The EPSRC Centre for Doctoral Training in Aerosol Science

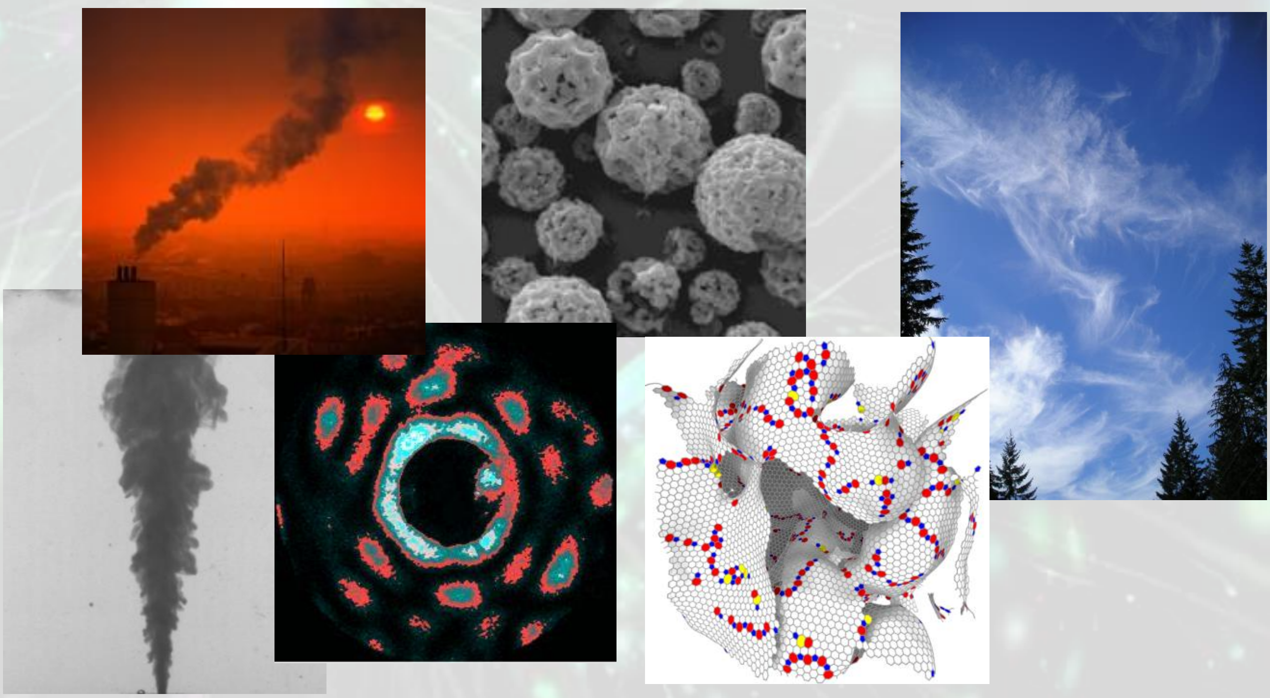
UKRI Engineering and Physical Sciences Research Council

University of Bristol
University of Hertfordshire
University of Bath
Manchester 1824 The University of Manchester
Imperial College London
University of Cambridge
University of Leeds

Partner Guide and Core Aerosol Science Training Prospectus

Aerosol science is crucial to disciplines as broad ranging as drug delivery to the lungs, the transmission of disease, climate change, combustion science, novel routes to materials, and consumer and agricultural products.

The EPSRC Centre for Doctoral Training in Aerosol Science ('CDT') brings together a multi-disciplinary team of academics from 7 UK universities spanning the physical, environmental and health sciences, and engineering. We will train 80 post-graduates over 5 cohorts, 2019-2027.



The CDT in Aerosol Science will deliver a paradigm shift in the training of future scientists and engineers, lay the foundations for enhanced national research capacity, and redefine and strengthen the interdisciplinary community of aerosol science. We will deliver practitioners with a mastery of the fundamental principles of aerosol science, an ability to apply their knowledge across disciplinary boundaries, and the agility to be at the forefront of these rapidly evolving fields.

Working with industrial and public-sector partners in the areas of healthcare, materials science, energy and transport, environment, consumer products and agrochemicals, we aim to tackle some of the most challenging and important problems in aerosol science, delivering world-leading research. Our graduates will be capable of addressing the important societal, technological and environmental challenges where aerosols play a critical role.

Working in Partnership with the Aerosol Science CDT

Partnerships between the academic, industrial, governmental and public sectors are crucial to train and mentor the next generation of practitioners, to equip and upskill the current workforce, and to deliver transformative research.

The CDT has established three tiers for partnerships, offering flexible and accessible engagement.

- **Tier 1 – Student Mentoring:** Partners contribute to the delivery of elements of training, act as a professional mentor for students undertaking research in an area relevant to partner expertise, host the student on placement, access annual conferences and receive a monthly e-newsletter.
- **Tier 2 – Building National Capability:** Partners receive access to the e-training portal and to the core aerosol science training courses, valuable for continuing professional development, and can stream the weekly research webinar from experts around the world.
- **Tier 3 – Delivering Research for Partners**: Partners shape a PhD research project to their needs, play a more active role in student supervision with longer student placements and access the IP rights from the research.

Introducing the Core Team

We would like to introduce you to the core team with responsibilities for different aspects of the delivery of the CDT.

Prof Jonathan Reid
Director

University of BRISTOL

Prof Darragh Murnane
Deputy Director

University of Hertfordshire UH

Dr Adam Boies
Partnerships Chair

UNIVERSITY OF CAMBRIDGE

Dr Kerry Knox
Science Education Specialist

UNIVERSITY of York

Dr Rachael Miles
Course Manager

University of BRISTOL

Prof Andrew Orr-Ewing
Equality, Diversity & Inclusion

University of BRISTOL

Prof Sheena Cruikshank
Public Engagement and Outreach

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The University of Manchester

Yaelle Hartley
Partnerships Administrator

University of BRISTOL

Kate Lucas
CDT Administrator

University of BRISTOL

The Centre for Doctoral Training in Aerosol Science is committed to furthering issues of equality, diversity and inclusion. Further information can be found at: http://www.bristol.ac.uk/inclusion/

The Academic Team

As well as delivering the core aerosol science training elements, the academic team will lead in the development of PhD research projects. At Tier 3, these projects may be focussed on delivering research defined by, and important to, our partners. We include a directory of the academic team below.

UNIVERSITY OF BATH

Andrew Johnson	Chemistry	Aerosol-assisted chemical vapour deposition (AACVD); thin films; coatings; semiconductors; photo-catalysis
Matthew Jones	Pharmacy & Pharmacology	Inhaler devices; usability; dry powder inhalations; respiratory drug delivery
Anton Souslov	Physics	Theory and modelling of soft materials
Adam Squires	Chemistry	Basic process studies; new techniques for aerosols (e.g. synchrotron small-angle X-ray)

University of BRISTOL

Karen Aplin	Engineering	Instrumentation and measurement; atmospheric aerosols; electrostatics; ionisation; microphysics
Bryan Bzdek	Chemistry	Single particle; optical tweezers; mass spectrometry; indoor air; surfaces
Michael Cotterell	Chemistry	Aerosol optical properties; cavity ring-down spectroscopy; photoacoustic spectroscopy; single particle trapping
Alberto Gambaruto	Engineering	Computational fluid dynamics; applied mathematics; upper respiratory airways; transport and deposition; multiphysics modelling
Darryl Hill	Cellular and Molecular Medicine	Microbiology
Anwar Khan	Chemistry	Dispersion models; secondary organic aerosol; gas-particle partioning
Rachael Miles	Chemistry	Single particle; microphysical properties; heat and mass transfer; light scattering; reactions

UNIVERSITY OF BRISTOL CONTINUED OVERLEAF

University of BRISTOL

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Andrew Orr-Ewing	Chemistry	Extinction; refractive index; spectroscopy; CRDS; trapping
Jonathan Reid	Chemistry	Atmospheric aerosols; drug delivery to the lungs; droplet drying and phase change; airborne disease transmission; formulation science
Alison Rust	Earth Sciences	Volcanology; fluid dynamics; ash; dispersion; nucleation
Walther Schwarzacher	Physics	Ice nucleation and supercooled droplets
Dudley Shallcross	Chemistry	Metals; modelling; SOA; Criegee intermediates; climate change
Matthew Watson	Earth Sciences	Volcanology; remote sensing; UAVs; volcanic ash and gas; climate engineering

UNIVERSITY OF CAMBRIDGE

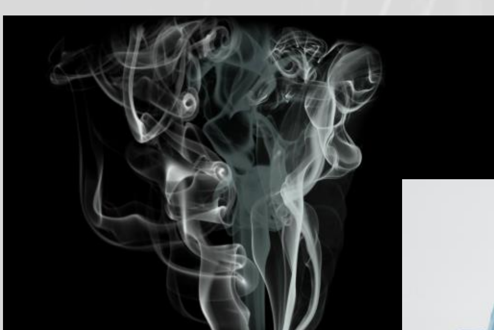
Jethro Akroyd	Chemical Engineering & Biotechnology	Detailed particle model; Kinetic Monte Carlo; population balance modelling; carbon; titanium dioxide
Adam Boies	Engineering	Carbon; aerosol instrumentation; COVID; carbon nanotube; soot
Megan Davies Wykes	Engineering	Laboratory experiments; fluid dynamics; pollution dispersion
Chiara Giorio	Chemistry	Atmospheric chemistry; aerosol; analytical environmental chemistry; mass spectrometry; chemometrics
Simone Hochgreb	Engineering	Nanoparticle measurement; soot measurement; instrument development; aerosol flow; sprays
Markus Kraft	Engineering	Particle synthesis using aerosol flow reactors (e.g. carbon nanotubes, carbon black)

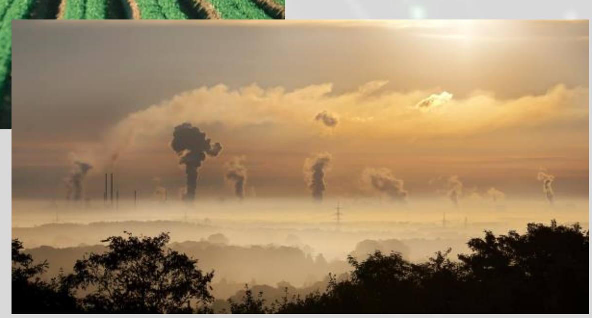
Robert Chilcott	Life and Medical Sciences	Aerosol exposure; particle size analysis; SEM-XDS
Loic Coudron	Engineering and Computer Science	Digital microfluidics; aerosol collection; detection; biosurveillance; electrowetting; electrostatic precipitation
Richard Greenaway	Physics, Astronomy and Mathematics	Particulates; light scattering; respirable; software design; data analysis; instrumentation
Victoria Hutter	Life and Medical Sciences	Drug delivery to the lungs; in vitro modelling of inhaled therapeutics
Ian Johnston	Physics, Astronomy and Mathematics	Collection, microfluidics, identification, sample-prep, protection
Joanne Larner	Life and Medical Sciences	Chemical analysis of aerosol composition, bio-exposure
Daniel McCluskey	Engineering & Computer Science	Biodetection; collection systems; pathogen; sample processing; mechatronic systems

Darragh Murnane	Life and Medical Sciences	Drug delivery; inhalation; formulation sciences; particle engineering; pharmaceutical aerosols
Benjamin Richard	Life and Medical Sciences	Airborne fungal spore dispersal; climate change; disease forecasting; plant pathology; modelling
Chris Stopford	Physics, Astronomy and Mathematics	Real time particulate aerosol detection
Laura Urbano	Clinical and Pharmaceutical Science	High content imaging; in vitro model; formulation; micro & nanoparticles; microfluidics

Imperial College London

Wendy Barclay	Infectious Disease	Droplet, aerosol, coronavirus, influenza, transmission
Denis Doorly	Aeronautics	Fluid Mechanics
Matthew Fisher	Public Health	Bioaerosols, Fungi, infection, health, disease
David Green	Public Health	Aerosol measurement; source apportionment; health impacts; chemical composition; particle size distribution
Yannis Hardalupas	Mechanical Engineering	Atomisation; sprays; laser diagnostics; turbulent dispersion; particulate emissions
Jerry Heng	Chemical Engineering	Surface properties; nucleation; crystallisation; wettability
Peter Lindstedt	Mechanical Engineering	Combustion and soot
Marc Masen	Mechanical Engineering	Tribology; particles; wear; contact mechanics
Asha Patel	National Heart & Lung Institute	Inhaled delivery of advanced therapeutics such as mRNA
Alexandra Porter	Materials	Toxicology of particles; enhanced electron microscopic imaging
Marc Stettler	Civil and Environmental Engineering	Aerosol sources; combustion aerosols; air pollution; aerosol measurement; morphology
Terry Tetley	National Heart & Lung Institute	Inhalation toxicology; particulate air pollution; nanodrug development; respiratory disease
Omar Usmani	National Heart & Lung Institute	Inhalation therapeutics; drug delivery to the lungs



UNIVERSITY OF LEEDS

Andrew Bayly	Chemical & Process Engineering	Droplet and aerosol dynamics; droplet and particle drying; particle structure formation; formulation science; spray drying
Dwayne Heard	Chemistry	Air-aerosol interface; heterogeneous atmospheric chemistry; chemical kinetics; photochemical oxidation; atmospheric modelling
Nik Kapur	Mechanical Engineering	Droplets; sprays and coatings; fluid flow; heat transfer
Ben Murray	Earth & Environment	Laboratory studies of atmospheric aerosols including ice
Catherine Noakes	Civil Engineering	Indoor air quality and airborne infection; ventilation and building performance
John Plane	Chemistry	Planetary atmospheric chemistry; cosmic dust; mesospheric clouds; stellar outflows

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Hugh Coe	Earth & Environmental Sciences	Particle detection; physical and chemical characterization; gas/ particle conversion; instrumentation; sampling and data analysis methods
Paul Connolly	Earth & Environmental Science	Clouds, aerosols, mixed-phase, nucleation, meteorology
Sheena Cruikshank	Biological Sciences	Immunology; epithelial cells; microbiome; pathogen; innate cells
Amanda Lea-Langton	Mechanical, Aerospace & Civil Engineering	Smoke formation; organic carbon emissions; environmental aerosol
Gordon McFiggans	Earth & Environmental Science	Atmospheric composition; clouds & aerosols; computer modelling; marine atmospheric chemistry
Benedict Rogers	Mechanical, Aerospace & Civil Engineering	Smoothed Particle Hydrodynamics (SPH); numerical methods
Holly Shiels	Cardiovascular Sciences	Heart, physiology, metabolism, environment, pollution
David Topping	Earth & Environmental Science	Computational models; machine learning; data
Paul Williams	Earth & Environmental Science	Aircraft emissions; small sensors; experimentalist

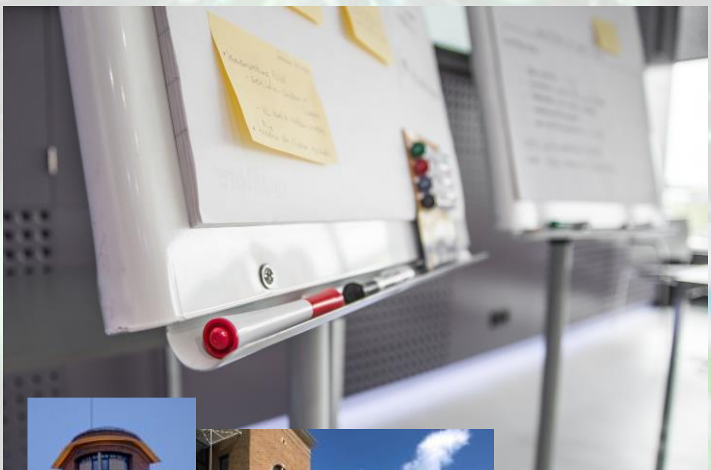
Our Partners—exploring the (Inter!)National Skills Gap in Aerosol Science

Malvern Panalytical
CEH Centre for Ecology & Hydrology NATURAL ENVIRONMENT RESEARCH COUNCIL
The Aerosol Society
LettUs Grow
Biral
CAMBUSTION
TORTECH nano fibers
Upperton Pharma Solutions
VECTURA
dyson
OXFORD LASERS
OXFORD INSTRUMENTS
Steer Energy
ROLLS ROYCE
ROTHAMSTED RESEARCH
Met Office
RSK
OzUK
MedPharm
Agilent
THE Pirbright INSTITUTE
Kindeva DRUG DELIVERY
PHILIPS RESPIRONICS
FIL Filtration and Particle Science
DROPLET MEASUREMENT TECHNOLOGIES
EMISSIONS ANALYTICS
Chiesi People and Ideas for Innovation in healthcare
AstraZeneca
dstl
CERC
syngenta
TROLEX
Mylan®
Rentokil Initial
Environment Agency
nanopharm Your specialists in respiratory R&D
TSI®
asthma UK
CRODA
Alphasense
VENATOR
Waters THE SCIENCE OF WHAT'S POSSIBLE.™
Lamellar Biomedical
EPAG
BAYER
Department for Environment Food & Rural Affairs
Johnson Matthey Inspiring science, enhancing life
NPL National Physical Laboratory

Aerosol Science Training

Overview

The following pages contain synopses for the programme of core training in the underlying physical science governing the properties and transformation of aerosols. Training will be provided by academics and industrial partners spanning a broad range of sectors using a flipped classroom and Team-Based Learning approaches. This essential training forms the core structure of the first 7 months of PhD training for our doctoral researchers. Individual courses are available to partners for Continuing Professional Development (CPD).



The e-Training Portal and Online Training Courses

Prior to the online two-day training intensive for each topic, attendees will have access to the e-training portal. This will host directed learning resources including instructional videos, lecture slides, smart worksheets and reading resources. These e-training materials will be accessible to Tier 2 partners registered for CPD in advance of the relevant training events, and at all times thereafter.

A calendar of online training days for each topic will be released during summer 2020. Partners with Tier 2 membership and doctoral students wishing to complete training in specific areas are encouraged to register for these events.

Training aims and approaches

Our graduates will be practitioners with a mastery of the fundamental principles of aerosol science and the ability to apply this knowledge across disciplinary boundaries. We have captured our training vision in the 9 key competencies shown below. In-person events will involve Team-Based Learning (TBL).

TBL is an evidence-based pedagogy known to be effective for both conceptual learning and developing communication and teamworking skills, and hence is ideally suited to our aims. It creates a powerful connection between participants and the expertise of educators. Instructional events follow a structured path which tests participant preparation, corrects misunderstandings and addresses gaps, and then engages participants in collaborative exercises. The expertise of the educator is captured in the design of the in-class exercises, and through responsive interactions throughout the instructional meetings.

Graduates will be able to demonstrate these competencies:

1. Apply theoretical knowledge of aerosol science across a range of problems of a chemical, physical, biological or technological nature.
2. Undertake independent design and conduct experiments/models with technical mastery, as well as analyse and interpret data.
3. Identify, formulate, critique and solve research problems within their specialised context to advance the understanding of aerosols.
4. Develop or adapt advanced methodological approaches to contemporary problems, recognising the complexity and tolerating the ambiguity that arises in real-world systems.
5. Synthesise new approaches to meet an identified outcome within realistic constraints such as economic, environmental, social, political, ethical, safety, manufacturability, and/or sustainability.
6. Act in congruence with professional & ethical values, & manage ethical dilemmas in formulating scientific solutions.
7. Function effectively and confidently in multidisciplinary teams, acting autonomously and taking responsibility for the scientific activity of others.
8. Communicate and share research knowledge to both expert and non-expert audiences, and guide the learning of those from outside their discipline.
9. Manage personal intellectual development as a self-critical, reflective scientist with the agility to respond to new challenges.

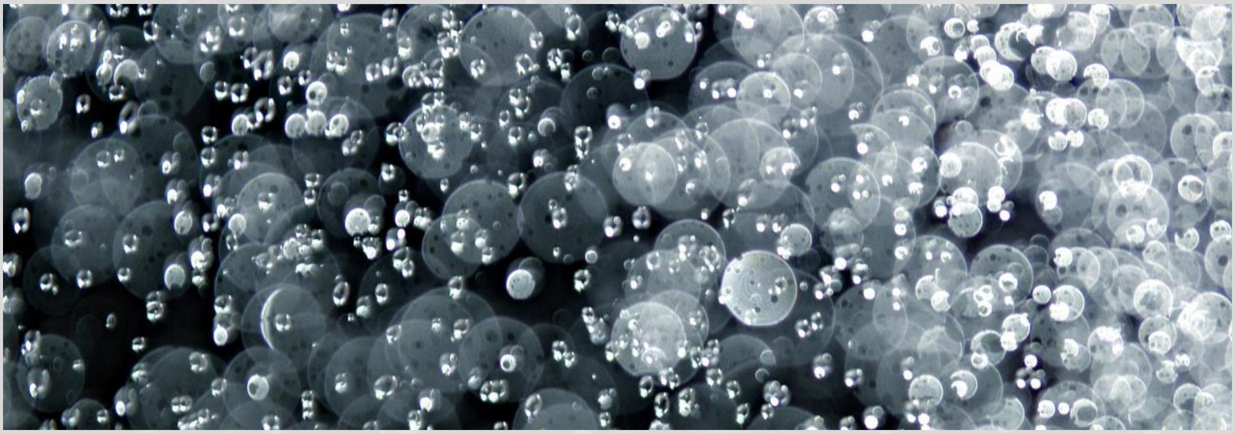
Certification of CPD activities

Participation in training events will lead to a Certificate of Attendance. Attendees may also participate in an optional online assessment to gauge their progress towards achieving the learning outcomes.

The Core Aerosol Science Topics

The core aerosol science training will cover the sixteen topics listed below. In summer each year, we will return to these core topics in contextual summer schools, building on the concepts learned.

Identifier	Core Aerosol Science Course Title
CAS 1.1	Size distributions, shape and concentrations
CAS 1.2	Aerosol mechanics
CAS 1.3	Deposition, filtration and sampling
CAS 1.4	Nucleation and new particle formation
CAS 1.5	Electrical properties
CAS 1.6	Aerosol phase and thermodynamics
CAS 1.7	Optical properties
CAS 1.8	Analysis: Size, concentration, shape and mass
CAS 2.1	Particle coalescence and adhesion
CAS 2.2	Aerosol evaporation and condensation
CAS 2.3	Inhaled aerosols and health
CAS 2.4	Particle sources and materials synthesis
CAS 2.5	Analysis: Composition, phase and volatility
CAS 2.6	Introduction to biological aerosol
CAS 2.7	Heterogeneous chemical reactions
CAS 2.8	Collective motion and transport of aerosols



For more information and instructions on how to register, please contact aerosol-science@bristol.ac.uk

Synopses for Core Aerosol Science Topics

Synopses for each course are provided below. Topics prefaced with “1.” will be delivered during autumn 2020 and with “2.” during spring 2021.

CAS 1.1: Size distributions, shape and concentrations

Aerosols particles are typically polydisperse in size, with particle diameters spanning from the nanometre to the millimetre scale. Particles of different size can have different sources leading to multimodal distributions, and have differing suspension lifetimes exhibiting different loss mechanisms. They also show different deposition patterns in the respiratory tract. Aerosol particle size distributions may be reported as number concentration, surface area or volume distributions, each having value in different applications. The smallest particles might be very large in number, but may represent only a very small fraction of the total aerosol surface area or condensed phase mass. Even then, the health impacts of nanoparticles may be disproportionately important. It is common, for example in air quality studies, to report particle mass concentrations for all particulate matter less than 2.5 or 10 μm in diameter. Particles may also have aerodynamic diameters that differ from their geometric size, they may be highly non-spherical, and may be heterogeneous in composition and phase in internal and external mixtures. We will examine the different frameworks for reporting the physical characteristics of aerosol, the common requirement to consider variations in size over many orders of magnitude, and the analytical instruments available for characterising aerosol samples.

CAS 1.2: Aerosol Mechanics

The dynamics of aerosols dictate the motion of particles in the suspending medium, and dictates phenomena such as pollution dispersion, lung deposition and nanomaterial collection. Aerosol particles obey Newtonian laws of motion and allow for a description of aerosol motion in relation to the fluid dynamics of the system. The size of the suspended particles dictates whether continuum mechanics or molecular dynamics best describes the particle motion, and in many cases the particles lie within a transition regime between the bounding length scales. The course will introduce the aerosol general dynamic equation, which is the basis of aerosol mechanics and dynamics. Transport due to diffusion, external forces and advection will be described in relation to practical applications such as inertial impaction and particle size selection.

CAS 1.3: Deposition, filtration and sampling

The focus of this module is to enable students to develop an understanding of the importance of aerosol filtering and capture systems, whether this is to reduce disease transmission, minimise exposure to harmful allergens or to capture airborne material for further analysis. The engineering approaches to system design require a comprehensive understanding of the natural deposition processes and deposition modes, methods of capture (filtration, cyclonic separation, deposition) and subsequent analysis techniques. Furthermore, the principles of inertial impaction sampling as applied to aerosol capture are applicable to a variety of transport phenomena, and analytical and aerosol sizing. The cohort will explore several prototype systems developed by the academic team for real-world environmental challenges including food security (protecting crops from airborne disease), environmental stewardship (detection of the fungal spores in forests), infection control (protect patients from airborne hospital acquired infection) and the challenges of biowarfare detection (for both military and civilian applications). In addition, the cohort will investigate the operating principles of inertial impaction samplers and subsequent mass analysis. Covering a broad range of inter-disciplinary factors, students will be equipped with an understanding of the challenges facing aerosol scientists when sampling airborne material both in the laboratory and the field.

CAS 1.4: Nucleation & new particle formation

Nucleation involves the formation of particles from gas phase precursors. New particle formation is a two step processes first involving nucleation of new particles followed by the growth of those particles to larger sizes. Nucleation and new particle formation are relevant across a wide range of industrial and environmental contexts. For example, synthesis of nano-materials can involve approaches like floating catalyst chemical vapour deposition, a gas-to-particle conversion process. In the atmosphere, new particle formation is known to be a ubiquitous but poorly understood source of ambient particles that ultimately constitute up to half of all cloud droplet seeds. Planetary dust and meteoric smoke also form through nucleation and growth. Classical nucleation theory is often applied to a range of nucleation and growth contexts. However, classical nucleation theory has important shortcomings that limit its applicability to many real-world systems. In recent years, advancements in instrumental approaches have enabled significant new insights into nucleation and growth mechanisms. We will discuss contexts where nucleation and growth are important, theoretical approaches to describe them, and instrumentation to study newly formed particles.

CAS 1.5: Electrical properties

Aerosol particles may be produced charged, for example in combustion or sprays, or they may acquire charge due to the attachment of ions naturally present in the air. Aerosol charging affects particle-particle collisions (coagulation), particle-surface interactions (deposition), particle collection by droplets (scavenging) and droplet evaporation. For example, the presence of charge on inhaled pharmaceutical aerosol may increase deposition within the lung due to the generation of image charges in the airway epithelial layer. Additionally, the scavenging of ions by aerosol particles forms the basis of the operating principle of smoke alarms, with aerosol laden air having a higher charge concentration than clean air due to the preservation of charge through ion-aerosol attachment rather than its loss through ion-ion recombination. The presence of charge on aerosols can also be used as a diagnostic tool, with measurements of electrical mobility used to determine particle physical properties such as in the size distribution recorded by a Scanning Mobility Particle Sizer (SMPS). We will explore particle charging mechanisms and the different ways in which particle charge can be quantified and controlled, looking at the real-world consequences of particle charging and applications in which it can be exploited.

CAS 1.6: Aerosol phase and thermodynamics

As with all dispersion colloids, aerosols are thermodynamically unstable. However, they adopt a metastable composition with partitioning of components between the gas and condensed particle phases that can be treated using conventional equilibrium thermodynamics. Most commonly, the equilibrium response of solid and liquid particles to changes in gas phase humidity is used as an exemplar. Crystalline particles under dry conditions dissolve (deliquesce) and become solution droplets at high relative humidity. Water is removed reversibly on drying to low relative humidity, although a hysteresis in phase behaviour is often observed with particles crystallising only at a high degree of solute supersaturation. Other volatile and semi-volatile components similarly partition in equilibrium proportions between the gas and condensed phases, changing aerosol particle size and composition. For small particles, the surface curvature of the particle surface can be sufficient that the vapour pressures of volatile components, including water, are enhanced. Understanding all of these principles is crucial to predicting cloud droplet and ice particle formation, the mass concentrations of particulate matter in polluted urban centres, and the response of particles on inhalation to the respiratory tract. Complex phase behaviours can also be observed such as liquid crystals and glasses.

CAS 1.7: Optical properties

The interaction of light with aerosol particles is central in models of climate and regional air quality. Measurements of aerosol optical properties using optical spectroscopy facilitate non-contact studies of chemical reactions in aerosols and at their surfaces, while aerosol-light interactions are exploited in optical trapping techniques. This module provides a broad overview of the key parameters that govern aerosol-light interactions, including the theories that allow predictions of optical behaviour from aerosol microphysical properties. Key ideas include light scattering and absorption, aerosol optical cross sections, angular scattering and how these depend on the aerosol microphysical properties of particle size, composition, shape and phase. Then, the unit develops how the important intrinsic aerosol optical property of complex refractive index relates to molecular parameters and intermolecular interactions, providing an overview of mixing rule theories applied commonly to predicting refractive indices for internally-mixed aerosol systems. A broad overview will be presented of spectroscopic techniques applied commonly in both the laboratory and in the field to the measurement of optical properties including non-contact *in situ* instruments, filter-based methods and remote sensing principles. This module provides the fundamental ideas and theories that will underpin subsequent Aerosol Science modules and research projects involving optical and spectroscopic methods.

CAS 1.8: Analysis - Size, concentration, shape and mass

Measurements of the aerosols around us, in the atmosphere and in industrial processes, have been fundamental to the advancement of the field. The earliest measurements of aerosols and the principles by which they manipulated particles using electrical and aerodynamic forces are still widely used today. Aerosol measurements must deal with particle sizes that span more than four orders of magnitude: from nucleated clusters of a few molecules (~10^{-9} m, ~1 nm) to cloud droplets and dust particles that are up to tens of microns in size (~10^{-5} m, 10 µm). Particle composition and shape can vary significantly with size and time, reflecting the diverse origins of particles. Particles can be non-volatile such as salt, soot, and metals, and also contain semi-volatile compounds such as nitrates and many organic compounds. The distribution of semi-volatile compounds between the gas-phase, their nucleation as new particles and condensation onto non-volatile particles is dependent on the sampling and measurement conditions and affects the number, size distribution and shape of particles that we observe. We will see how aerosol measurements can be made of individual particles and of the collection of particles, how they can provide limited information integrated over time, and progress towards detailed resolution with respect to size and time.

CAS 2.1: Analysis: Particle coalescence and adhesion

Particle coalescence plays a key role in the evolution of size distributions and can be driven by Brownian motion or kinematic diffusion. The latter depends on the relative motion of particles and is important in aerosol scavenging and shear coagulation. Not all particle collisions lead to coagulation; depending on the physical properties of the particles and their relative velocity and angle of impact, bouncing, stretching separation and reflexive separation are also possible outcomes. While the former leaves the size distribution unchanged, the latter leads to droplet fragmentation. The coagulation/ agglomeration outcomes of particles are also dependent on whether the aerosol is a wet droplet or dried particulate dispersion. Understanding the evolving size distribution is important in fields as diverse as atmospheric aerosol, spray drying and drug delivery. Particle adhesion considers the adhesive forces that occur both between particles themselves and between a particle and a surface. This has implications for particle detachment, as in the separation of API from dry powder excipient particles in a DPI, the dispersion of aerosolisable particles in suspension sprays, and for particle impact at surfaces, such as particle bounce in an impactor. We will look at different ways of modelling particle coalescence and the impact of physical properties on the outcome of both particle-particle and particle-surface collisions.

CAS 2.2: Aerosol evaporation and condensation

Aerosols are dynamic with the evaporation or condensation of volatile and semi-volatile components changing the phase, composition and size distributions of dispersed particles. Ultimately the aerosol heads towards a state of equilibrium, with thermodynamic factors governing the distribution of components between the gaseous and condensed phases. Water condensation leads to the activation of aerosol particles to form cloud droplets in the atmosphere. Propellants evaporate from pharmaceutical aerosol generated from metered dose inhalers. The rapid evaporation of solvent can lead to the fabrication of micro-structured particles in spray dryers. Mechanistically, the mass and heat transfer can be intimately coupled, with changes in particle temperature leading to unsteady evaporation. Rates of particle compositional and size change can also be limited by gas transport, interfacial exchange or slow transport within the particle bulk, dependent on particle size, composition and viscosity, gas composition, temperature and pressure. Developing inhomogeneities in composition can lead to surface enrichment of solutes and the formation of core-shell or hollow particles. We will explore the experimental tools used to benchmark models and the factors influencing the mechanisms of aerosol evaporation and condensation.

CAS 2.3: Inhaled aerosols and health

The course will cover the physics, biology and behaviour of inhaled aerosols, either intentional for delivery of drugs or unintentional caused by atmospheric aerosols, e.g. air pollution particles. The approach is multidisciplinary and covers the consequences on human health, including scientific and clinical aspects, the physics of the flow of aerosols, including the fluid mechanics of the human airways, the relevant characteristics of the aerosols that determine the interaction and bioreactivity with the human airways. The characterisation of the aerosols, including sizing and physicochemical characteristics, is an important component in optimising, for example, drug delivery, or in predicting deposition of airborne aerosols. A mathematical description of the fluid mechanics and the particle motion will be delivered to ensure understanding of the approaches used for these detailed predictions as well as simplified evaluation of design parameters that determine particle deposition and delivery efficiency of drugs. The description of the characterisation methods of aerosols will include intrusive (probe based) and non-intrusive (optical) methods and provide the principle of operation, measurement accuracy and limitations.

CAS 2.4: Aerosol particle sources for materials synthesis

Aerosol synthesis of materials is a vibrant field of particle technology and chemical reaction engineering. The aim of this unit is to give students an understanding of, and to critically apprise the key concepts involved in the use and production of aerosolised materials, specifically aerosolised chemicals, and their application in the manufacture of high end ceramics, metal oxides, as well as other materials that impact transportation, construction, pharmaceuticals, energy and communications. Students will be exposed to state of the art literature and research underpinning fundamental concepts and physiochemical phenomena involved in generating aerosols (e.g. gas to particle conversions, spray processes, droplet generation and size distribution) and in the use of aerosols in the synthesis of materials (e.g. aerosol assisted chemical vapour deposition and flame aerosol synthesis) and fabrication of devices (e.g. aerosol jet printing). Topics such as the application of rapid expansion of supercritical solutions will also be explored in the context of current literature. Emphasis will also be placed on scale up of aerosol processing methods to larger levels of production manufacturing.

CAS 2.5: Analysis: Composition, phase and volatility

Aerosol analysis is central to identifying the mechanisms by which aerosols form and are transformed in various environments, including in ambient air and during nanomaterials synthesis. Chemical composition analysis provides information about the elements and molecules present in an aerosol sample, which may provide information about the sample's source and impacts with respect to health or, in the case of nanomaterials synthesis, purity. The phase of aerosol (e.g. solid, liquid, viscous/glassy) can crucially affect both composition and reactivity, for example by inhibiting diffusion of reactive molecules within the particle thereby limiting reactivity to only portions of the particle (e.g. on the surface). The volatility of organic molecules has a large impact on the fraction of molecules partitioned to the particle phase, and this partitioned fraction can change based on ambient conditions like particulate mass concentrations. A wide array of approaches have been developed to address all of these key properties of aerosols. We will explore these approaches, including conventional ones that involve collecting the aerosol onto filters for off-line sample analysis, as well as the diverse array of online approaches for aerosol analysis, including ones involving mass spectrometry, volatility and equilibrium partitioning, and phase state.

CAS 2.6: Introduction to biological aerosol

Bioaerosols, suspensions of airborne particles that contain or are derived from living organisms, are ubiquitous in the environment. They include viruses, bacteria, fungi, pollen, plant or animal debris, as well as fragments and products of these organisms. There are currently a wide variety of bioaerosol sampling methods available, but a major challenge in bioaerosol research is that no standard protocols have been established. Bioaerosols are an important transmission route for infectious and sensitization agents, inducing infectious and non-infectious diseases in both animals and humans. In this module we will discuss the pros- and cons- of the various sampling and analysis methods, explore bioaerosol sources in indoor and outdoor environments including considering their impact on cloud microphysics. The training will provide a detailed understanding of infection transmission and control in indoor environments including healthcare settings. We will also introduce the concept of the microbiome, exploring the influence aerosols have on our own microbiome and how this can further impact our health.

CAS 2.7: Heterogeneous chemical reactions

Aerosols provide a reactive surface area upon which heterogeneous reactions can occur which change gas-phase composition, enable the synthesis and manufacture of novel materials, and modify the properties of the aerosol itself, for example their toxicity and ability to scatter and absorb radiation. A famous example is the formation of the stratospheric ozone hole over Antarctica, which is the result of chemical reactions on the surface of polar stratospheric clouds that activate chlorine compounds. The rates at which these processes occur depend critically on the chemical nature of the adsorbed gaseous molecule, the aerosol size, its physical properties (solid or liquid, bulk viscosity, morphology) and its chemical composition (e.g. salt, dust, inorganic or organic). The fundamental principles of the physical and chemical processes which control the accommodation of reactive gases at aerosol surfaces and their subsequent fate (at the surface or within the bulk of the aerosol) will be discussed together with important applications of heterogeneous chemical processing. Experimental techniques to probe the details of heterogeneous chemical or photochemical reactions involving aerosols, for example to determine reactive uptake coefficients and reaction mechanisms, as well as the use of electronic structure calculations to complement understanding, will also be discussed.

CAS 2.8: Collective motion and transport of aerosols

We will start from the conservation equations for single particles, including, mass, momentum and energy for dilute, non-interacting single particles, balanced by a range of source terms including evaporation, condensation, coalescence and reaction. Additional (often coupled) terms appear in the momentum equation for the gas and condensed phase due to drag, gravitational and electrostatic forces. We will introduce pdf approaches for the population balance for the conservation equations, and transformation of the conservation equations into pdf equations. We will also discuss strategies for solution of population balance equations, implications for solutions for large numbers of particles, and the trade-offs between Lagrangian and population balance methods.

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