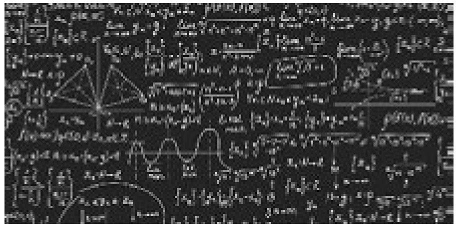

British Towns and Villages Network
British Towns and Villages Network
British Towns and Villages Network


NO SCHOOL

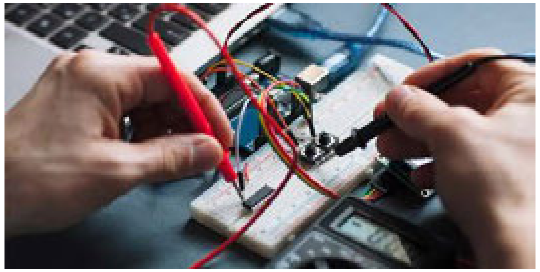
Profile

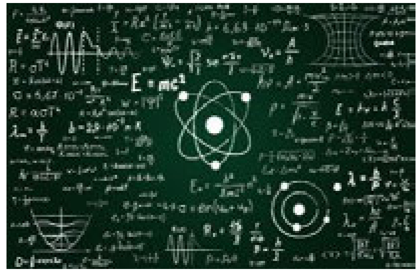
13 March 2021

Electronics

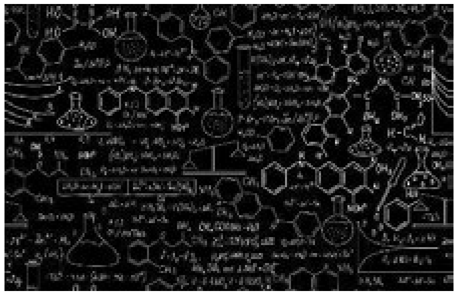


Maths



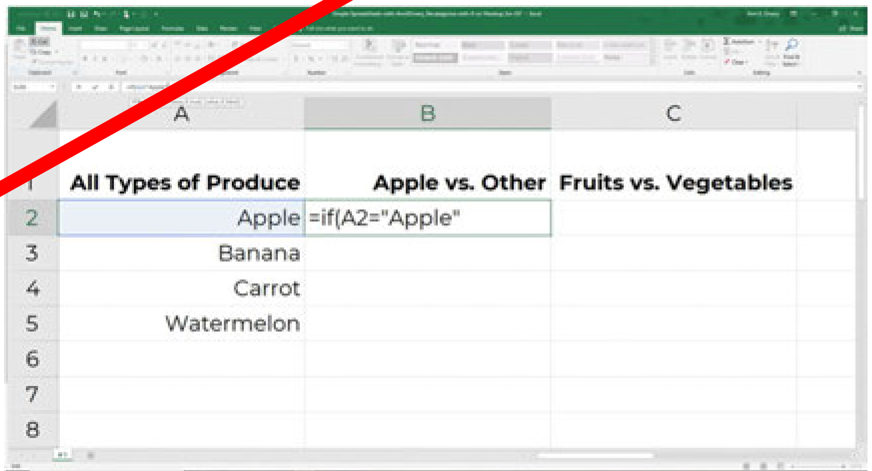


Chemistry



Physics

Profile



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Engineering and Physical Sciences Research Council

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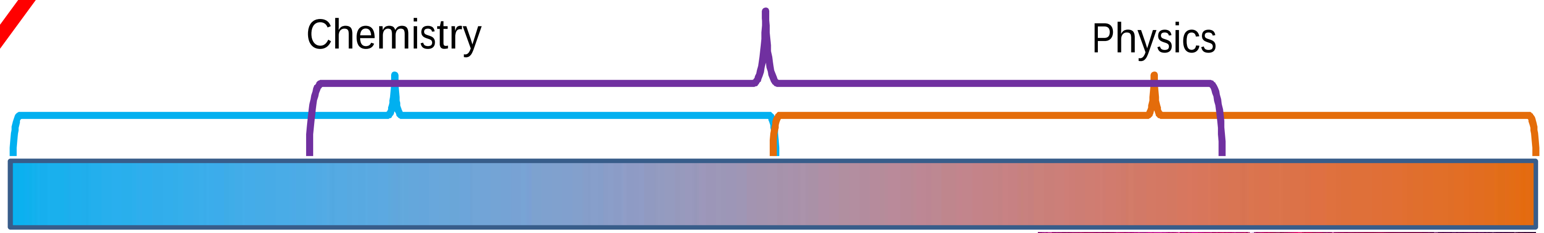
WEB OF SCIENCE

Scopus

Profile

University of BRISTOL

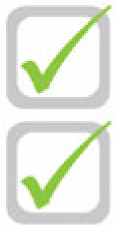
Undergraduate at University of Bristol



Profile

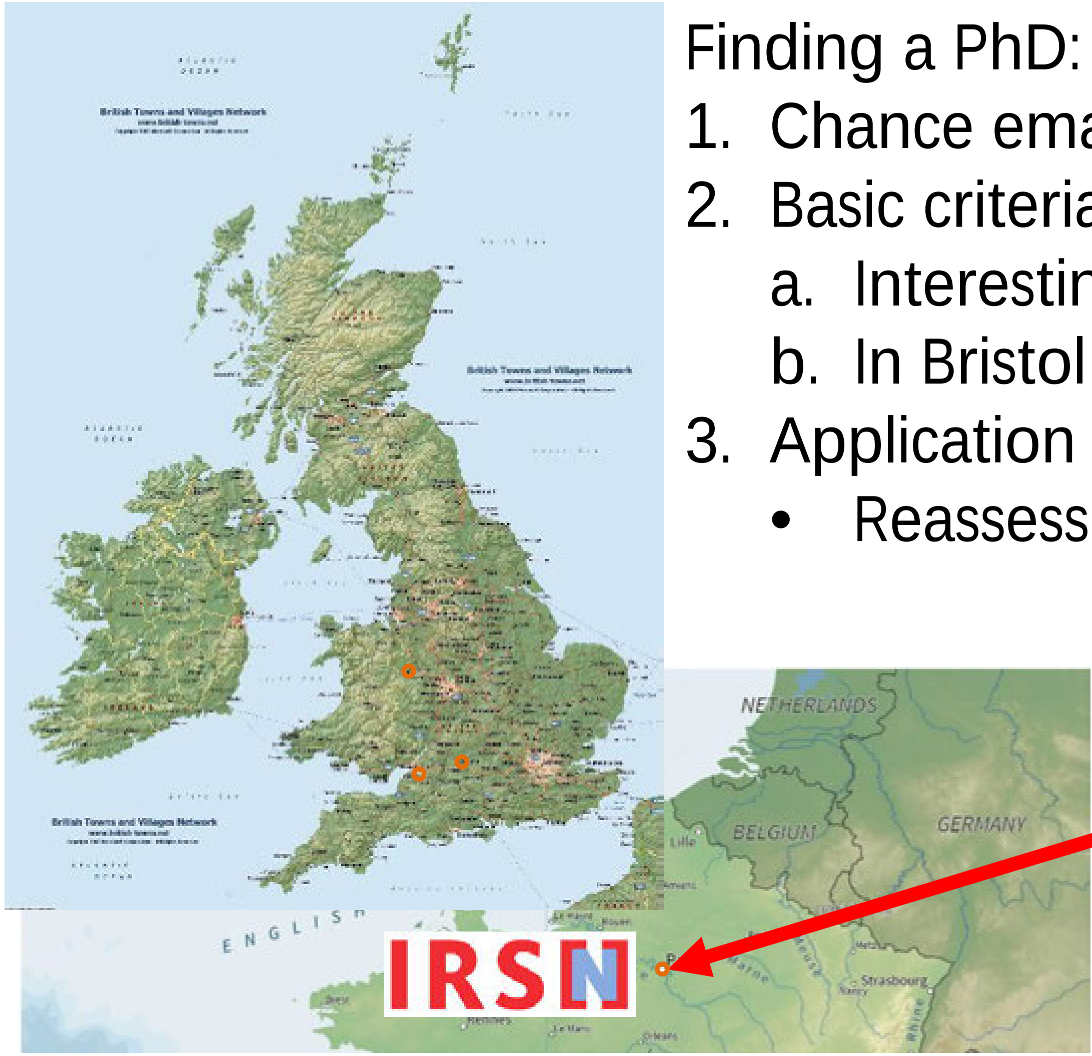
Finding a PhD:

1. Chance email
2. Basic criteria:
   a. Interesting
   b. In Bristol



Profile

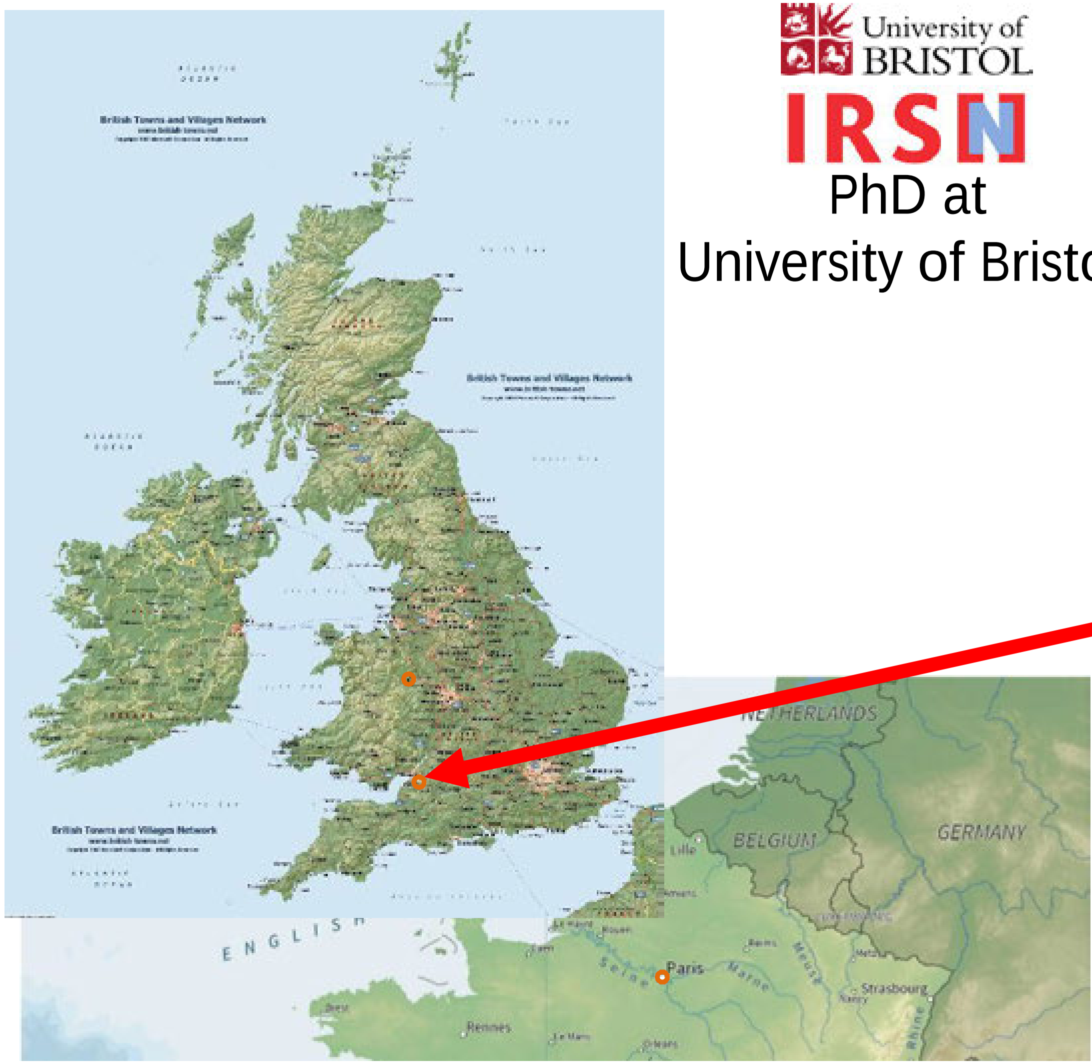
13 March 2021



Finding a PhD:

1. Chance email
2. Basic criteria:
   a. Interesting ✓
   b. In Bristol ✓
3. Application process progressed
   - Reassess criteria

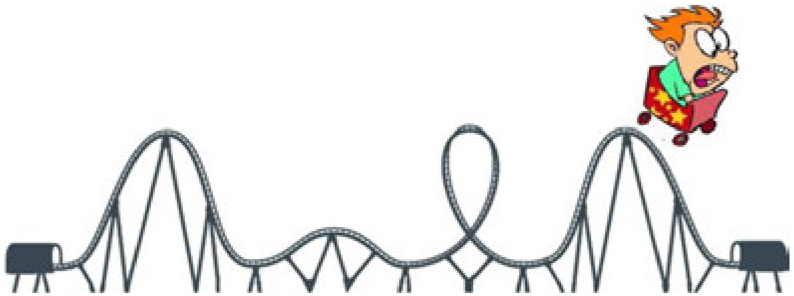
Profile



PhD at
University of Bristol

Bristol Aerosol Research Centre
+
Institute for Radiological Protection and Nuclear Safety

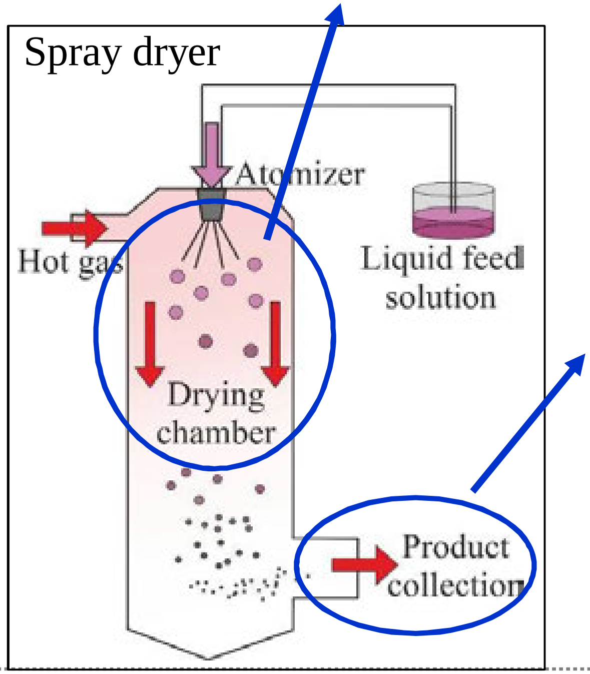
What next?



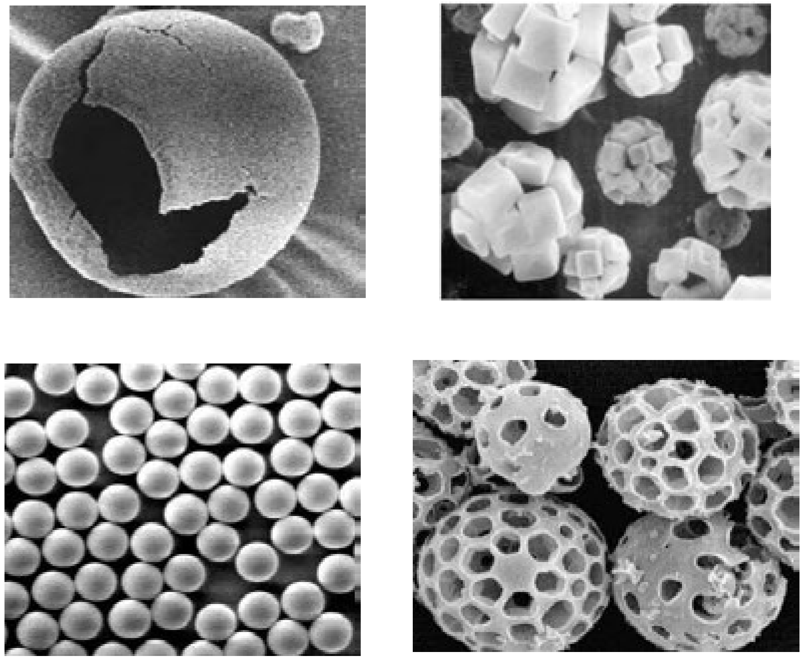
Things I have enjoyed:

- Instrument development
- Data analysis and modelling
- Aerosol Science
- Bristol

Spray Drying – From Droplets to Particles



Formation of micro-structured particles



Spray Drying – Food and Drink

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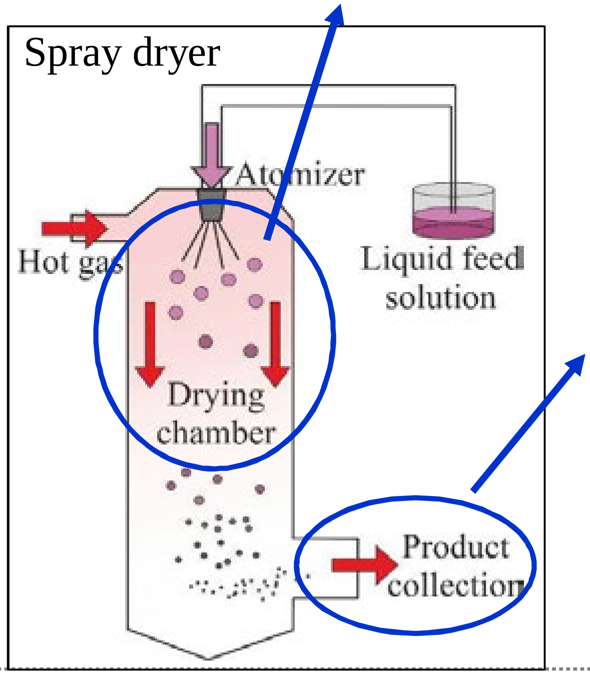
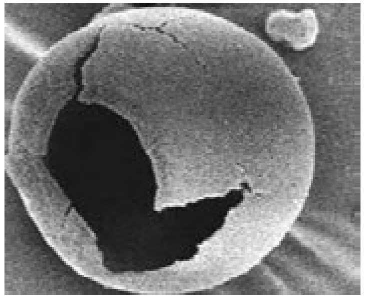
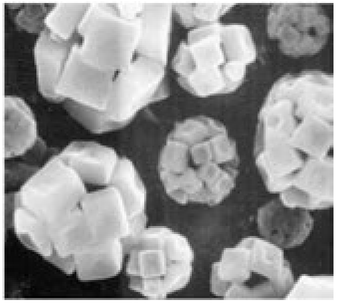
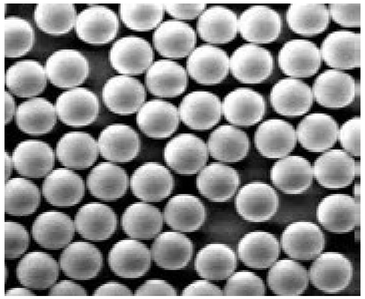
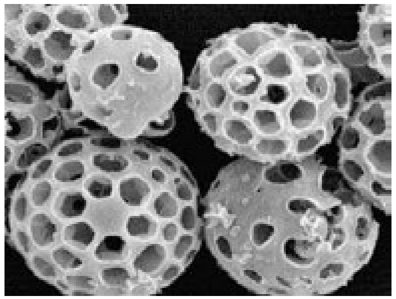
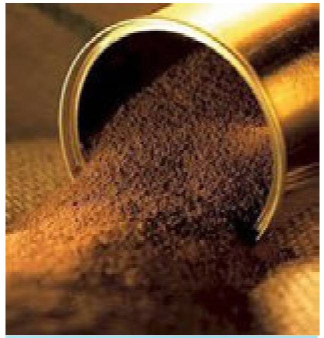












Spray Drying – Other Scenarios

Pharmaceutical Industry

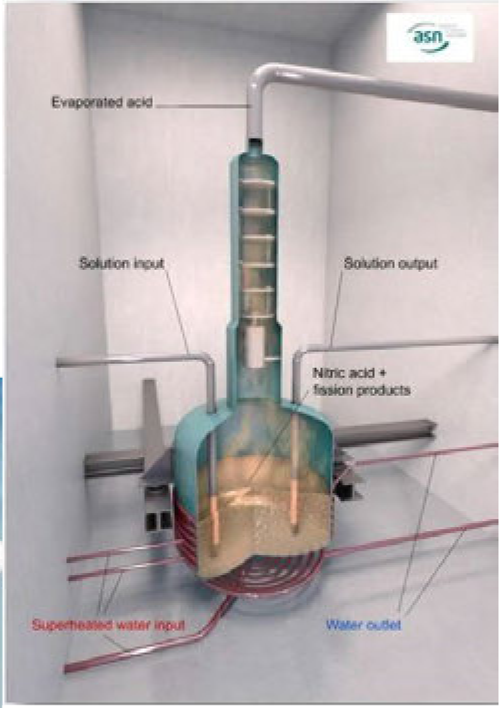
- Powder production
- Drug delivery to the lungs

Zang el.al., doi.org/10.1073/pnas.2009637117

Spray Drying – Other Scenarios

Pharmaceutical Industry
- Powder production
- Drug delivery to the lungs

Nuclear Industry
- Release of contamination via aerosol
- Waste processing
  - Fission product evaporators



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Spray Drying – Other Scenarios

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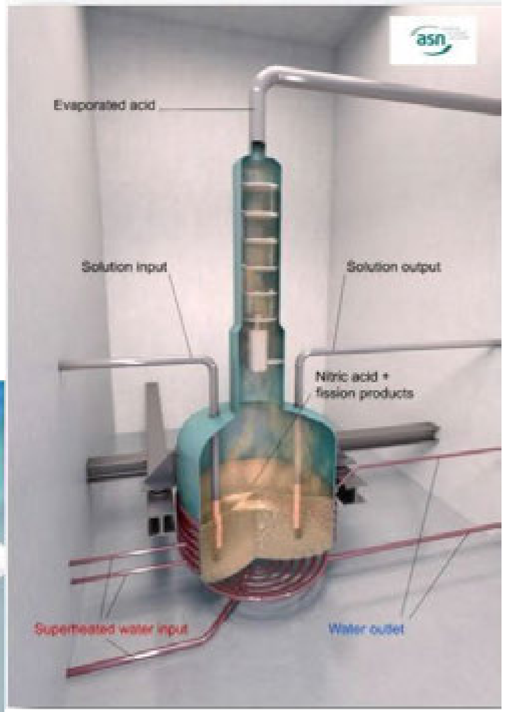
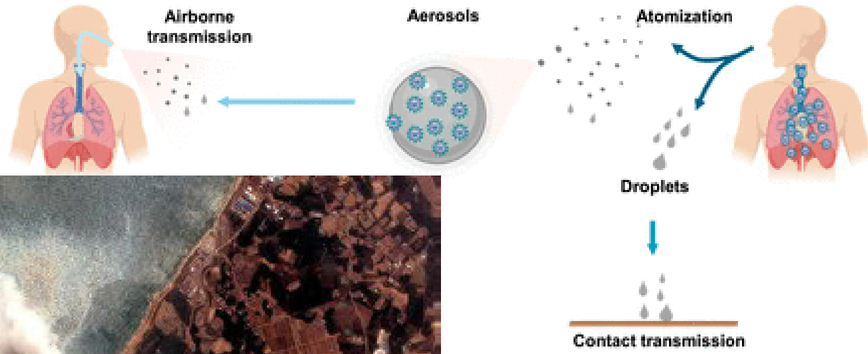


Airborne transmission of disease

- Release of bioaerosol
- Viability of pathogens in aerosols



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Spray Drying – Other Scenarios

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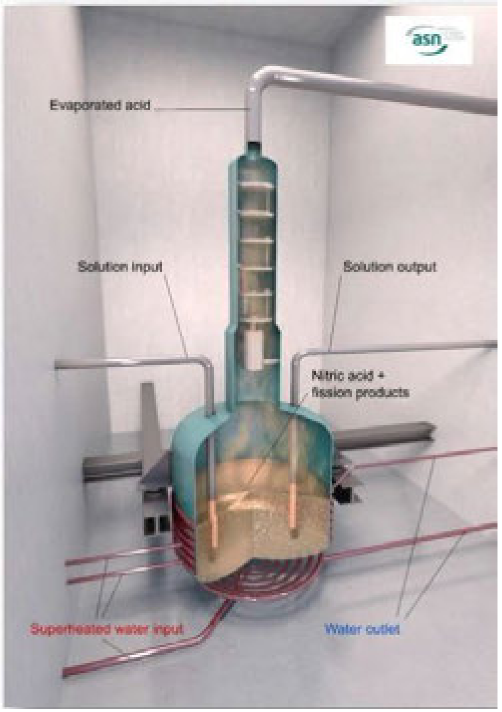


IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Determination of the transport properties of aerosol particles produced by droplet drying

Zang el.al., doi.org/10.1073/pnas.2009637117

University of BRISTOL
IRSN

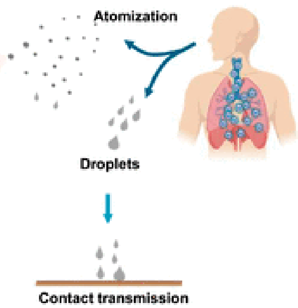
Spray Drying - processes

13 March 2021

Initial composition

Environmental conditions

Drying kinetics and particle formation → Particle properties → Powder properties



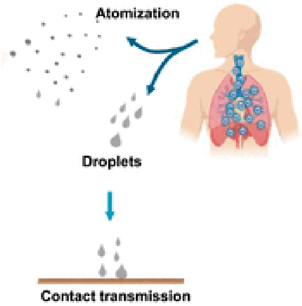
Zang el.al., doi.org/10.1073/pnas.2009637117

Spray Drying - processes

13 March 2021

Aim: Understanding and control of particle properties

Initial composition / Environmental conditions	→	Drying kinetics and particle formation	→ Particle properties	→ Powder properties



Zang el.al., doi.org/10.1073/pnas.2009637117

Spray Drying - processes

Aim: Understanding and control of particle properties

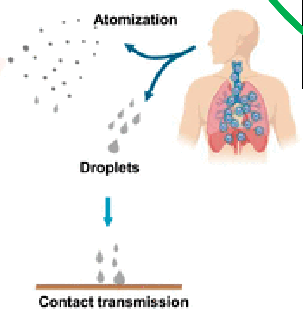
Initial composition

Environmental conditions

Drying kinetics and particle formation

Particle properties

Powder properties



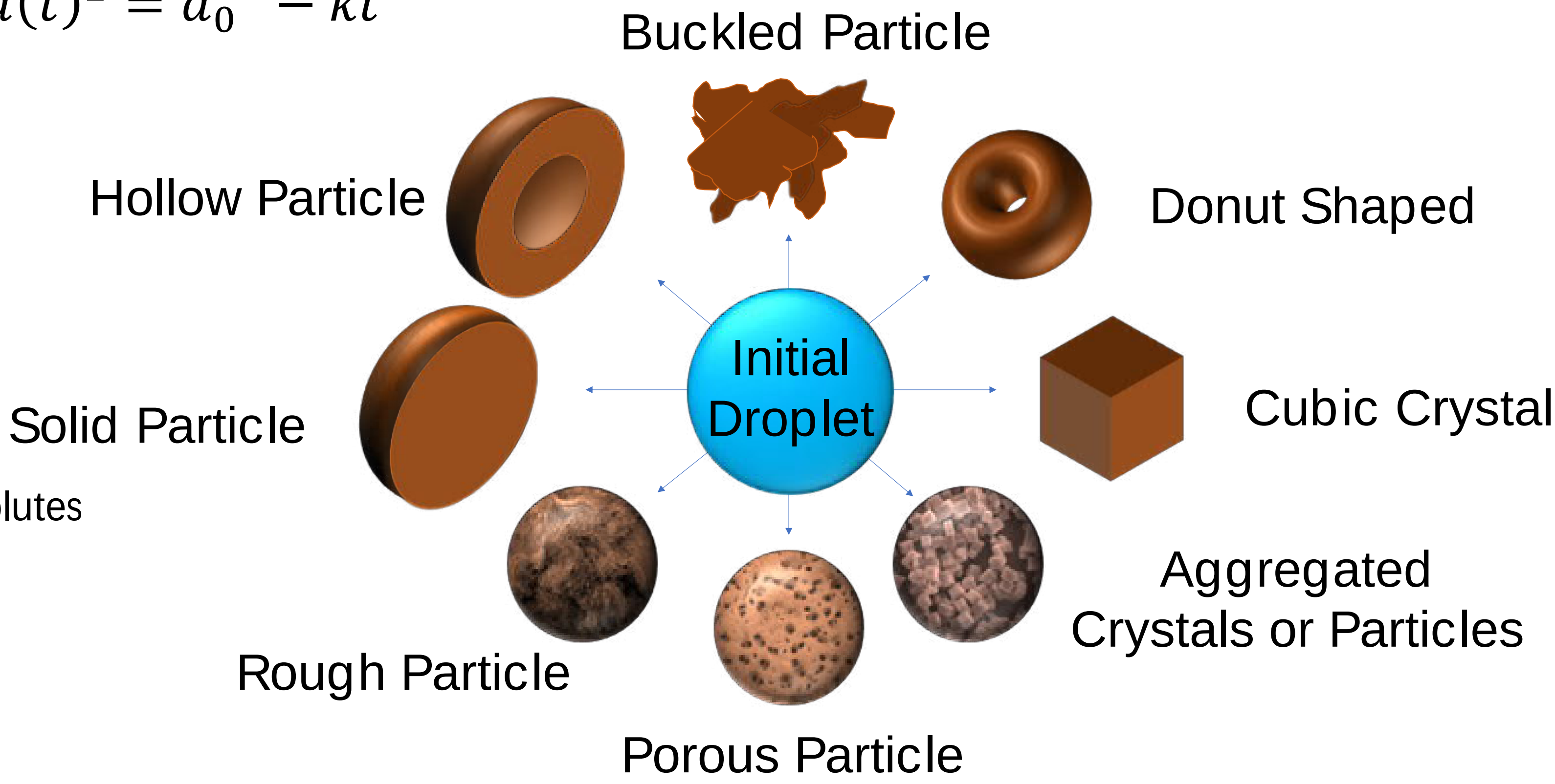
To achieve this, we must understand the preceding stages

Spray Drying – physical driving forces

- Droplet evaporation $d(t)^2 = {d_0}^2 - \kappa t$
  - Solvent properties
  - Drying conditions
  - Particle composition

Spray Drying – physical driving forces

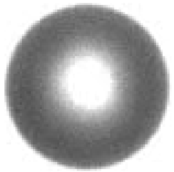
- Droplet evaporation $d(t)^2 = {d_0}^2 - \kappa t$
    - Solvent properties
    - Drying conditions
    - Particle composition
- Particle formation
    - Solidification behavior of solutes or colloidal particles
    - Solvent properties
    - Solvent/solute interactions



Experimental Design

Study dry particle formation
from aerosol droplets

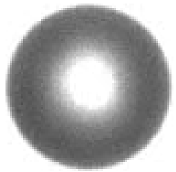
- Contact free behaviour
- Droplet dimensions
- Droplet density

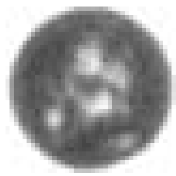


Experimental Design

Study dry particle formation from aerosol droplets

- Contact free behaviour
- Droplet dimensions
- Droplet density
- Droplet phase





Study dry particle formation from aerosol droplets

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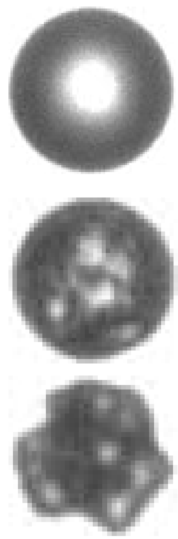

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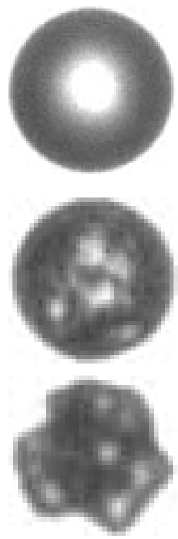
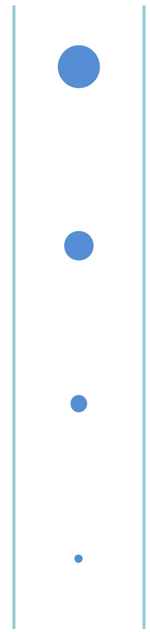


Falling Droplet Chain Instrument

- Monodisperse droplet chain



Experimental Design

Study dry particle formation from aerosol droplets

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- Droplet phase
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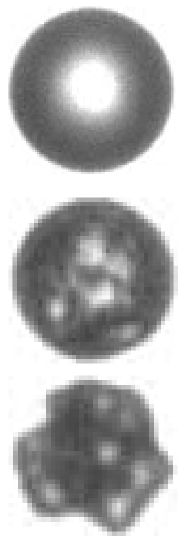
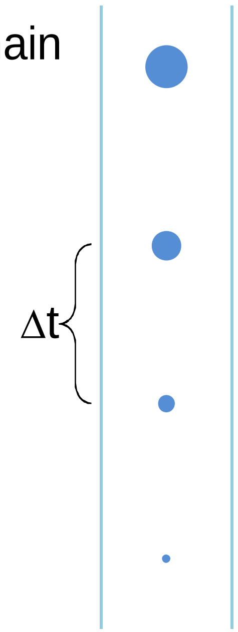


Falling Droplet Chain Instrument

- Monodisperse droplet chain
- Stroboscopic imaging



Experimental Design

Study dry particle formation from aerosol droplets

- Contact free behaviour
- Droplet dimensions
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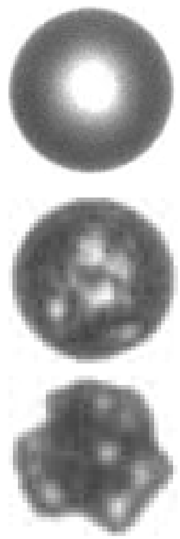
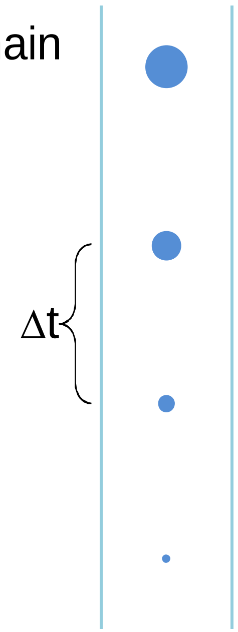


Falling Droplet Chain Instrument

- Monodisperse droplet chain
- Stroboscopic imaging
- Observation throughout evaporative lifetime



Experimental Design

Study dry particle formation from aerosol droplets

- Contact free behaviour
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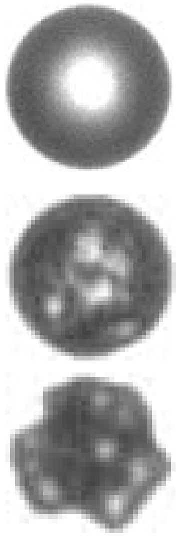
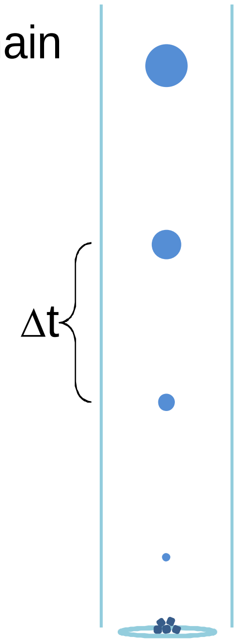


Falling Droplet Chain Instrument

- Monodisperse droplet chain
- Stroboscopic imaging
- Observation throughout evaporative lifetime
- Collect final particles for SEM imaging

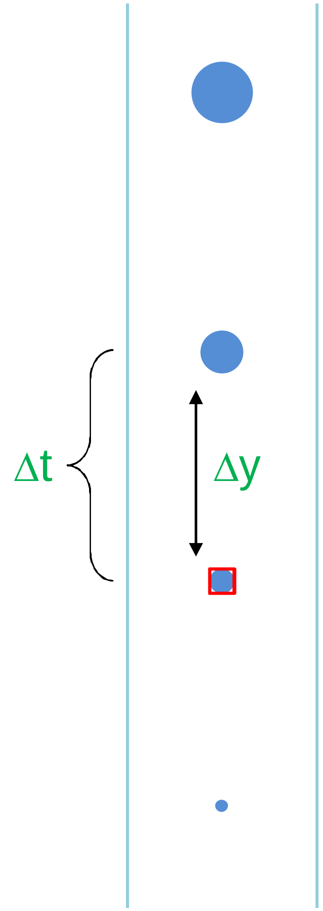


Measuring Droplet Diameter

Aerodynamic Diameter

Diameter of a sphere with a density of 1 gcm^{-3} that has a settling velocity, v_s, equal to a droplet in question.

$$\frac{\Delta y}{\Delta t} = v_s = \frac{\rho g d(t)^2}{18\mu} \qquad d_a = \sqrt{\frac{18\mu v_s}{\rho^* g}}$$



Measuring Droplet Diameter

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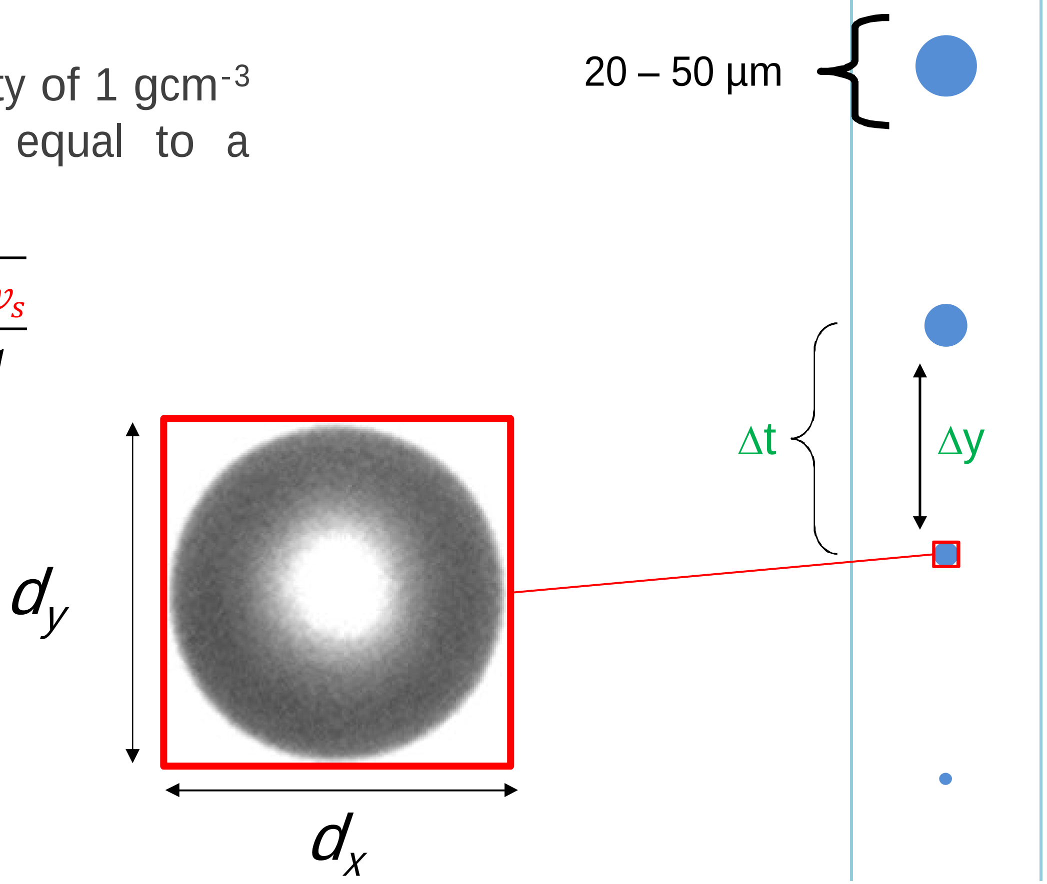
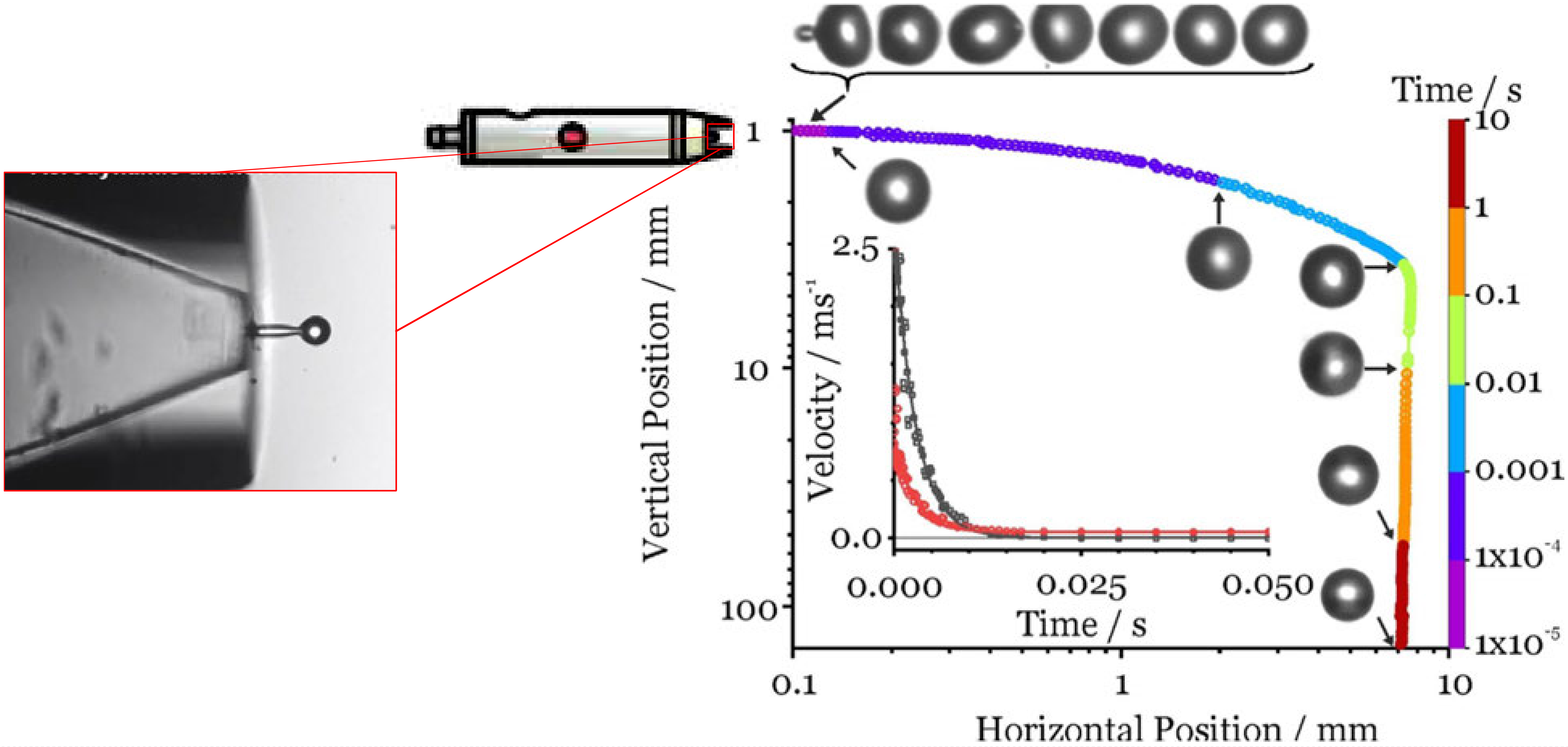
Geometric diameter



Observing Droplet Trajectories



Sample: Water, 75% RH, 294K, V_{gas} = 20.8mms^{-1}
Dispenser Nozzle position (0.1, 1)

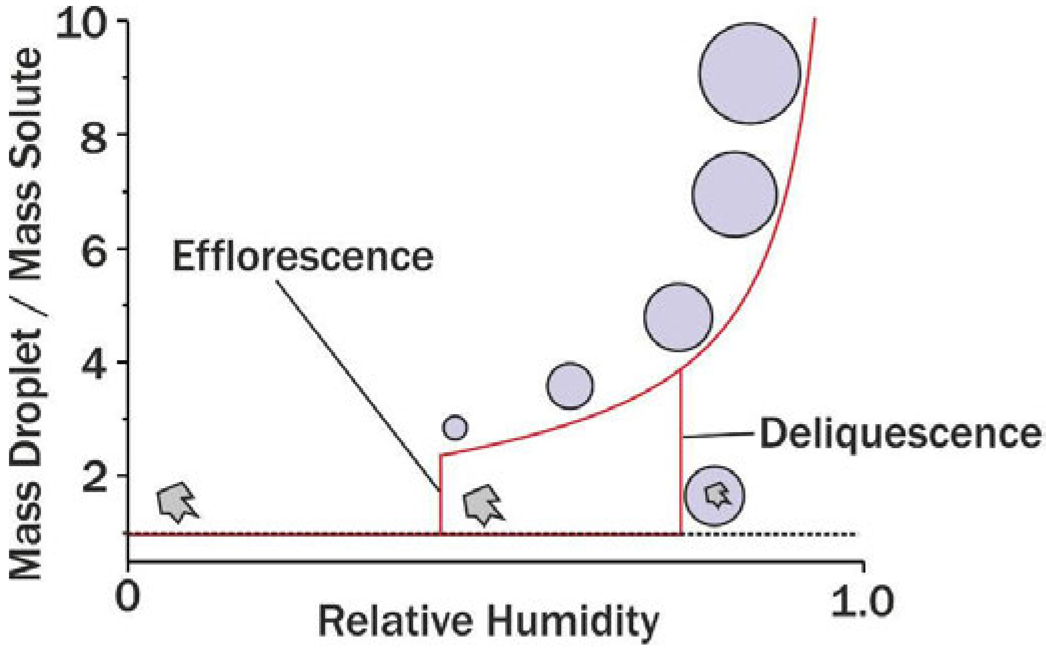
Sodium chloride:

- Solute, not colloidal
- Ideal solute

Sodium Chloride

Sodium chloride:

- Solute, not colloidal
- Ideal solute
- Well known behaviour in aerosol phase
- Clear solidification behaviour



0.1 mfs NaCl, 295K

Sodium Chloride

Sodium chloride:

- Solute, not colloidal
- Ideal solute
- Well known behaviour in aerosol phase
- Clear solidification behaviour

- Understand the phenomena that occur

0.1 mfs NaCl, 295K

Sodium Chloride

Sodium chloride:

- Solute, not colloidal
- Ideal solute
- Well known behaviour in aerosol phase
- Clear solidification behaviour

- Understand the phenomena that occur

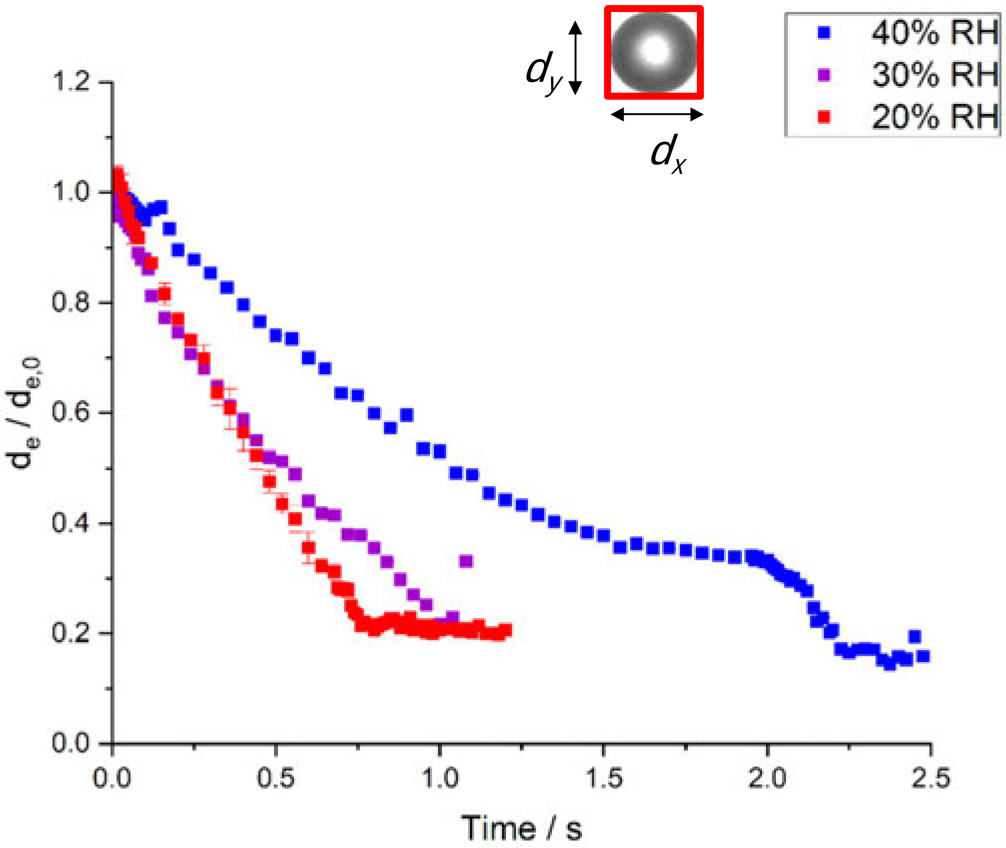
- Relevant to food the food industry
- Nuclear industry involves mixed solutions

- Apply to more complex scenarios

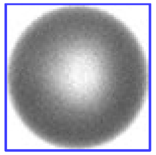
0.1 mfs NaCl, 295K

‘In-flight’ images of NaCl crystallisation

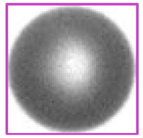
13 March 2021



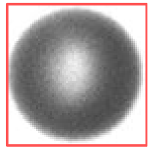
40% RH



30% RH



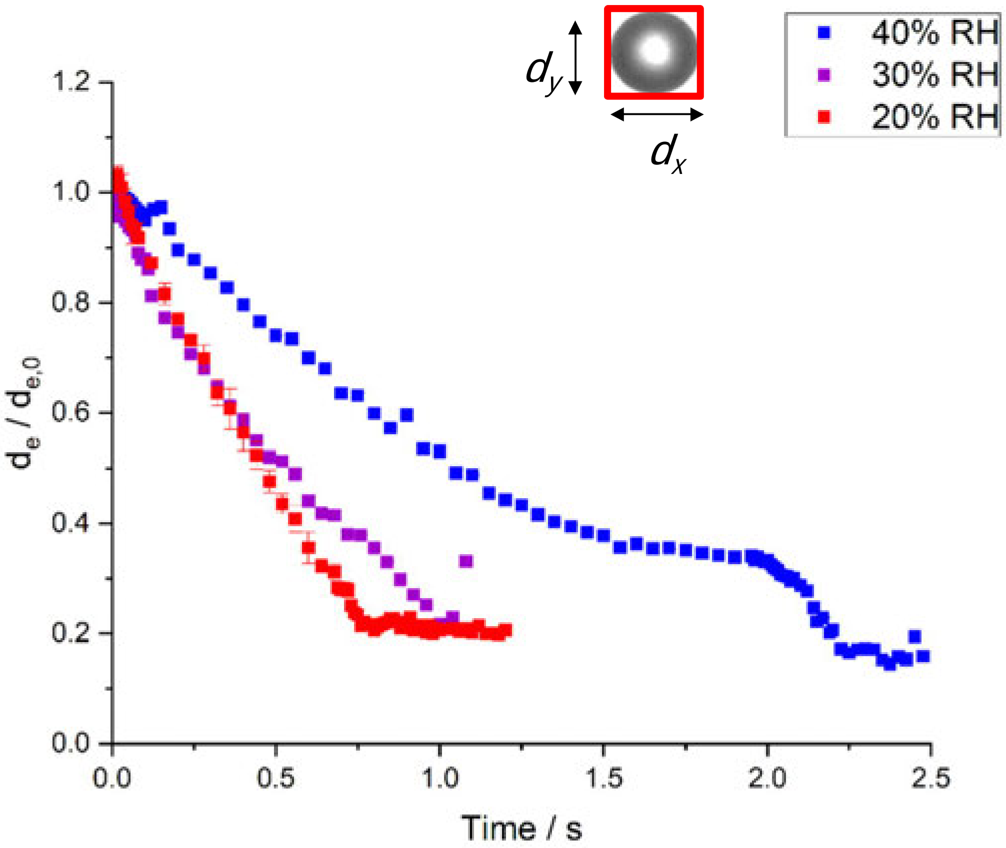
20% RH

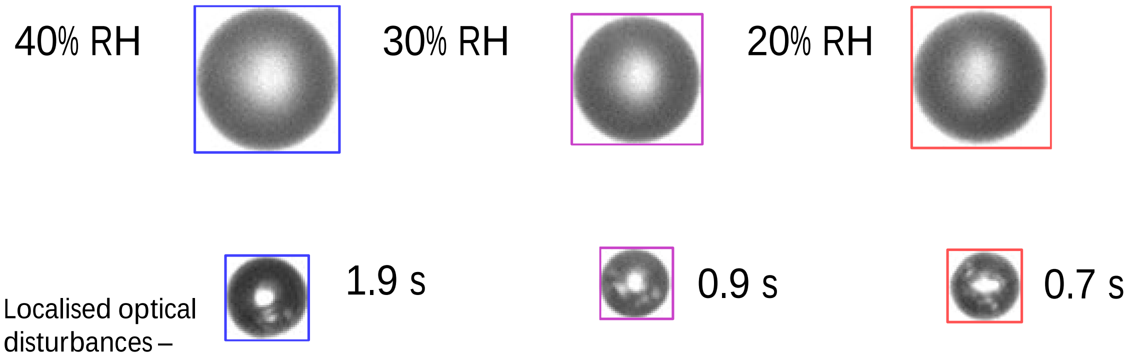


0.1 mfs NaCl, 295K

'In-flight' images of NaCl crystallisation

13 March 2021

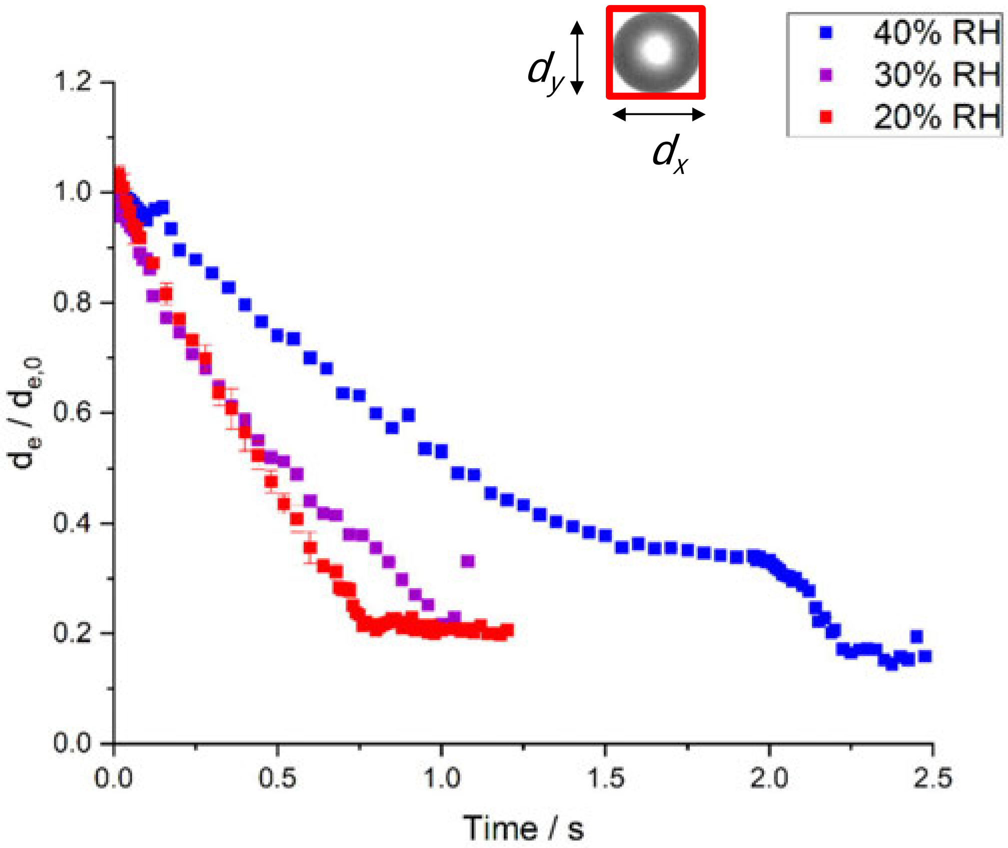


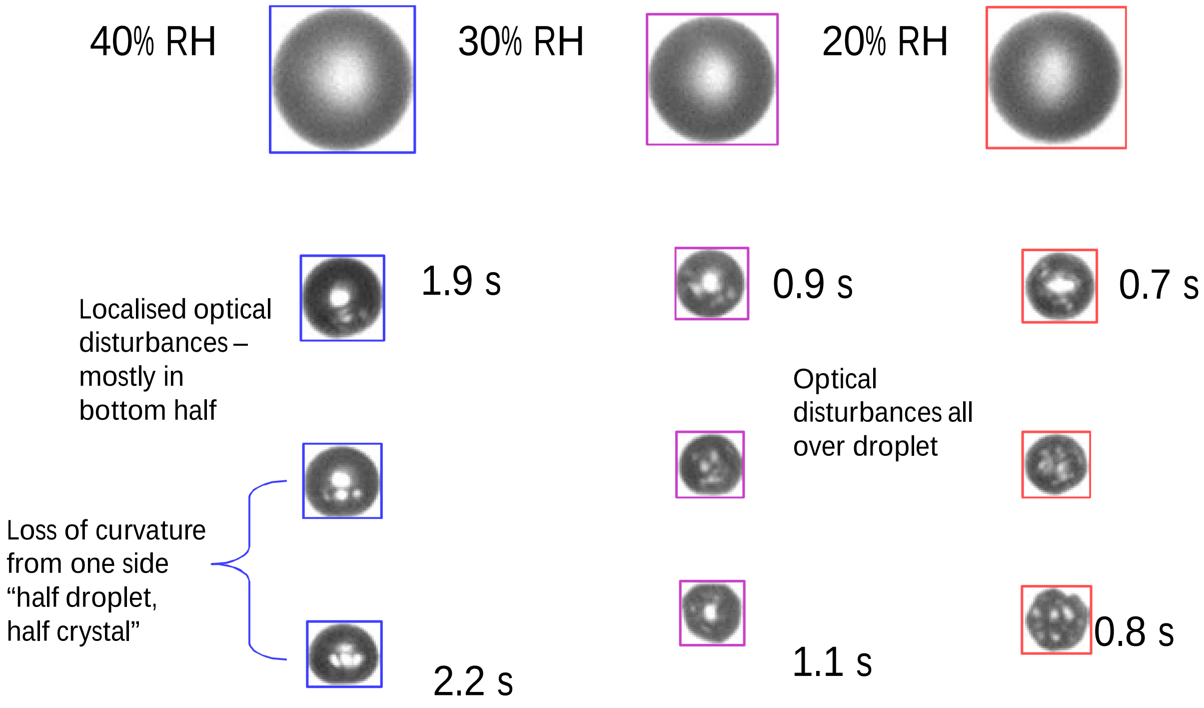


Localised optical disturbances – mostly in bottom half

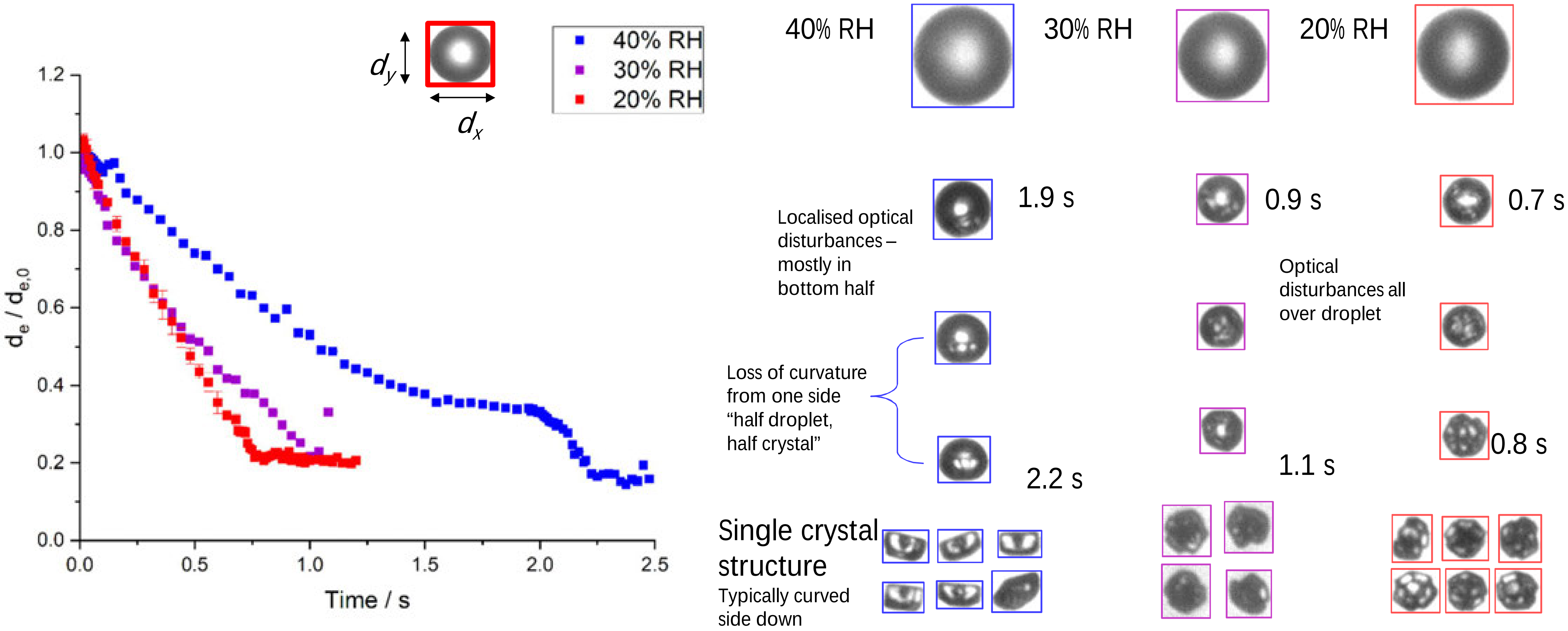
0.1 mfs NaCl, 295K

‘In-flight’ images of NaCl crystallisation





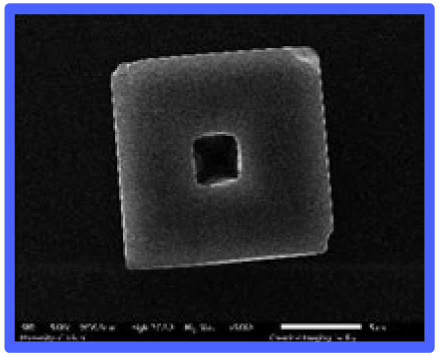
‘In-flight’ images of NaCl crystallisation

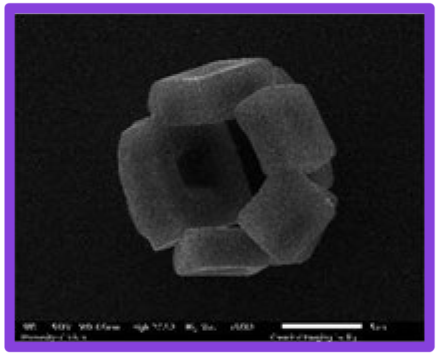


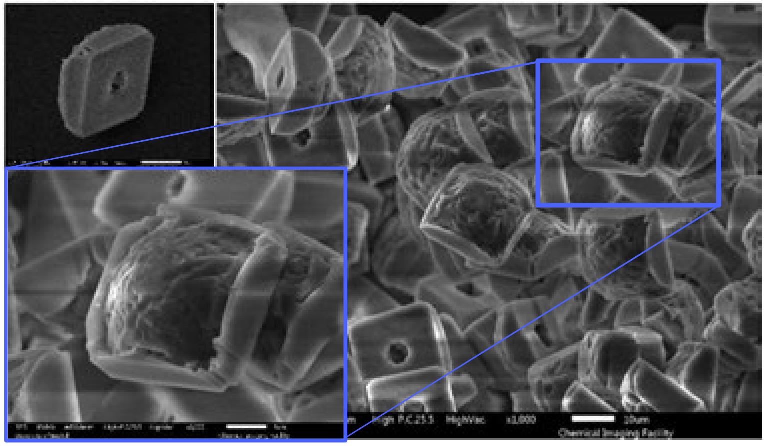
0.1 mfs NaCl, 295K

SEM Analysis
– Understanding Morphology

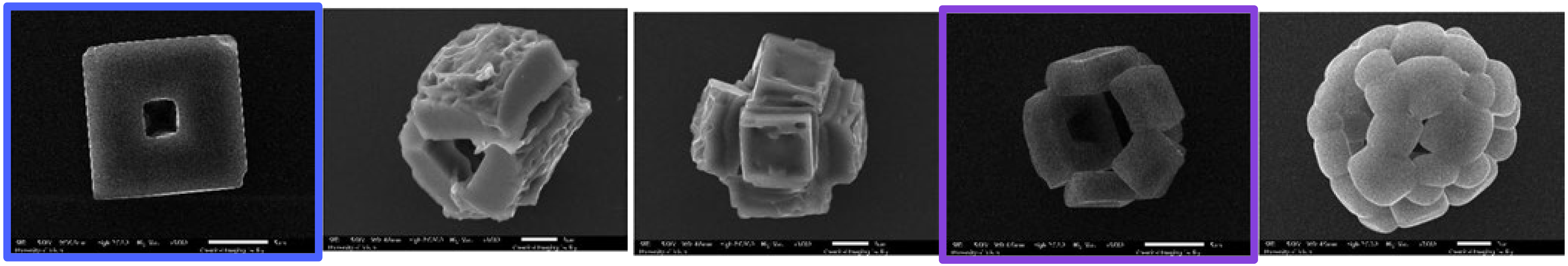
13 March 2021





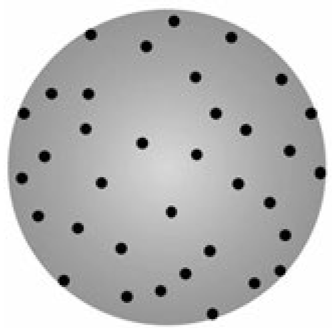


SEM Analysis
– Understanding Morphology

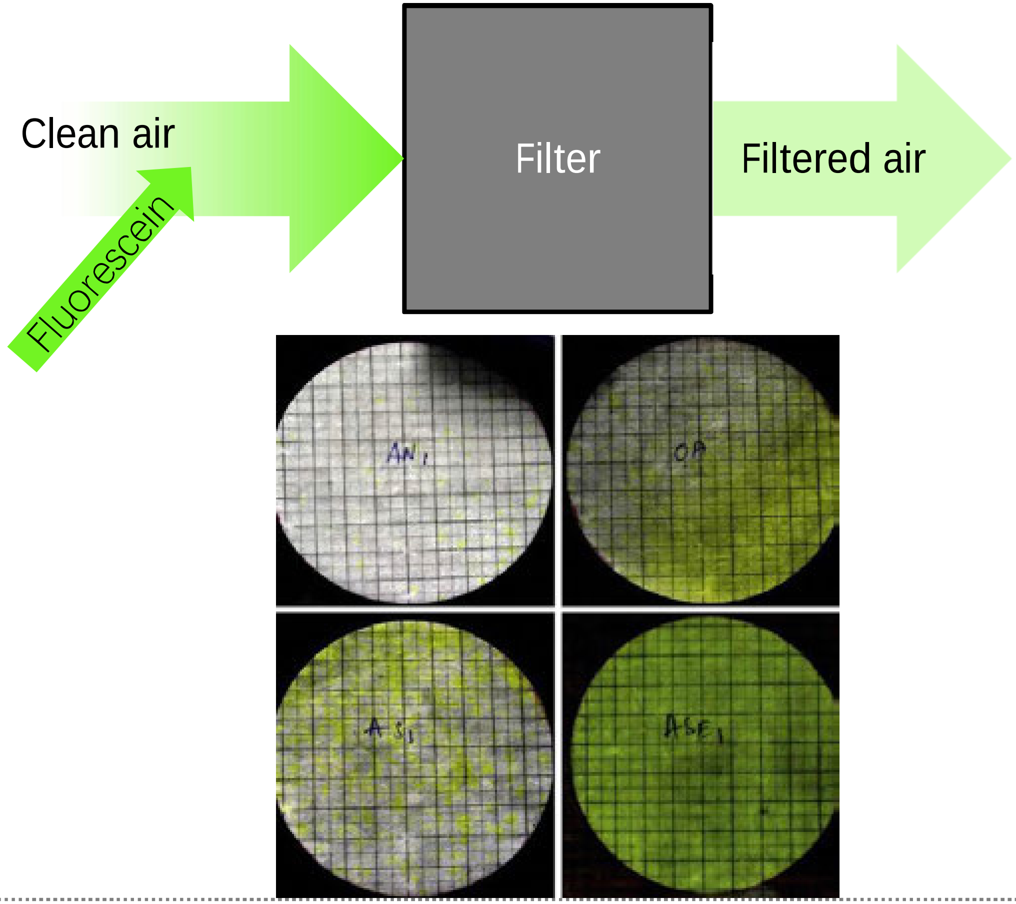


Increasing evaporation rate, κ

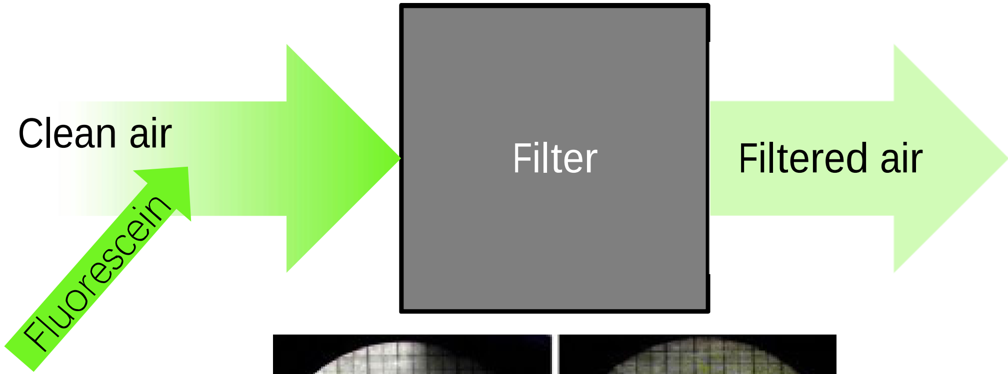
Peclet Number $$Pe = \frac{\kappa(RH,T)}{8D(T)}$$

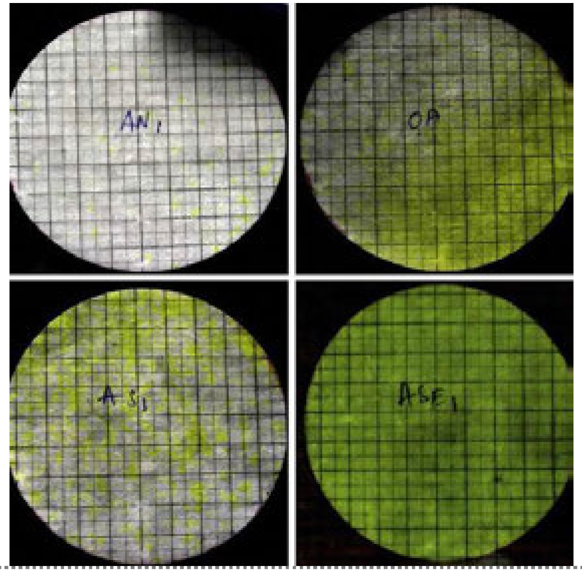


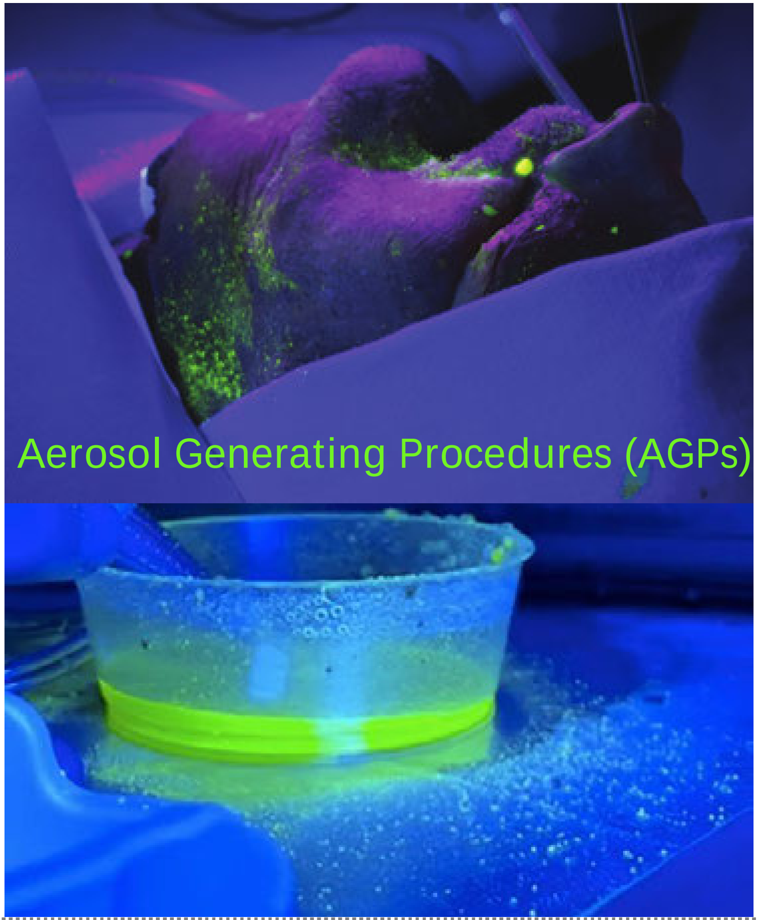
Real World Systems
- Sodium Fluorescein



Real World Systems
- Sodium Fluorescein







RH 20% ± 5%
15ºC ± 2ºC

Real World Systems
- Sodium Fluorescein

Sodium fluorescein:

- Less ideal solute
- Slower diffusion

Real World Systems - Sodium Fluorescein

Sodium fluorescein:

- Less ideal solute
- Slower diffusion
- Less well known behaviour in aerosol phase

RH 20% ± 5%
15ºC ± 2ºC

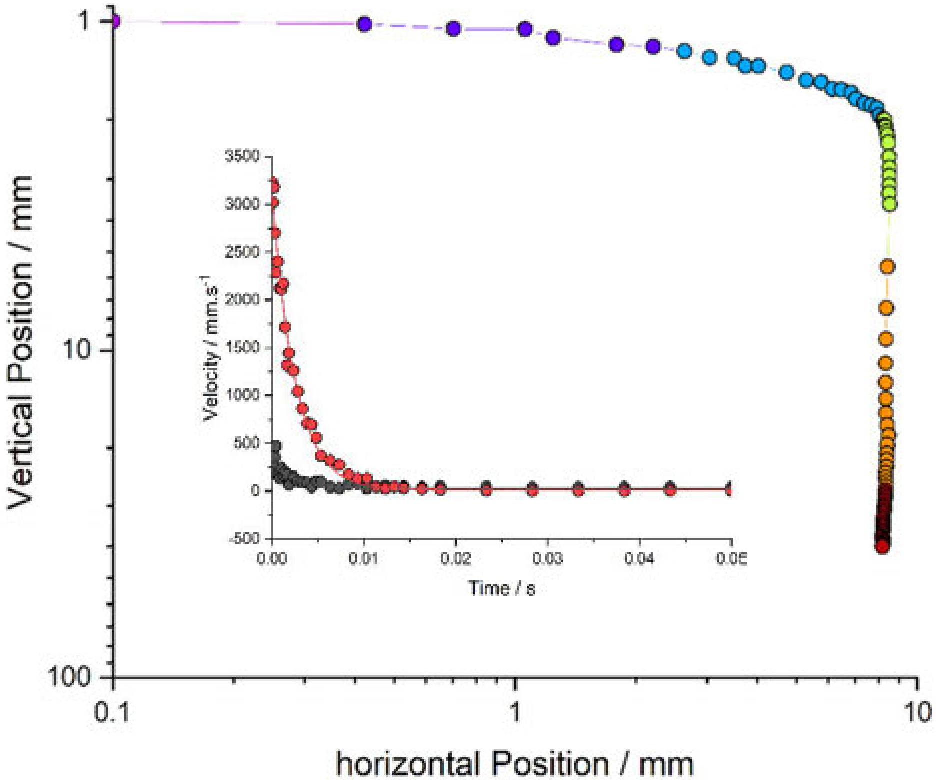
Real World Systems
- Sodium Fluorescein

Sodium fluorescein:

- Less ideal solute
- Slower diffusion
- Less well known behaviour in aerosol phase
- Poorly understood solidification behaviour
  - Amorphous?
  - Solid?
  - Ruptured?

Real World Systems
- Sodium Fluorescein

- Fluorescein

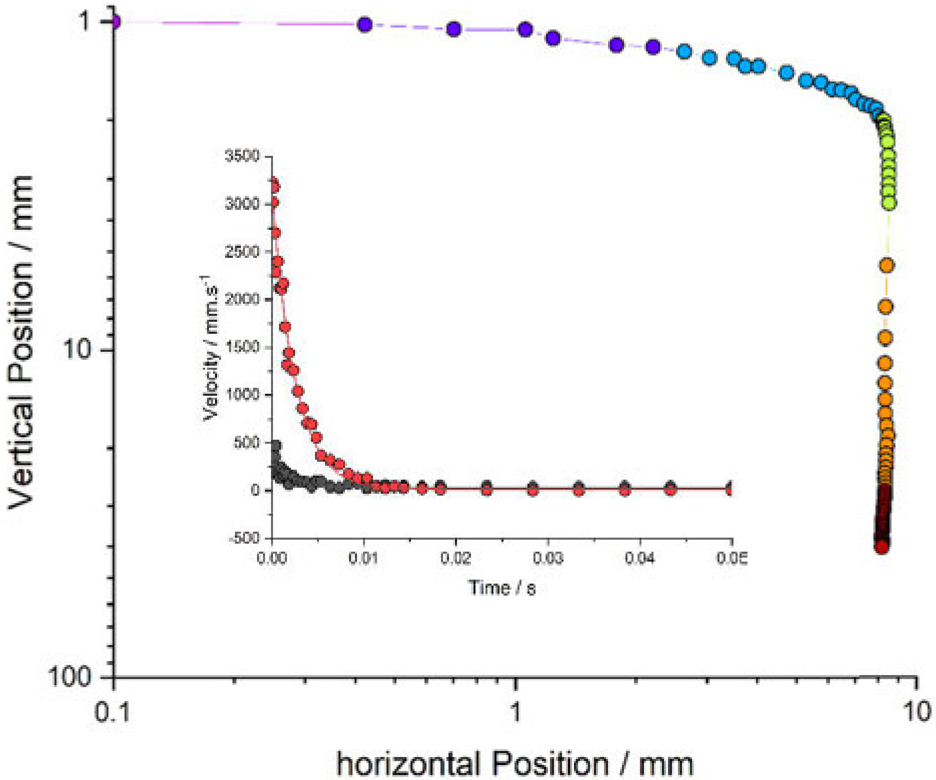


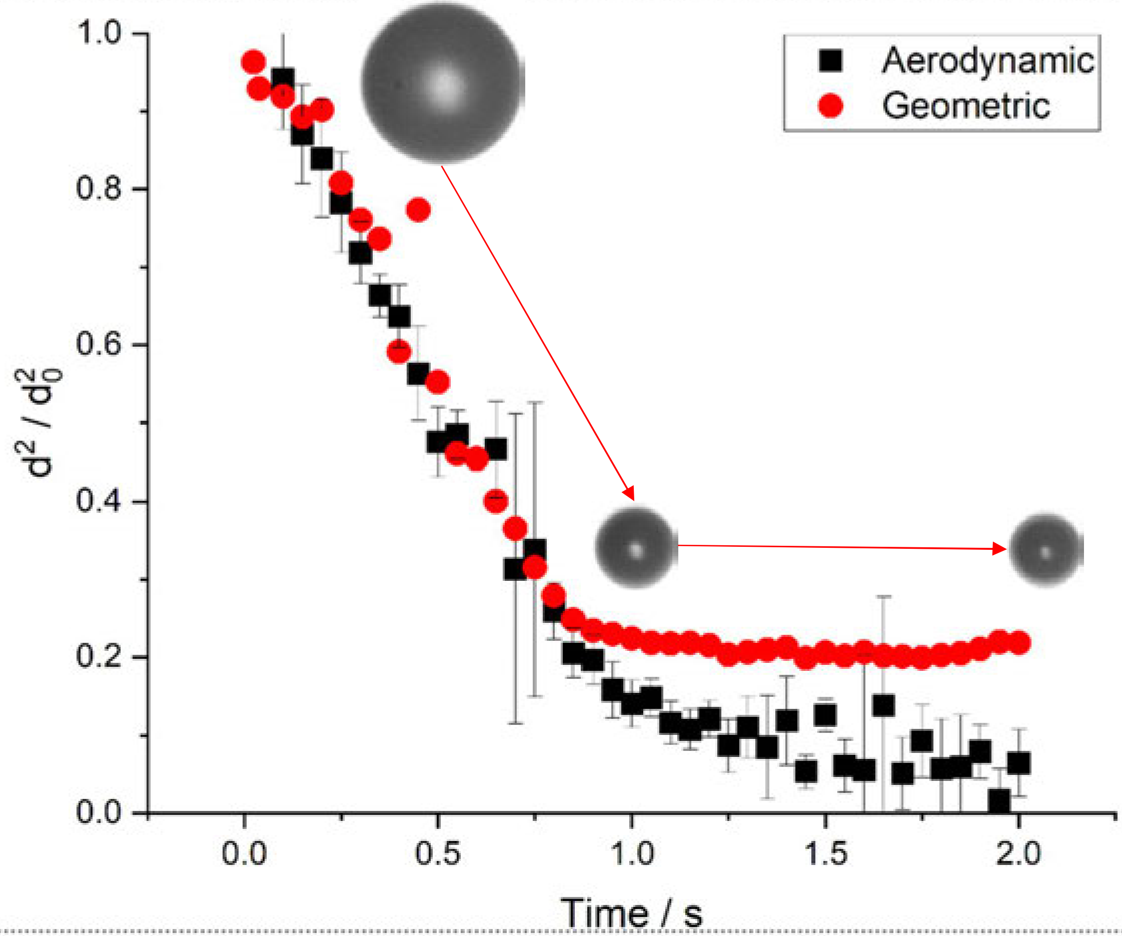
RH 20% ± 5%
15ºC ± 2ºC

Real World Systems
- Sodium Fluorescein

13 March 2021

- Fluorescein





RH 20% ± 5%
15ºC ± 2ºC

Real World Systems - Modelling

ACS central science

http://pubs.acs.org/journal/acscii
Research Article

Accurate Representations of the Microphysical Processes Occurring during the Transport of Exhaled Aerosols and Droplets

Jim S. Walker, Justice Archer, Florence K. A. Gregson, Sarah E. S. Michel, Bryan R. Bzdek, and Jonathan P. Reid*

Cite This: https://dx.doi.org/10.1021/acscentsci.0c01522
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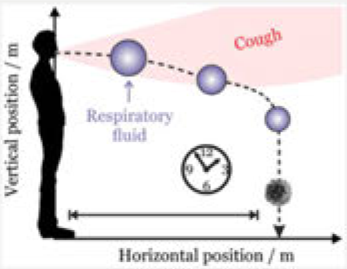
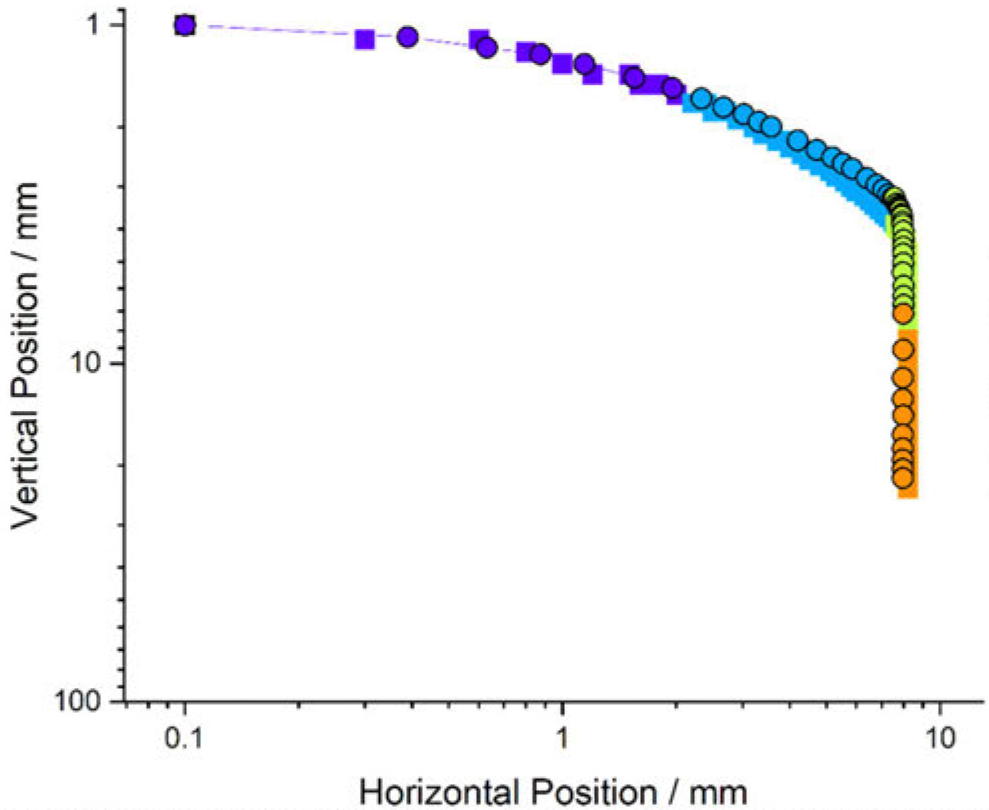
ABSTRACT: Aerosols and droplets from expiratory events play an integral role in transmitting pathogens such as SARS-CoV-2 from an infected individual to a susceptible host. However, there remain significant uncertainties in our understanding of the aerosol droplet microphysics occurring during drying and sedimentation and the effect on the sedimentation outcomes. Here, we apply a new treatment for the microphysical behavior of respiratory fluid droplets to a droplet evaporation/sedimentation model and assess the impact on sedimentation distance, time scale, and particle phase. Above a 100 μm initial diameter, the sedimentation outcome for a respiratory droplet is insensitive to composition and ambient conditions. Below 100 μm, and particularly below 80 μm, the increased settling time allows the exact nature of the evaporation process to play a significant role in influencing the sedimentation outcome. For this size range, an incorrect treatment of the droplet composition, or imprecise use of RH or temperature, can lead to large discrepancies in sedimentation distance (with representative values >1 m, >2 m, and >2 m, respectively). Additionally, a respiratory droplet is likely to undergo a phase change prior to sedimenting if initially <100 μm in diameter, provided that the RH is below the measured phase change RH. Calculations of the potential exposure versus distance from the infected source show that the volume fraction of the initial respiratory droplet distribution, in this size range, which remains elevated above 1 m decreases from 1 at 1 m to 0.125 at 2 m.



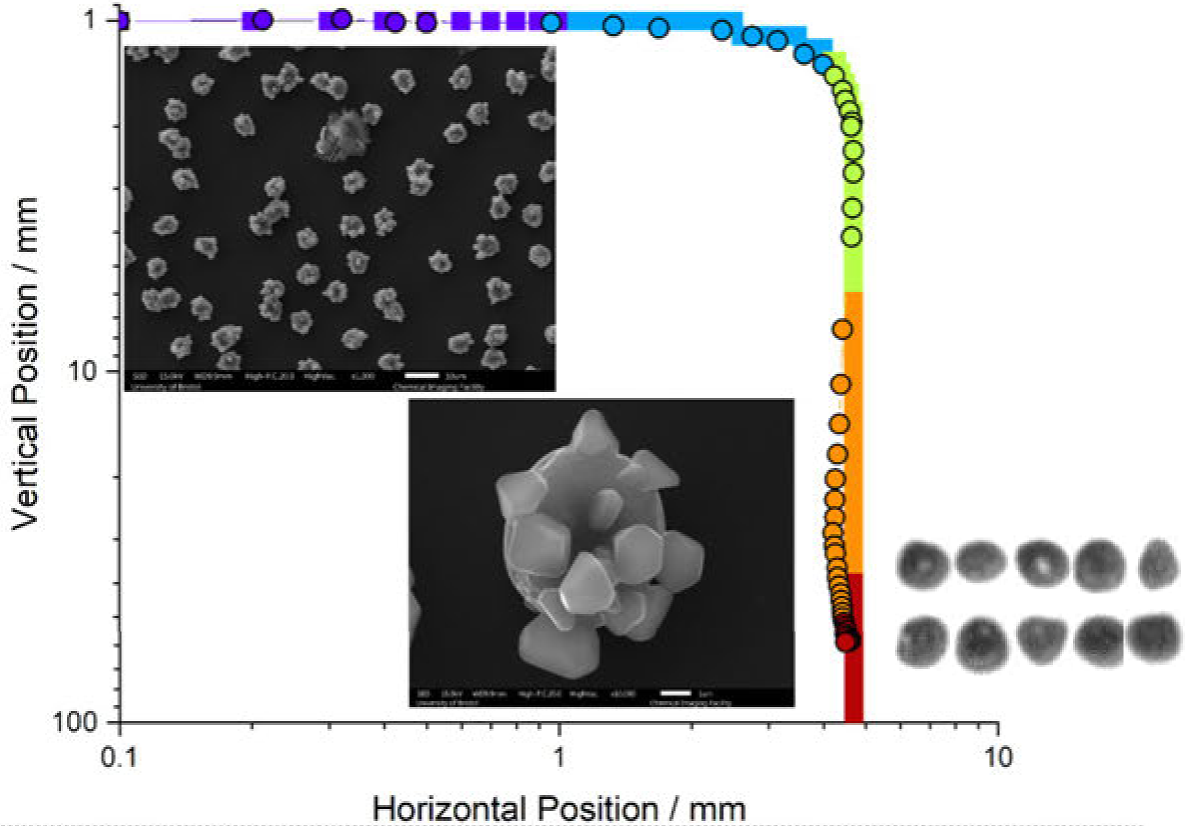
$$
\begin{cases}
\dfrac{dr_p}{dt} = \dfrac{CM_v D_\infty p Sh}{\rho_p r_p R T_\infty} \ln\left(\dfrac{p-p_{va}}{p-p_{v\infty}}\right) = f_1(r_p, T_p, \vec{V}_p) \\[2ex]
\dfrac{dT_p}{dt} = 3K_g \dfrac{T_\infty - T_p}{c_p r_p^2} Nu - \dfrac{L_v I}{m_p c_p} - \dfrac{3\Gamma(T_p^4 - T_\infty^4)}{r_p c_p} = f_2(r_p, T_p, \vec{V}_p) \\[2ex]
\dfrac{d\vec{V}_p}{dt} = \vec{g}\left(1 - \dfrac{\rho_p}{\rho_g}\right) - \dfrac{3C_d \rho_g |\vec{V}_p - \vec{V}_g|(\vec{V}_p - \vec{V}_g)}{8\rho_p r_p} = f_3(r_p, T_p, \vec{V}_p) \\[2ex]
\dfrac{d\vec{x}_p}{dt} = \vec{V}_p = f_4(\vec{V}_p)
\end{cases}
$$

Real World Systems - Respiratory Fluids

- Artificial Saliva



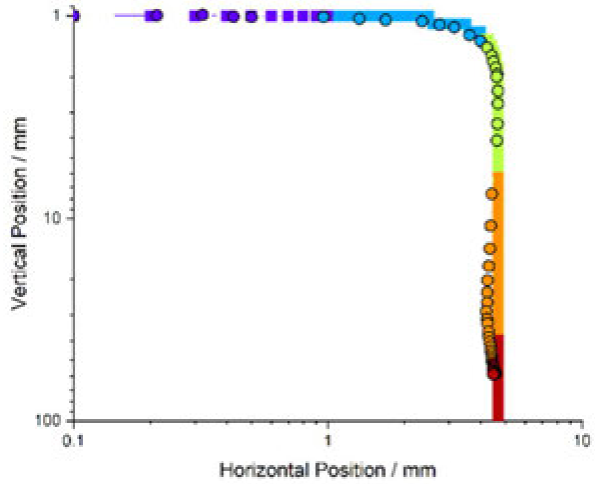
- Deep Lung Fluid



Conclusion

Falling Droplet Column Capability

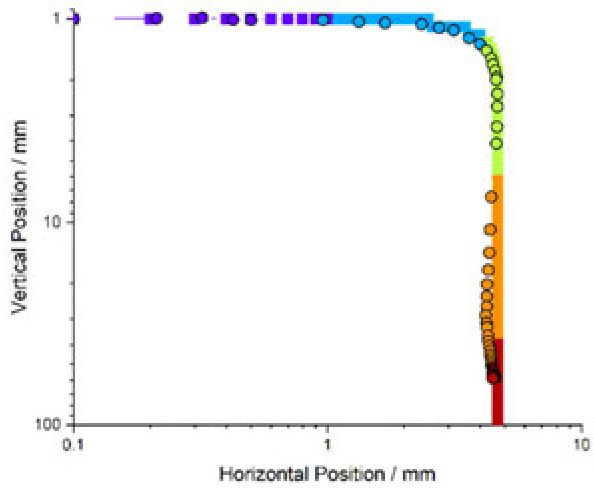
- Observe and model freefalling droplet trajectories

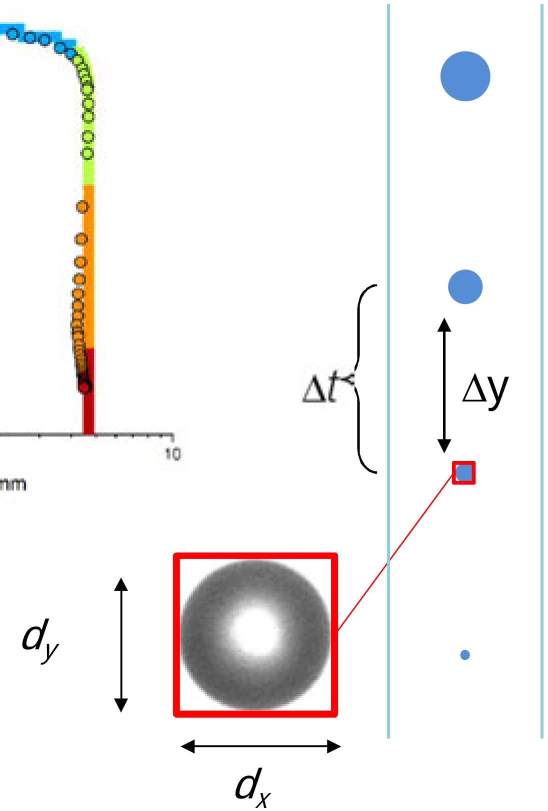


Conclusion

Falling Droplet Column Capability

- Observe and model freefalling droplet trajectories
- Image droplets throughout drying process
- Measure geometric and aerodynamic diameter

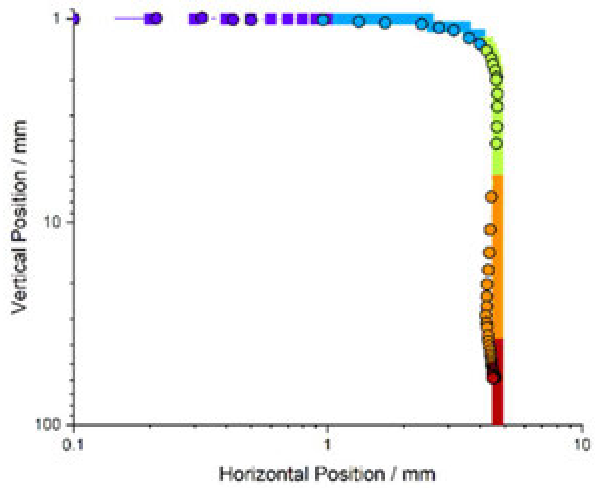


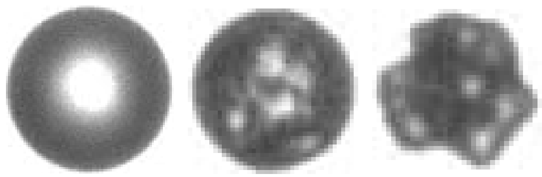


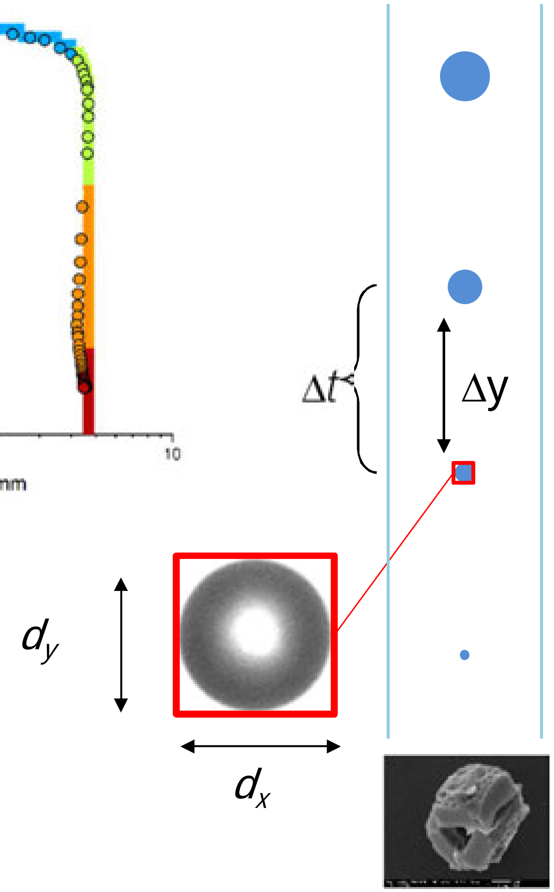
Conclusion

Falling Droplet Column Capability

- Observe and model freefalling droplet trajectories
- Image droplets throughout drying process
- Measure geometric and aerodynamic diameter
- Observe phase changes
- SEM analysis of dry particles







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Pascal Lemaitre and the IRSN

Jonathan Reid and the BARC group

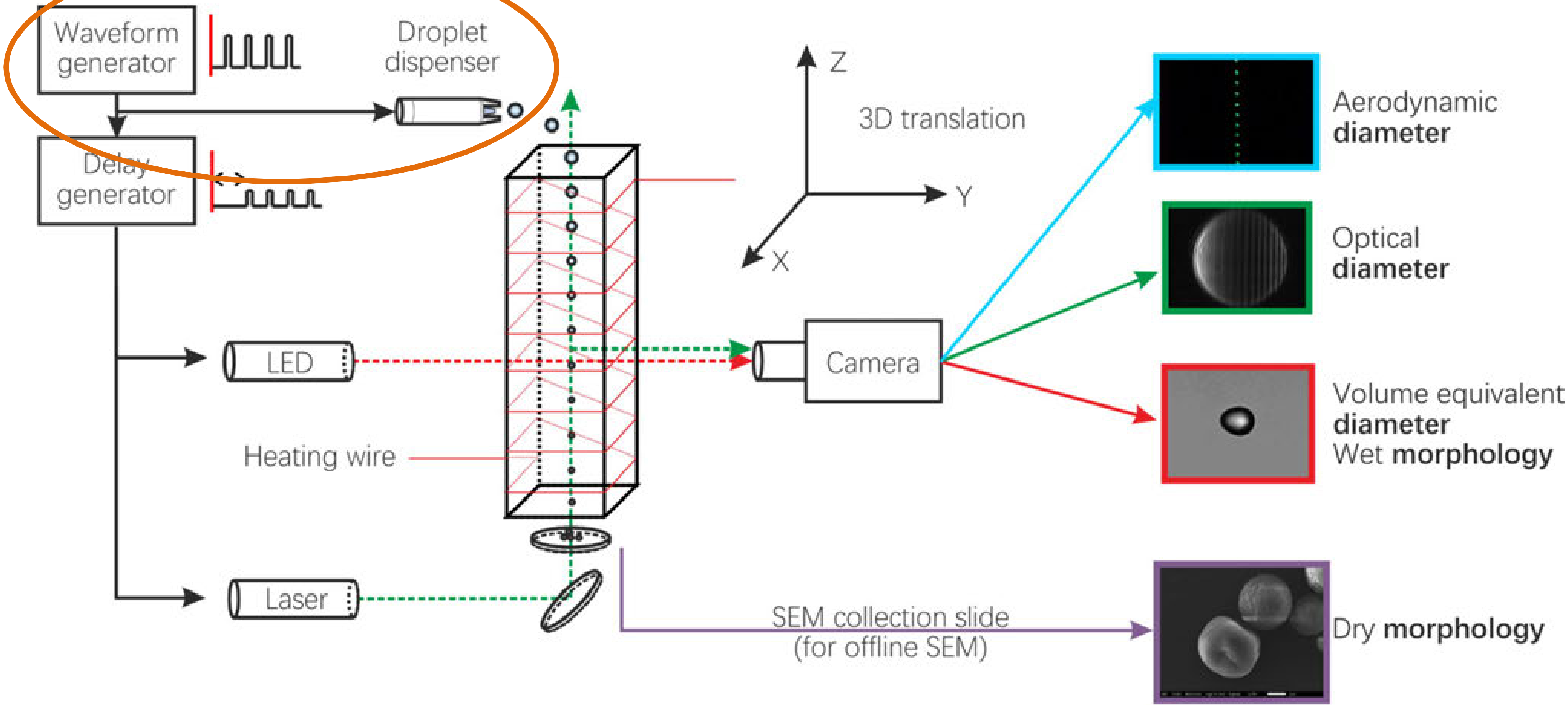
Jim Walker

Flo Gregson

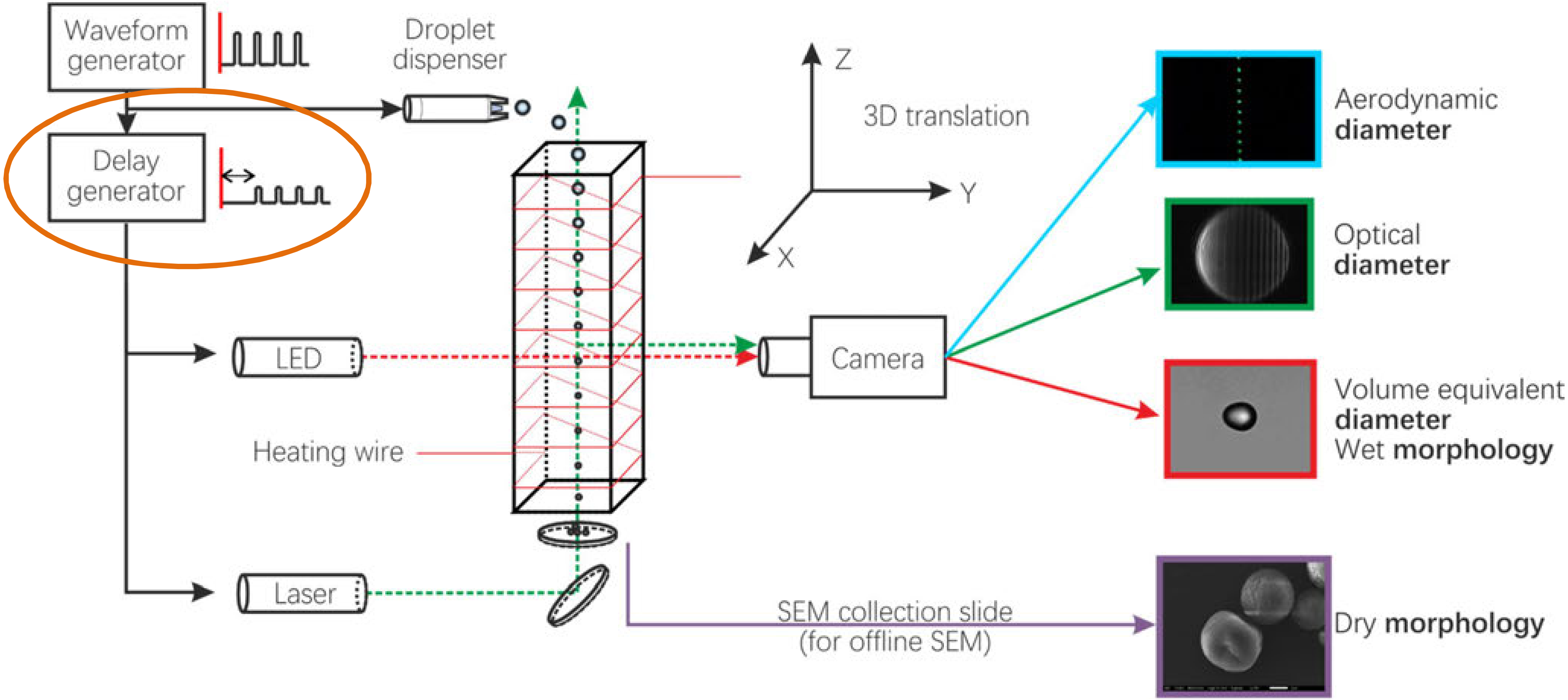
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Thank you for listening

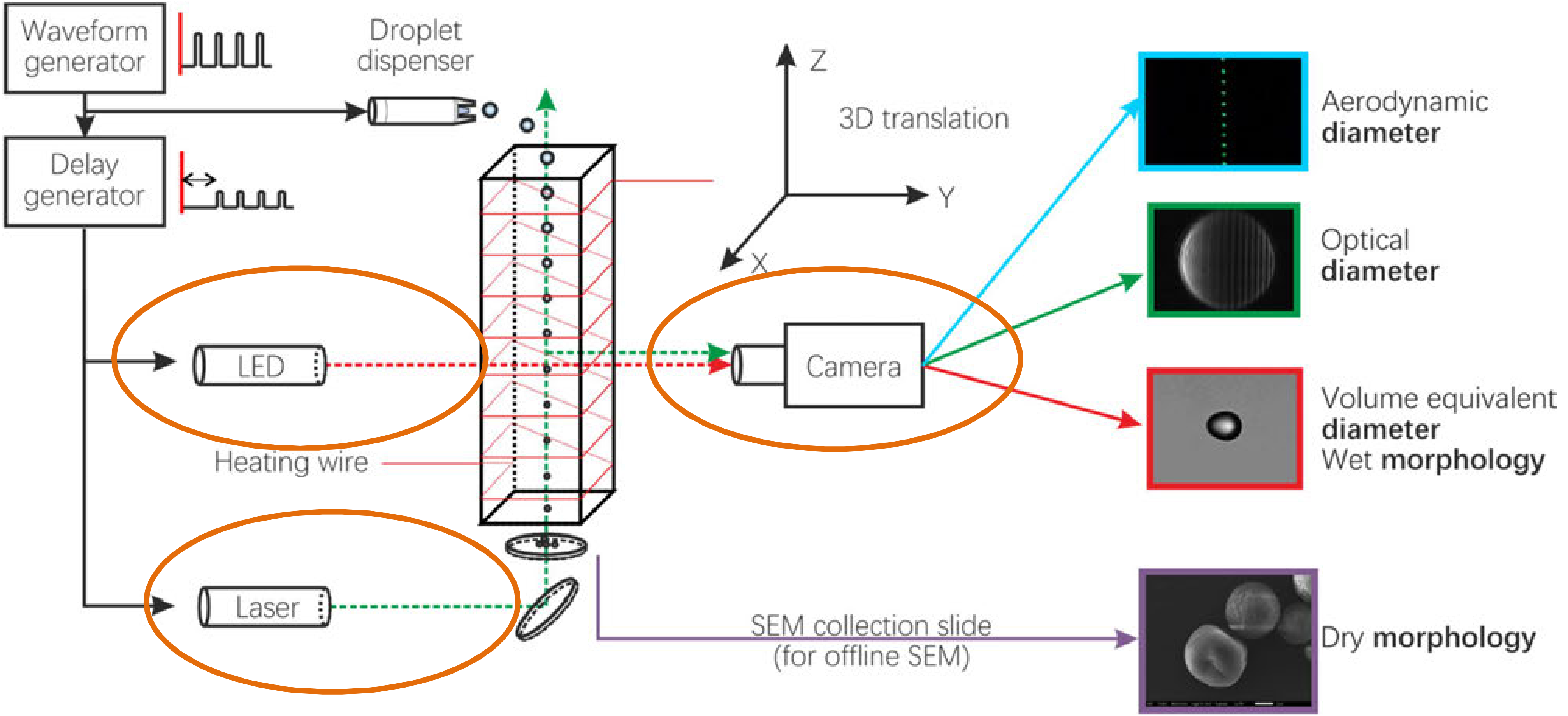
Falling Droplet Column



Falling Droplet Column

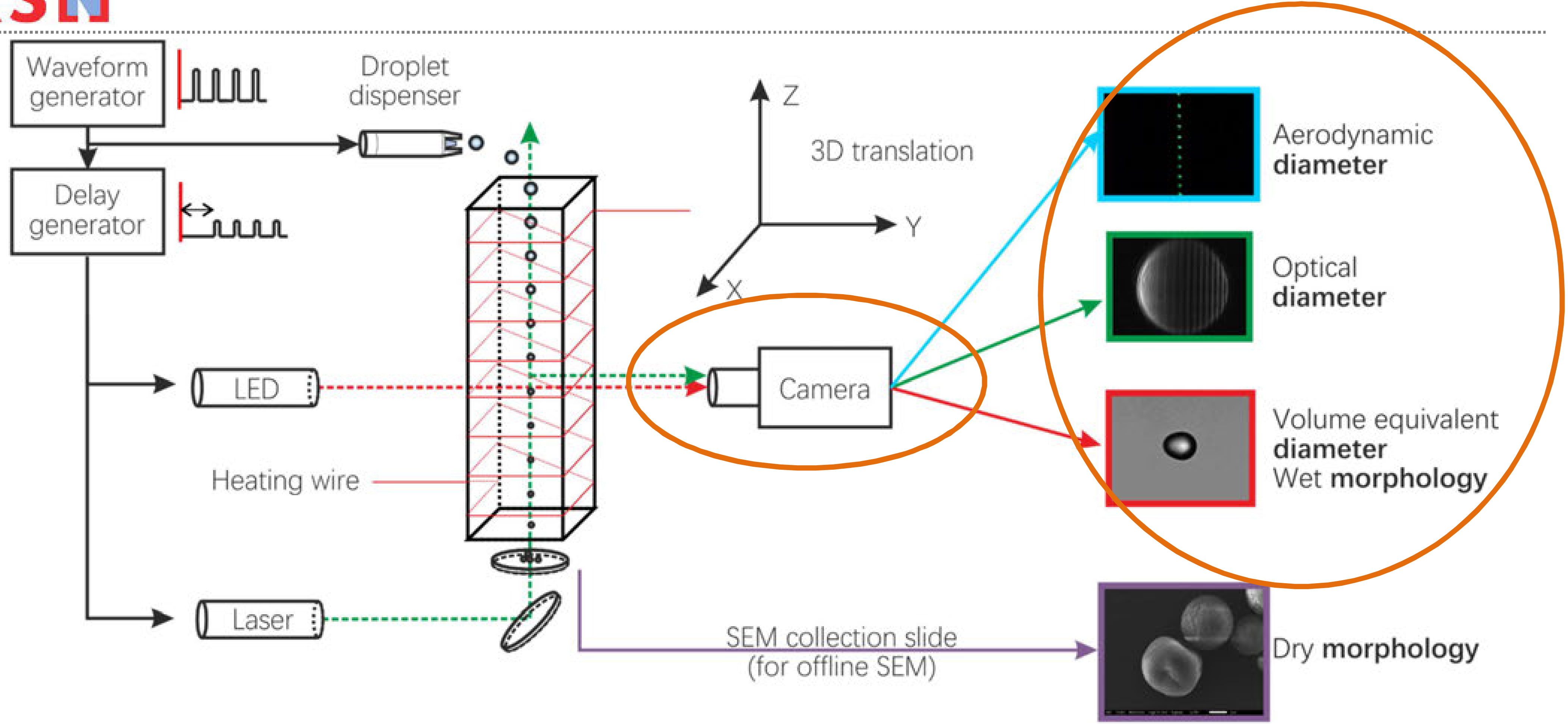


Falling Droplet Column

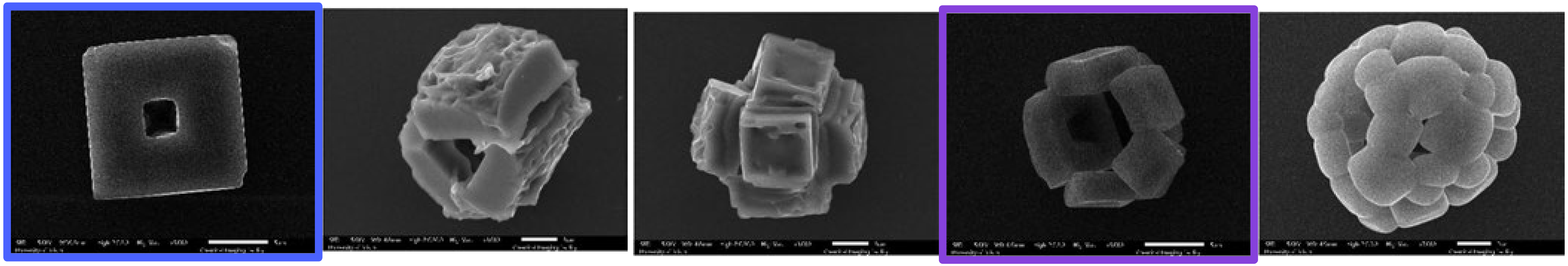


Falling Droplet Column

13 March 2021



SEM Analysis
– Understanding Morphology



Increasing evaporation rate, κ ↑ Temperature ↓ Relative Humidity

Pe < 1 Diffusion dominates, homogeneity maintained

- Fewer nucleation sites
- Crystal growth on earliest nucleation site

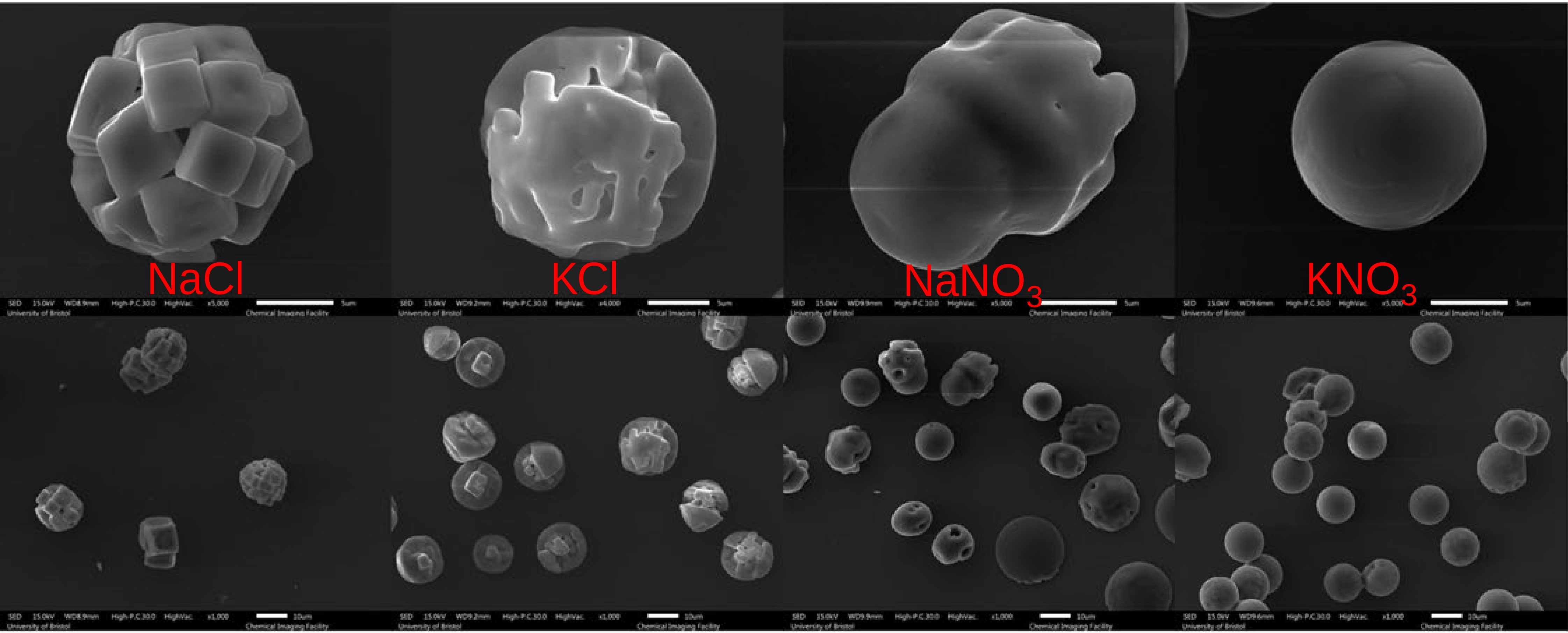
Peclet Number

$$Pe = \frac{\kappa(RH,T)}{8D(T)}$$

Pe > 1 Leads to surface enrichment

- Many nucleation sites
- Parallel crystal growth
- Surface crust / shell formation

SEM Analysis



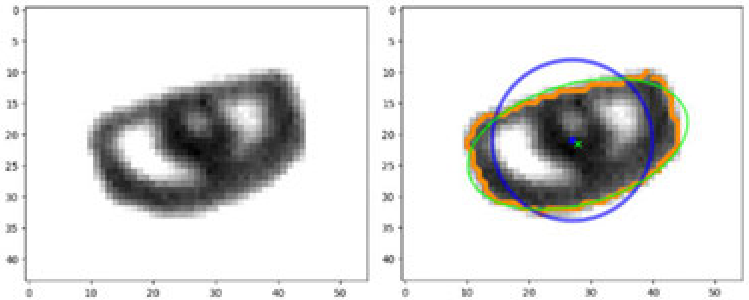
RH 20% ± 5%
15ºC ± 2ºC

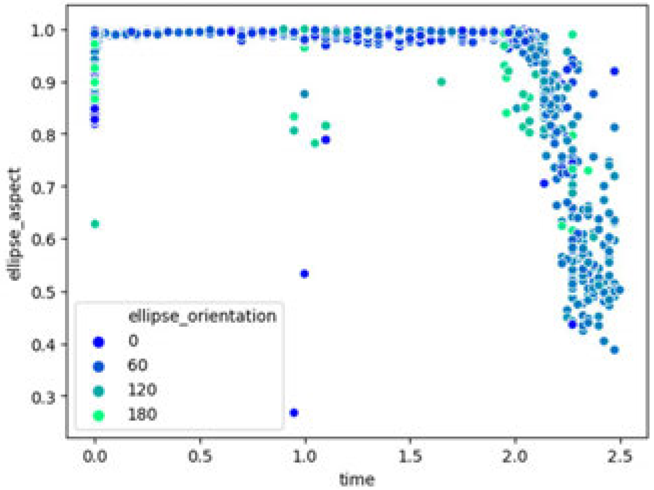
Future Work

- Further experiments on:
  - Industrially relevant compounds
  - Compounds forming amorphous particles
- Parameterisation of sodium fluorescein aerosol properties
  - For use in model
- Further development of model
  - To include surface enrichment

Future Work

- Image analysis
  - Particle morphology





  - Particle orientation