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iceAccretionFoam: Rime and Glaze Ice Accretion

SAE AC-9C Oct 2025 @ CIRA
Capua – Italy

Dr. G. A. Lima da Silva

All skills in a single company

- Engineering Solutions
- Simulation, Test & Certification

18 years of experience applying engineering and CFD in the industry

Associate Engineer throughout the development process

Multi-disciplinary team

Fidelity and long-term partnership

Experience-ready for complex projects

ATS Expertise Areas for Aerospace

Ice Protection

- System Performance
- Ice Accretion and Shapes
- Performance Degradation
- Escaping conditions
- Atmospheric Studies
- Air Data Probes Ice Protection
- Engine Ice Ingestion

Environmental Control Systems ECS

- Air Condition Distribution and Control
- Thermal Comfort
- Avionics Cooling and Dedicated Systems
- Pneumatic System and Ducting
- Smoke Evacuation, Prevention, and Detection
- Oxygen Systems and Pressurization
- Battery Thermal Management System

System Engineering

- System and component failure Analysis
- Design and Development
- Certification Requirements
- Operational Difficulties
- Tests
- Reports at Certification Level

Stress Analysis

- Conceptual design
- ASME, ASTM and ABNT Standards
- Analysis of Reactions and Displacements Thermal
- Expansion
- Hyper elasticity. Fluids and Nonlinearity
- Vibrations

Clients

EMBRAER
VERTICAL
Joby
ARCHER
akaer
TURKISH AEROSPACE
SAFRAN
NewAvionics ICE ✱ DETECTORS
ZODIAC AEROSPACE
Collins Aerospace
AVIBRAS
ITT
MARINHA DO BRASIL
MEGGiTT
enviro A ZODIAC AEROSPACE COMPANY
DROPLET MEASUREMENT TECHNOLOGIES

iceAccretionFoam Project

It is a collaboration between ATS-Aerothermal solutions and Dr. Jasak, original foam developer, Cambridge Univ.

Work Sharing

- **Dr. Jasak:** Initial Code Skeleton, Main Existent foam-ext Core, Solving Issues
- **Dr. Lima da Silva:** Physics, Equations implementation, Coding, Literature Research, Supervising
- **Teixeira da Silva:** Coding to Extend and Improve foam-ext Functions and implement key parts of the iceAccretionFoam, Interface Cambridge-ATS
- **Carvalho:** Support Coding and Validation, Operation and Run of Test Cases

Participation of Dr. Jasak

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- Instructions on using finite areas for simulating liquid water rivulets and films on highly curved surfaces. Dr. Jasak's unique expertise enabled transferring his foam-ext finite-area code to official OpenFoam.

- Guidance on immersed boundaries with ice-driven growth, only available in foam-ext by Dr. Jasak.

- Supervising ATS developers for implementing advanced code parts, like finite-area interfaces with immersed boundaries, not ready in the base code. External flow immersed boundary values must be mapped to finite area and back for ice growth simulation.

- Dr. Jasak built preliminary code skeletons, but ATS implemented the final complete version. Collaboration focused on meetings for guidance on foam-ext classes and objects.

- His participation was vital; the work involves core foam-ext modifications requiring unique, non-market knowledge not available or standard OpenFoam training.

Code Development

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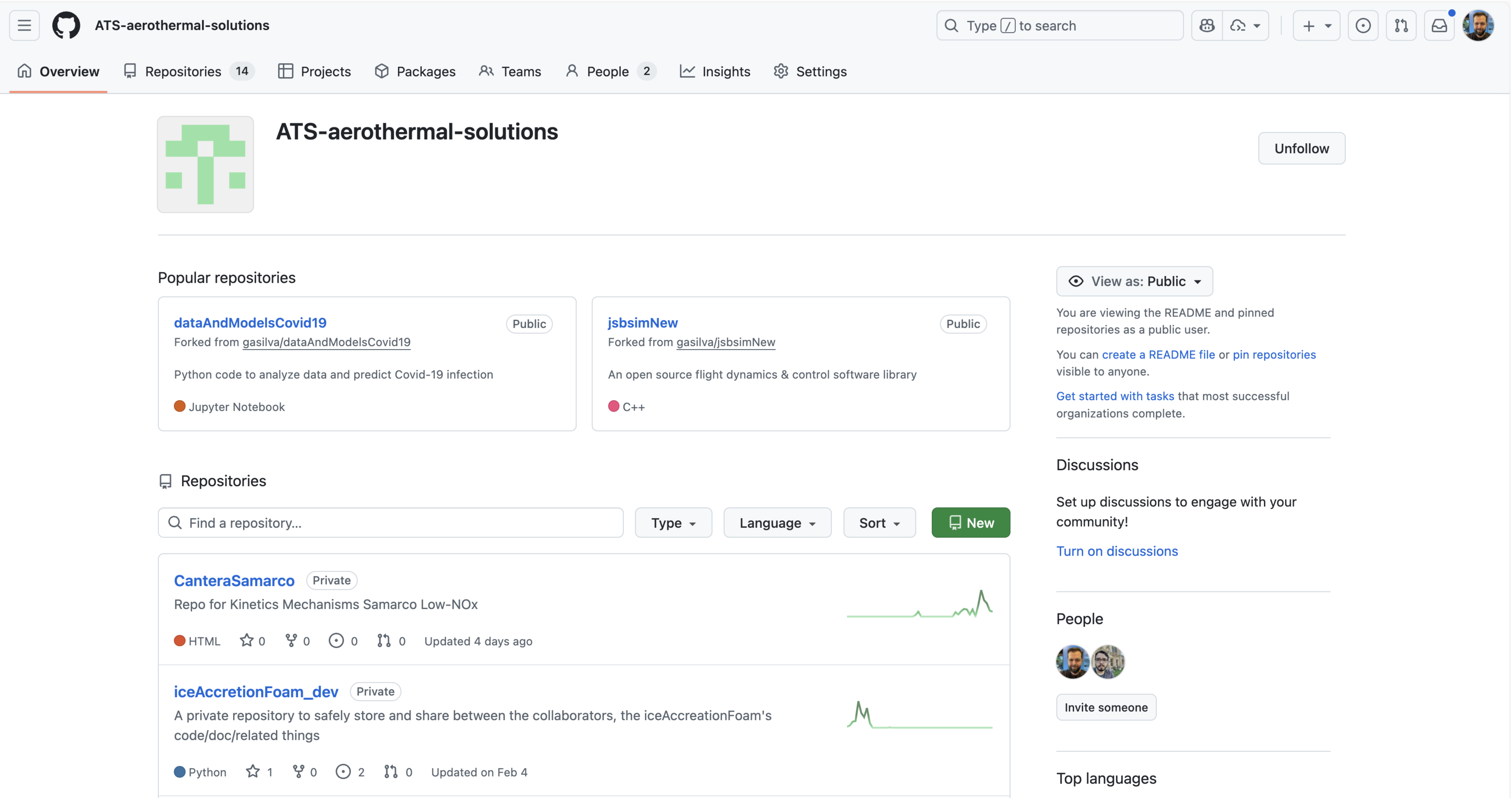
- Using GitHub as a *git* repository and version control system, we can manage our code effectively and safely.
- When we make significant changes to a branch, we validate and test them before merging them into the main branch.
- On the other hand, for minor changes, we implement and test them in the main branch.
- Additionally, we can create test versions to demonstrate concepts before merging them into the main branch.
- Employ the repository as a secure backup for versions that have proven successful. You can select which version is acceptable or not to safely continue the development process.
- Accessible to everyone in the project but it is not public for all

ATS gitHub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Type / to search
Overview
Repositories 14
Projects
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Teams
People 2
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Popular repositories
dataAndModelsCovid19
Public
Forked from gasilva/dataAndModelsCovid19
Python code to analyze data and predict Covid-19 infection
Jupyter Notebook
jsbsimNew
Public
Forked from gasilva/jsbsimNew
An open source flight dynamics & control software library
C++
View as: Public
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You can create a README file or pin repositories visible to anyone.
Get started with tasks that most successful organizations complete.
Discussions
Set up discussions to engage with your community!
Turn on discussions
Repositories
Find a repository...
Type
Language
Sort
New
CanteraSamarco
Private
Repo for Kinetics Mechanisms Samarco Low-NOx
HTML 0 0 0 0 Updated 4 days ago
iceAccretionFoam_dev
Private
A private repository to safely store and share between the collaborators, the iceAccreationFoam's code/doc/related things
Python 1 0 2 0 Updated on Feb 4
People
Invite someone
Top languages

Physical Model

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∇FOAM

$$\frac{\partial \rho\delta}{\partial t} + \nabla_s \cdot [\rho\delta\mathbf{U}] = S_{\rho\delta}$$

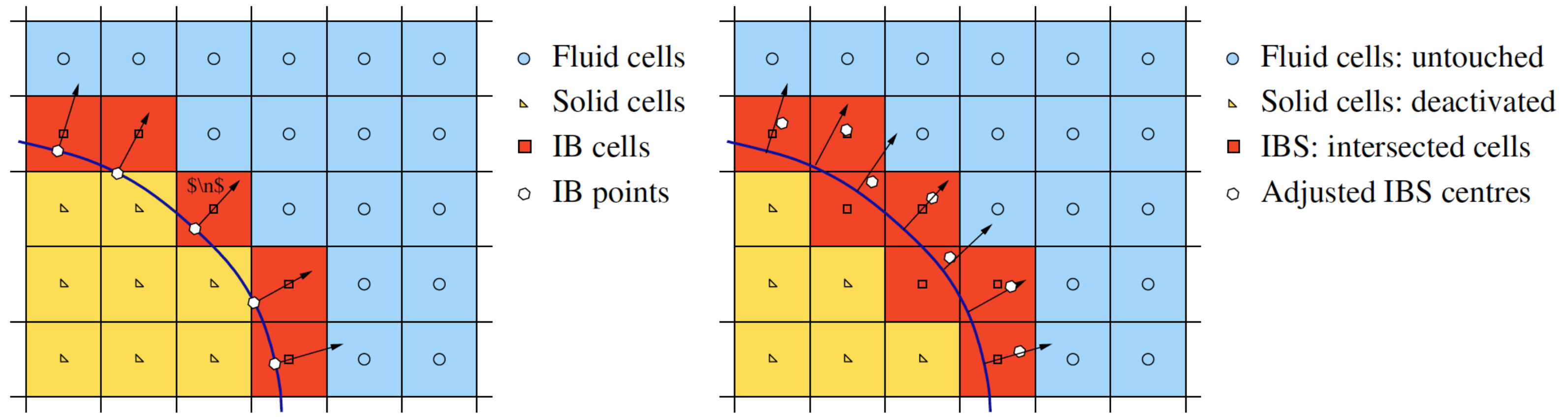
$$\frac{\partial \rho\delta\mathbf{U}}{\partial t} + \nabla_s \cdot [\rho\delta\mathbf{U}\mathbf{U}] = \underbrace{-\delta\nabla_s p}_{\text{pressure based}} + \underbrace{\mathbf{S}_{\rho\delta\mathbf{U}}}_{\text{stress based}}$$

$$p = p_\sigma + p_\delta + p_g$$

The pressure term, p, is comprised of forces in the wall-normal direction and consists of capillary effects (p_σ), hydrostatic pressure head (p_δ), and local gas-phase pressure (p_g).

$$\mathbf{S}_{\rho\delta\mathbf{U}} = \boldsymbol{\tau}_g + \boldsymbol{\tau}_w + \rho\mathbf{g}_t\delta + \boldsymbol{\tau}_\theta$$

The stress term, $\mathbf{S}_{\rho\delta\mathbf{U}}$, includes the viscous shear stresses ($\boldsymbol{\tau}_g, \boldsymbol{\tau}_w$), gravity body force ($\rho\mathbf{g}_t\delta$), and stress related to contact-angle force ($\boldsymbol{\tau}_\theta$).



python™

ENNOVA TECHNOLOGIES

tecplot 360 AND pytecplot

CFD 3D

Water Film Model
Immersed Boundary

Heat Transfer
and Freezing

Results

Why Foam-Ext?

- **Recognized** CFD 3D Software (not new and not from scratch)
- **Finite Area** to simulate runback water hydrodynamics and thermal
- **Immersed Boundary** to simulate ice growth without mesh deformation or local/global re-meshing
- Turbulent Rough **Heat Transfer** implemented in OpenFoam of a new wall function specific for icing surfaces based on traditional modeling (Lewice/Stanford)
- Implementations of Laminar-Turbulent **Transition** available in literature for OpenFoam/foam-ext triggered by roughness size
- **driftEulerFoam** already implemented for Eulerian droplets trajectories, including clouds and distributions
- **Possibility** to **run in the cloud** through web interface - SAAS

iceAccretionFoam

- Compressible Full 3D Solver with Eulerian Phase
- Immersed Boundary (shape changes)
- Finite Area Method (liquid water flow)
- Rough Turbulent Convective Heat Transfer Wall Function
- Laminar-Turbulent Transition on Rough Surface
- 2D Shell Thermal Conduction Heat Transfer

iceAccretionFoam implemented as a solver of foam-ext 5.0

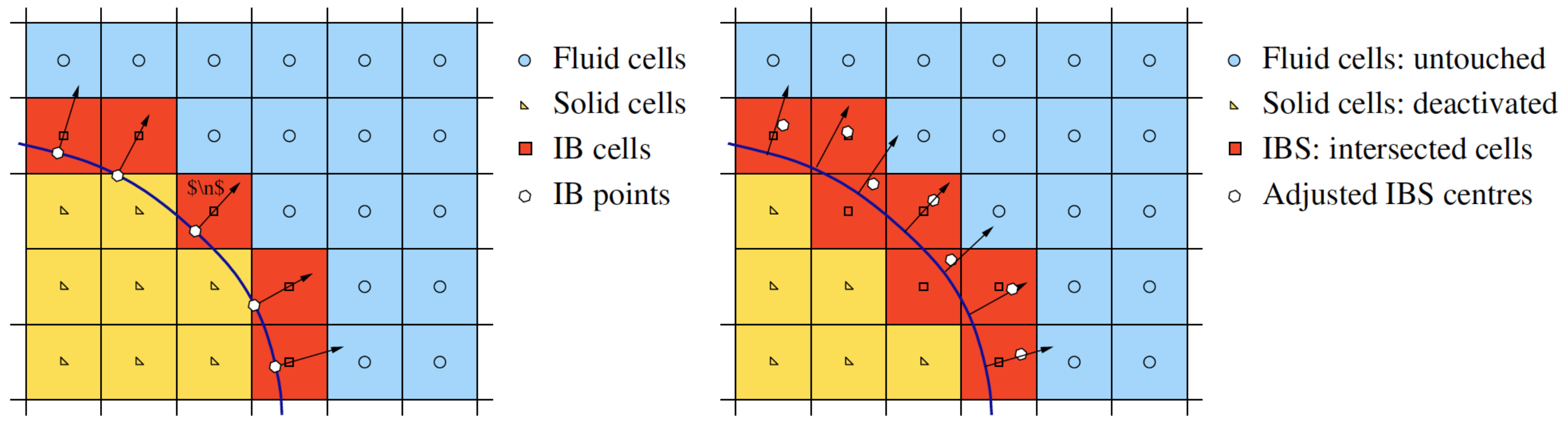


Figure 2: Traditional IBM and New Implementation of IBS after Jasak (23)

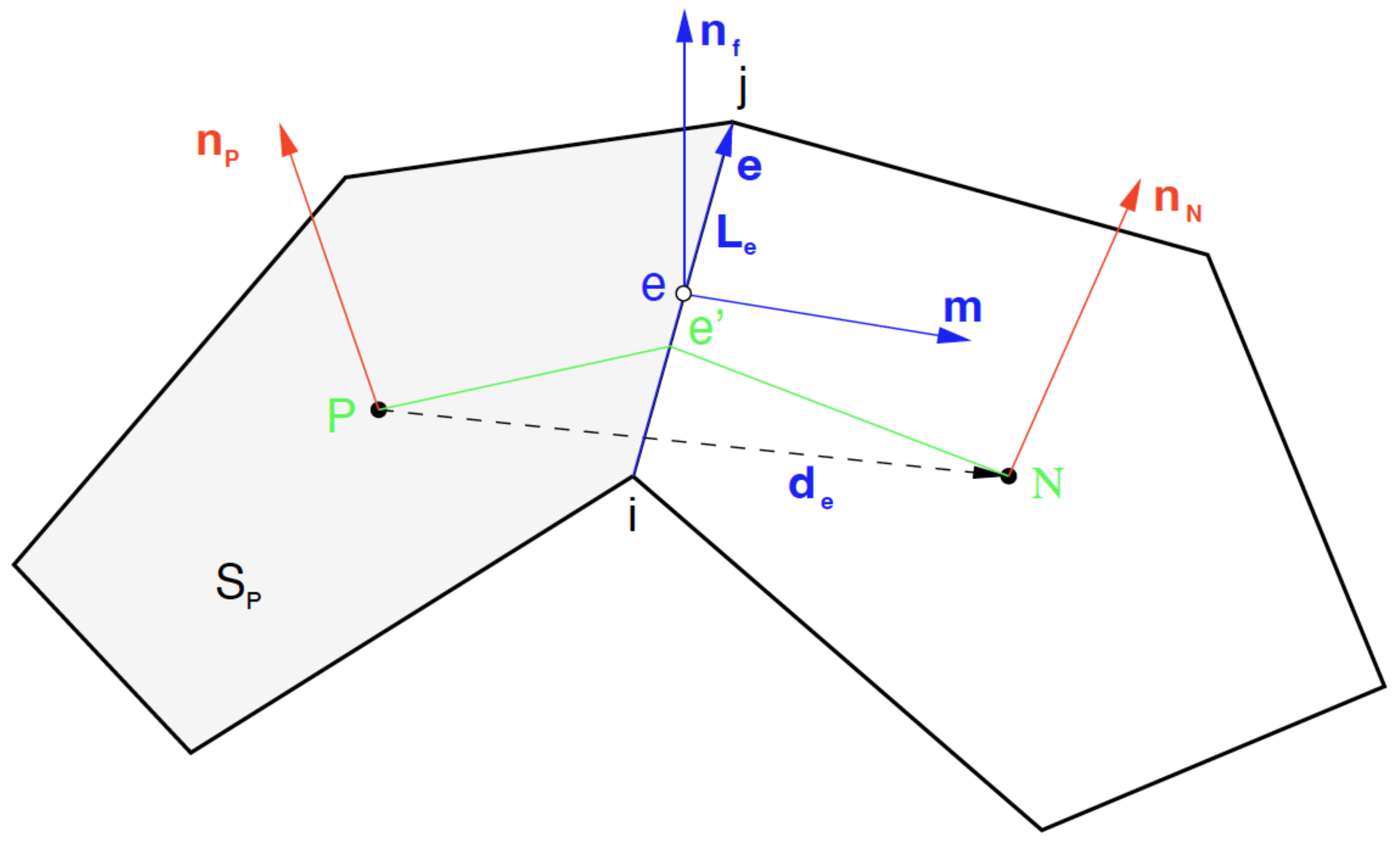


Figure 1: Face-edge interpolation in edge based local coordinate system after Jasak (18)

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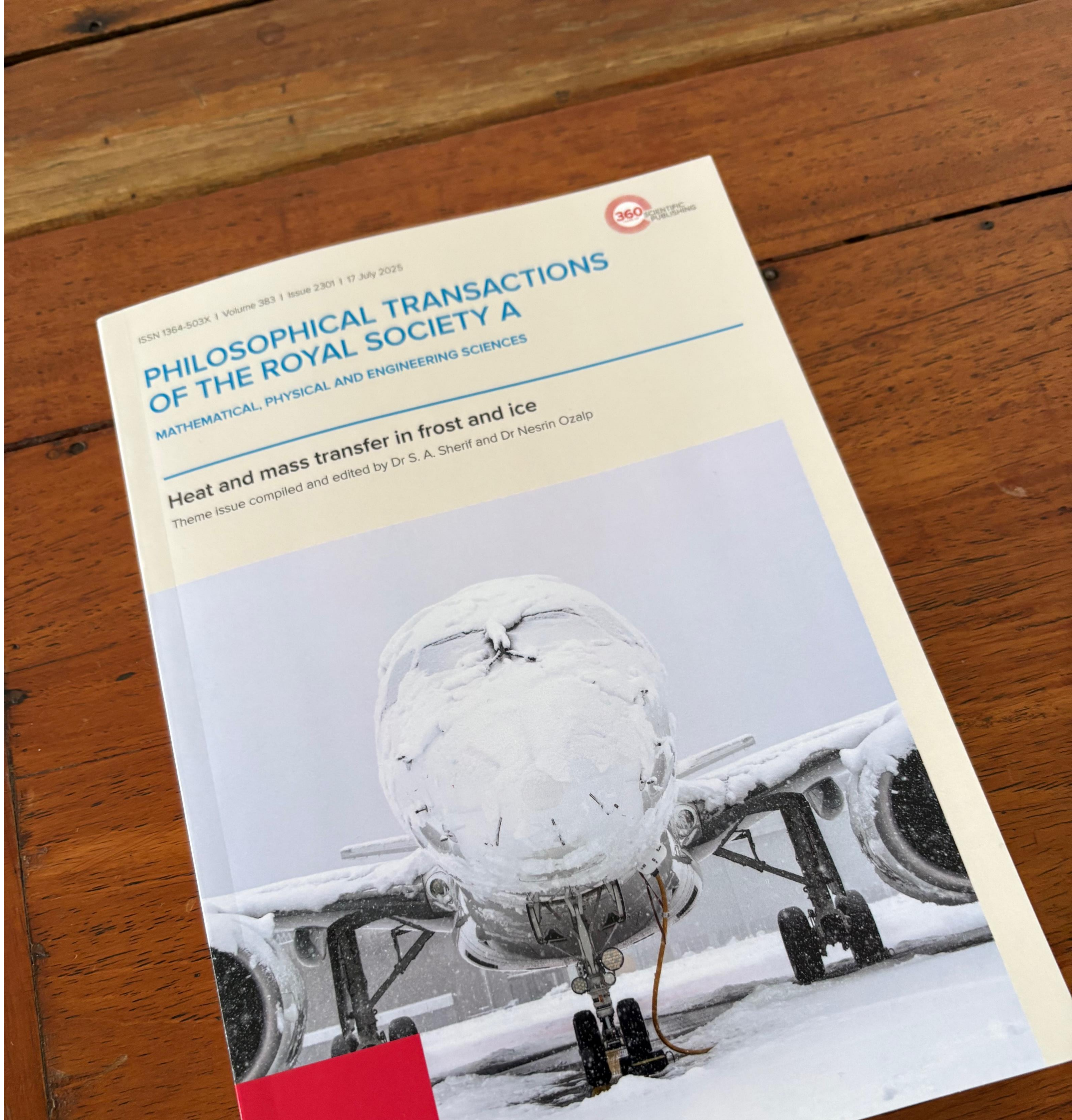
iceAccretionFoam Publications

Three papers published:

- Carvalho et al. (2025). Advancing the iceAccretionFoam Solver: Glaze Ice Accretion. **Phil. Trans. R. Soc.** DOI: 10.1098/rsta.2024.0361

- Teixeira da Silva et al. (2025). Introducing the iceAccretionFoam Solver: Impingement and Rime Ice. **Phil. Trans. R. Soc.** DOI: 10.1098/rsta.2024.0362

- Teixeira da Silva et al. Initial Development of a CFD Icing Tool. **ICAS 2024-1112**



iceAccretionFoam Code

Current Scope

- A transient solution of the flow by using **Unsteady Reynolds Averaged Navier-Stokes compressible equations** (URANS) in a **multi-step** approach;
- Compressible flow **energy equation** with kinetic heating;
- Fully turbulent **momentum and heat transfer** over a sand-grain rough surface
- An **immersed boundary method** that updates the frontier of the solid surface;
- A **finite-area method** that simulate the water hydrodynamics on the airfoil surface;
- A Eulerian-dispersed phase model with **driftEulerFoam** solver for **compressible flow**.

Main Physical Assumptions

1) All impinging supercooled liquid water will form a film with → no surface tension breakdown
2) A normal growth of ice rule is applied based on growth rate of ice in the film;
3) A simplistic mathematical freezing fraction is implemented preliminarily;
4) Water thermal balance and convective heat and mass transfer are considered;
5) Air kinetic heating and pressure effects are calculated in compressible flow;
6) Liquid water film exist on the surface of the airfoil;
7) The **liquid film is solved in the non-deformed** solid surface but with effects of pressure gradient, shear, heat transfer, water droplets momentum and mass flux **from deformed surface at immersed boundary** (external flow over ice shape);

Numerical Model

1) rhoPimpleFoam* for main flow compressible URANS with added kinetic heating

2) Special wall functions implemented for fully rough surface

3) Water mass, momentum and energy conservation for water film

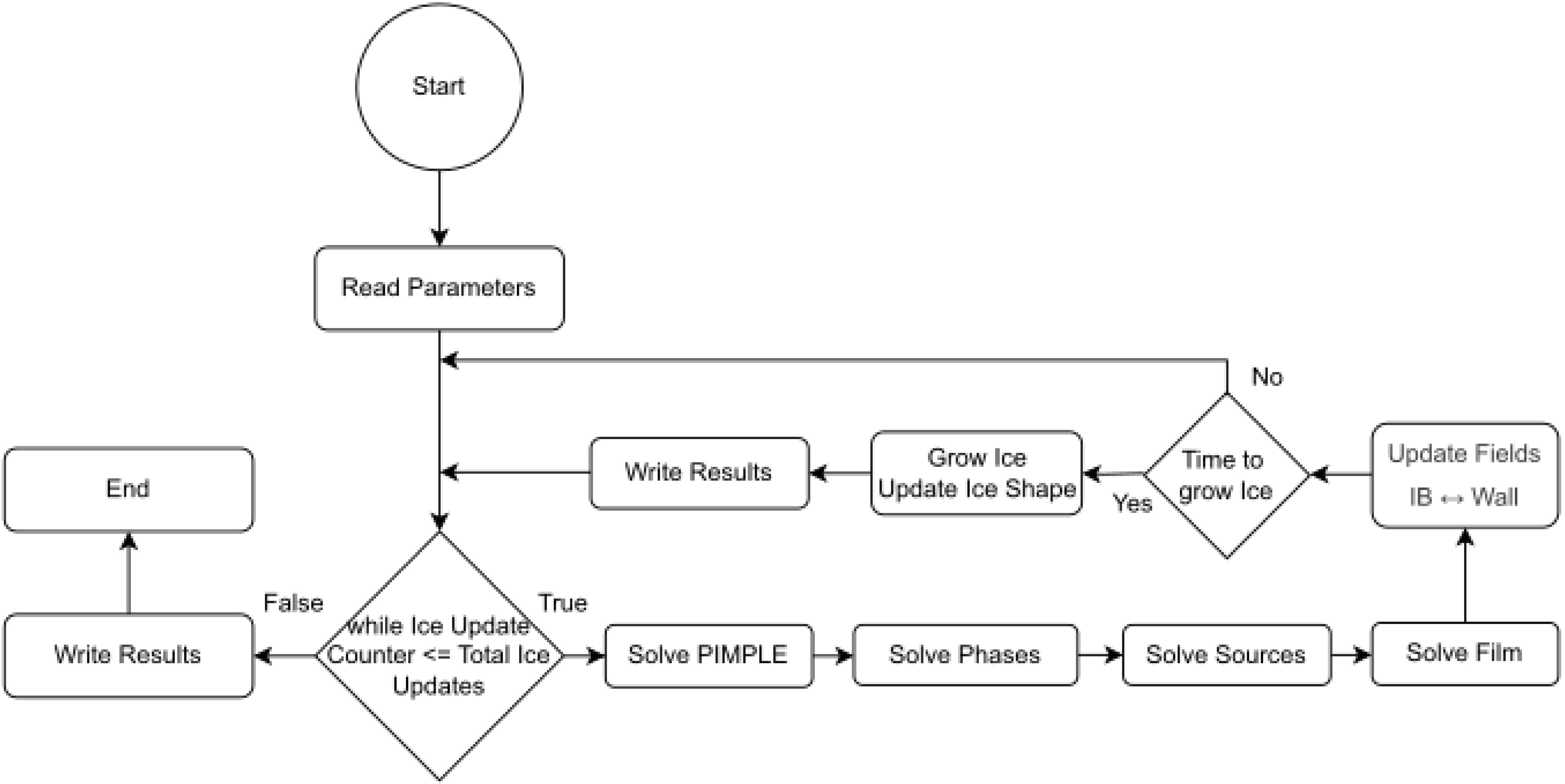
4) Eulerian droplets trajectories – U_phase and α for each diameter

5) **<u>In each time step a height value is added</u>**: $h_{ice,i} = \Delta t_{accretion} \cdot \alpha_i \cdot U_{phase,i} \cdot \frac{\rho_{water}}{\rho_{ice}}$

6) Lewice Ice density model: $\rho_{ice} = 1000 \cdot \exp\left[0.15 \cdot (1 + 6043 \cdot S^{-2.65})\right]$

$$S = \frac{\text{MVD}^{0.82} \cdot U_\infty^{0.59} \cdot \text{LWC}^{0.21}}{d_{le}^{0.48} \cdot (-T_{rec}^{0.23})}$$

Code Implementation



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Planned Validation Process

- Cp & Beta
- 2D Rime Ice
- 2D Glaze Ice
- 3D Shapes & SLD
- Thermal Ice Protection

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Roadmap

Beta — 2026
MVP — 2027/8

- **2001** — Certification
  New process generated for probes with OEM and Authorities
- **2003** — Physics Model M.Sc. and Ph.D. UFRJ Tunnel
- **2015**
- **2019** — Ideation based on customer requirements
- **2022** — OpenFoam Selection
  - Finite Area
  - Immersed boundary
  - Full 3D
- **2023/4** — Collaboration with Dr. Jasak Foam-Ext. 5
- **2026** — Beta
- **2027/8** — MVP

Technology is designed to be a step ahead

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Definitions

Droplet Distribution

Table 2 – Distribution of Wright [16] with MVD = 21 μm

%LWC	D(I)
0.1390	8.6
0.0958	12.5
0.0997	15.5
0.1220	18.5
0.1208	21.5
0.1115	24.5
0.0917	27.5
0.0946	31.6
0.0899	48.2
0.0350	95.9

Definitions

Pressure Coefficient

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2},$$

$$C_p^* = C_p \cdot \frac{1}{\sqrt{1 - M_\infty^2}}$$

Collection Efficiency

$$\beta_i = \frac{\alpha_i \cdot \vec{U}_{phase,i} \cdot \vec{n}}{\alpha_\infty \cdot |\vec{U}_{phase,\infty}|}$$

$$\beta_{tot} = \sum_{i=1}^{n} \frac{\alpha_i \cdot \beta_i}{\alpha_\infty}$$

$$\alpha_\infty = \sum_{i=1}^{n} \alpha_i$$

Freestream α

$$\alpha_\infty = \frac{LWC_\infty}{\rho_{water}}$$

Simplistic Freezing Fraction

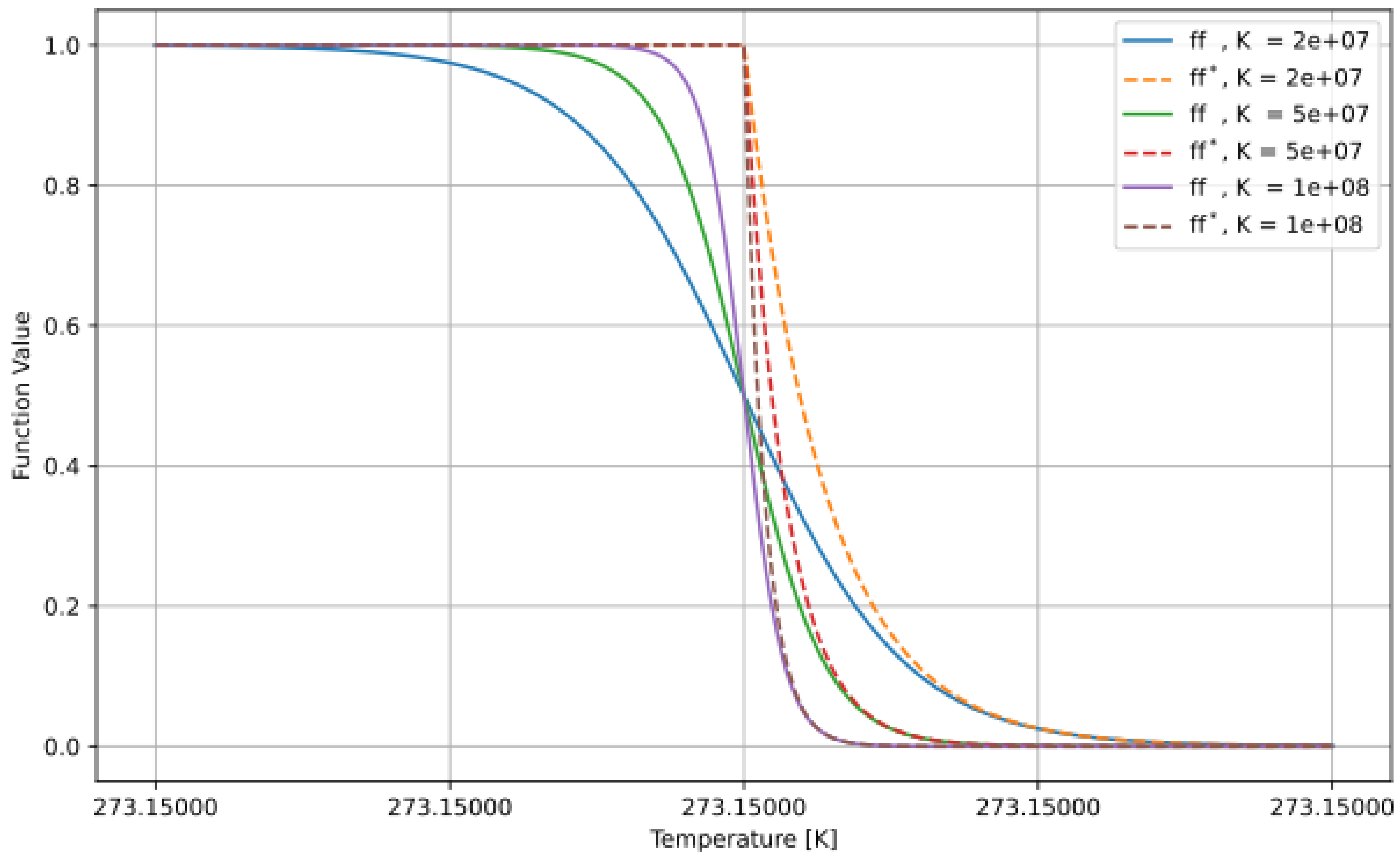
$$T_{diff} = \frac{T_f - 273.15}{273.15}$$

$$ff = 1 - \left(0.5 + 0.5 \tanh\left(K_{Freezing} \cdot T_{diff}\right)\right).$$

$$\left.\frac{\partial m}{\partial t}\right|_{ice,cv} = ff \cdot \left.\frac{\partial m}{\partial t}\right|_{total,cv} = ff^* \cdot \left.\frac{\partial m}{\partial t}\right|_{liquid,cv}$$

$$\left.\frac{\partial m}{\partial t}\right|_{total,cv} = \left.\frac{\partial m}{\partial t}\right|_{liquid,cv} + \left.\frac{\partial m}{\partial t}\right|_{ice,cv}$$

$$\Rightarrow ff^* = \frac{ff}{1 - ff}$$



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Freezing and Thermal Model

Water Film Conservation Finite Area Formulation

Mass =
Film Height

$$\frac{\partial h_{\mathrm{f}}}{\partial t} + \nabla \cdot (\phi_s \cdot h_{\mathrm{f}}) = 2 \cdot S_m - S_{\mathrm{f}} - S_e$$

$$S_m = \frac{\sum \alpha_i \cdot \phi_{\mathrm{phase},i}}{|A|}$$

$$S_{\mathrm{f}} = \mathrm{ff}^* \cdot \frac{\partial h_{\mathrm{f}}}{\partial t}_{\mathrm{cv}}$$

$$S_e = \frac{\dot{m}''_{\mathrm{evap}}}{\rho_w},$$

Momentum =
Film Height X Velocity

$$\frac{\partial h_f \vec{U}_s}{\partial t} + \nabla \cdot (\phi_{2s} \cdot \vec{U}_s) + 0.0125 \cdot C_{f,w} |\vec{U}_s| \cdot \vec{U}_s = (S_\tau + S_i + S_g) \cdot \vec{b}_{\|} + S_{\mathrm{grad}P} + S_{\mathrm{bl}}$$

$$\phi_{2s} = \phi_s \cdot h_f$$

$$S_\tau = \frac{\vec{\tau} \cdot h_f}{\rho_w}$$

$$S_i = \frac{\sum \alpha_i \cdot \phi_{\mathrm{phase},i} \cdot \vec{U}_{\mathrm{phase},i}}{|A|}$$

$$S_g = \vec{g} \cdot h_f$$

$$S_{\mathrm{gra}P} = -\vec{\nabla}(p_s \cdot h_f) = \frac{p_s}{\rho_w} \cdot \vec{\nabla} h_f.$$

Energy =
Film Height X Temperature

$$\frac{\partial h_f \cdot T_f}{\partial t} + \nabla(\rho_w \cdot C_w \cdot \phi_{2s} \cdot T_f) - k \cdot h_f \cdot \nabla^2 T = h_{\mathrm{conv}} \cdot (T_\infty - T_f) + S_{\mathrm{mi}} + S_{\mathrm{Hf}} + S_{\mathrm{He}}$$

$$S_{\mathrm{mi}} = \rho_w \cdot C_w \cdot S_m \cdot T_d$$

$$S_{\mathrm{Hf}} = \mathrm{ff}^* \cdot \frac{\partial h_f}{\partial t} \cdot \rho_w \cdot h_{\mathrm{ls}}$$

$$S_{\mathrm{He}} = (1 - \mathrm{ff}^*) \cdot m''_{\mathrm{evap}} \cdot h_{\mathrm{lv}}.$$

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Rough Wall Functions Immersed Boundary

Stanford Rough Wall

$$\Delta B = \begin{cases} 0 & Ks^+ \leq 2.5 \\ \frac{1}{\kappa} \ln\left[\frac{K_s^+ - 2.25}{87.75} + C_s K_s^+\right] \sin[0.4258 \cdot (\ln K_s^+ - 0.811)] & 2.5 < Ks^+ < 90 \\ \frac{1}{\kappa} \ln(1 + C_s K_s^+) & Ks^+ \geq 90 \end{cases}$$

Where C_s depends on the shape and distribution of the roughness elements and,

$$y^+ = y\frac{\rho C_\mu^{0.25} k^{0.5}}{\mu} \quad and \quad K_s^+ = K_s\frac{\rho C_\mu^{0.25} k^{0.5}}{\mu}$$

$$\mu_t = \mu\left(\frac{y^+\kappa}{\ln(Ey^+/e^{\kappa\Delta B})} - 1\right)$$

Double Resistance Analogy
Not Reynolds Analogy

$$\frac{u_\tau}{u} = \sqrt{C_f/2} \quad \text{and} \quad u_\tau = \sqrt{\tau/\rho} \quad \text{with} \quad \tau = (\mu + \mu_t) \cdot |\nabla U \cdot \vec{n}|,$$

$$\alpha_t = \frac{\mu_t \cdot \eta \cdot A}{Pr_t}. \qquad \eta = \frac{1}{Pr_t + \frac{\sqrt{C_f/2}}{St_k}}$$

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Heat and Mass Transfer Imersed Boundary

$$T_d = T_\infty + \frac{V_d^2}{2 * C_w}$$

$$\dot{q}''_{\text{wall}} = \alpha_{\text{eff}} \cdot \nabla h = \alpha_{\text{eff}} \cdot c_p \cdot \nabla T$$

$$h_{\text{conv}} = \left| \frac{\dot{q}''_{\text{wall}}}{T_{\text{wall}} - T_\infty} \right|,$$

$$B_m = \frac{\text{mf}_{\text{H}_2\text{O},S} - \text{mf}_{\text{H}_2\text{O},G}}{\text{mf}_{\text{H}_2\text{O},S} - 1},$$

$$\dot{m}''_{\text{evap}} = g_m \cdot \text{B}_m$$

$$g_m = \frac{h_{\text{conv}}}{c_p} \cdot \text{Le}^{2/3} \cdot \frac{\ln(1 + \text{B}_m)}{\text{B}_m},$$

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Ice Growth for Rime and Glaze

$$h_{\text{ice}} = \text{ff}^* \cdot \left(\frac{dh_f}{dt}\right)_{\text{cv, liquid}} \cdot \frac{\rho_{\text{liquid}}}{\rho_{\text{ice}}} \cdot \Delta t_{\text{ice}},$$

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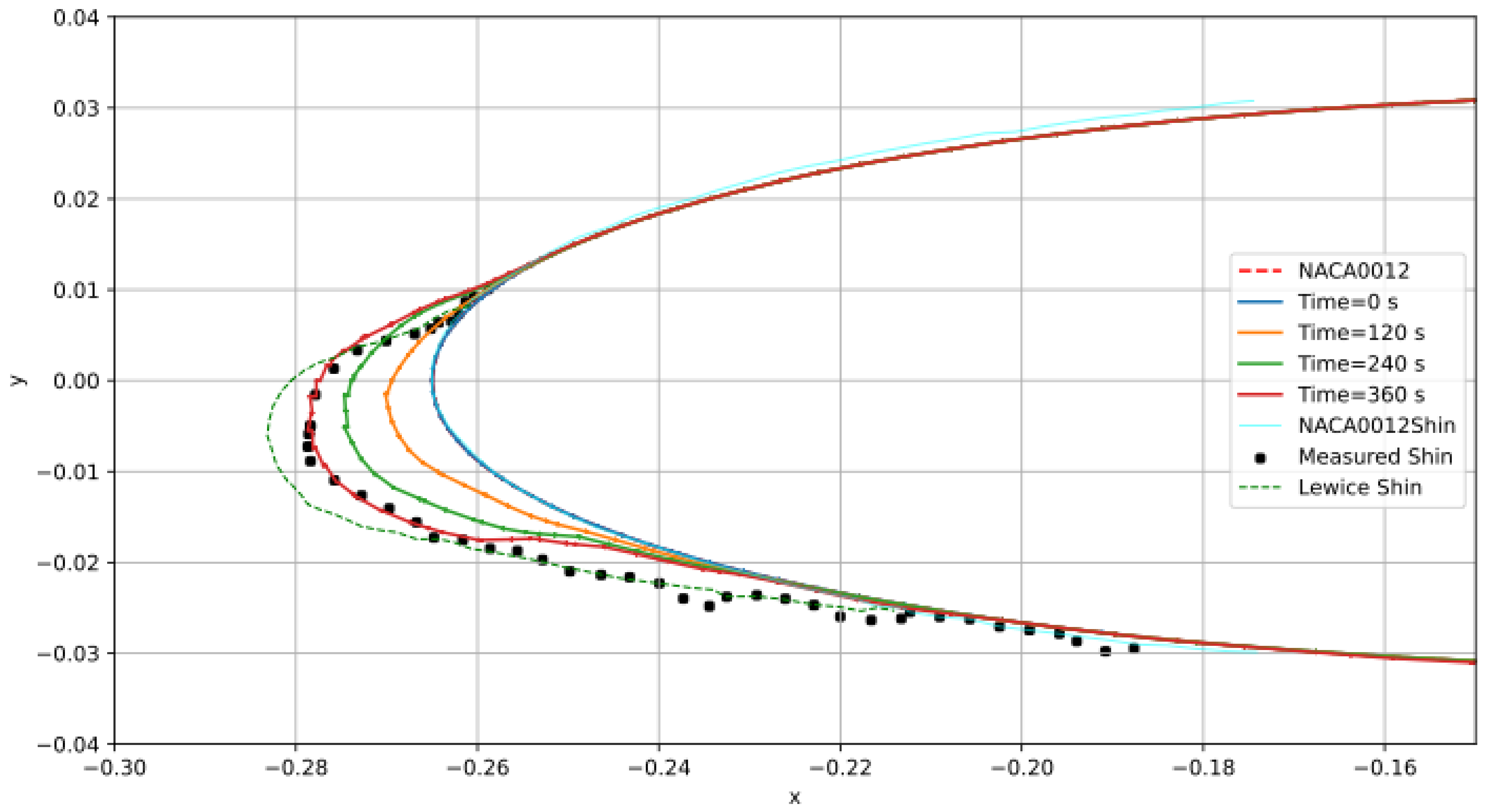
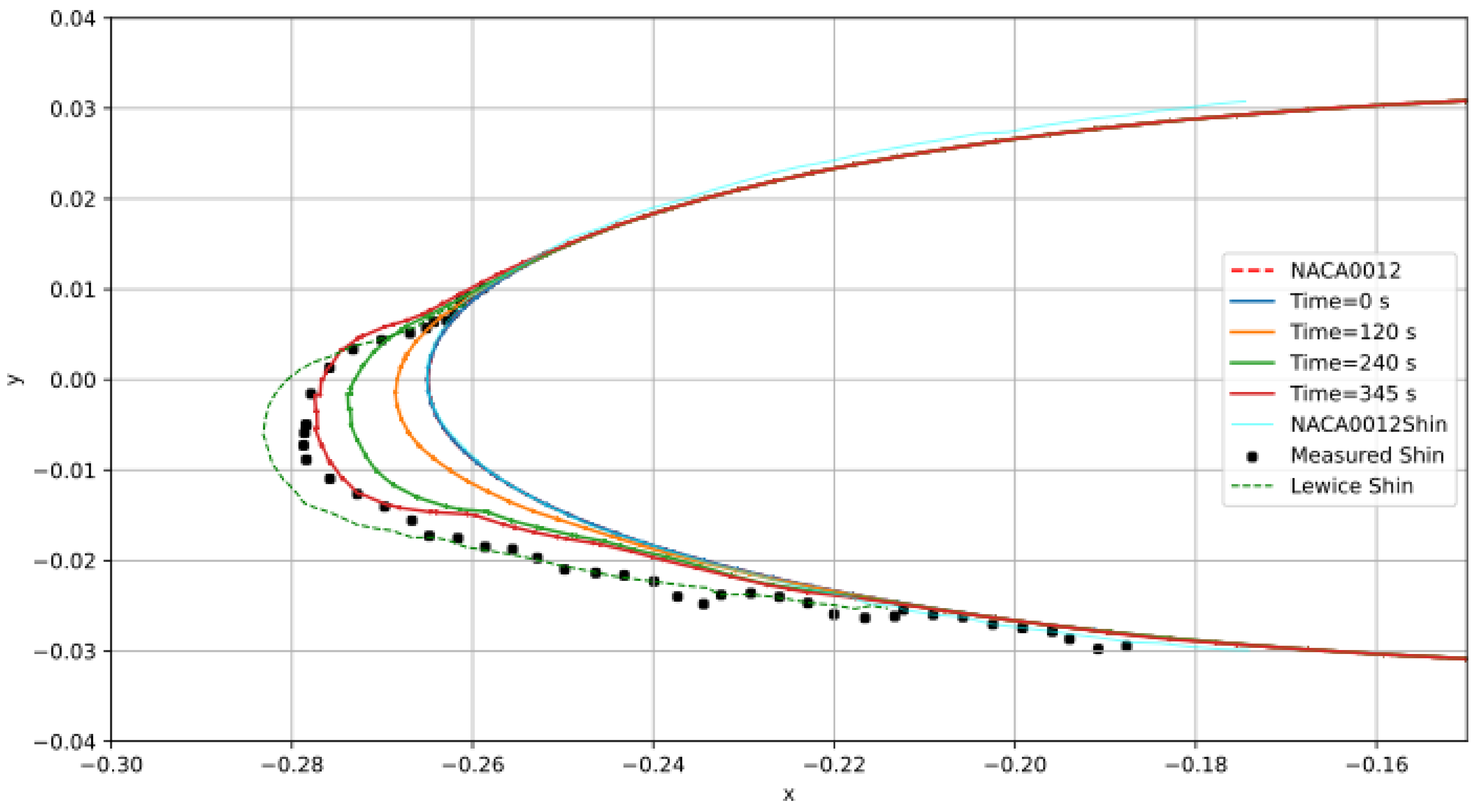
Results

Rime Ice Case



. Transfer function with source normal and cell centres vectors.



. Transfer function with alignment of cell source and target normals.

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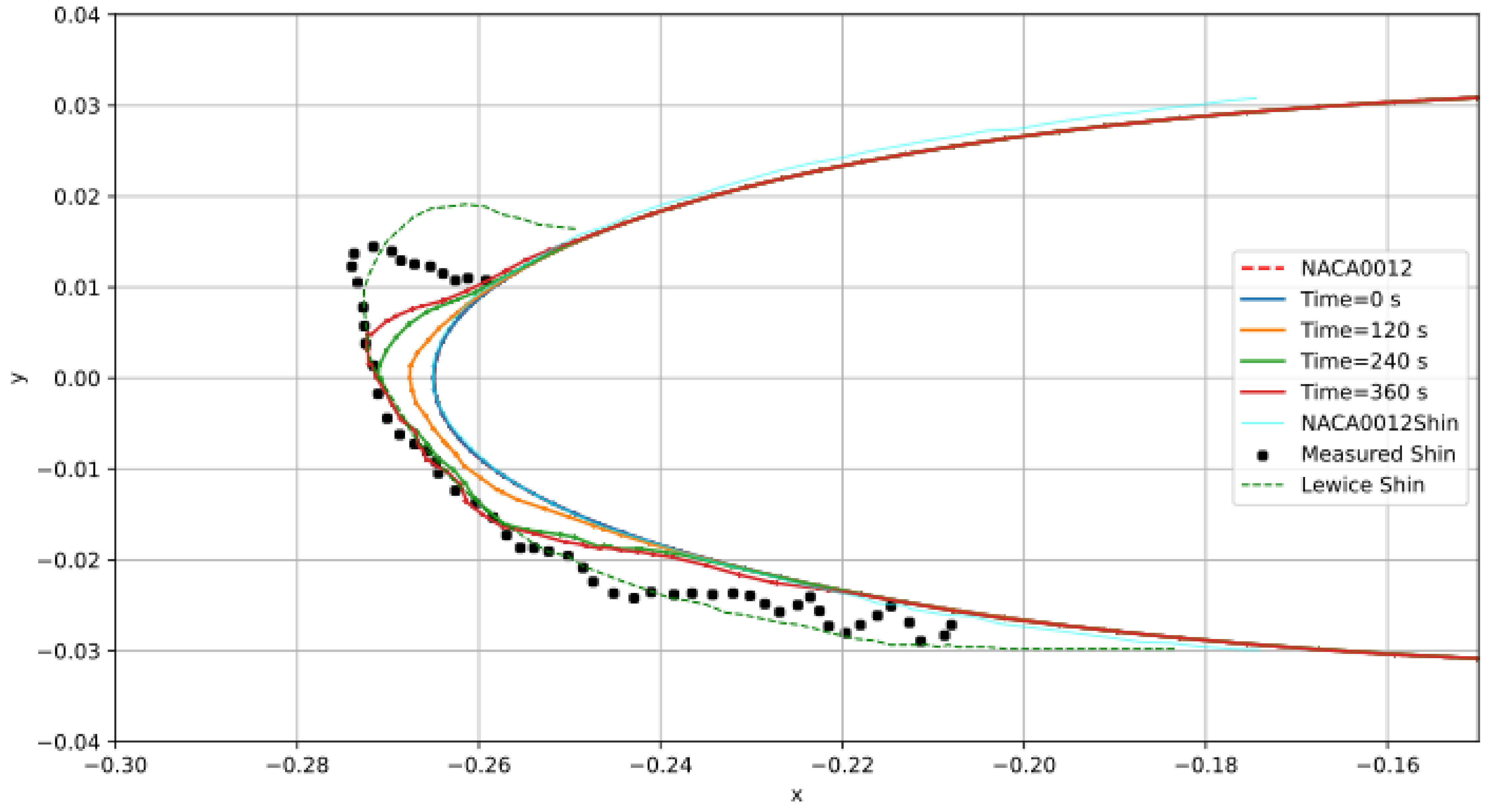
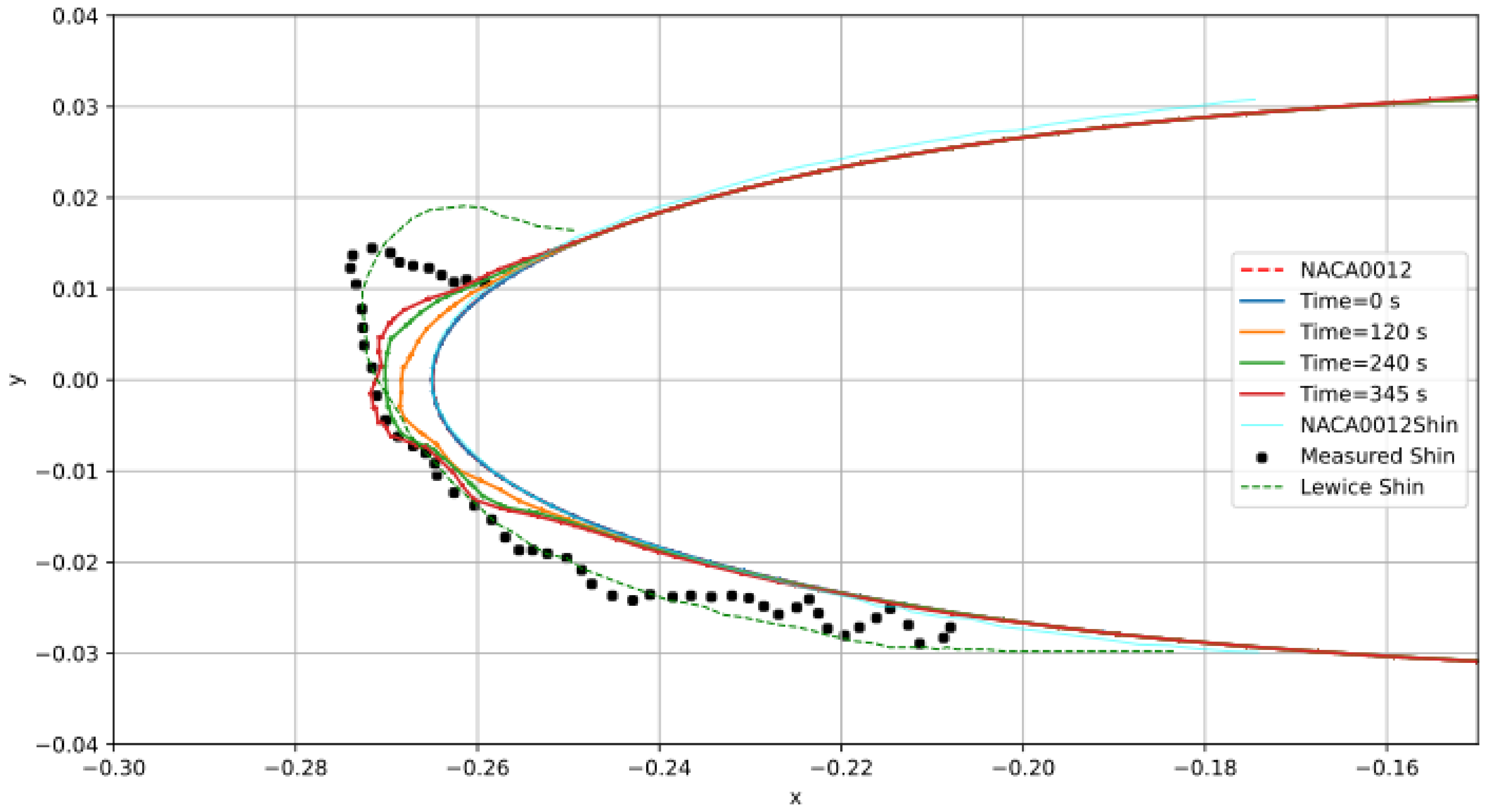
Glaze Ice Case



. Transfer function with source normal and cell centres vectors.



. Transfer function with alignment of cell source and target normals.

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Discussion

- Rime and glaze ice are working with same equations
- Rime is considered acceptable
- Glaze shows a correct behavior but requires adequate:

  i. thermal freezing fraction - Messinger
  ii. mapping by cells following the ice growth deformation
  iii. convective heat and mass transfer with transition

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Next Steps

Next Steps

This work has introduced a mature (less risk) development phase of a **rime and glaze 3D ice accretion tool, built on foam- extend 5.0.**

The nexts steps are:

- Beta version release 10 months ahead
- MVP in 2 years with application to real cases

Thank you for your attention

ATS is Global

USA, Europe and Brazil

São Paulo - Brazil, since 2007
Miami - USA, since 2018
São José dos Campos - Brazil, since 2019
Munich - Germany, since 2022

ATS combines high-tech computational methods with traditional engineering analysis to provide accurate solutions for thermal and fluid dynamic systems

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About ATS

The Client Challenges

To have one contract with ONE multi-skilled and experienced company

In addition

- To cover peak workloads.
- To mitigate risks by hiring experience.
- To support the internal team with missing specific skills.
- To decrease the number of prototypes and tests.

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All skills in a single company

- End-to-end Solutions
- Turnkey Job

Engineering, Simulation, Testing and Certification

17 years of experience applying engineering and CFD in the industry

Associate Engineer throughout the development process

Multi-disciplinary team

Multidisciplinary Team

Guilherme Lima da Silva,
Ph.D, CEO, founder

Air Liquide · EMBRAER · USP · Shell · ipt

Pedro Villela
CTO, System Engineer, Associate

EMBRAER · AIRBUS HELICOPTERS

Caio Rafael
CFD Thermal Engineer, Associate

INPE

Odair Lima
CFO

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PALL · Braskem · Shell

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