Radioactive Aerosols in Wall-Bounded Turbulent Flow

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What Are Radioactive Aerosols?

Sources of Radioactive Aerosols[1,2]

Laser Cutting & Ablation

Accidents & Incidents

Droplet Dispersion

Resuspension of Irradiated Material

Properties of Radioactive Aerosols[1-4]

- Aerosols Containing Material Undergoing Radioactive Decay
- Large Variations in Morphology
- Number Concentration May Exceed 10^7 particles cm^{-3}
- Radiogenic Self-Charging May Affect Electrophoresis
- Triboelectric Charging Affected By Radiogenic Self-Charging
- Size Range of <0.1 to >100 µm
- Mass Concentration Can Exceed 100 g/m³
- Composition Dependent Upon Origin
- Radiogenic Self-Heating May Affect Thermophoresis

Wall-Bounded Turbulent Flow[1-4]

Wall-bounded turbulent flow is characterised by **chaotic motion** and the formation of **eddies** of many different length scales, and depends upon the ratio of **inertial** to **viscous forces**. It may be found in:

Pipe Bends & Corners

Merging or Diverging Pipes

Narrowing or Expanding Pipes

Why Study Radioactive Aerosols?

'Evaluating the fate of these particles after their emission is one of the… key issues for these dismantling operations' [5]

Modelling is full of **assumptions** such as: spherical particles; absence of collision and coalescence mechanics; and the absence of electric fields. Consolidating, cataloguing, and combining data and techniques from various industries and disciplines may lead to a **new understanding** of the **microphysics** of radioactive aerosols in wall-bounded turbulent flow, as well as allow for **new large-scale correlations** to be discovered.

Fig. 1. The aerial view looking south of the Sellafield nuclear complex in Cumbria, UK[6].

Reducing the **inherent risks** of nuclear decommissioning activities by allowing safe exposure times, distances, and appropriate levels of shielding to be **predicted**.

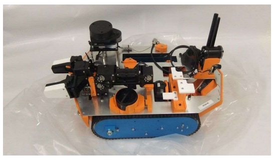

Fig. 2. In April 2022, the robot Lyra completed a survey of a 140m long radioactive ventilation duct below a disused laboratory at the Dounreay nuclear complex[7].

Assisting the use of **robotic** and **AI technologies** to solve challenges faced by the nuclear industry; for example, **identifying** radioactive **'hot spots'** where human access may be challenging.

How To Study Radioactive Aerosols?

Objectives

1. Create a **small-scale Lagrangian model** of the transport, deposition mechanics, and coupled physics of individual radioactive particles in wall-bounded turbulent flow.
2. Create a **large-scale Eulerian mode**l of the transport and deposition mechanics of a concentration of radioactive particles undergoing wall-bounded turbulent flow.
3. Apply **reduced order modelling** to the large-scale Eulerian model to decrease its computational cost.
4. Validate approaches used to **reduce computational cost** across the stages of the project as modelling takes place.

Methodology

Computational Fluid Dynamics[1]

Computational Fluid Dynamics (CFD) provides a **virtual laboratory** in which problems involving fluid flows (e.g. aerosols transported through air) are solved using **numerical analysis** and **data structures.**

Lagrangian Modelling[1]

In the Lagrangian approach, the equations of motion of each individual particle are solved by the addition of all of the forces acting upon the particle, according to Newton's 2nd Law, $\sum \boldsymbol{F} = m\frac{d\boldsymbol{u}}{dt}$.

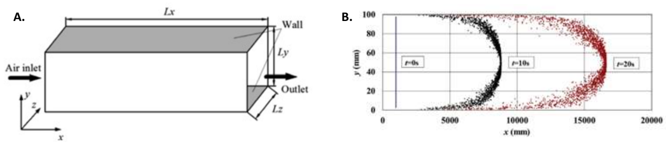

Fig.3. Adapted from Gu *et al*. A. An example of a computational domain used to model wall-bounded turbulent flow. B. The simulated distribution of particles in the x-y plane at t=0, 10, and 20s respectively[3].

Methodology (Cont.)

Eulerian Modelling[1]

In the Eulerian approach, the particulate mass conservation equation is solved, as opposed to solving equations of motion for individual particles. This can be expressed as the Aerosol General Dynamic Equation (ADGE).

The Aerosol General Dynamic Equation[1]

The aerosol general dynamic equation describes the conservation of particulate mass and is given by

$$I\left\{\begin{matrix}\text{Rate of}\\ \text{Change in } dV\end{matrix}\right\} = II\left\{\begin{matrix}\text{Transfer of}\\ n_i \text{ into } dV\end{matrix}\right\} + III\left\{\begin{matrix}\text{Rate of}\\ \text{Generation in } dV\end{matrix}\right\},$$

where n_i is the concentration of all aerosol particle *n* of species *i* in volume d*V*.

Reduced Order Modelling[8-12]

By reducing the degrees of freedom found within the original model, we can reduce the computational complexity of mathematical models. In this way, an approximation to the original ('full-order') model is created.

Numerous approaches have been used in other fields of study, such as in the modelling of coal and of haemodynamics, which could be adapted to this context, such as using look up tables to store key values, employing structured-tree models, and director theory.

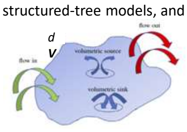

Fig.4. A schematic representation of a balance law in a volume dV [13].

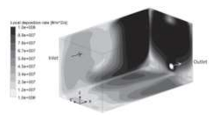

Fig.5. Adapted from Guichard and Belut. The computed local deposition rate of the CuO aerosol, given as an example of the desired use of CFD to identify the 'hot spots' of radioactive aerosol deposition[14].

How Will I Study Radioactive Aerosols?

Challenges

- The phenomena to be studied are of a **multi-scale** nature. The periods of time and dimensions of space to study within the remit of this project range from seconds to hours, and the size of models to be produced may vary from centimetres through metres to kilometres of pipe networks.
- Modelling the **wide range** of **morphologies** of radioactive aerosols and their **varying** size, volume, surface area, and mass **distributions** will prove challenging.
- Radioactive aerosols are often modelled as spheres of equivalent: surface area; volume; mass; or other parameters. Determining **which equivalent sphere** models have been **used** in comparing models to experimental evidence by whom, and **why**, will be a key outcome of the literature review.

Proposed Timeline of Research

Literature Review → Microscale Modelling → Macroscale Modelling → Reduced Order Modelling

Responsible Innovation

- The nuclear industry operates on long time scales; if the project is successful, the knowledge produced may be in use or development for decades.
- Unintended applications of radioactive aerosol modelling may be used to cause harm.
- Computational modelling of the cardiovascular system has been integrated into products for the clinical market. The feasibility and likelihood of this project leading to a commercial product or service is unknown at this stage of the project.

Desired Outcomes

Inform Pipe Network Design

Industrial-Academic Knowledge Transfer

Interdisciplinary Knowledge Transfer

1. P. Kulkarni, P.A.B., K. Willeke, *Aerosol Measurement: Principles, Techniques, and Applications*. 3 ed. 2011: John Wiley & Sons, Incorporated. 904.
2. Chamberlain, A., *Radioactive Aerosols*. Cambridge Series in Chemical Engineering. 1991, Cambridge: Cambridge University Press.
3. Gu W, H.J., Wang D, He Y, *The transport and decay of radioactive aerosols in a wall-bounded turbulent flow.* Annals of Nuclear Energy, 2019.
4. Vasilakos P, K.Y., Pierce JR, Yiacoumi S, Tsouris C, Nenes A, *Studying the impact of radioactive charging on the microphysical evolution and transport of radioactive aerosols with the TOMAS-RC v1 framework.* Journal of Environmental Radioactivity, 2018.
5. Thomas Gelain, D.R., Emmanuel Porcheron, Christophe Chagnot, , *CFD Simulations of Aerosol Dispersion and Agglomeration During the Laser Cutting of Fukushima Fuel Debris Simulants*, in *ICONE 26*. 2018: London.
6. Ledingham, S., *Aerial view Sellafield, Cumbria*. 2005: https://www.geograph.org.uk/photo/50827. p. 2005 aerial view looking south toward the Sellafield nuclear nuclear site, Cumbria. The large fell behind is Black Combe
7. Robotics, H. *Lyra: Best Invention of 2022*. 2023 [cited 2023 07/05/2023]; Available from: https://hotrobotics.co.uk/project/lyra-best-invention-of-2022/
8. Kim YH, Y.S., Nenes A, Tsouris C, *Incorporating radioactive decay into charging and coagulation of multicomponent radioactive aerosols*. Journal of Aerosol Science, 2017.
9. Johnson PL, *Predicting the impact of particle-particle collisions on turbophoresis with a reduced number of computational particles*. International Journal of Multiphase Flow, 2020.
10. Webster, M.J., *Application of Director Theory to Models of Flow in Straight and Curved Pipes*, in *Department of Mechanical Engineering*. 2021, The University of Bristol: Bristol Doctoral College.
11. Anders Brink, D.L., Mikko Hupa, Marta Escoto de Tejada, Manoj Paneru, Jörg Maier, Günter Scheffknecht, Alessandro Pranzitelli, Mohamed Pourkashanian,, *A temperature-history based model for the sticking probability of impacting pulverized coal ash particles,*. Fuel Processing Technology,, 2016. **141**: p. 210-215.
12. Duanmu, Z., et al., *A One-Dimensional Hemodynamic Model of the Coronary Arterial Tree.* Frontiers in Physiology, 2019. **10**.
13. R. Sacco, G.Guidoboni, A. G. Mauri, *Chapter 4 - Elements of Physics,*, in *A Comprehensive Physically Based Approach to Modeling in Bioengineering and Life Sciences,*, G.G. Riccardo Sacco, Aurelio Giancarlo Mauri, Editor. 2019, Academic Press.
14. R. Guichard, E.Belut, *Simulation of airborne nanoparticles transport, deposition and aggregation: Experimental validation of a CFD-QMOM approach.* Journal of Aerosol Science, 2017. **104**: p. 16-31