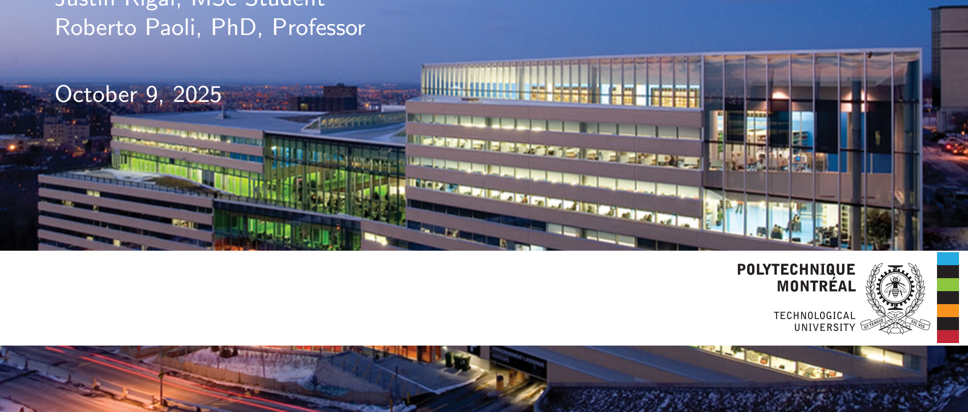
ChapelCon '25: Recent Developments in the CHApel MultiPhysics Simulation Software (CHAMPS)

Anthony Chrun, MSc Student
Baptiste Arnould, PhD Student
Karim Mohamad Zayni, PhD Student
Guillaume Auger, MSc Student
Maxime Blanchet, PhD Student
Éric Laurendeau, PhD, Professor
Justin Rigal, MSc Student
Roberto Paoli, PhD, Professor

October 9, 2025



POLYTECHNIQUE MONTRÉAL
TECHNOLOGICAL UNIVERSITY

Table of Contents

Aircraft Emissions : aiming for net zero carbon

Multiple Levers of Improvement

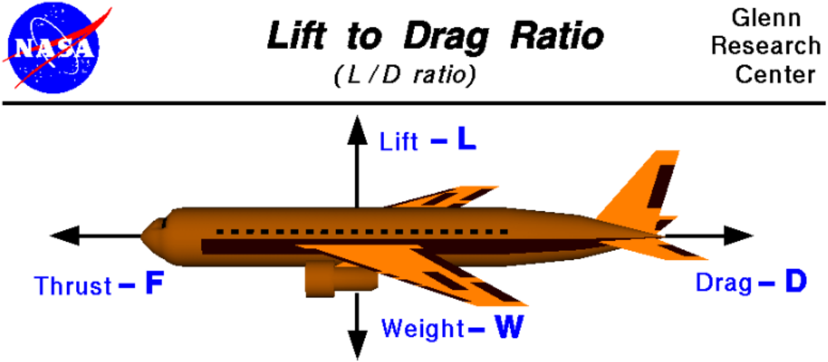
- Sustainable Aviation Fuel (SAFs)
- Operational Improvements (Air traffic and flight planning optimization)
- Novel aircraft & propulsion technologies (Engines, Aerodynamics)

Jet fuel mixed with SAF

Blended wing body concept

Source: Airbus

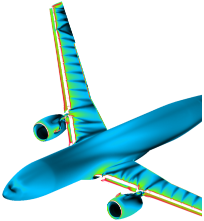
The key role of Aerodynamics



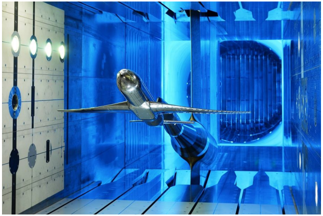
$$Range = \left(\frac{airspeed}{fuel_{consumption}}\right) * \left(\frac{lift}{drag}\right) * \ln\left(\frac{initial_{weight}}{final_{weight}}\right)$$

Lift to Drag ratio (Source : NASA)

Available tools in Aerodynamics



Computational Fluid Dynamics (CFD)
Cost $\sim$ 100 - 1000\$/hour (*Source: CHAMPS*)



Wind tunnel testing
Cost $\sim$ 1000 - 10000\$/hour (*Source: ETW*)

CRJ7000 Flight Test
Cost $\sim$ 100 000\$/hour (*Source: Bombardier*)

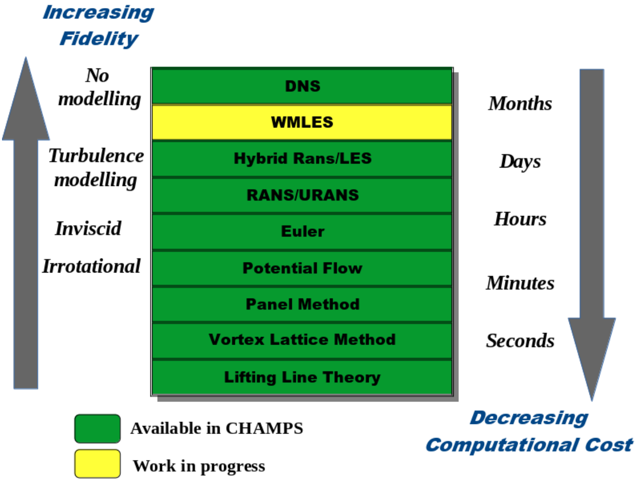
Aerodynamics: A Multidisciplinary Challenge

Ice accretion on the wing leading edge
(*Source: Flight Safety Foundation*)

Wing bending
(*Source: Aviation Stack Exchange*)

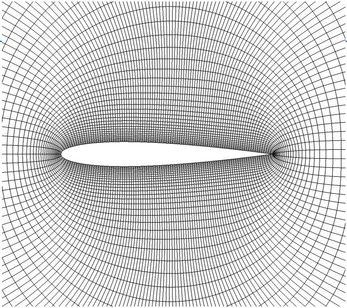
Contrail formation
(*Source: Spartan College*)

The Fidelity Spectrum in CFD



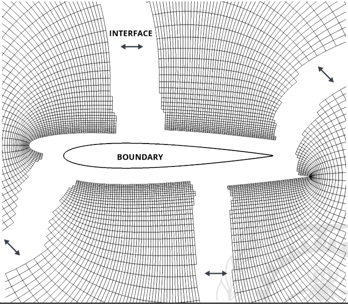
Classification of turbulence models

Parallel CFD for HPC



Solving Strategy

- **Volumetric Meshing** around complex geometries
- **2D Meshes**: Ranging from 0.5 to 1.0 Million Unknowns
- **3D Meshes**: Handling up to 1 Billion Unknowns
- **High-Performance Computing (HPC)**: Leveraged to significantly reduce computation time
- **Problem Decomposition**: The problem is partitioned into smaller sub-problems interconnected via interfaces
- **Task Parallelization**: Each sub-problem runs independently on dedicated tasks
- **Communication Optimization**: Minimizing communication overhead to maximize overall efficiency



CHAMPS: Advanced 2D-3D CFD Solver

CHAMPS (CHapel MultiPhysics Software)

- 2D-3D Unstructured Reynolds Average Navier Stokes Solver
- Second order finite volume
- Convective Fluxes : Roe, AUSM
- SA, k-ω SST-V and Langtry-Menter transitional turbulence models
- Explicit solver (Runge-Kutta) and implicit solvers (SGS, GMRES)
- Linked to external libraries: MKL, CGNS, METIS and PETSC
- Multi-Fidelity Solvers: Potential, Non Linear Vortex Lattice, Euler, RANS, URANS, LES, DNS
- Multi-Physics: Icing (Deterministic, Stochastic), Fluid-Structure Interactions, Contrails

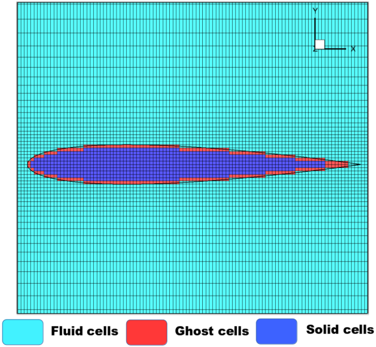
CHAMPS Software : 150,000 lines of code !

- Pre-Processor $\approx$ 17K lines
- Post Processor $\approx$ 2K lines
- Flow Solver $\approx$ 15K lines
- Turbulence Solver $\approx$ 13K lines
- Droplet Solver (Eulerian + Lagrangian) $\approx$ 24K lines
- Fluid-Structure Interaction Solver (Coupling + FEM) $\approx$ 15K lines

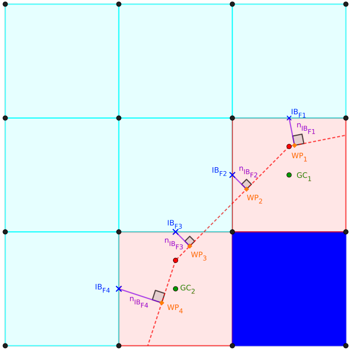
Medium Fidelity

Full Potential
via Immersed Boundary (IBM)

Full Potential via Immersed Boundary



Coarse Cell Classification w/ Cartesian Mesh

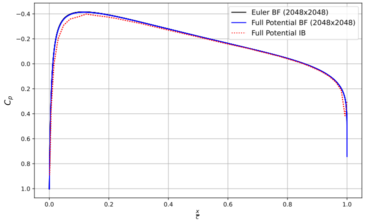


Wall Point identification procedure

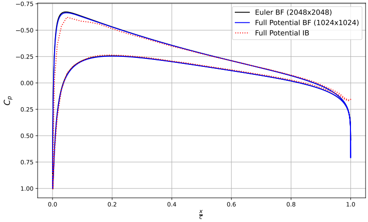
Full Potential flow via Immersed Boundary

- Using a cartesian mesh instead of a body-fitted mesh significantly expands the solver's practicality by significantly reducing meshing time and simplifying geometry handling, benefits that are particularly valuable in preliminary design phases.
- Its applicability is also enhanced as it facilitates multi-disciplinary simulations involving moving boundaries, such as icing and aeroelasticity.

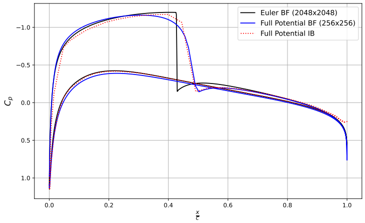
Full Potential via Immersed Boundary



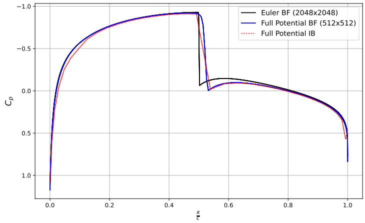
Mach = 0.1, AOA = 0.0°



Mach = 0.1, AOA = 1.5°



Mach = 0.8, AOA = 0.0°



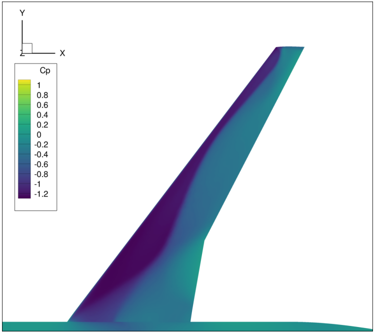
Mach = 0.75, AOA = 1.5°

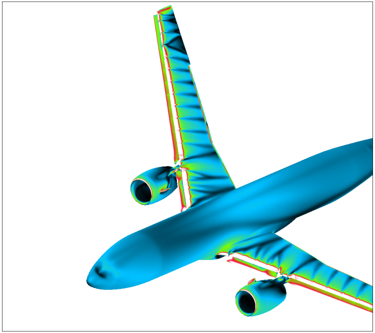
Body-fitted Euler vs body-fitted and IBM Full Potential pressure coefficient distributions for NACA0012 airfoil

High-Fidelity models

RANS, LES, DNS [1]

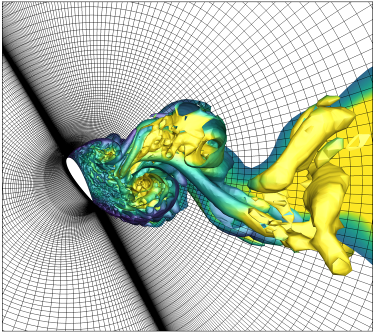
Reynolds-Averaged Navier Stokes (RANS)

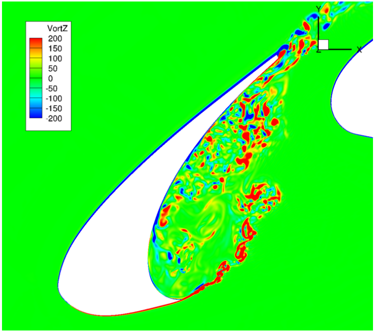




Left: Surface pressure coefficient for the Common Research Model in transonic regime.
Right: Skin friction coefficient of the Common Research Model in High-Lift conditions.

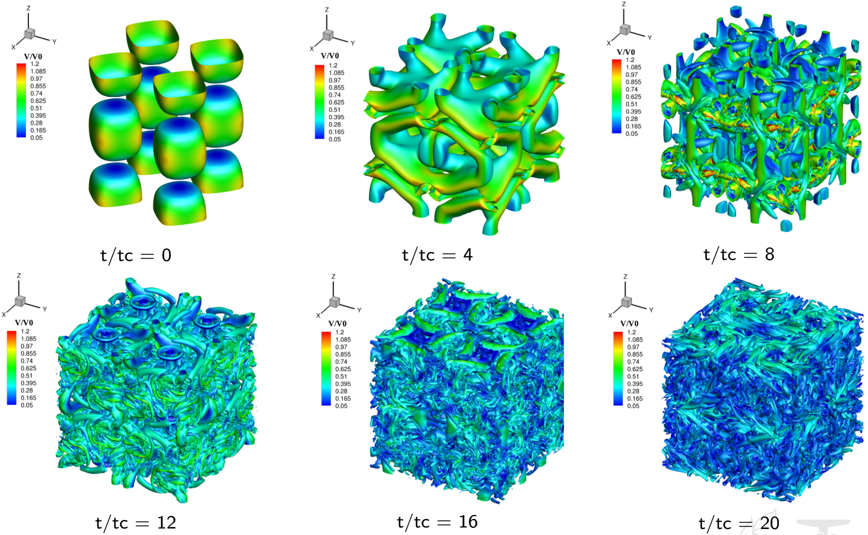
Hybrid RANS/LES





Isosurfaces of the Q-criterion identifying vortex regions.
Left: NACA0021 at 60° aoa.
Right: slat cove of a 30P30N airfoil;

Direct Numerical Simulation

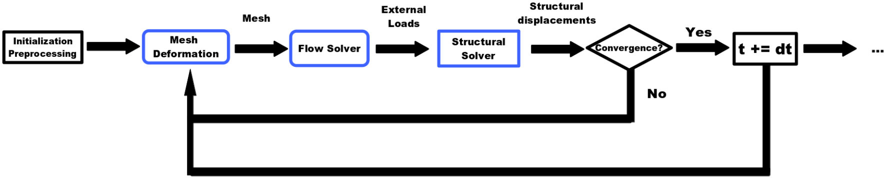


Isosurfaces of the Q-criterion identifying vortex regions, colored by the non-dimensional velocity magnitude
Direct numerical simulation model

Strongly Coupled Fluid-Structure Interaction

Nonlinear large displacements
Fluid-Structure Interaction

Strongly Coupled Fluid-Structure Interaction (FSI)

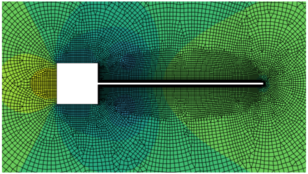


Partitioned Strongly Coupled FSI algorithm

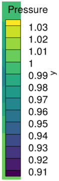
Large displacements FEM for Fluid-Structure Interaction simulations

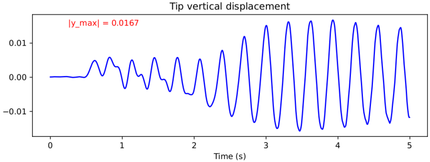
- FEM solver: Geometrically and materially nonlinear FEM, Generalized-α time integration.
- Element types: Euler-Bernoulli beam & Kirchhoff-Love plate models.
- CFD solver : Unsteady RANS/Euler .
- Displacement and load transfers using Radial Basis Functions.
- Iterative coupling between CFD and FEM solvers.

Large displacement FSI



t = 0, with undeformed mesh





Tip Y displacement

t = T/4

t = 3T/4

Box cantilever FSI validation case

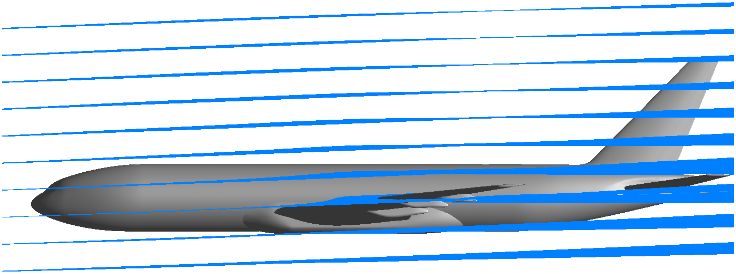
Non linear large displacements Fluid-Structure Interaction simulations

- Geometrically and materially nonlinear FEM, Euler-Bernoulli model, Generalized-α time integration.
- URANS.
- Displacement and load transfer using Radial Basis Functions.
- Strong coupling, convergence tolerance at 1/1000th of beam thickness.

Aero-Icing

Lagrangian Particle Tracker [2]

Lagrangian Particle Tracker

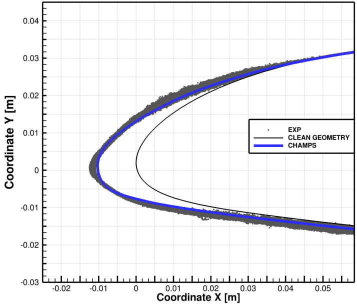


Droplet Trajectories around an Aircraft.

Particle Tracking For Ice Accretion

- Ray-tracing algorithms for efficient droplet–quad intersection detection
- Hybrid parallelization (MPI/OpenMP-like) in Chapel to accelerate trajectory computations
- Scalable framework capable of tracking 50M+ simultaneously
- Tracking individual droplets provides accurate estimates of water collection efficiency
- The computed water collection efficiency serves as input to the ice accretion simulation

Lagrangian Particle Tracker

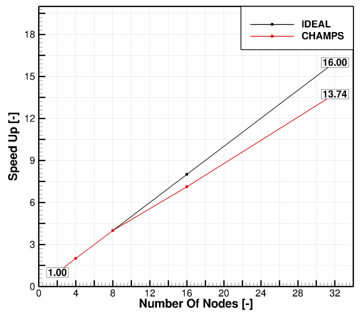


Ice Shape Comparison CHAMPS vs. Experimental Data.

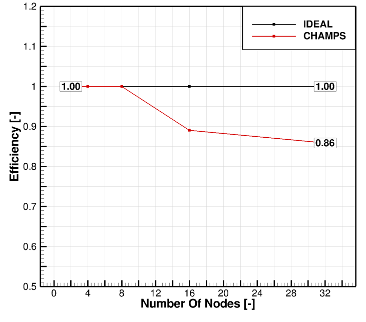
Particle Tracking For Ice Accretion

- Ray-tracing algorithms for efficient droplet–quad intersection detection
- Hybrid parallelization (MPI/OpenMP-like) in Chapel to accelerate trajectory computations
- Scalable framework capable of tracking 50M+ simultaneously
- Tracking individual droplets provides accurate estimates of water collection efficiency
- The computed water collection efficiency serves as input to the ice accretion simulation

Lagrangian Particle Tracker



(a) : Solver Speed Up.



(b) : Solver Efficiency

Lagrangian Solver Scalability

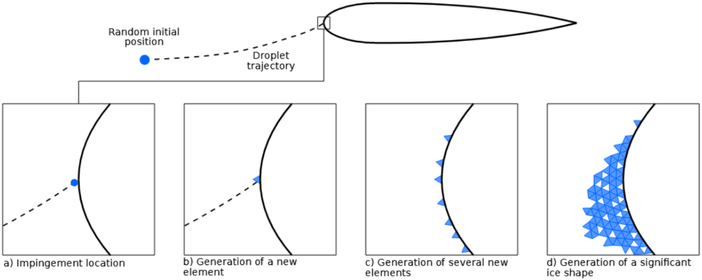
Particle Tracking For Ice Accretion

- Benchmark was run on the Niagara cluster (Intel Skylake 2.4 GHz, 40 cores/node) with up to 32 nodes (1280 cores), seeding 12.8M droplets for optimal load balancing.
- The benchmark used total computation time (including droplet tracking and collection efficiency) instead of iteration time as the key performance indicator.
- The solver achieved 86% efficiency at 32 nodes (1280 cores), showing strong scalability across the tested range.

Aero-Icing

Stochastic Icing
via Immersed Boundary [3]

Stochastic Icing via Immersed Boundary

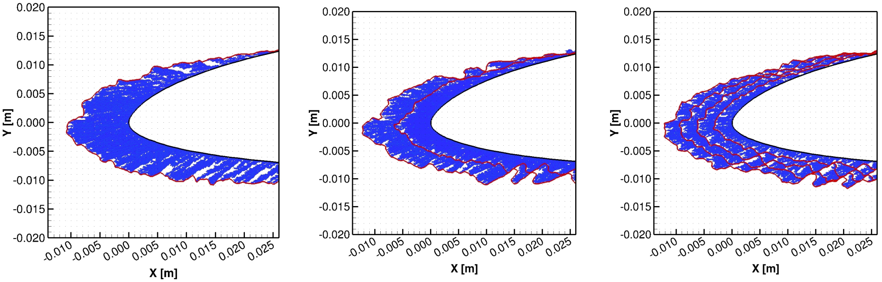


Stochastic ice accretion model using an unstructured advancing front technique

Front generation technique

- Accumulation of discrete elements with stochasticity in the accretion process.
- Droplets are emitted randomly from an initial emission plane.
- Upon impact, if the droplet freezes, a new element is generated; otherwise, the remaining mass flows downstream.
- These steps are repeated until a predefined criterion is reached (ice mass) [4].

Stochastic Icing via Immersed Boundary



1 layer 2 layers 4 layers

Comparison of ice shapes for different numbers of layers for the RG-15 UAV airfoil (laminar flow)

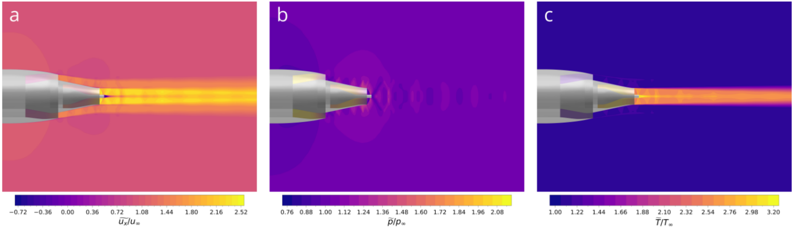
Multilayer stochastic icing for a laminar flow

- The ice feathers are well reproduced by the stochastic model.
- Highlights the importance of a fine mesh to capture small-scale structures.

Contrail Formation

Contrail Formation [5]

Contrail Formation - Airflow results

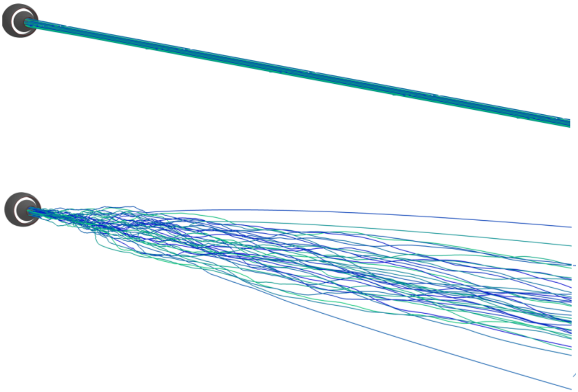


Mean flow contours of a) axial velocity, b) pressure, c) temperature

Flow solver conditions

- RANS solver.
- Real aircraft geometry of CFM56-5B3 (Safran).
- Freestream operating conditions at 35000 ft.

Contrail Formation - Stochastic Trajectories

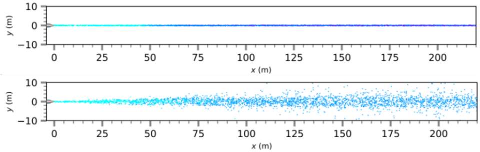


Mean flow streamtraces vs stochastic velocity trajectories

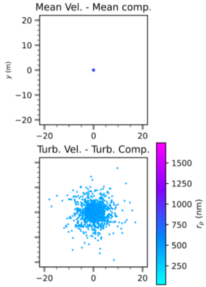
Flow solver conditions

- Stochastic model qualitatively produces expected dispersion and turbulent vortices.

Contrail Formation - Particle Distribution



Downstream distribution, colored by crystal radius



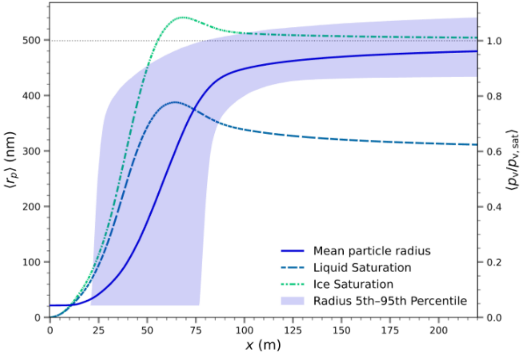
Cross-sectional distribution at x=220m

Particle spatial distribution : mean velocity & composition vs Langevin velocity & IEM temperature

Particle Distribution

- Langevin model effectively disperse particles.
- Mean composition exhibit a larger, less uniform, radii distribution.

Contrail Formation - Average evolution



Contrail downstream evolution, mean radius, saturation ratios

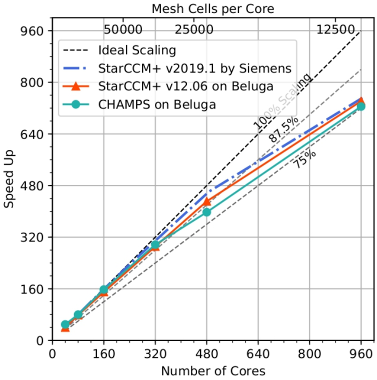
Flow solver conditions

- 5s with 25000 particles in domain was computed allowing mean fields convergence
- Average crystal radius increases smoothly towards a steady value.
- Particles activate between 25m and 75m (from soot to ice crystals).
- Particle activation is spread out.

CHAMPS Parallelization Performance

CHAMPS Parallelization Performance

CHAMPS Parallelization Performance

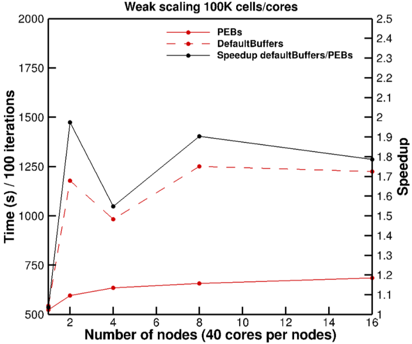


Parallel Scaling Efficiency of CHAMPS

Scaling test

- Civil airlines model: Speedup results are scaled from a 2-node baseline to highlight communication effects and are compared to the results obtained with the StarCCM+ software using the same mesh.
- Tests with and without reduction operations reveal CHAMPS' super scalability in the absence of reductions, indicating potential performance gains when I/O operations are performed "on-the-fly".

CHAMPS Parallelization Performance



Speedup with & without using Paired Exchange Buffers

Scaling Test

- Test done on 100 iterations of a 100k cell/core mesh.
- Shows optimizing inter-node communication is crucial for speedup: PEBs alone slash compute time by half.

Conclusion

Chapel Programming Language: Strong points & Things to work on

- Low barrier to entry, easy to learn for students.
- Easily transferrable to industry via staff rotations or interns.
- Easy to implement and parallelize.

- Compilation time can be reduced ($\approx$ 2-3 minutes).
- Scalability can still be improved.

Acknowledgments

Thank You

We would like to thank Engin Kayraklioglu, Jade Abraham, and Brad Chamberlain for their continuous support, insightful discussions, and encouragement throughout this work.

Questions

Thanks for listening !

Any questions?

References I

[1] Baptiste Arnould and Éric Laurendeau.
CHAMPS' fixed grid RANS simulations at fifth high lift prediction workshop.
In *AIAA Scitech 2025 Forum*, Orlando, FL, USA, January 2025. American Institute of Aeronautics and Astronautics.

[2] Mohamad Karim Zayni, Maxime Blanchet, and Éric Laurendeau.
Lagrangian particle tracking for ice accretion applications.
In *Proceedings of the 2024 AIAA Aviation Forum and ASCEND*, page —, Las Vegas, NV, USA, jul 2024.

[3] Maxime Blanchet, Mohamad Karim Zayni, Yannick Hoarau, and Éric Laurendeau.
Tridimensional multi-layer stochastic icing model utilizing a viscous immersed boundary method.
In *Proceedings of the 12th International Conference on Multiphase Flow (ICMF 2025)*, page Paper 360, Toulouse, France, May 2025. ICMF, International Conference on Multiphase Flow.

References II

[4] Hélène Papillon Laroche, Emmanuel Radenac, and Eric Laurendeau.
Stochastic ice accretion model using an unstructured advancing front technique.
Solar Energy, 268:70–85, 2023.

[5] Justin Rigal and Roberto Paoli.
Development of a RANS–stochastic model for contrail formation in jet engine plumes.
In *Proceedings of the 12th International Conference on Multiphase Flow (ICMF 2025)*, page Paper 430, Toulouse, France, May 2025. ICMF, International Conference on Multiphase Flow.