Title: HPC Application in Large Eddy Simulation of Fuel Spray / Air Jet interaction

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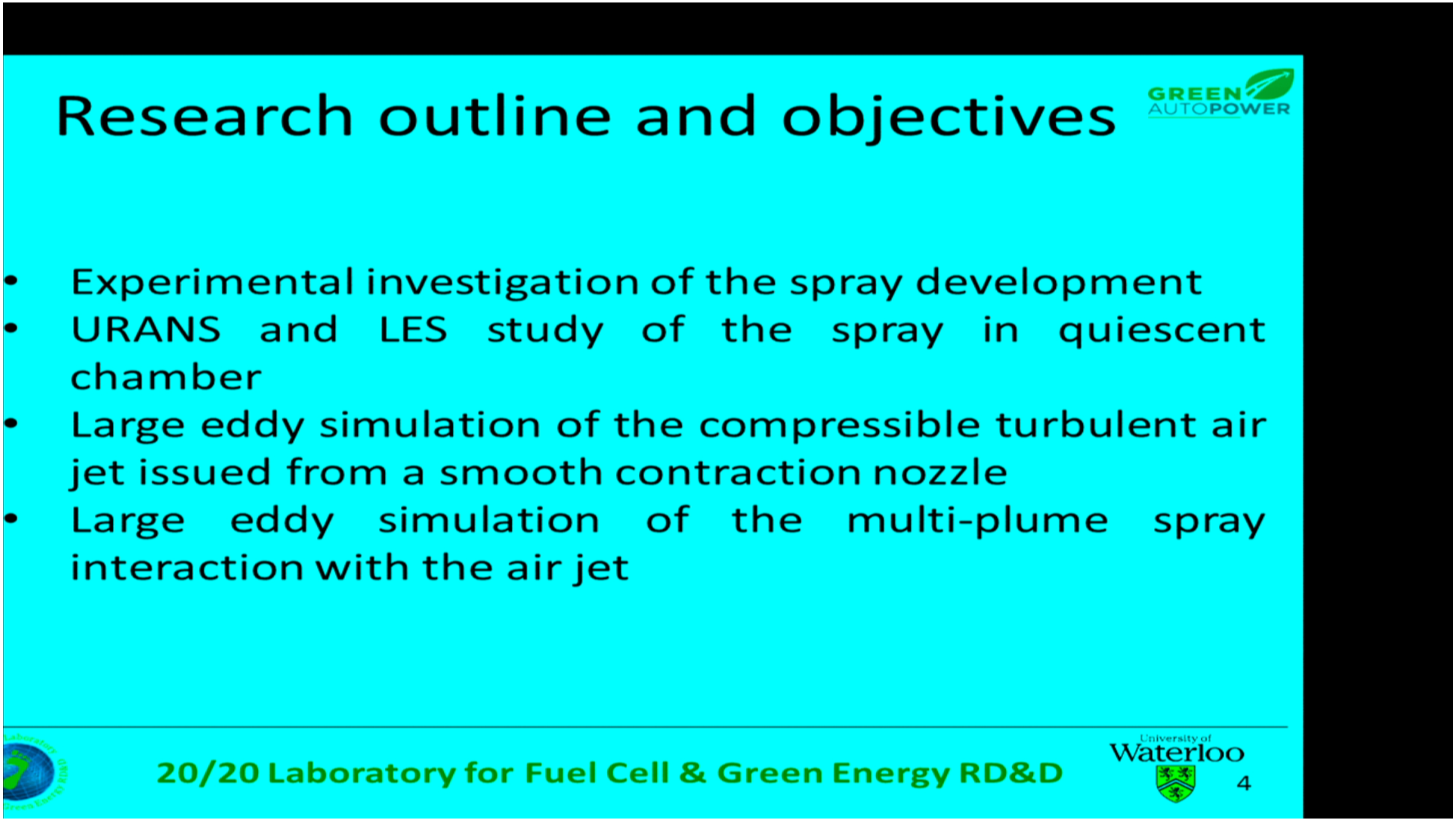
Abstract: Along with the development of computational resources computational fluid dynamics (CFD) has evolved in resolving the finest length scales and smallest time scales of the flow. Direct numerical simulation (DNS) resolves the finest flow scales known as Kolmogorov length scales which are responsible for the dissipation of the energy transferred from the large and intermediate length scales. However DNS simulations are computationally costly and demand very powerful resources which are not widely available to this day. Large eddy simulation (LES) is a more feasible tool to resolve the large flow scales and model the sub-grid scales using a Reynolds averaged modeling. High performance computing tools make it possible to perform high fidelity large eddy simulations which reasonably (almost twelve times the Kolmogorov length scale) resolve the flow structures.In the present study large eddy simulation is utilized to simulate interaction of a high speed compressible round air jet with a group of sprays injected from a six-hole nozzle injector into the shear layer of the air jet. Fuel sprays are injected with 10 and 15 MPa injection pressures in the jet cross flows of 125 and 215 m/s. Simulations are performed using 64 processors and 240 GB of memory. The focus of the study is on the spray atomization assisted by air jet cross-flow. Consequent processes of fuel/air mixing are also investigated by focusing on the role of vortical structures resolved using large eddy simulation.



Research outline and objectives

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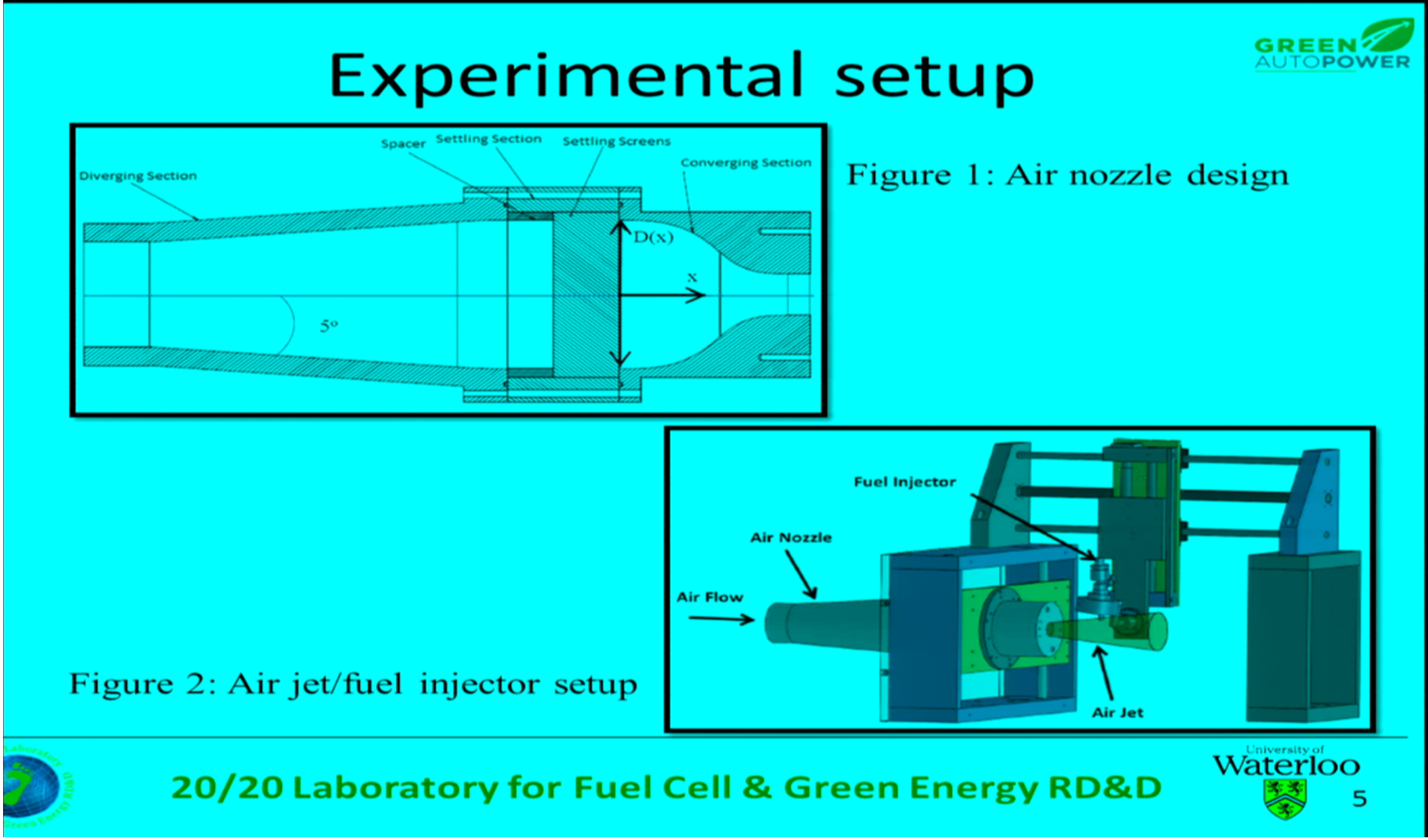
- Experimental investigation of the spray development
- URANS and LES study of the spray in quiescent chamber
- Large eddy simulation of the compressible turbulent air jet issued from a smooth contraction nozzle
- Large eddy simulation of the multi-plume spray interaction with the air jet



Experimental setup

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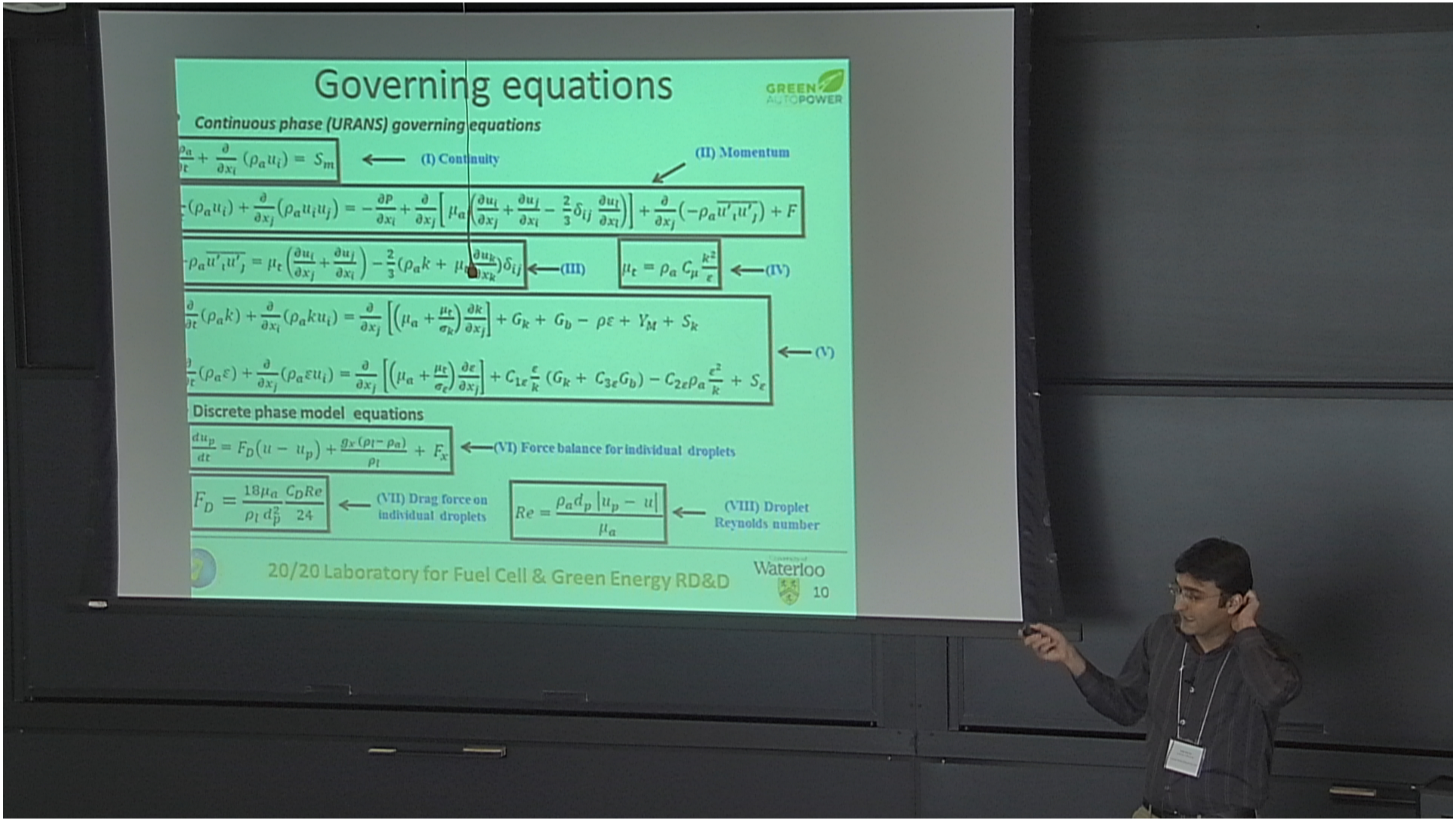
Figure 1: Air nozzle design

Figure 2: Air jet/fuel injector setup



Governing equations

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Continuous phase (URANS) governing equations

$$\boxed{\frac{\rho_a}{t} + \frac{\partial}{\partial x_i}(\rho_a u_i) = S_m} \longleftarrow \text{(I) Continuity}$$

(II) Momentum

$$\boxed{(\rho_a u_i) + \frac{\partial}{\partial x_j}(\rho_a u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_a\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho_a\overline{u'_i u'_j}\right) + F}$$

$$\boxed{\rho_a\overline{u'_i u'_j} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho_a k + \mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij}} \longleftarrow \text{(III)} \qquad \boxed{\mu_t = \rho_a C_\mu \frac{k^2}{\varepsilon}} \longleftarrow \text{(IV)}$$

$$\boxed{\begin{aligned} &\frac{\partial}{\partial t}(\rho_a k) + \frac{\partial}{\partial x_i}(\rho_a k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu_a + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon + Y_M + S_k \\ &(\rho_a\varepsilon) + \frac{\partial}{\partial x_j}(\rho_a\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu_a + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho_a\frac{\varepsilon^2}{k} + S_\varepsilon \end{aligned}} \longleftarrow \text{(V)}$$

Discrete phase model equations

$$\boxed{\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_l - \rho_a)}{\rho_l} + F_x} \longleftarrow \text{(VI) Force balance for individual droplets}$$

$$\boxed{F_D = \frac{18\mu_a}{\rho_l d_p^2}\frac{C_D Re}{24}} \longleftarrow \text{(VII) Drag force on individual droplets} \qquad \boxed{Re = \frac{\rho_a d_p |u_p - u|}{\mu_a}} \longleftarrow \text{(VIII) Droplet Reynolds number}$$

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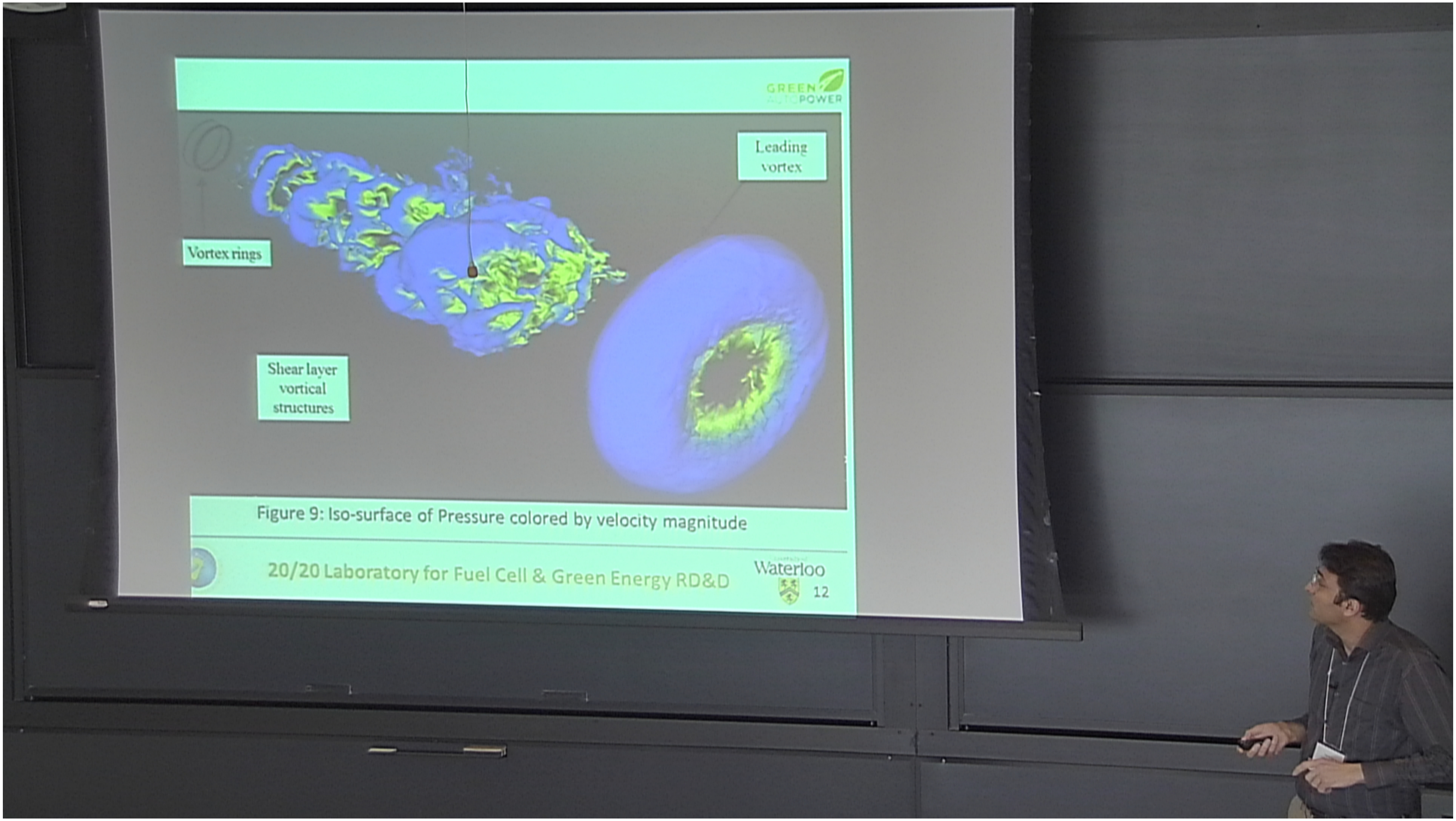

Leading vortex

Vortex rings

Shear layer vortical structures

Figure 9: Iso-surface of Pressure colored by velocity magnitude

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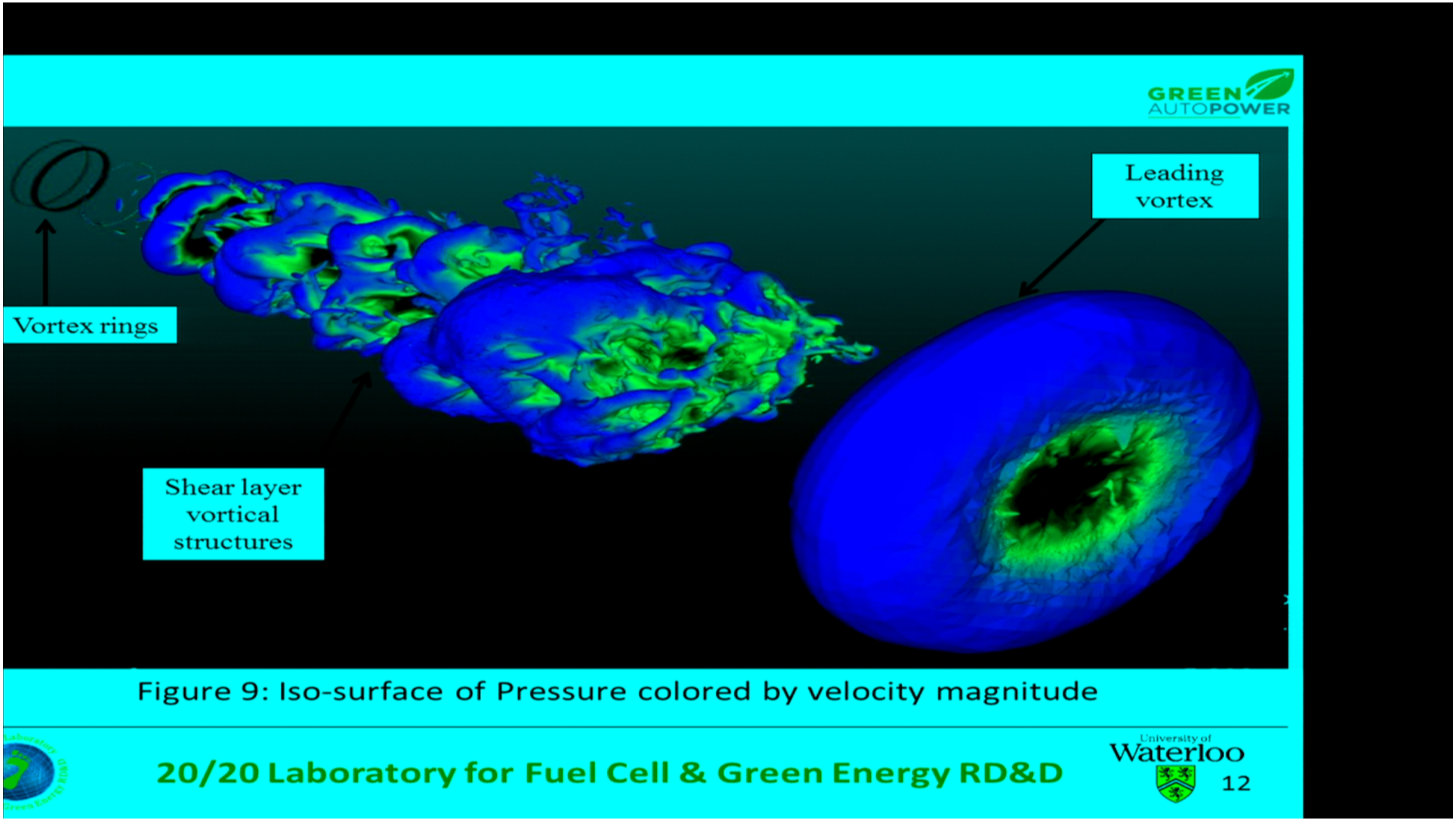

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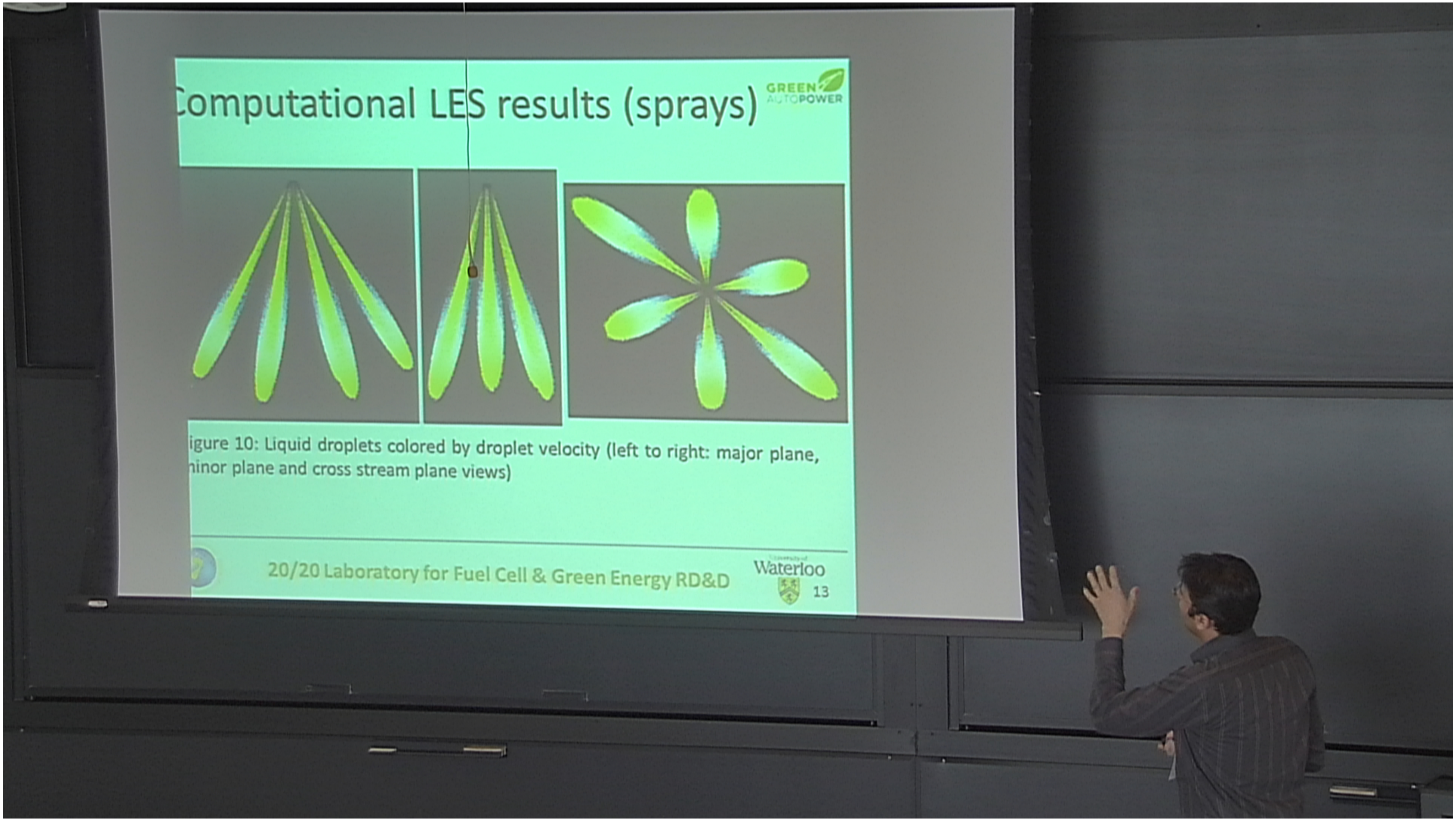

Computational LES results (sprays)

igure 10: Liquid droplets colored by droplet velocity (left to right: major plane, minor plane and cross stream plane views)

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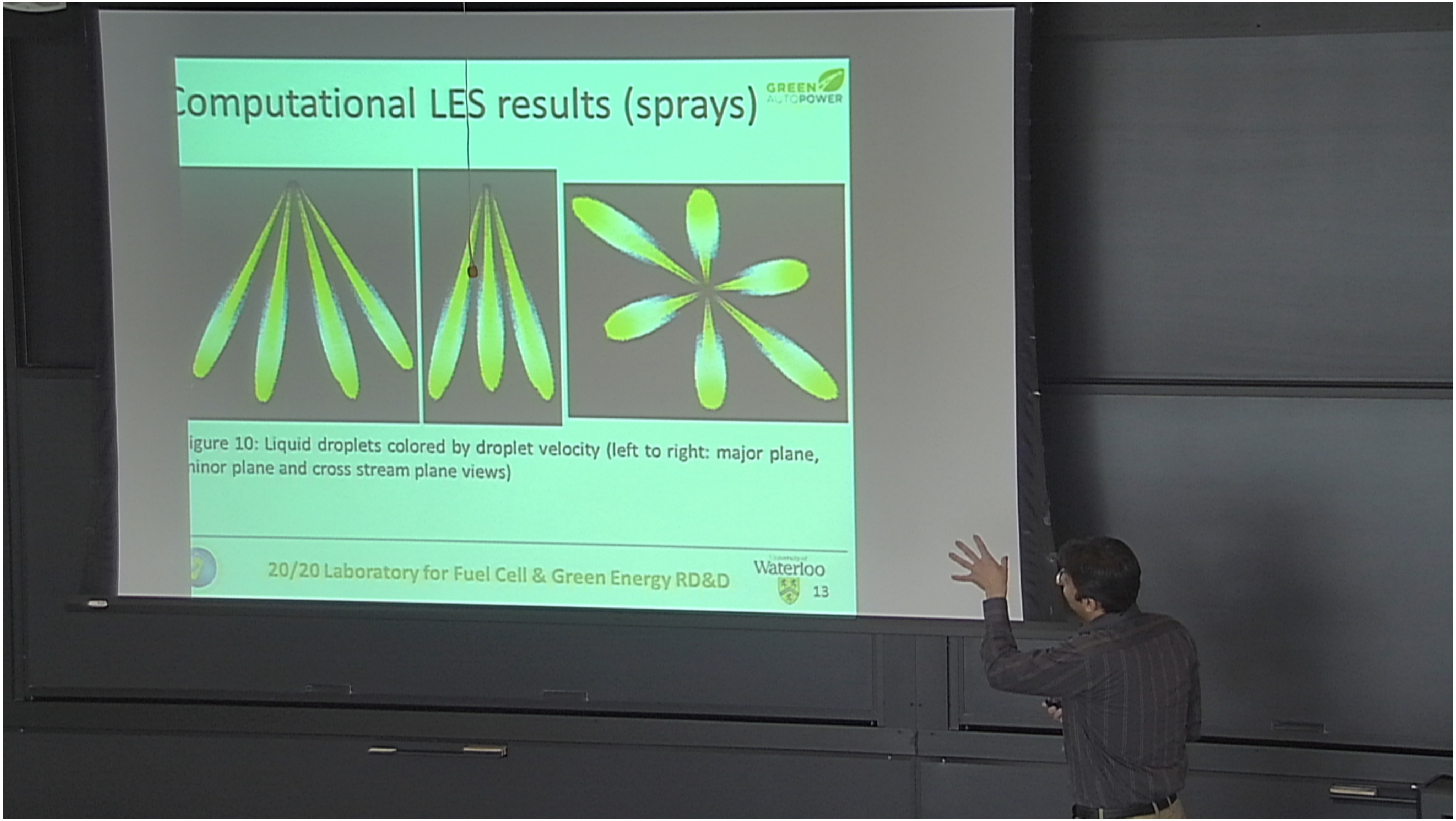

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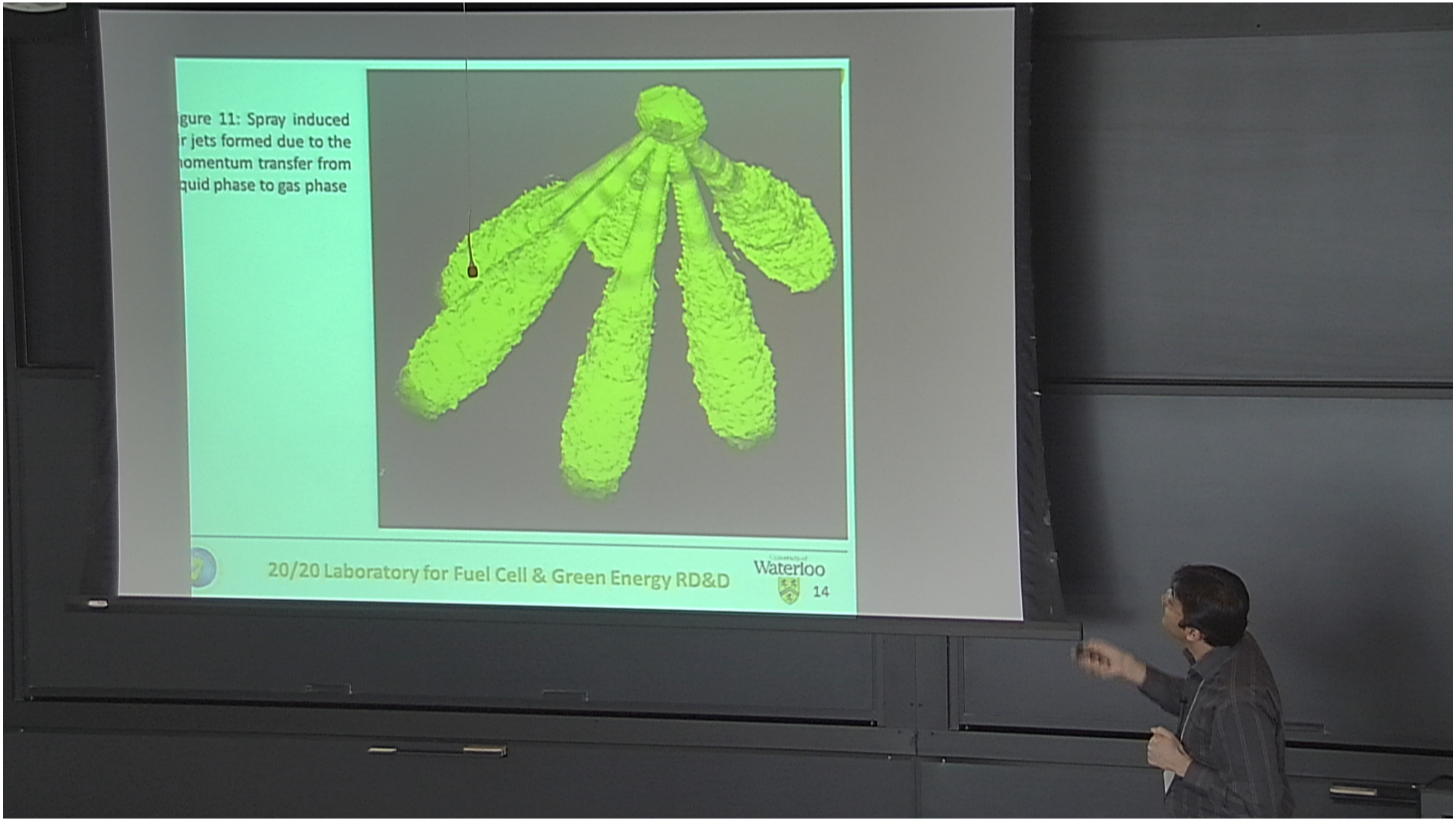

gure 11: Spray induced
r jets formed due to the
nomentum transfer from
quid phase to gas phase

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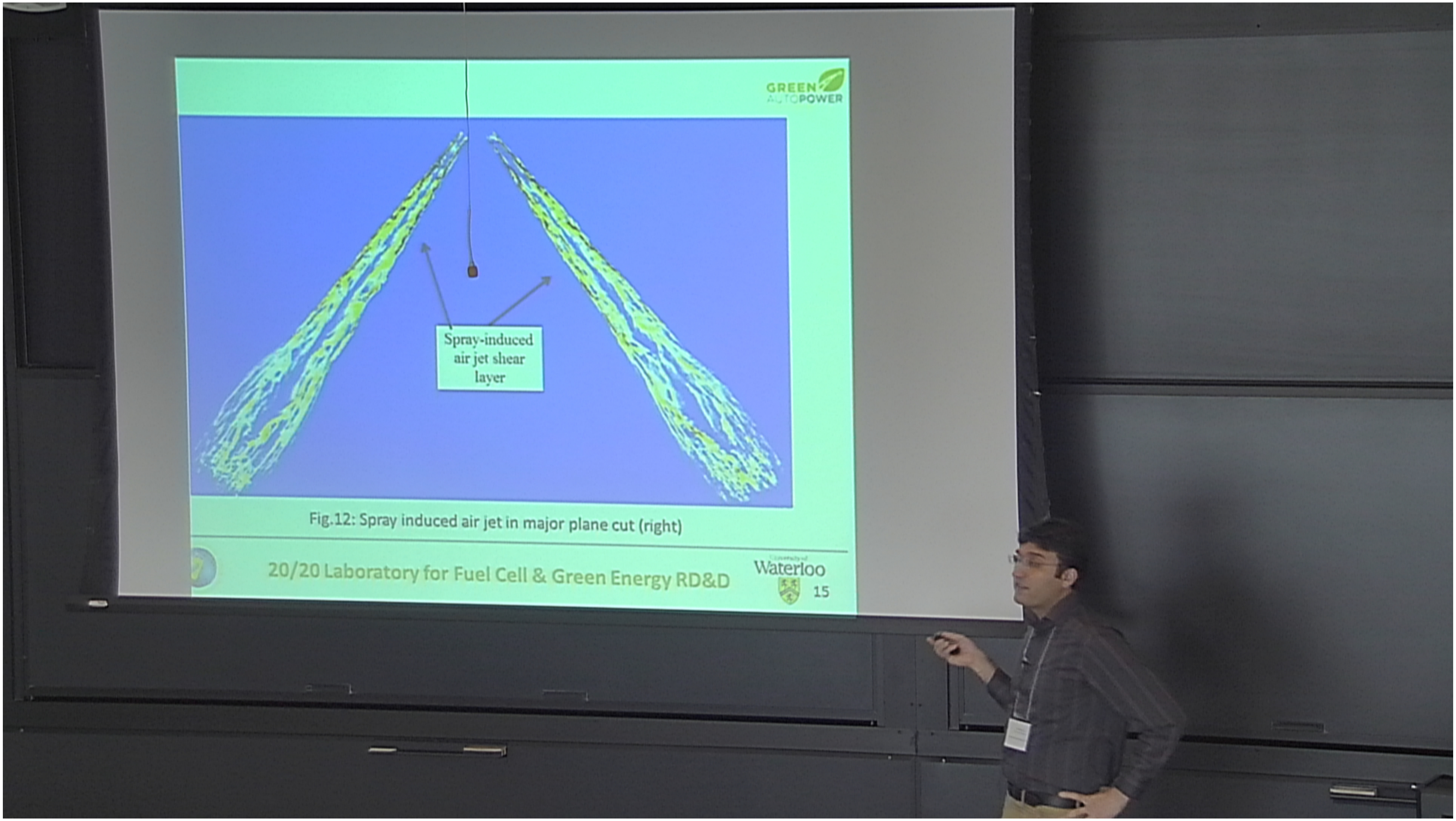

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Fig.12: Spray induced air jet in major plane cut (right)

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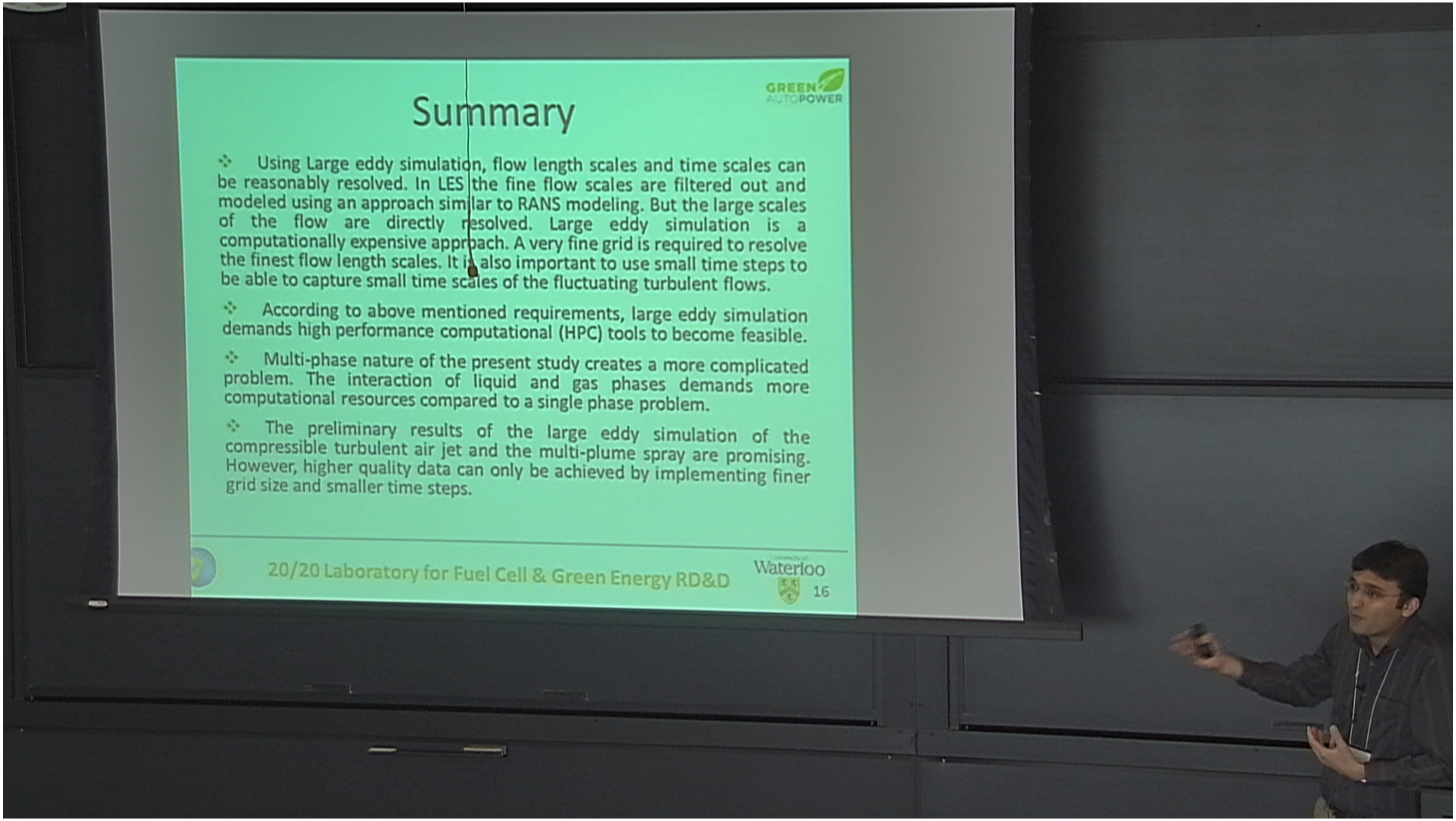

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Summary

- Using Large eddy simulation, flow length scales and time scales can be reasonably resolved. In LES the fine flow scales are filtered out and modeled using an approach similar to RANS modeling. But the large scales of the flow are directly resolved. Large eddy simulation is a computationally expensive approach. A very fine grid is required to resolve the finest flow length scales. It is also important to use small time steps to be able to capture small time scales of the fluctuating turbulent flows.
- According to above mentioned requirements, large eddy simulation demands high performance computational (HPC) tools to become feasible.
- Multi-phase nature of the present study creates a more complicated problem. The interaction of liquid and gas phases demands more computational resources compared to a single phase problem.
- The preliminary results of the large eddy simulation of the compressible turbulent air jet and the multi-plume spray are promising. However, higher quality data can only be achieved by implementing finer grid size and smaller time steps.

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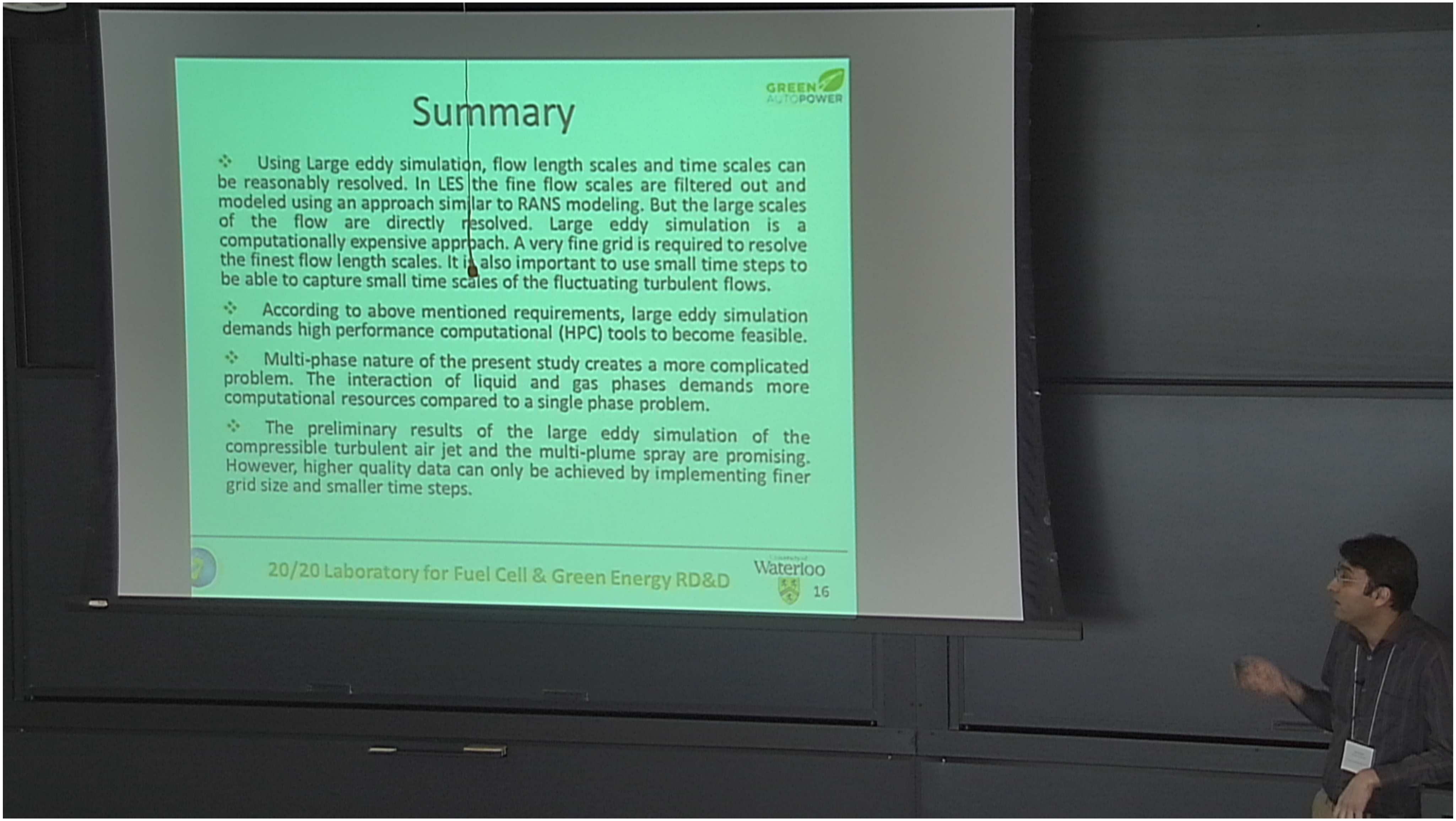

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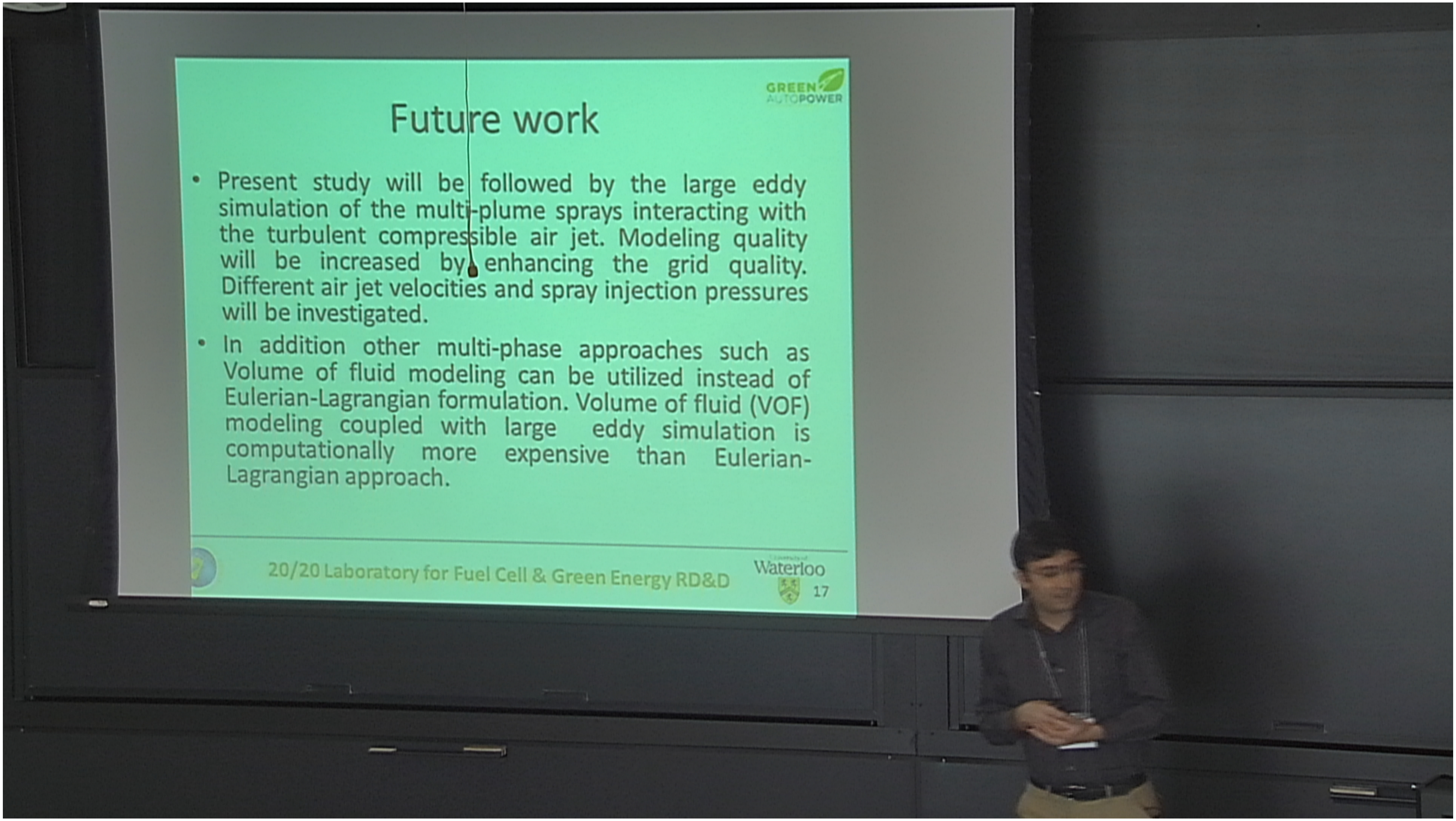

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Future work

- Present study will be followed by the large eddy simulation of the multi-plume sprays interacting with the turbulent compressible air jet. Modeling quality will be increased by enhancing the grid quality. Different air jet velocities and spray injection pressures will be investigated.
- In addition other multi-phase approaches such as Volume of fluid modeling can be utilized instead of Eulerian-Lagrangian formulation. Volume of fluid (VOF) modeling coupled with large eddy simulation is computationally more expensive than Eulerian-Lagrangian approach.

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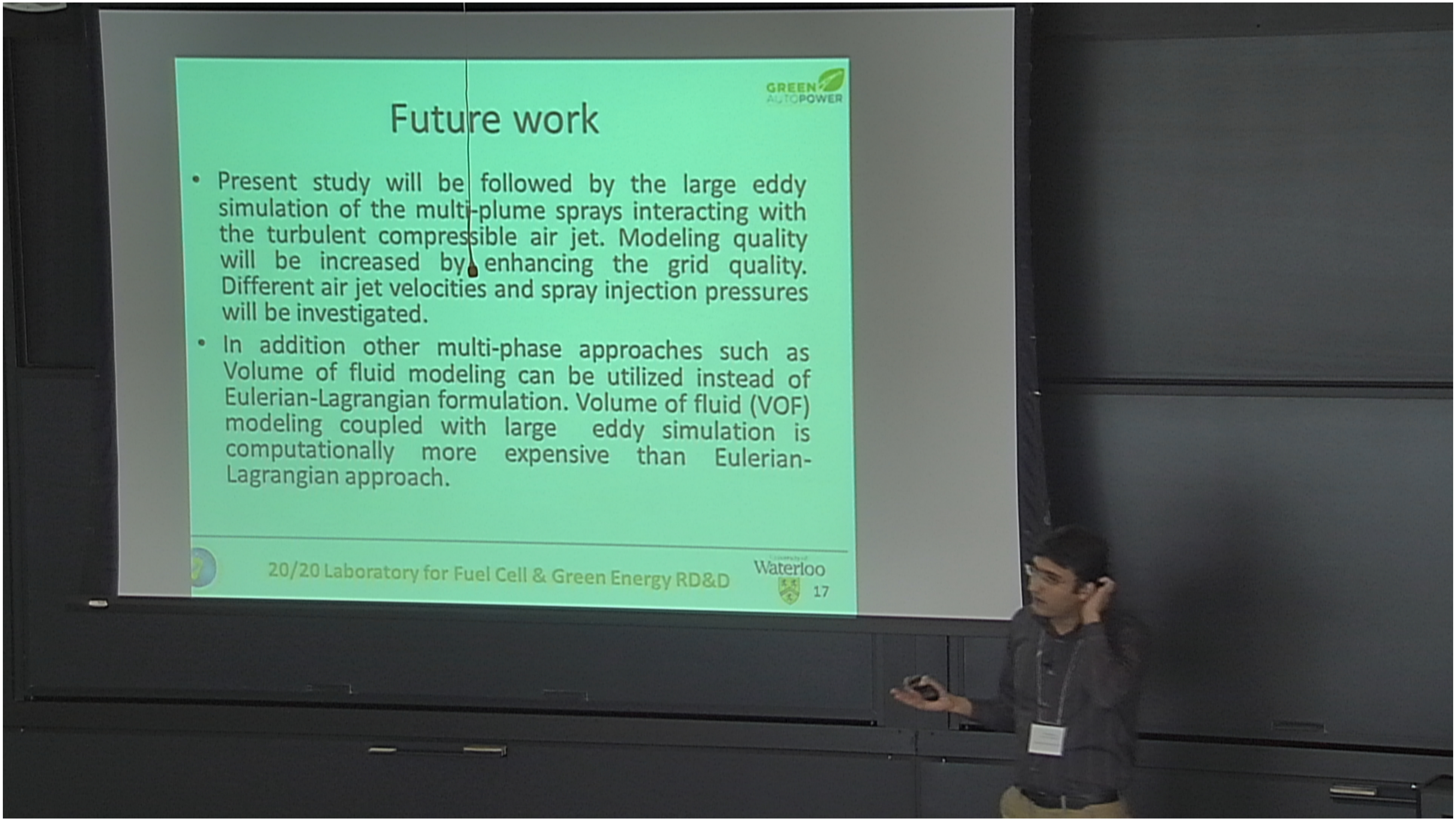

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