Anti-icing and de-icing issues

B. Aguilar[2], T. Alary[2], L. Bennani[2], P. Berthoumieu[2], G. Blanchard[2], V. Bodoc[2], M. Bouyges, B. Dejean[2], Q. Duchayne[2], C. Laurent[2], E. Radenac[2], O. Rouzaud[2], P. Trontin[1], P. Villedieu[2]

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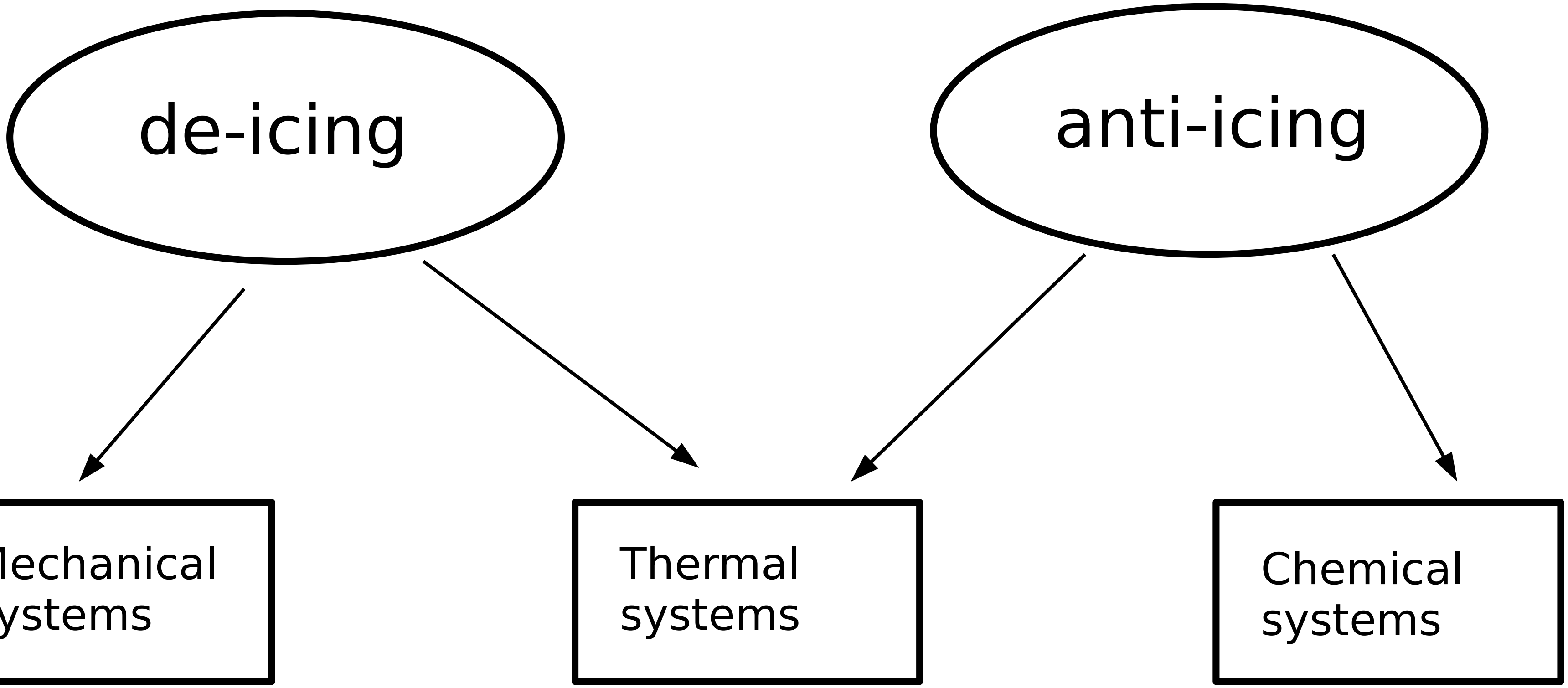
Ice protection systems

cyclic removal of already accumulated ice from the aircraft.

Prevention of ice from accumulating on surfaces or in aircraft systems.



- Pneumatic boot systems
- Electromechanical systems (EMPIS)

- Electrothermal-type systems (ETIPS)
- Bleed air systems

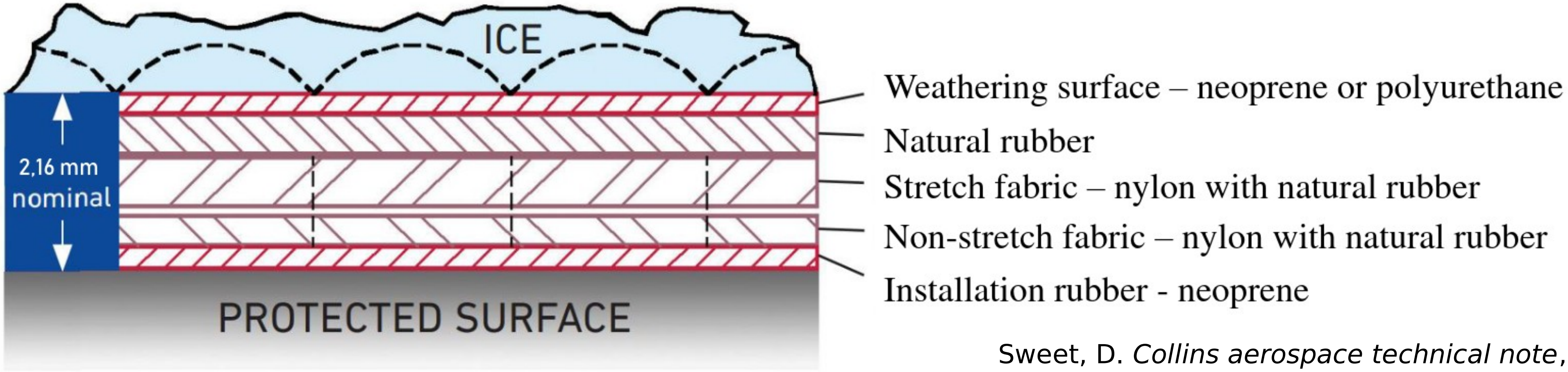
- spraying of an anti-icing fluid
- Passive anti-ice and de-ice systems

Ice protection systems: spraying of an anti-icing fluid

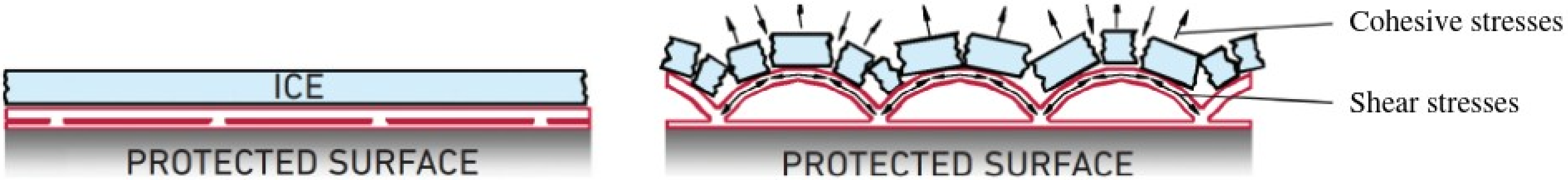
Pros:
- Simple and quick to implement.
- Process adapted to all aircraft.

Cons:
- High economic/environmental impact.
- Limited durability (effective only during the take-off stage).

Ice protection systems: pneumatic boot systems



Sweet, D. *Collins aerospace technical note*, 2019



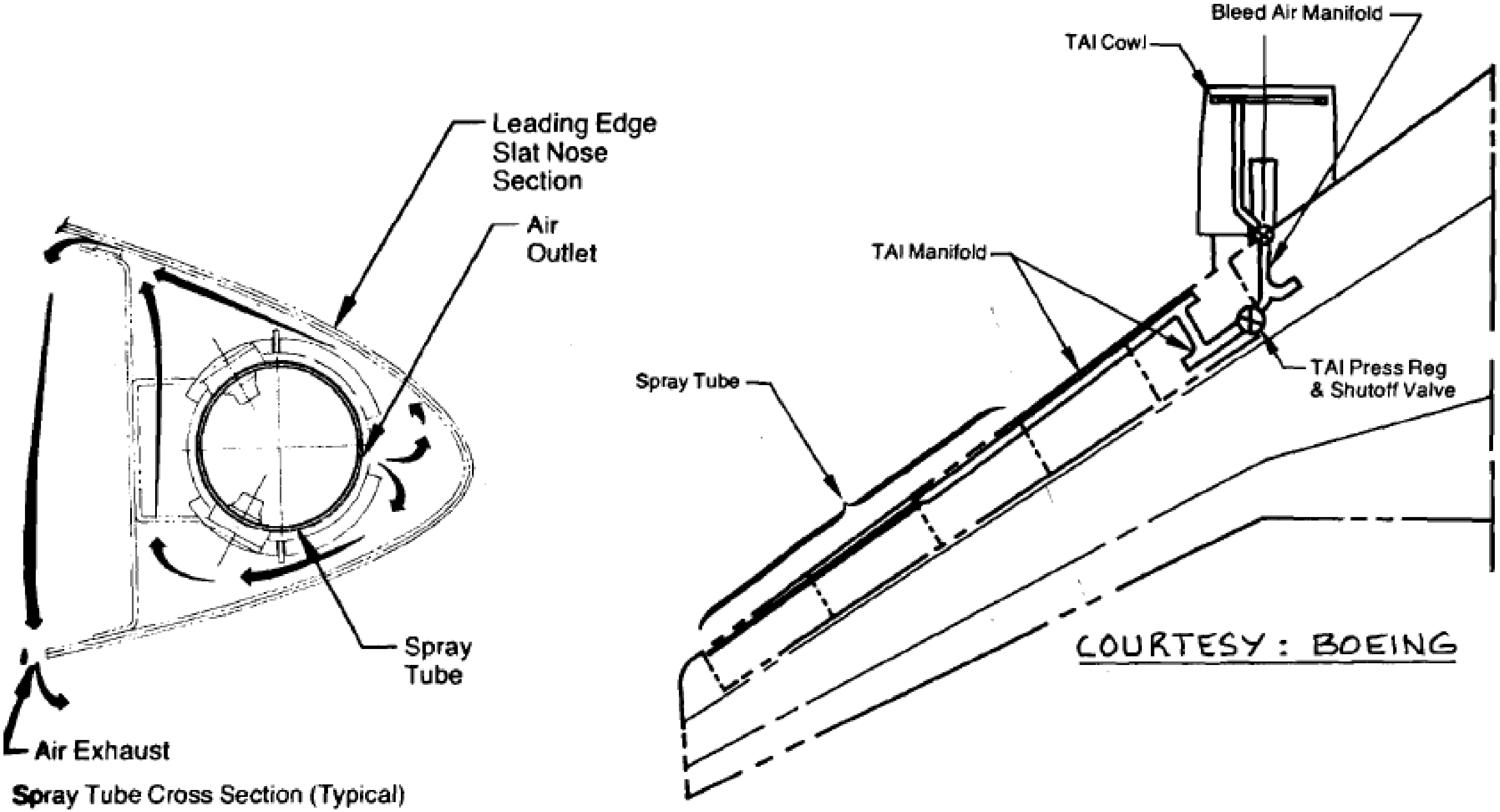
Sweet, D. *Collins aerospace technical note*, 2019

Pros:
- Moderate technological complexity.
- Reliability

Cons:
- « all or none » system.
- Low ice residue on the wall

https://www.youtube.com/watch?v=HrjP_iYlJ1k

Ice protection systems : bleed air system



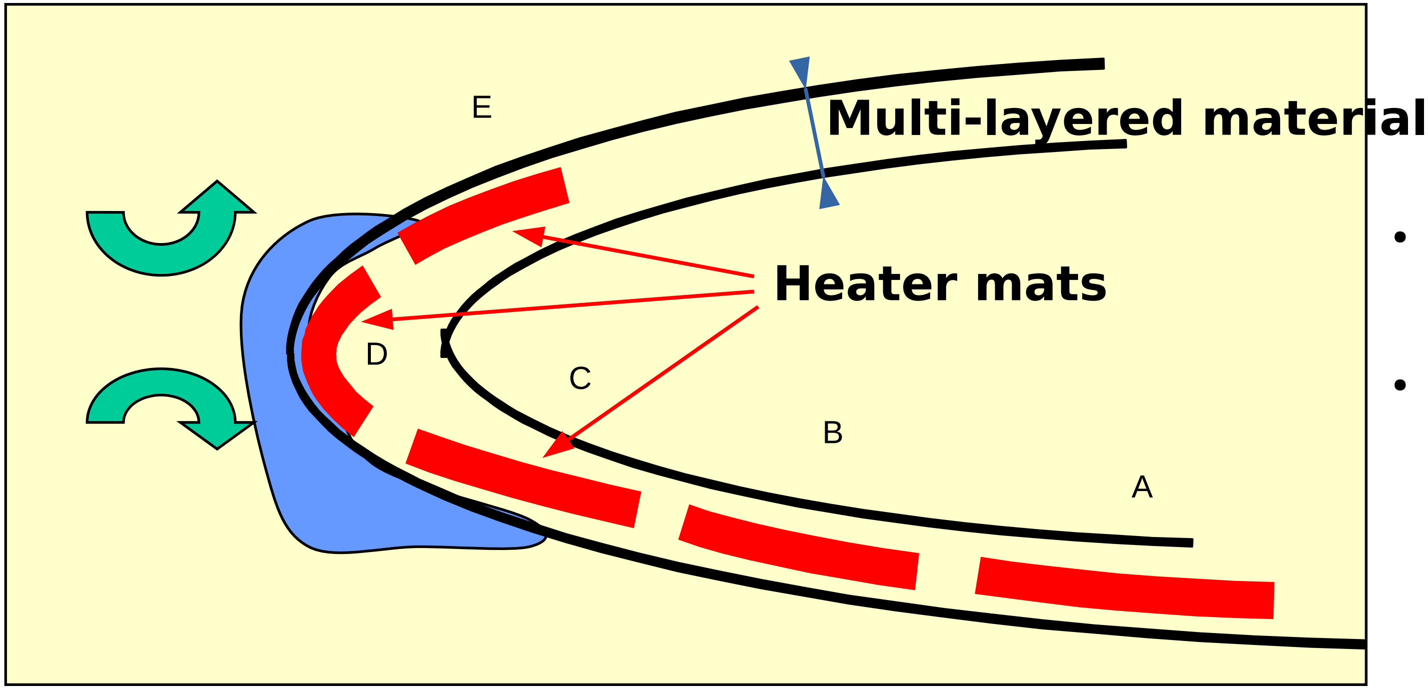
Spray Tube Cross Section (Typical)

COURTESY : BOEING

Air Heated Anti-Icing System: Boeing 767

- **Hot air extraction** from the engine.
- Injection into the leading edge of the wing (via **piccolo tube**).
- **Low** energy efficiency.

Ice protection systems : electro-thermal systems



- More and more developed in **"all electric" aircrafts**.
- In de-icing mode: **cyclic activation** of the heater mats.

- Composed of several **heater mats**.
- Integrated in a **multi-layered material.**
- Can be used in two ways:
  - Anti-icing : the protected surface is constantly heated so as to prevent ice formation (ex: Helicopter tail rotor)
  - De-icing : Ice accretes and the heaters are activated according to a **predefined cycle**. Therefore, melted regions at the ice/surface interface appear and reduce the ice block’s adhesion, which eventually leads to ice shedding.

Ice protection systems : electro-mechanical systems

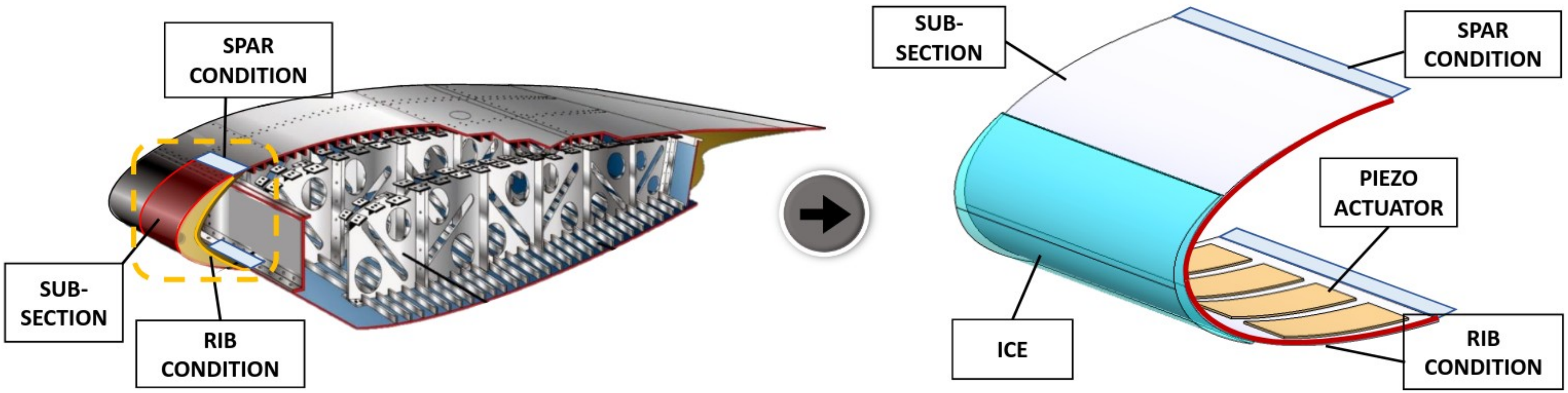
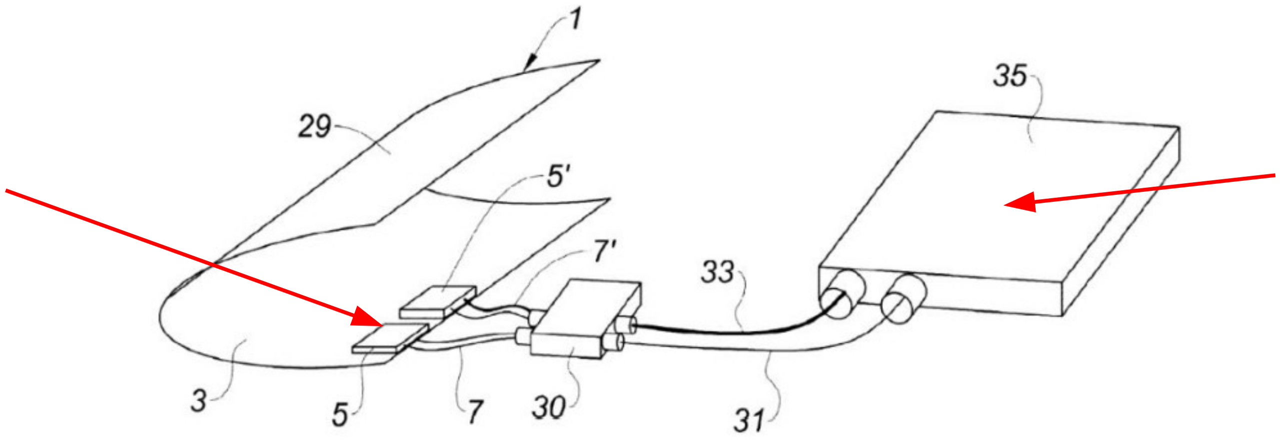


Figure 1.2 Leading edge reduction to an airfoil skin with boundary conditions

(V. Palanque, PhD, 2022)

The objective of the system is to trigger **the natural frequencies** of the airfoil to achieve de-icing.



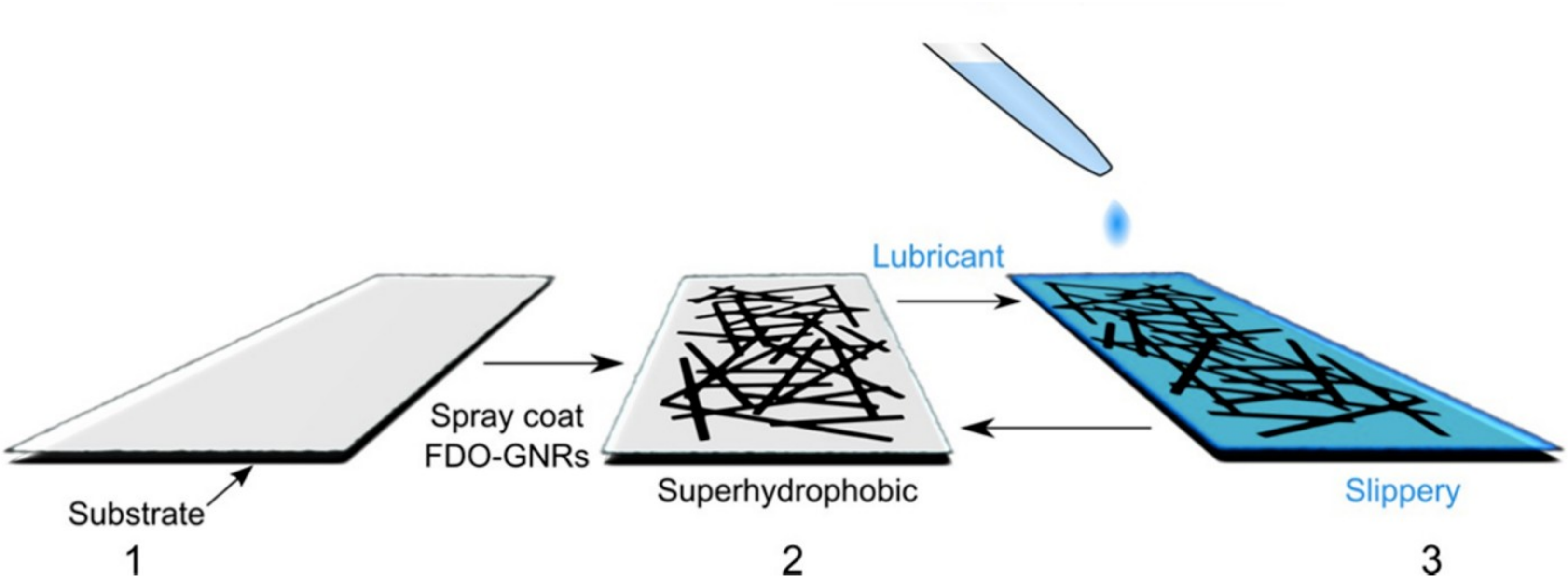
Piezoelectric actuator

Electric supply device

Gonidec, et al. (2019). Procédé d’alimentation électrique d’un dégivrage et d’un antigivrage de nacelle par ultrasons. Library Catalog: Google Patents.

Ice protection systems : passive anti-ice and de-ice systems

- Surface treatment or coating.
- Hydrophobic and/or icephobic properties



FDO-GNR films. Both anti and de-icing propertie. (Wang et al., ACS Appl. Mater. Interfaces, 2016)

- Main difficulty : coating **durability**, surface treatment **renewal**.
- Deteriorated surface condition may lead to enhanced accretion rate ⇒ May be counterproductive.
- Best option : **combine both passive and active** protection systems.

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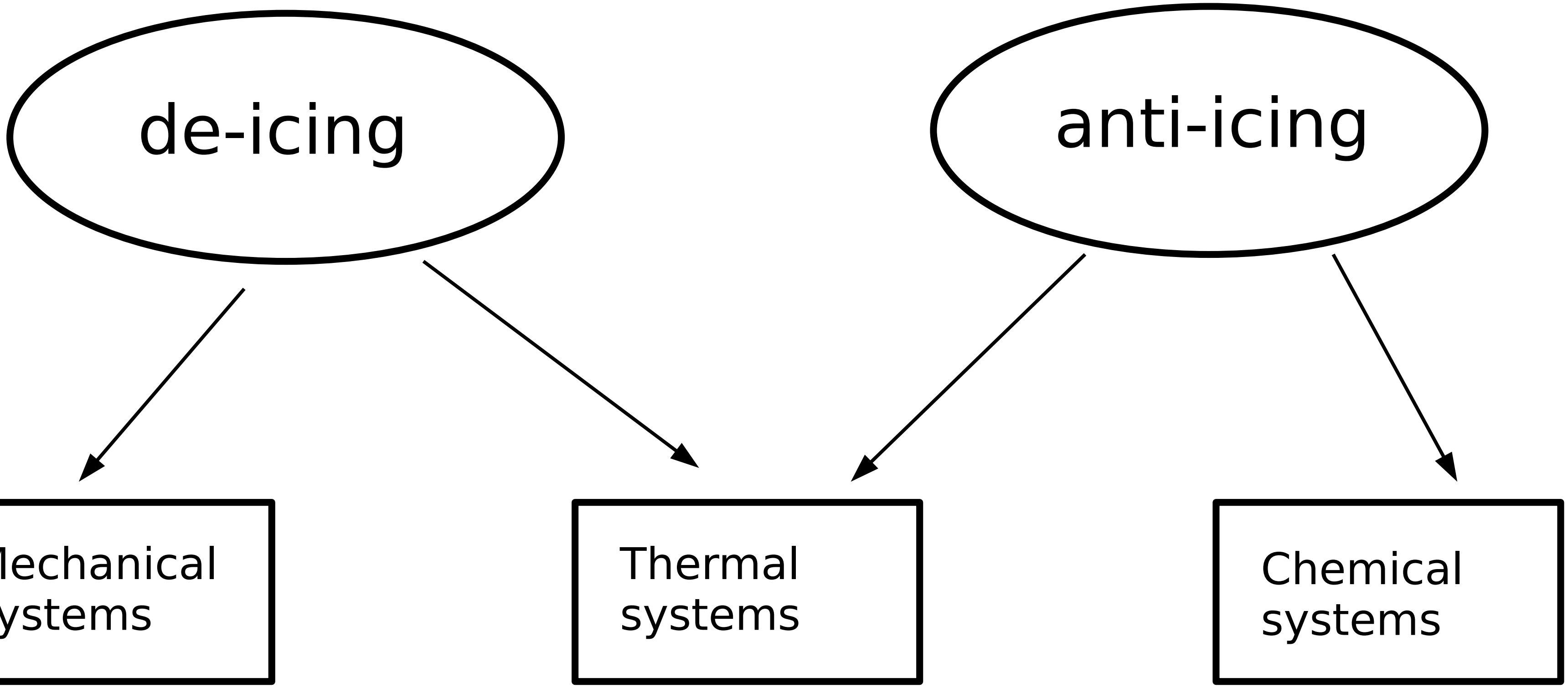
Prevention of ice from accumulating on surfaces or in aircraft systems.



de-icing

anti-icing

Mechanical systems

Thermal systems

Chemical systems

- Pneumatic boot systems
- Electromechanical systems (EMIPS).

- Electrothermal-type systems (ETIPS).
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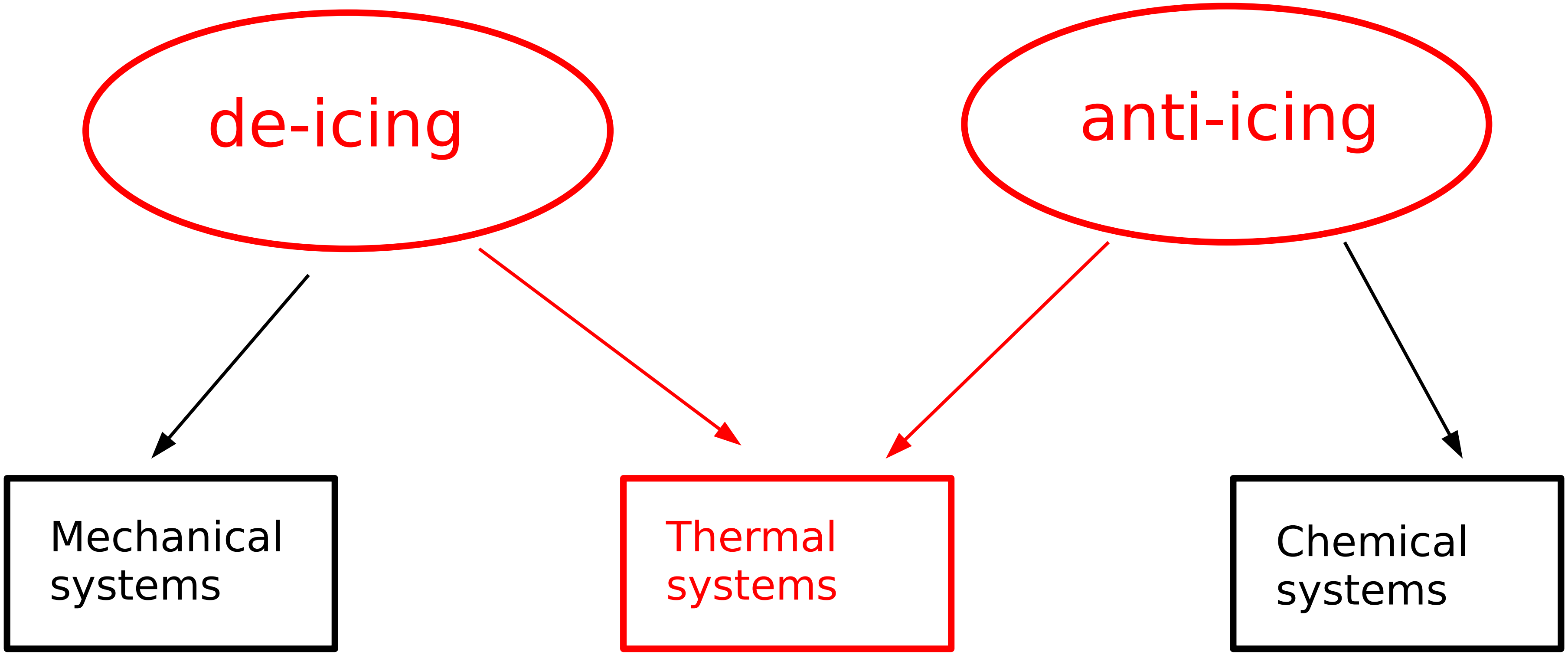

de-icing

anti-icing

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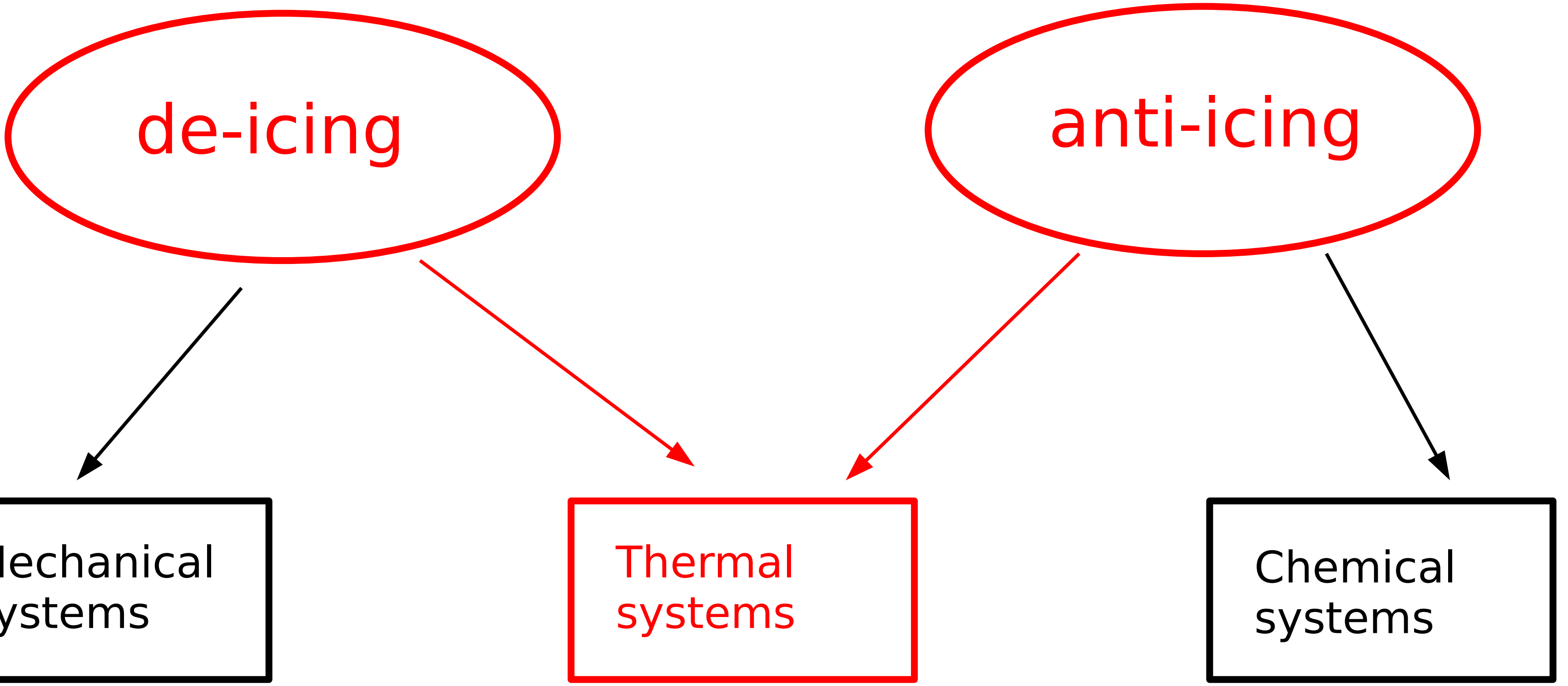

- Pneumatic boot systems
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- **Electrothermal-type systems (ETIPS).**
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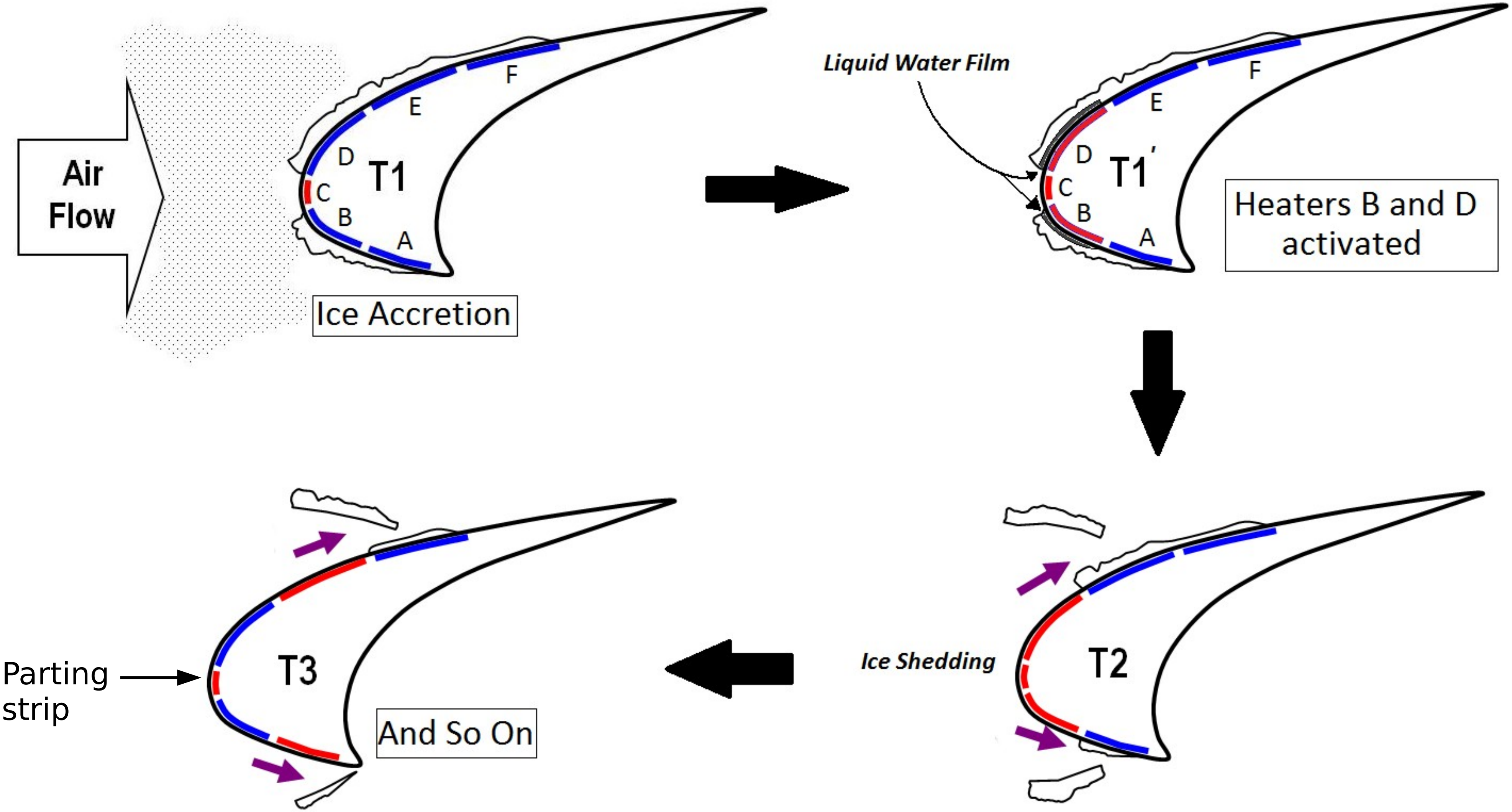
Electro-thermal ice protection system (ETIPS) : an unsteady phenomenon by nature



Operating of an ETIPS (Aerospace 2023)

Electro-thermal ice protection system (ETIPS) : physical phenomena

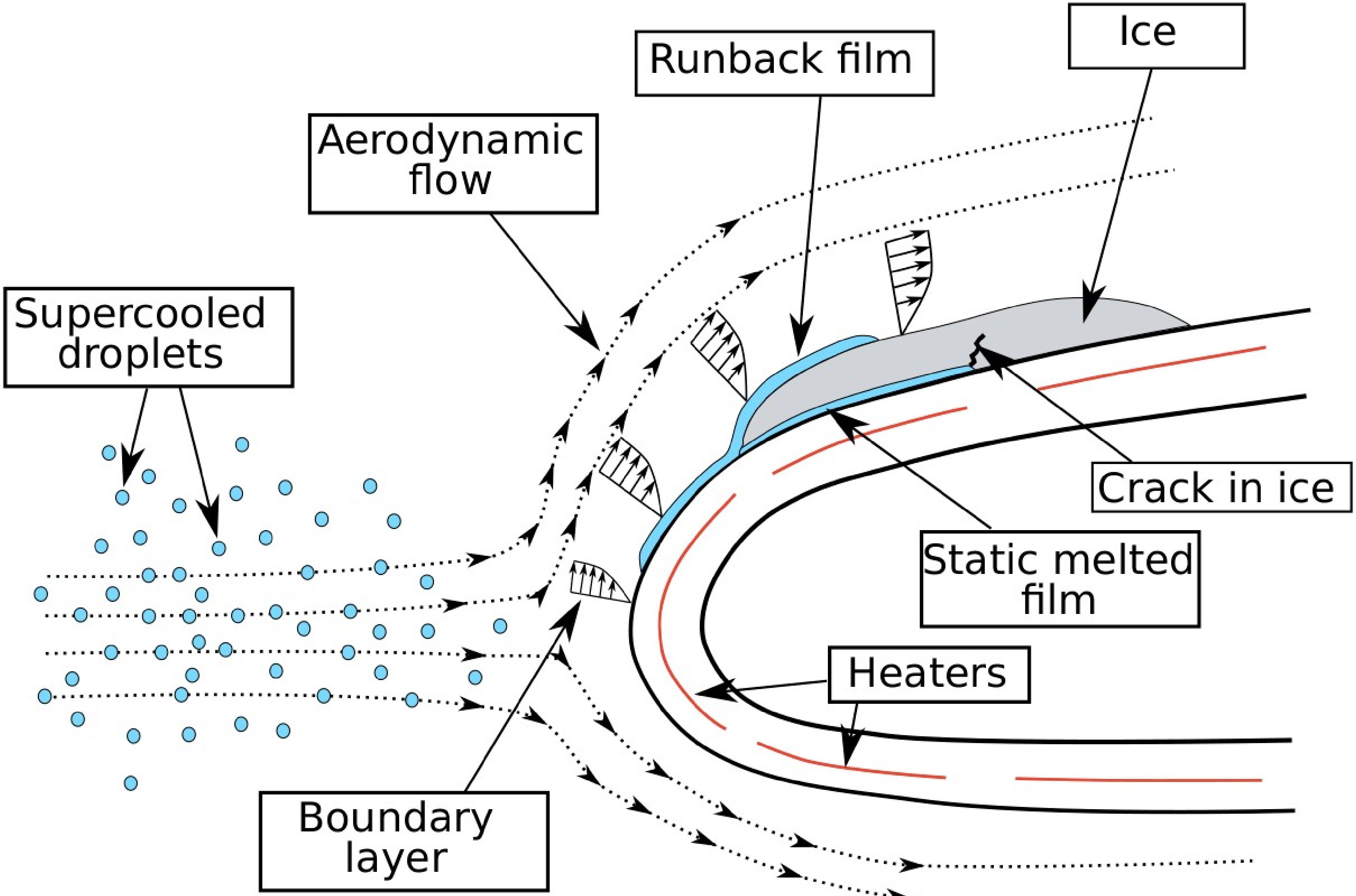
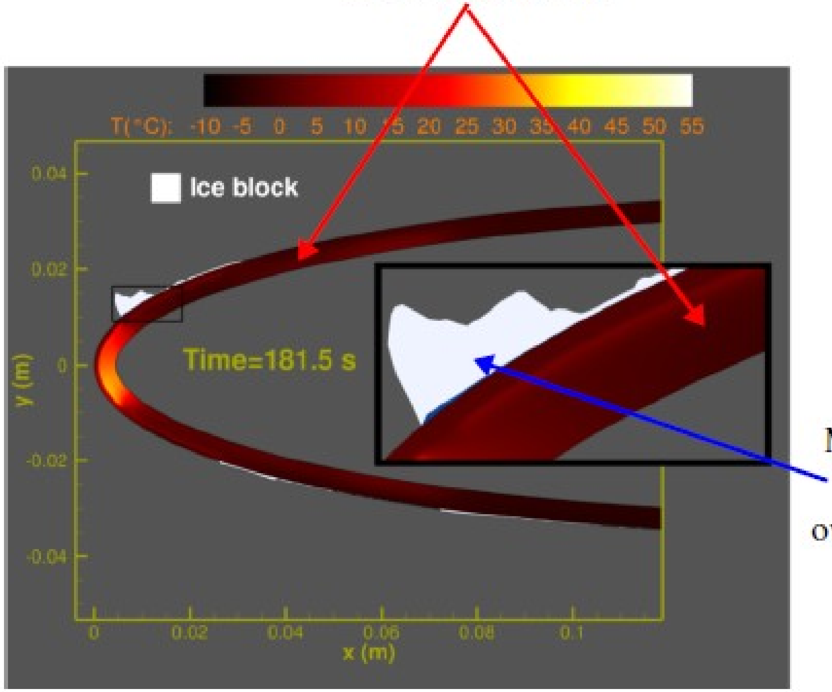


Illustration of the different physical phenomena taking place when an electrothermal ice protection system is being operated (Aerospace 2023)

Electro-thermal ice protection system (ETIPS) : shortcomings of the classical Messinger approach

- The Messinger balance is a steady state model unsuitable for the deicing mode where the phenomena are **intrinsically unsteady** (like ice shedding for instance).
- An uniform temperature. Needs to compute the **temperature gradients**.
- **No dynamics** for the liquid film which runbacks.



ETIPS2D: heat equation
inside the metal thickness
of the leading edge

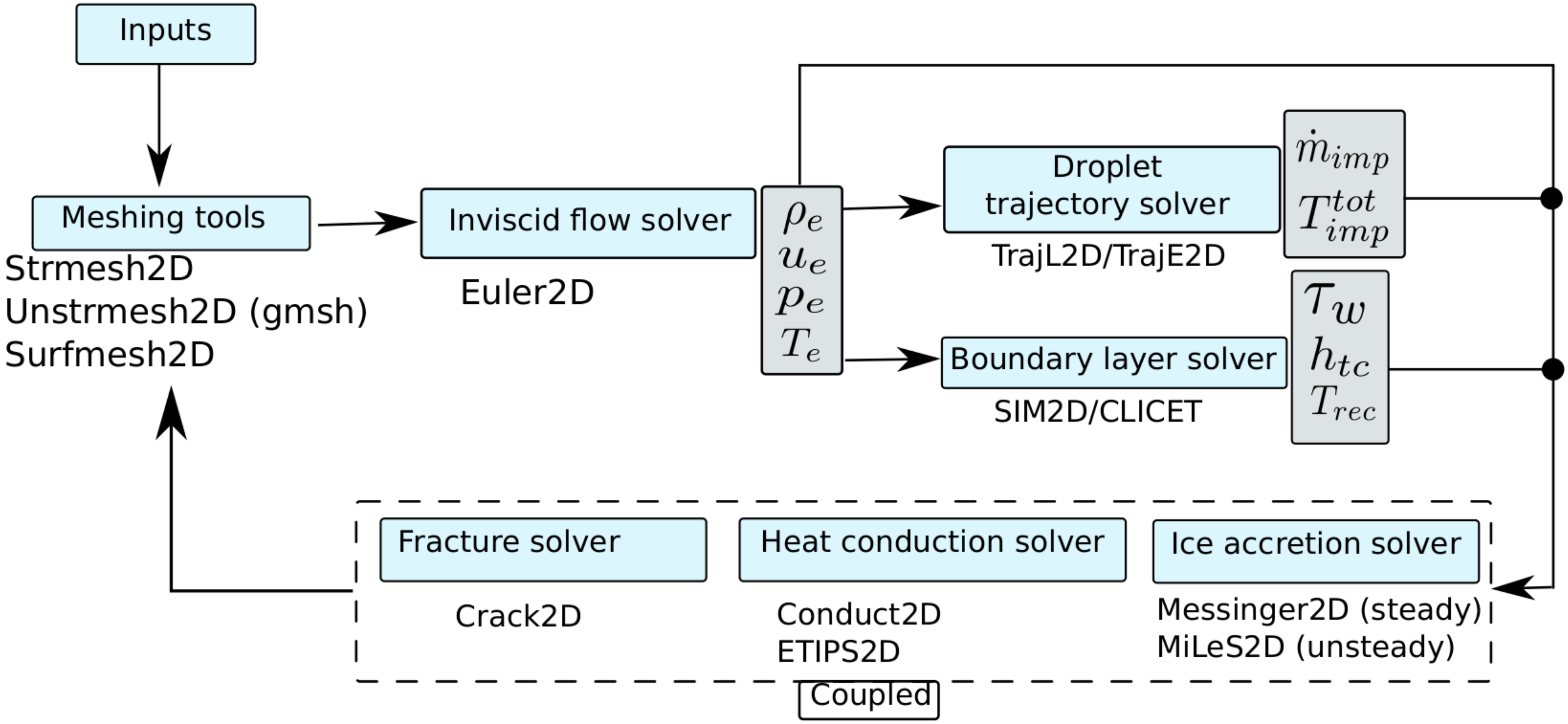
MiLeS2D: multi–layer solver
solid ice block (white)
over a static liquid water film (blue)

⇒ Need of a more sophisticated approach to compute ice shape

⇒ **The triple layer approach**

PhD works of Chauvin & Bennani

Electro-thermal ice protection system (ETIPS) : typical architecture of an icing suite



Inputs

Meshing tools

Strmesh2D
Unstrmesh2D (gmsh)
Surfmesh2D

Inviscid flow solver

Euler2D

ρ_e
u_e
p_e
T_e

Droplet trajectory solver

TrajL2D/TrajE2D

$\dot{m}_{imp}$
T_{imp}^{tot}

Boundary layer solver

SIM2D/CLICET

τ_w
h_{tc}
T_{rec}

Fracture solver

Crack2D

Heat conduction solver

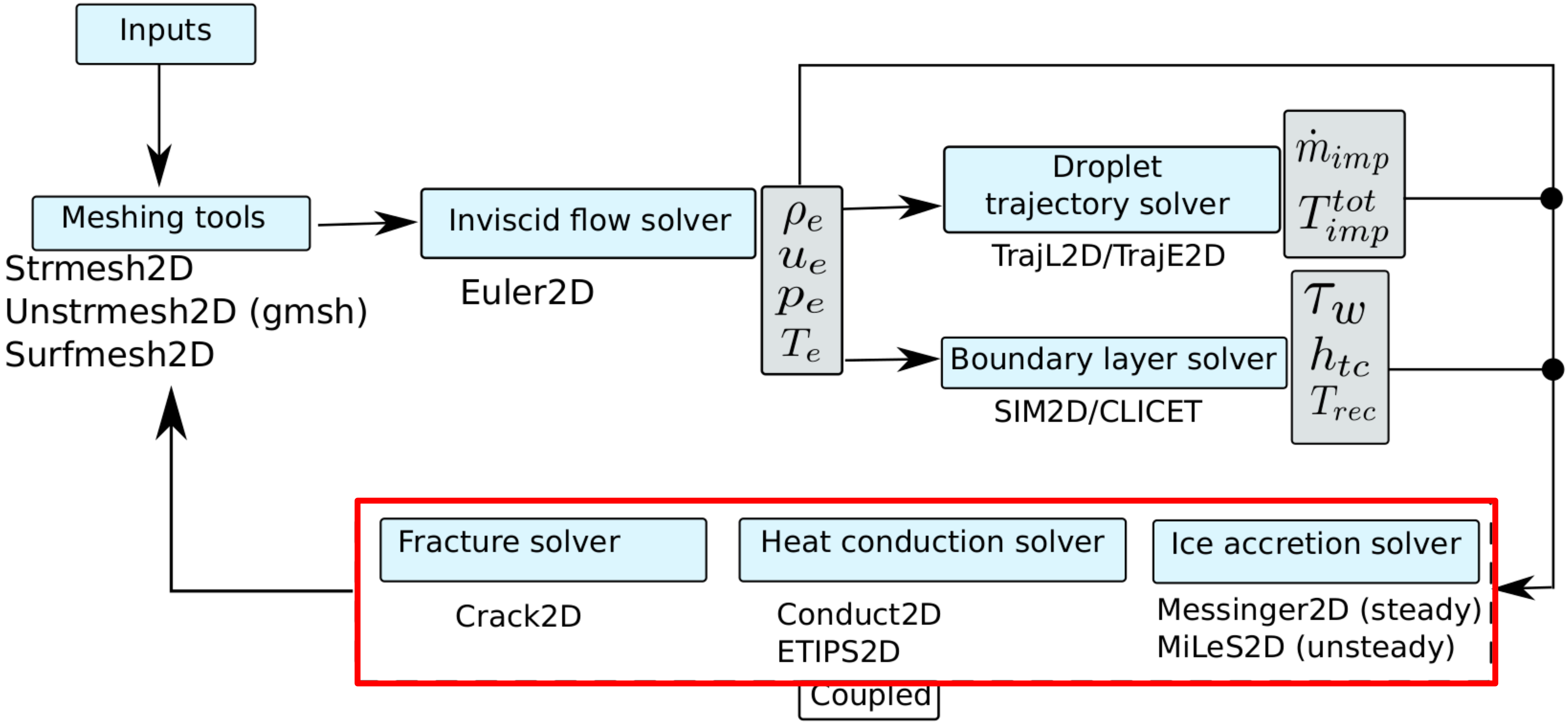
Conduct2D
ETIPS2D

Ice accretion solver

Messinger2D (steady)
MiLeS2D (unsteady)

Coupled

Electro-thermal ice protection system (ETIPS) : typical architecture of an icing suite



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τ_w
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Fracture solver

Crack2D

Heat conduction solver

Conduct2D
ETIPS2D

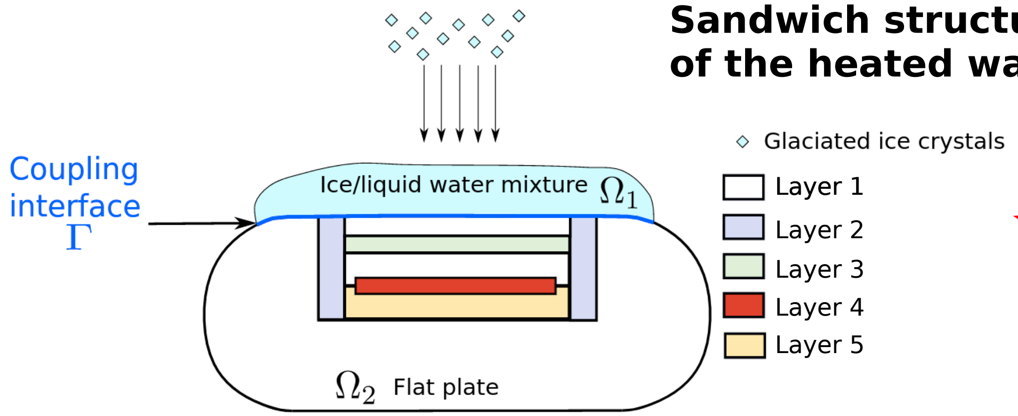
Ice accretion solver

Messinger2D (steady)
MiLeS2D (unsteady)

Coupled

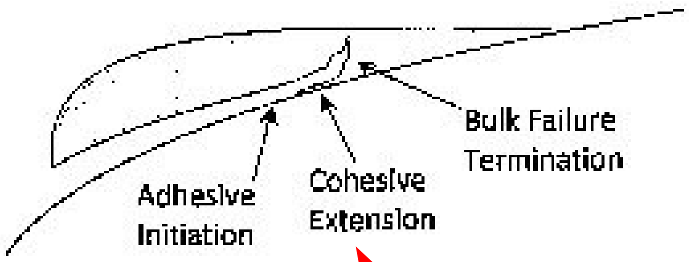
Electro-thermal ice protection system (ETIPS) : typical architecture of an icing suite

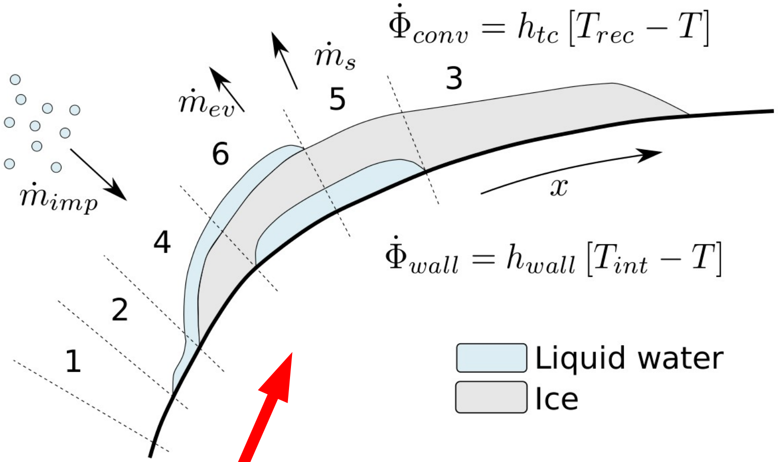
Sandwich structure of the heated wall.



Strong coupling

Fracture solver



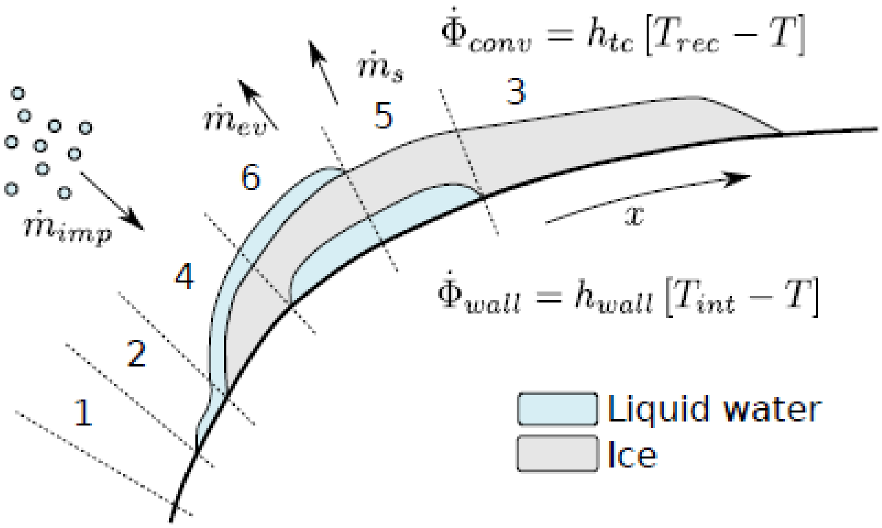


Triple layer approach

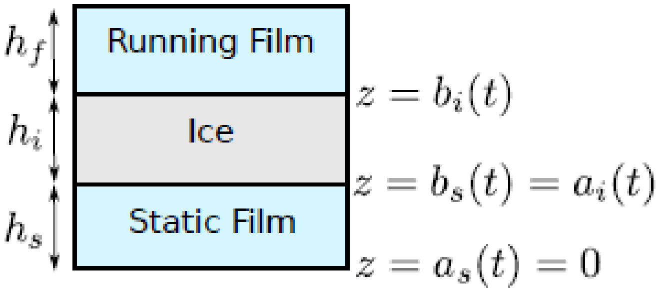
Fracture solver	Heat conduction solver	Ice accretion solver
Crack2D	Conduct2D ETIPS2D	Messinger2D (steady) MiLeS2D (unsteady)

Coupled

Electro-thermal ice protection system (ETIPS) : the triple layer approach



(a) Illustration of a generic icing situation.



6 possible modes :

1) full evaporative,
2) running wet,
3) rime ice,
4) glaze ice,
5) Rime ice+static film
6) Glaze ice+static film

- **Running film layer:**
  - ✓ Lubrification theory: $v_x(h_f) = \frac{\tau_a}{2\mu_w} h_f + \frac{1}{3\mu_w}\left(-\frac{\partial p}{\partial x} + \rho_w g_x\right) h_f^2$
  - ✓ Mass conservation: $\frac{\partial \rho_w h_f}{\partial t} + \frac{\partial \rho_w h_f v_x}{\partial x} = \Gamma_f$
  - ✓ Energy conservation: $\frac{\partial \rho_w c_w h_f T_f}{\partial t} + \frac{\partial \rho_w c_w h_f v_x T_f}{\partial x} = \Phi_f$

Classical **finite volume method**

- **Ice layer and melted film layer**
  - ✓ Heat transfer in the tangential direction is neglected
  - ✓ Mass conservation: $\frac{\partial \rho_k h_k}{\partial t} = \Gamma_k$
  - ✓ Energy conservation: $\frac{\partial \rho_k c_k T_k}{\partial t} = \lambda_k \frac{\partial^2 T_k}{\partial z^2}$ + **boundary conditions**

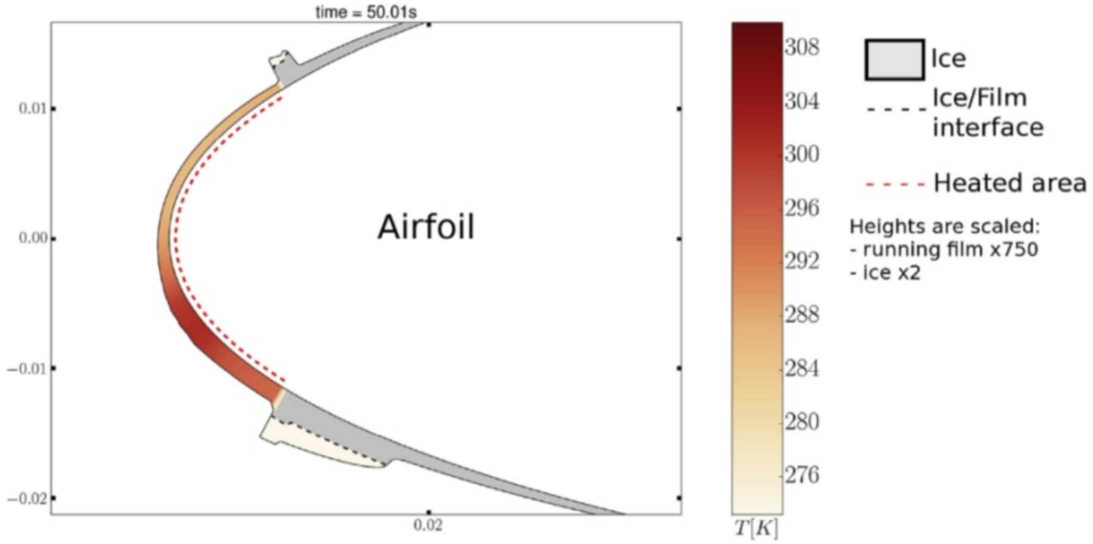
Finite element method

$$T_k(t, \bar{z}) = \sum_{j=1}^{n} \theta_{kj}(t)\psi_j(\bar{z})$$

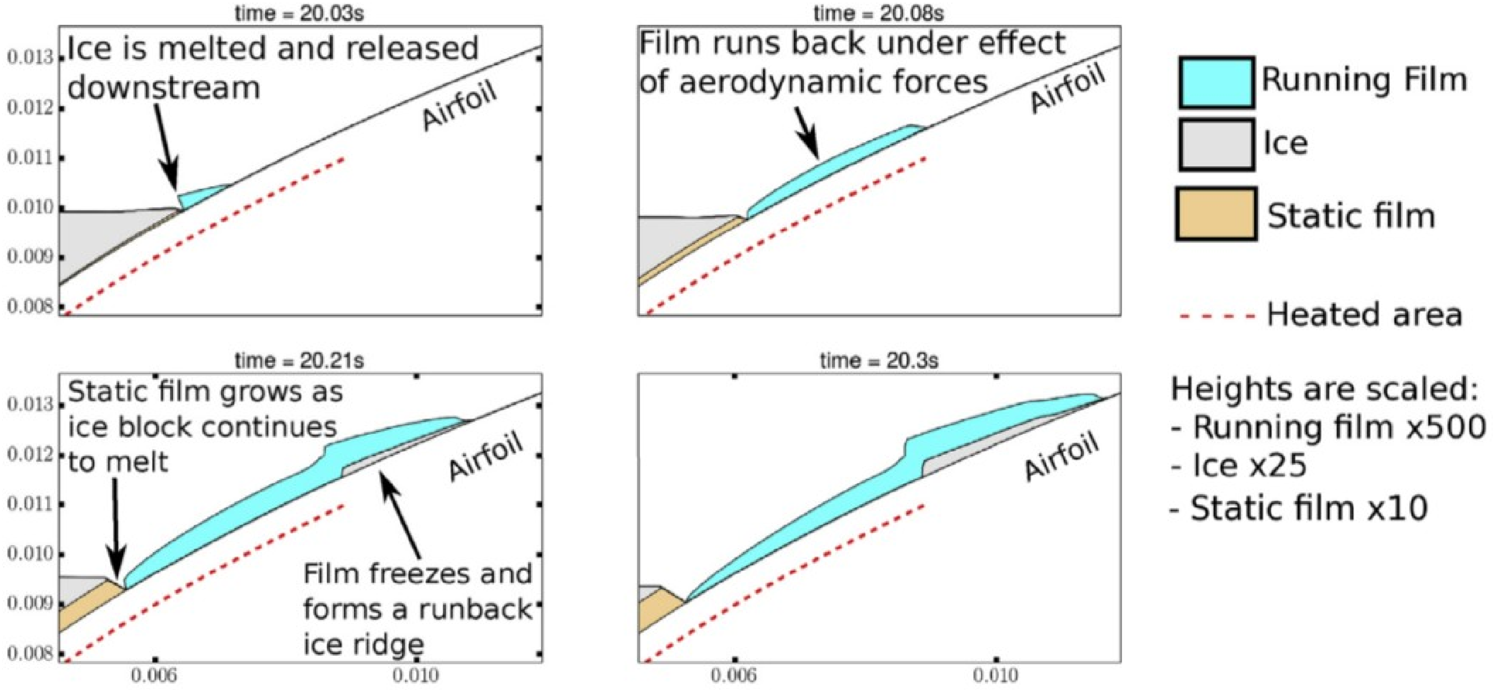
Chauvin et al., FINEL 2018

Electro-thermal ice protection system (ETIPS) : the triple layer approach. An illustration.

runback ice build-up (ice ridges).



Heights are scaled:
- running film x750
- ice x2



Ice is melted and released downstream

Film runs back under effect of aerodynamic forces

Static film grows as ice block continues to melt

Film freezes and forms a runback ice ridge

Heights are scaled:
- Running film x500
- Ice x25
- Static film x10

Chauvin et al., FINEL 2018

Electro-thermal ice protection system (ETIPS). Coupling between the ice accretion solver and the heat conduction solver.

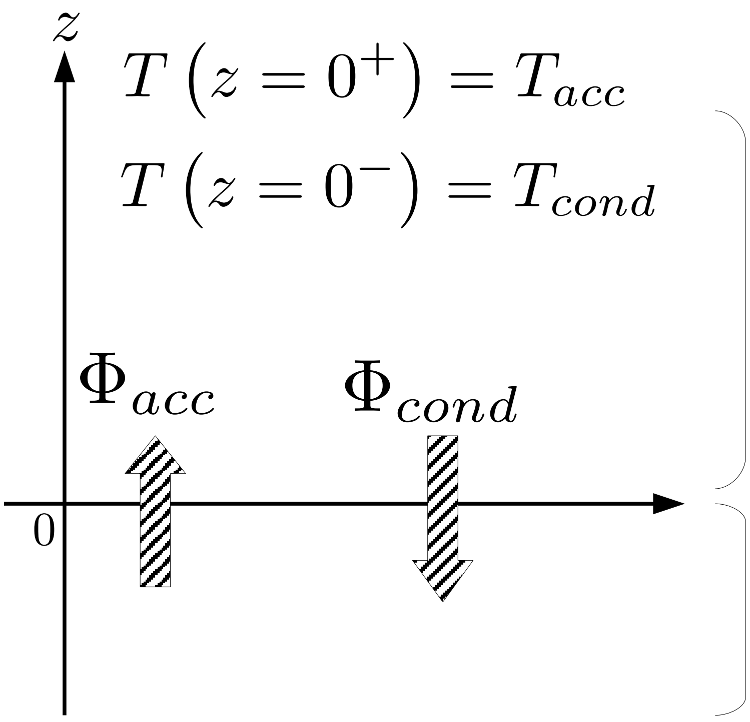
Loop on *(k)* :

$$-\Phi_{acc}^{(k)} = \omega_1 \left(T_{cond}^{(k-1)} - T_{acc}^{(k)}\right) - \Phi_{cond}^{(k-1)}$$

Boundary condition from the **heat conduction solver (wall)** to the **accretion solver**.

$$\Phi_{cond}^{(k)} = \omega_2 \left(T_{acc}^{(k)} - T_{cond}^{(k)}\right) + \Phi_{acc}^{(k)}$$

Boundary condition from the **accretion solver** to the **heat conduction solver (wall).**



$$T\left(z = 0^{+}\right) = T_{acc}$$

$$T\left(z = 0^{-}\right) = T_{cond}$$

Accretion solver

Heat conduction solver (wall)

- The coupling coefficients ω_1 and ω_2 are optimized by a **Schwarz algorithm**.
- **Mathematical** framework for unsteady problems with linear BC and steady problems with non-linear BC.
- To convergence :

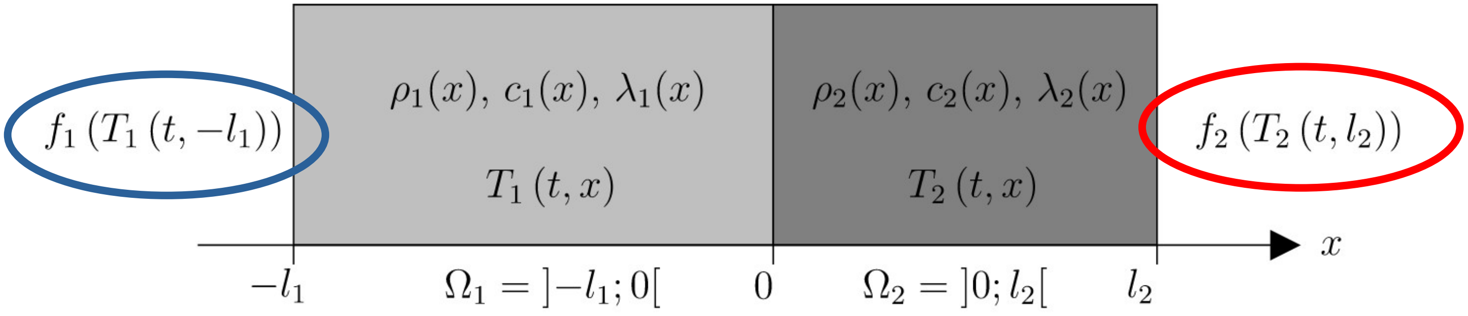
$$T_{cond}^{\infty} = T_{acc}^{\infty}$$

$$\Phi_{cond}^{\infty} = \Phi_{acc}^{\infty}$$

Chauvin et al., FINEL 2018

Electro-thermal ice protection system (ETIPS). Schwarz coupling. Illustration on solving the heat equation.

Conduction solver



Material	ρ_i (kg m^{-3})	$c_{p,i}$ (J kg^{-1} K^{-1})	λ_i (W m^{-1} K^{-1})	$h_{tc,i}$ (W m^{-2} K^{-1})	$T_{r,i}$ (K)
1	1000	4181	0.6	200	313.15
2	2700	900	167	500	300

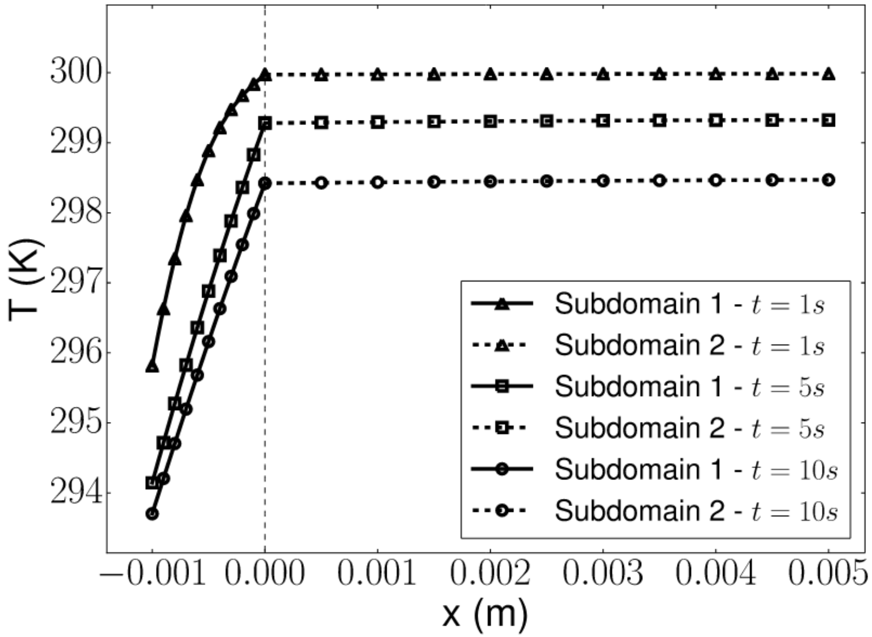
$$f_1\left(T_1\left(-l_1\right)\right) = \underbrace{\dot{m}_{ev}(T_1\left(-l_1\right))\left(c_{p,1}T_1\left(-l_1\right) + L_v(T_1\left(-l_1\right))\right)}_{\text{Non-linear contribution (evaporation)}} + \underbrace{h_{tc,1}\left(T_1\left(-l_1\right) - T_{r,1}\right)}_{\text{Linear contribution}}$$

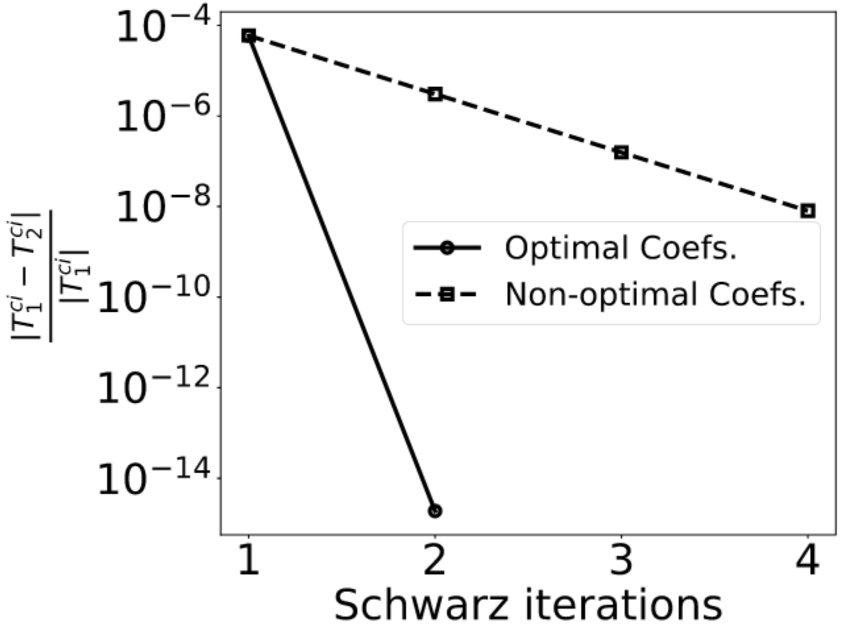
$$f_2\left(T_2\left(l_2\right)\right) = h_{tc,2}\left(T_2\left(l_2\right) - T_{r,2}\right)$$ Linear contribution

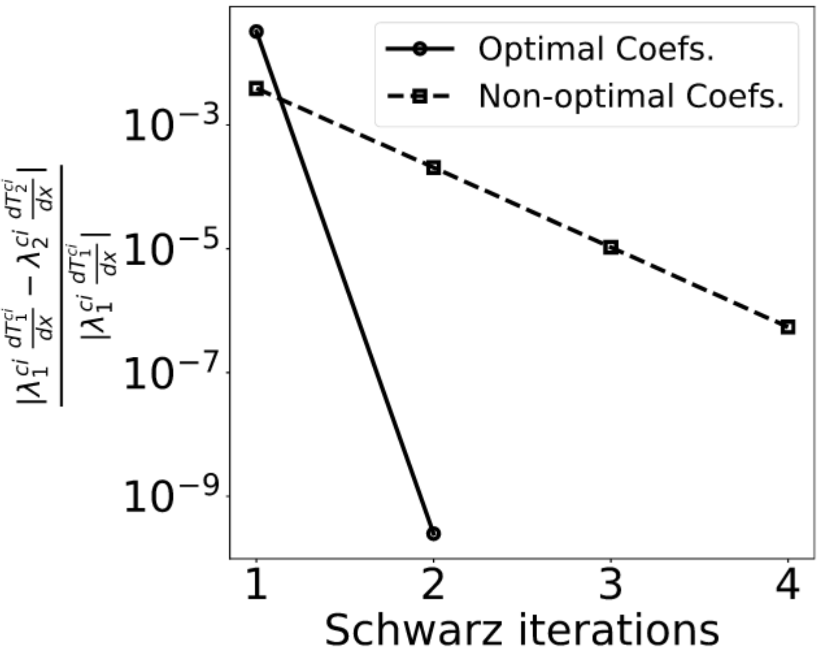
Bennani et al., CAMWA 2020

Electro-thermal ice protection system (ETIPS). Schwarz coupling. Illustration on solving the heat equation.

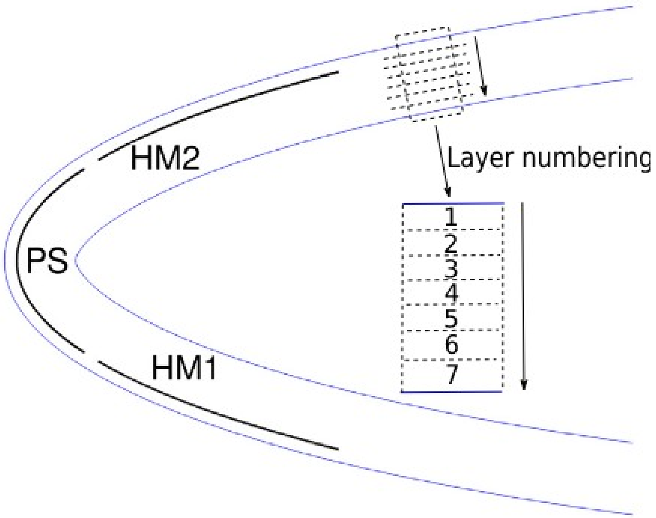
Bennani et al., CAMWA 2020





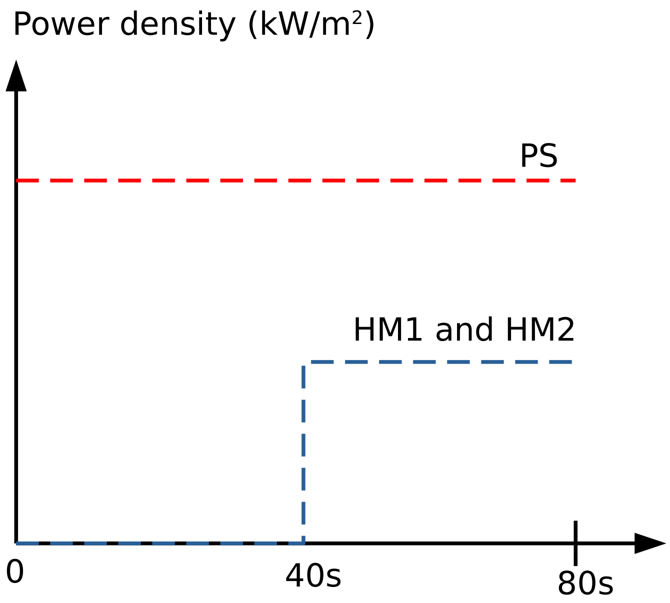


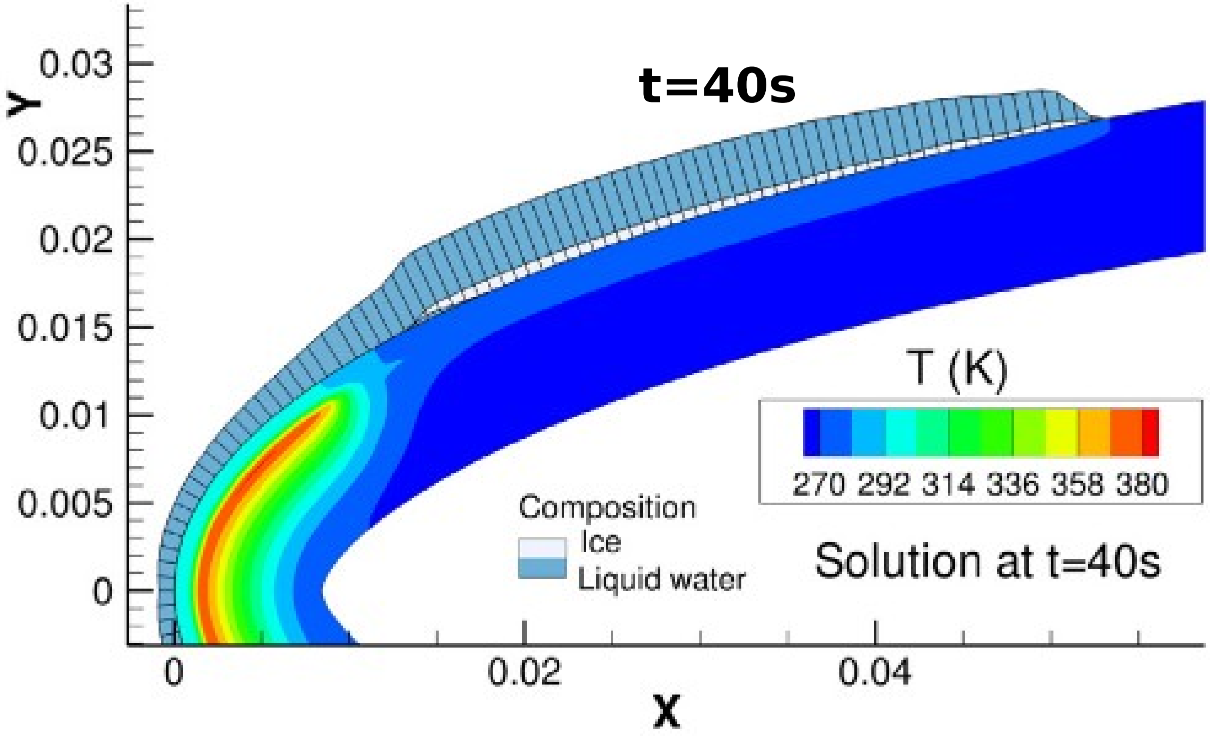
Electro-thermal ice protection system (ETIPS). Schwarz coupling. Illustration on a real accretion problem (1/2).



Heated leading edge :

- 1 parting strip (PS) permanently on.
- 2 symetric heater mats (HM).
- Unsteady (deicing) mode

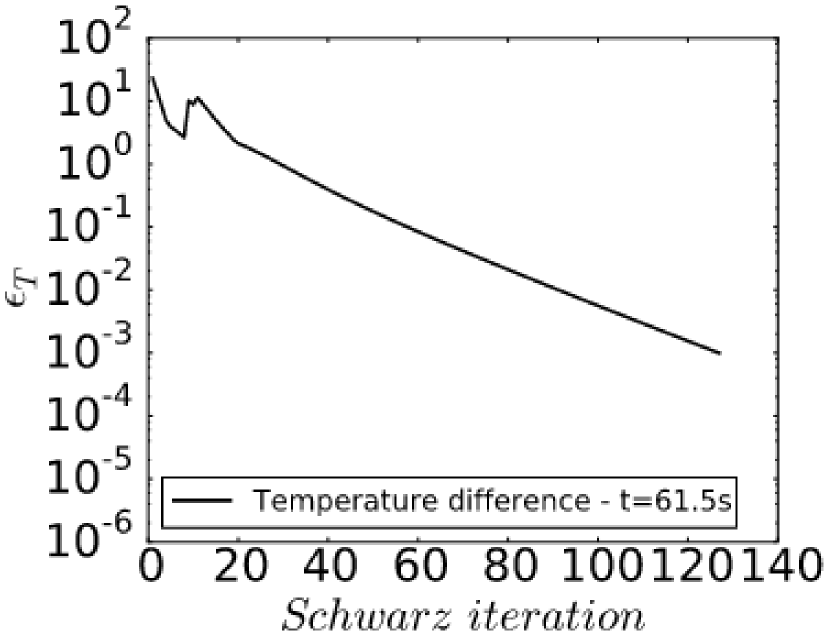


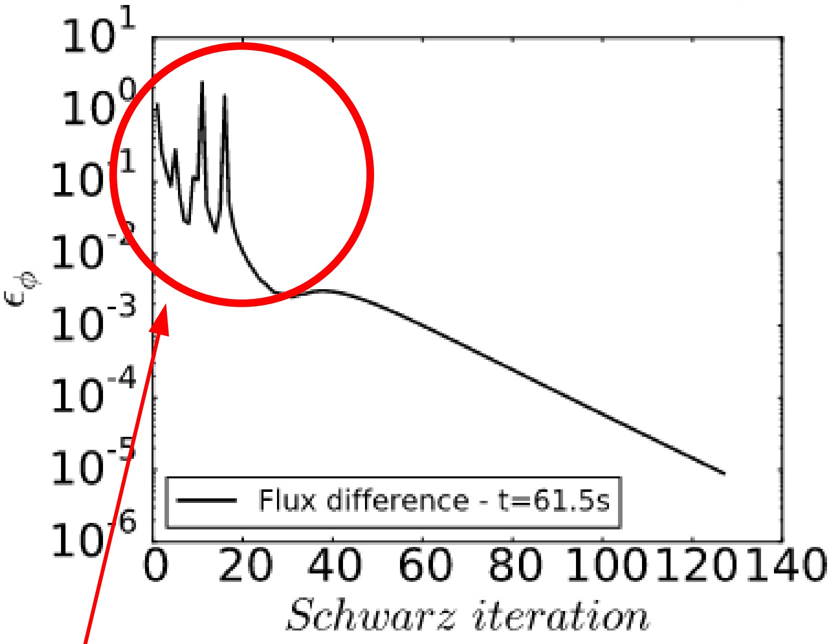


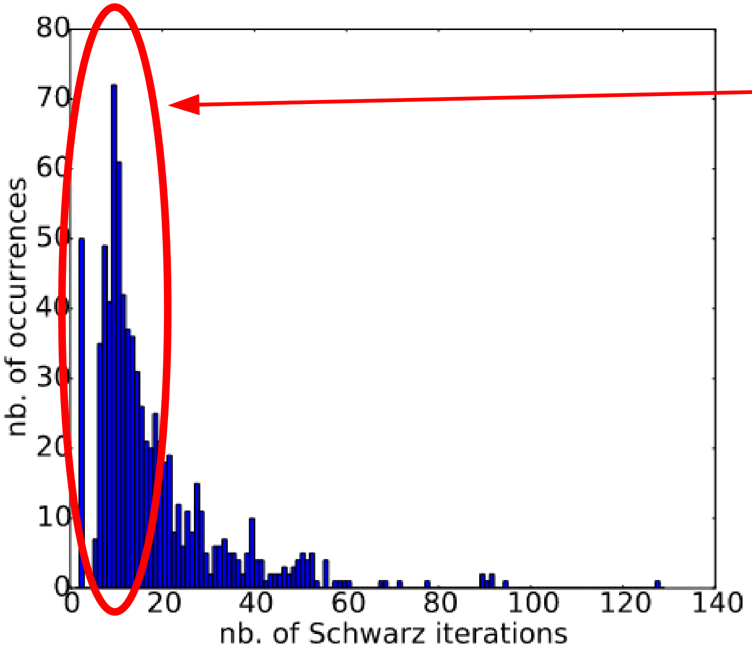
Bennani et al., CAMWA 2020

Electro-thermal ice protection system (ETIPS). Schwarz coupling. Illustration on a real accretion problem (2/2).

Bennani et al., CAMWA 2020





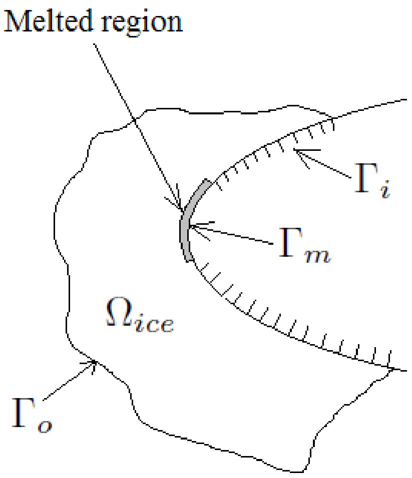


Oscillations between accretion modes : rime, glaze, running wet, static film, ...

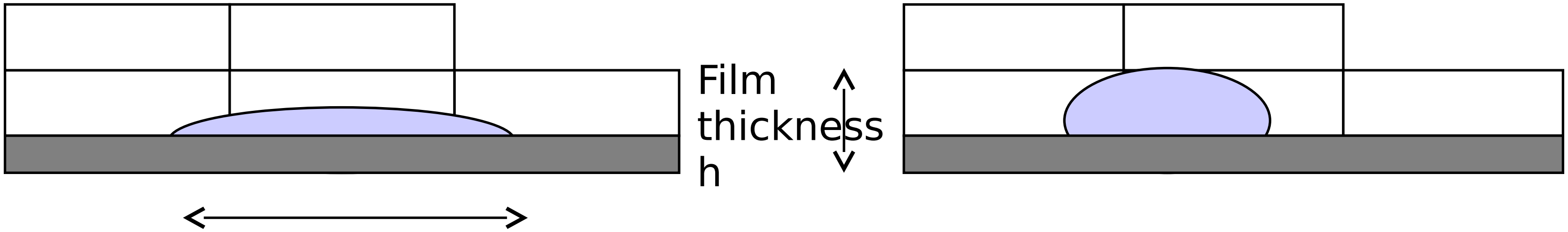
- **Stiff coupling** for real applications.
- Justifies an **optimization** of the coupling coefficients to **maximize and sometimes make possible** the convergence.

Electro-thermal ice protection system (ETIPS). Ice shedding.

Theoretically, ice shedding due to heating and aerodynamic forces



- No **reliable correlations** available with aerodynamic forces
- **Empirical criteria** based on L (film width) and h (film thickness)



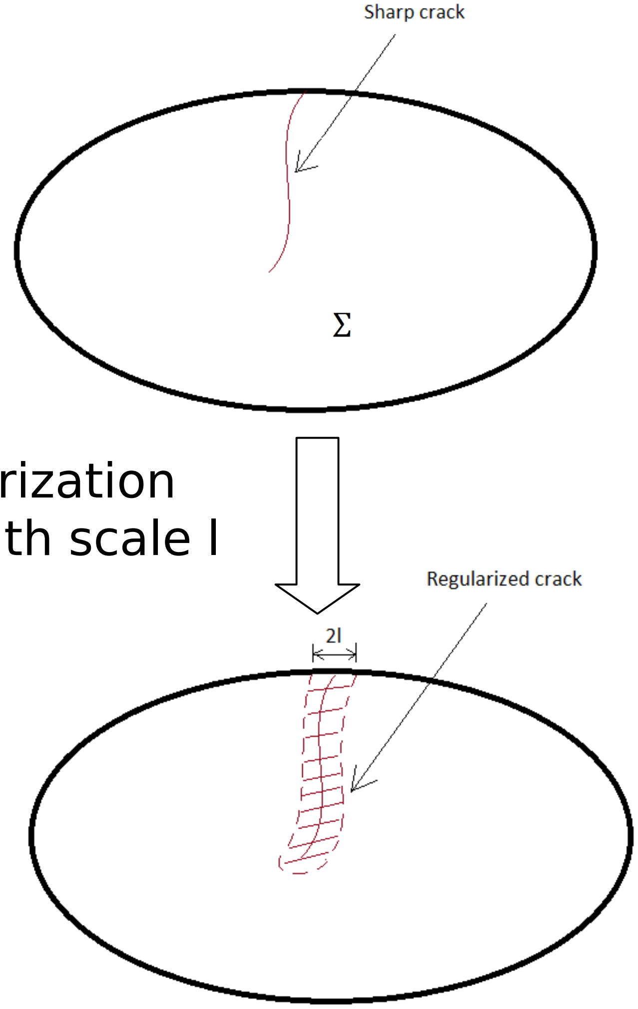
Film thickness h

film width L

Electro-thermal ice protection system (ETIPS). Modeling the mechanical behavior and shedding of ice

Physical model

- General idea: evaluate the energy required to create/propagate a crack and compare to available internal energy



Regularization
by length scale l

Crack energy:

$$\rightarrow \quad E_\Gamma = g_c \mathcal{A}(\Sigma)$$

g_c : crack energy release rate

Regularized crack energy
(Bourdin *et al.*, 2008):

$$\rightarrow \quad E_\Gamma = \int_\Omega g_c \gamma \, dV$$

$$\gamma = \underbrace{\frac{1}{2l} d^2}_{\text{Tends to localize}} + \underbrace{\frac{l}{2} |\nabla d|^2}_{\text{Tends to spread}}$$

d : Damage function

(Christian Miehe, Martina Hofacker, Fabian Welschinger, A phase field model for rate-independent crack propagation: Robust algorithmic implementation based on operator splits, Computer Methods in Applied Mechanics and Engineering, 2010)

Electro-thermal ice protection system (ETIPS). Modeling the mechanical behavior and shedding of ice

Physical model

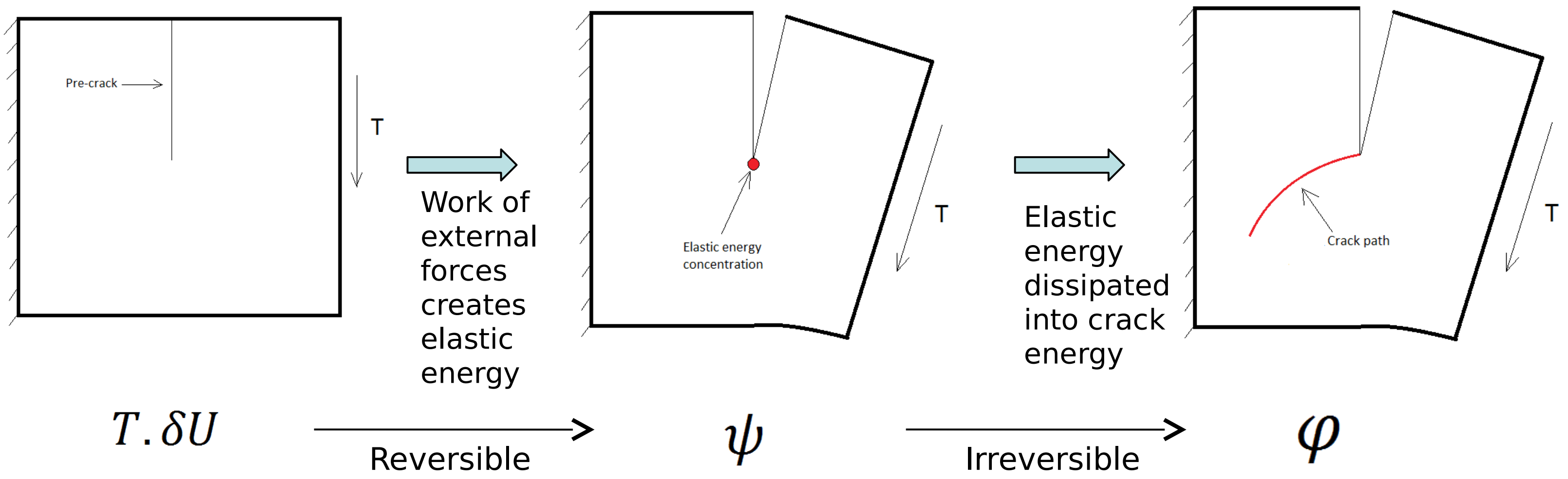
- Total energy balance: $E_{tot} = E_{int} + E_{crack}$

$$\int_\Omega \psi \, dV \qquad\qquad \int_\Omega \varphi \, dV = \int_\Omega g_c \gamma \, dV$$

- Conservation of energy: $\delta E_{tot} = W_{ext} = \int_{\partial\Omega} T . \delta U \, dS$

Allows to write a **stationary damaged equilibrium state** compatible with the external constraints + **equation on the damage function *d*.**

- Energy transfer illustration:



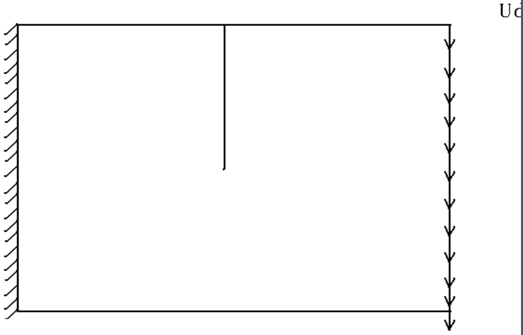
Work of external forces creates elastic energy

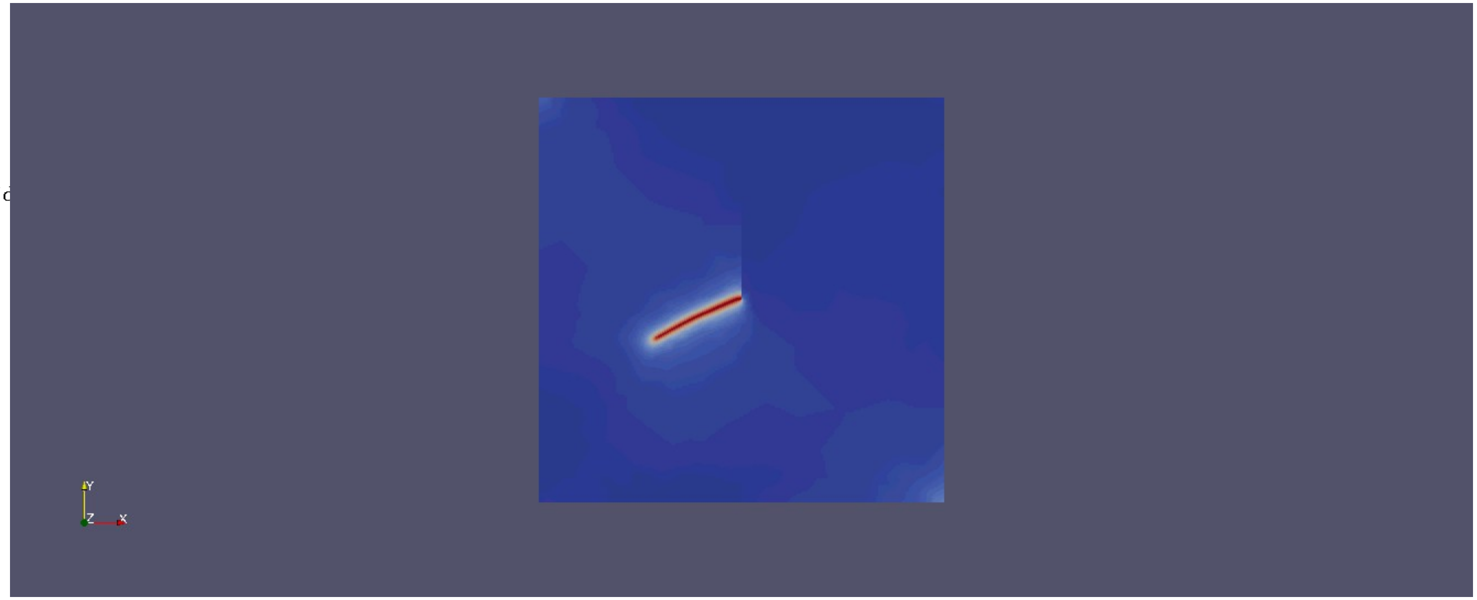
Elastic energy dissipated into crack energy

$T . \delta U \xrightarrow[\text{Reversible}]{} \psi \xrightarrow[\text{Irreversible}]{} \varphi$

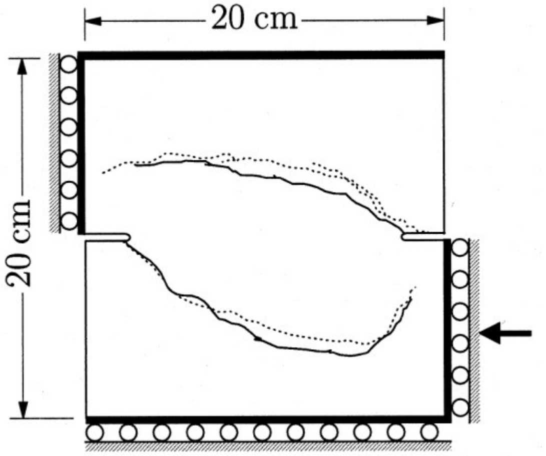
Electro-thermal ice protection system (ETIPS). Modeling the mechanical behavior and shedding of ice. Basic tests.

- ➢ Shear test (fine mesh)

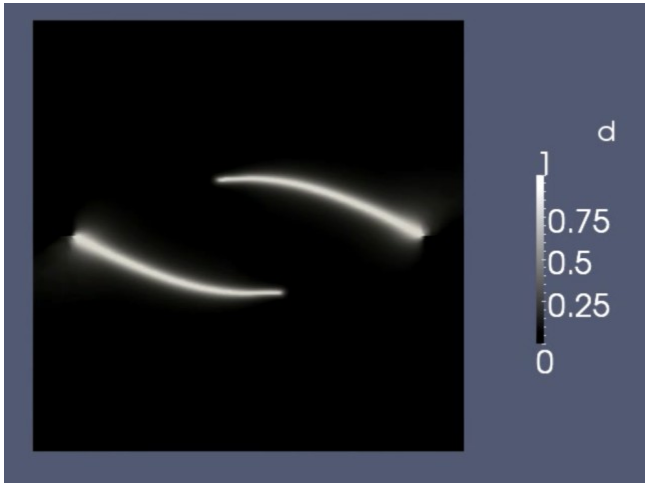




- ➢ Mixed Mode, comparison with experiments:



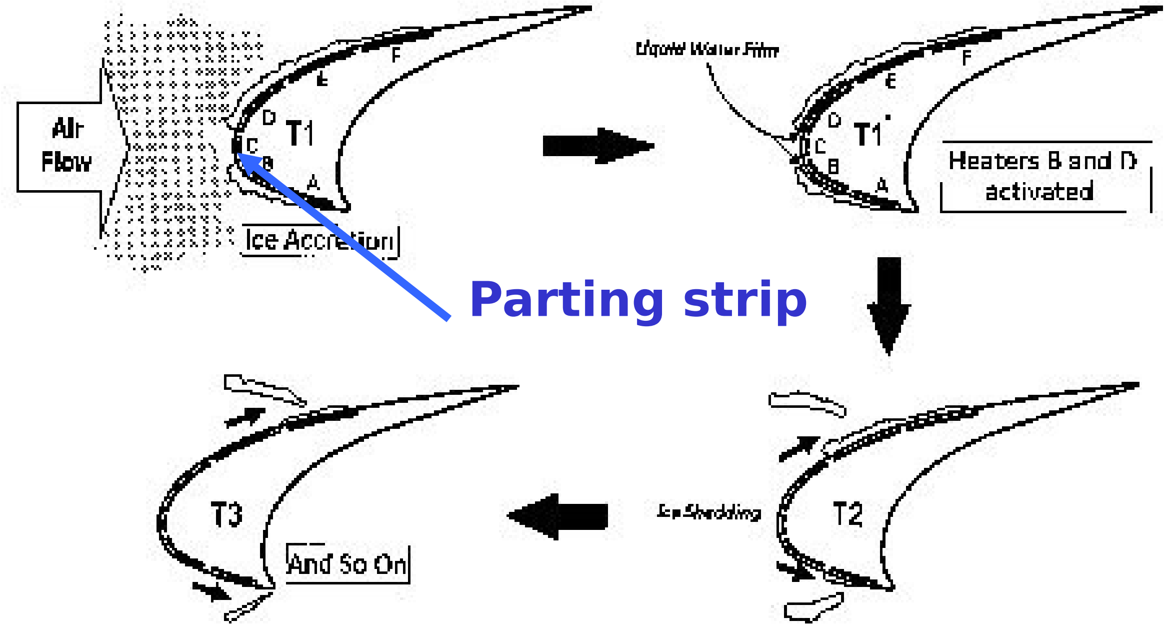
Experiment



Simulation

Bolander *et al.* Fracture analyses using spring networks with random geometry, Engineering Fracture Mechanics 61 (1998) 569-591

Electro-thermal ice protection system (ETIPS). Scenario.



Parting strip

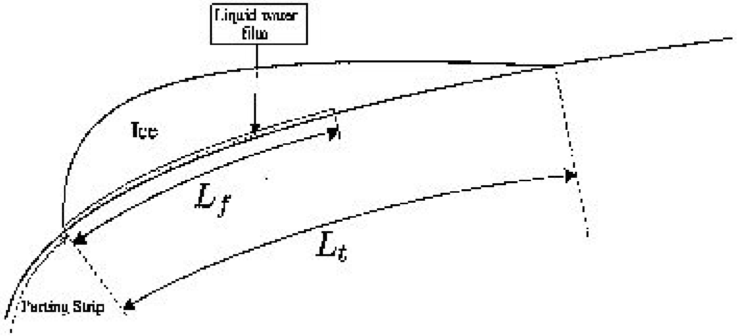
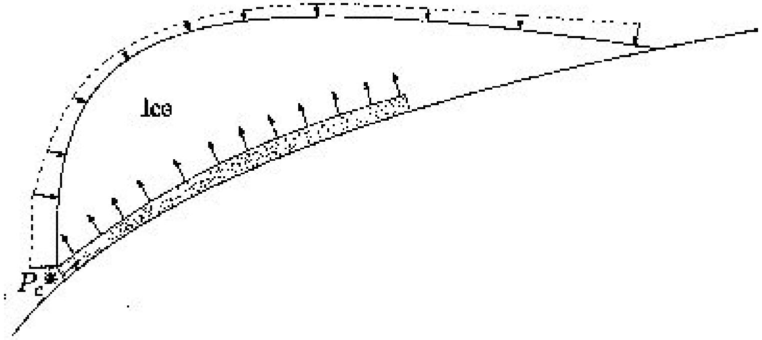


Figure 5.2: Geometrical Illustration



- Pressure in Pc* transferred entirely into the film (hydrostatic balance).

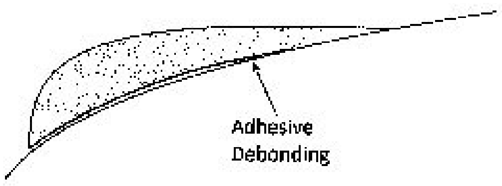
- Air flow accelerates to bypass the ice layer => pressure in the film > external pressure.

- => A force appears. Added to this are the viscous effects

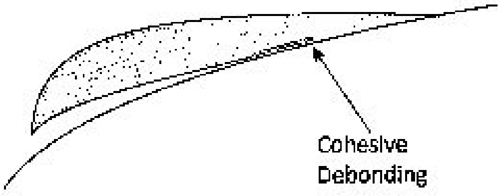
PhD thesis, Bennani, 2014

Electro-thermal ice protection system (ETIPS). Scenario.

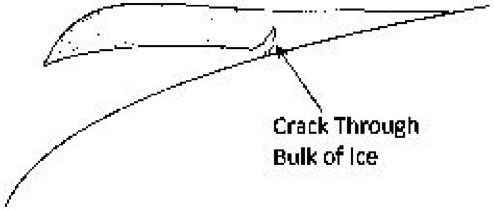
- **Shedding in adhesive mode**. Part of the interface is melted and the adhesive forces holding the ice to the surface are no longer sufficient.



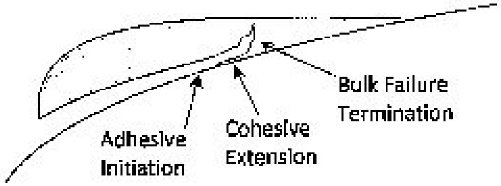
- **Shedding in cohesive mode**. Part of the interface is melted. Ice may still adhere, but a crack may initiate near the stress concentration zone and propagate along the surface.



- **Fracture in the core of the ice.** Part of the interface is melted. Ice can still adhere, but a crack can initiate near the stress concentration zone and propagate into the core of the ice block.

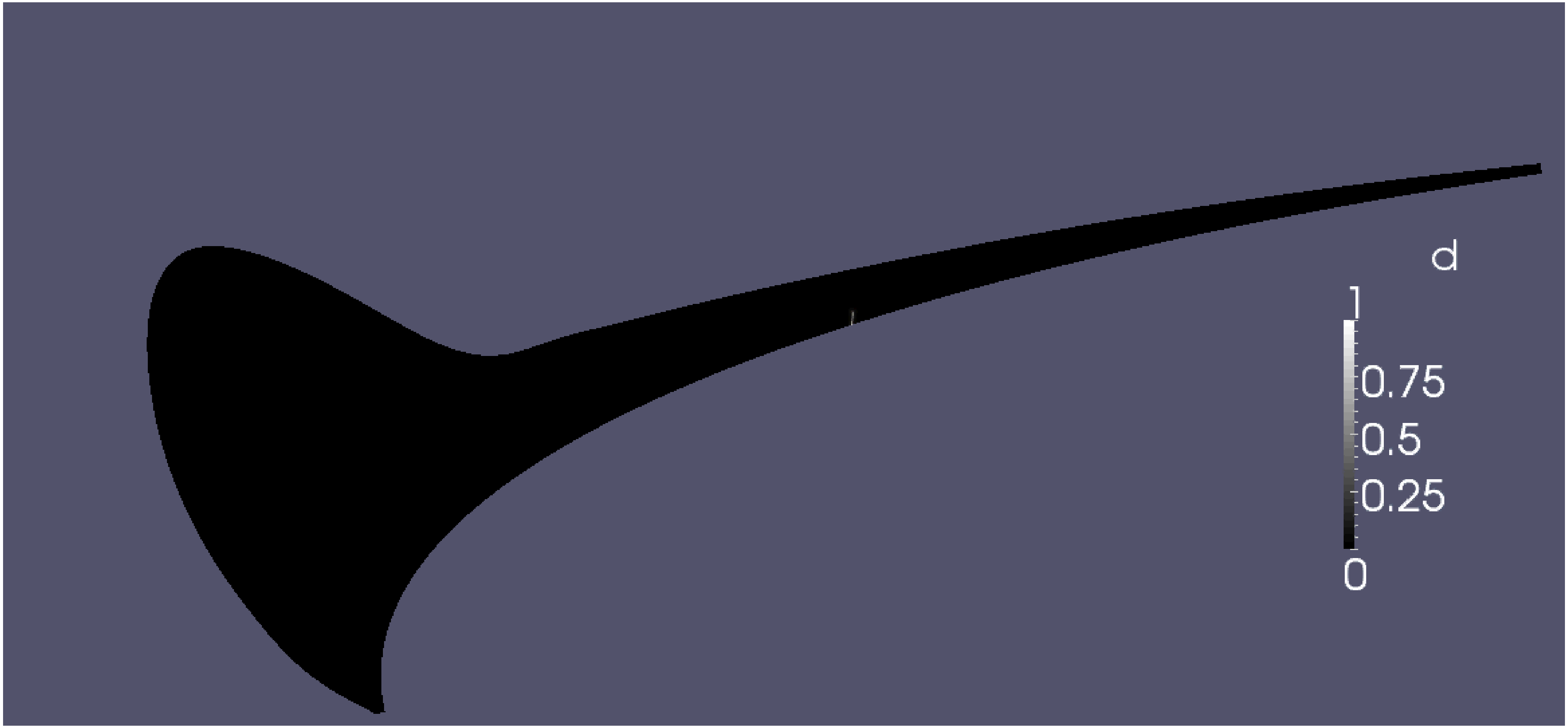


- Ice shedding is an **interaction** of all the above phenomena.



PhD thesis, Bennani, 2014

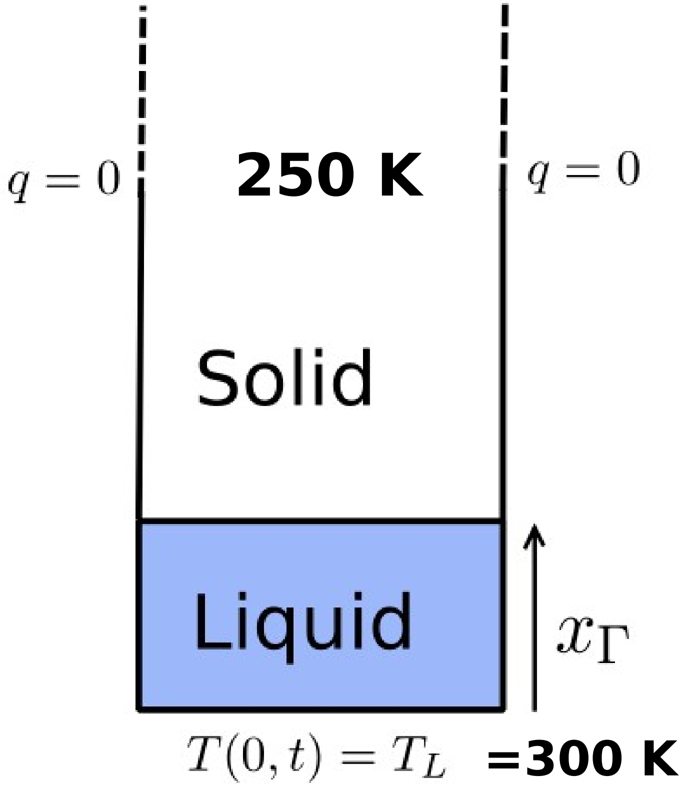
Electro-thermal ice protection system (ETIPS). Scenario.

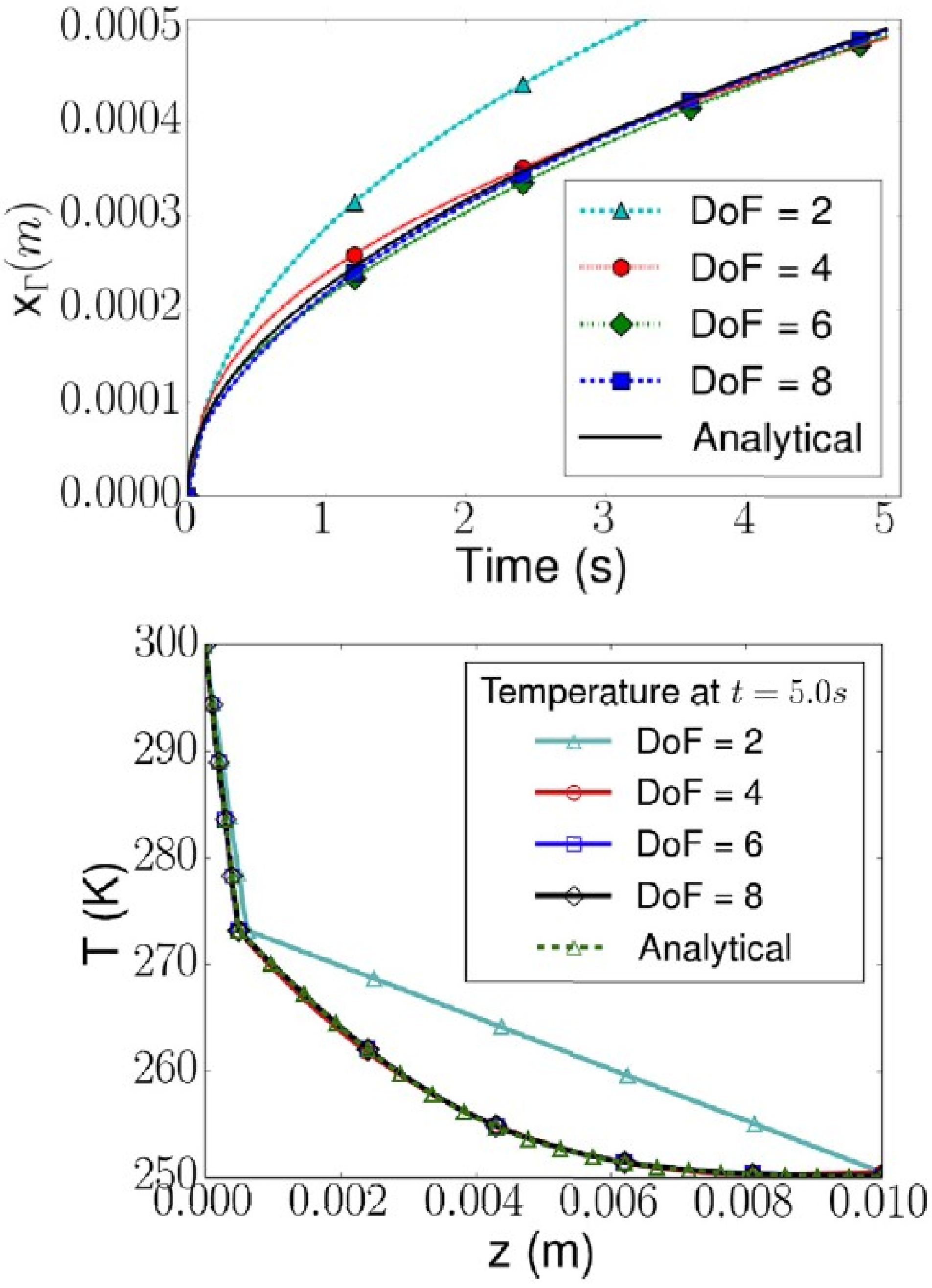


PhD thesis, Bennani, 2014

Electro-thermal ice protection system (ETIPS). Illustrative test cases.

Stefan problem

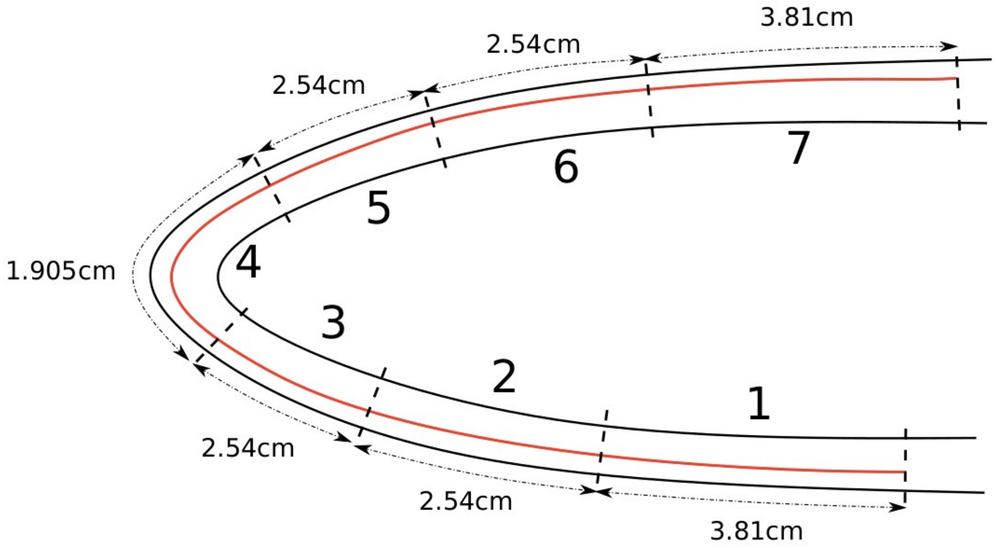


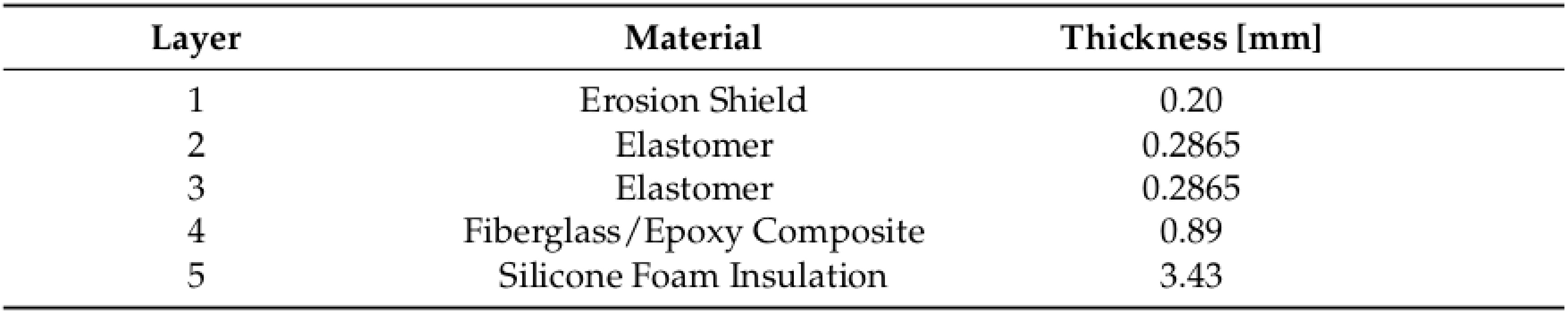


(b) Temperature profile at $t = 5s$

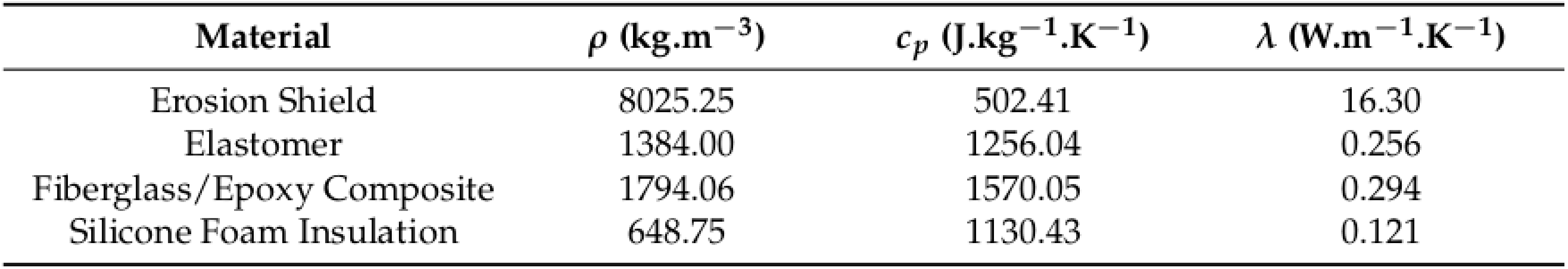
Chauvin et al., FINEL 2018

Electro-thermal ice protection system (ETIPS). Illustrative test cases.





Layer	Material	Thickness [mm]
1	Erosion Shield	0.20
2	Elastomer	0.2865
3	Elastomer	0.2865
4	Fiberglass/Epoxy Composite	0.89
5	Silicone Foam Insulation	3.43



Material	ρ (kg.m^{-3})	c_p (J.kg^{-1}.K^{-1})	λ (W.m^{-1}.K^{-1})
Erosion Shield	8025.25	502.41	16.30
Elastomer	1384.00	1256.04	0.256
Fiberglass/Epoxy Composite	1794.06	1570.05	0.294
Silicone Foam Insulation	648.75	1130.43	0.121

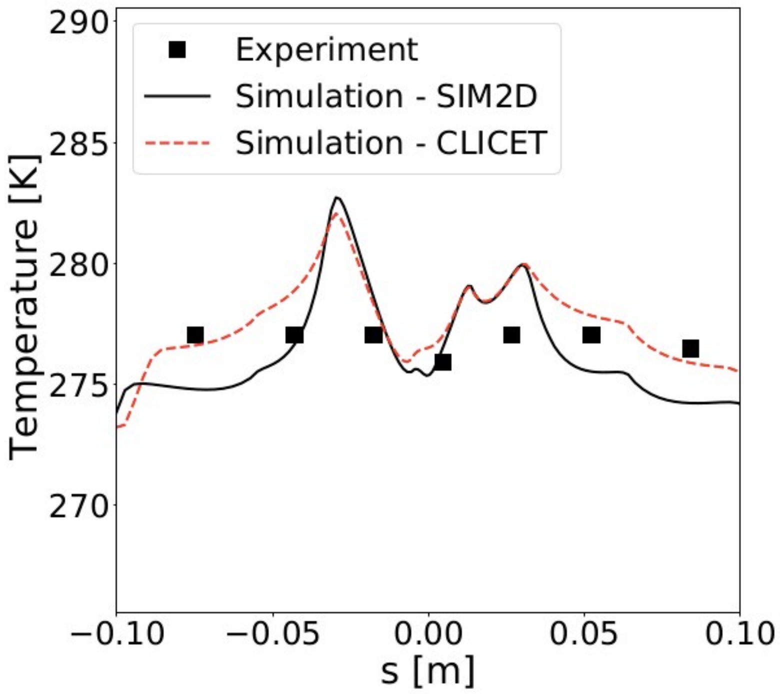
Bennani et al., Aerospace 2023

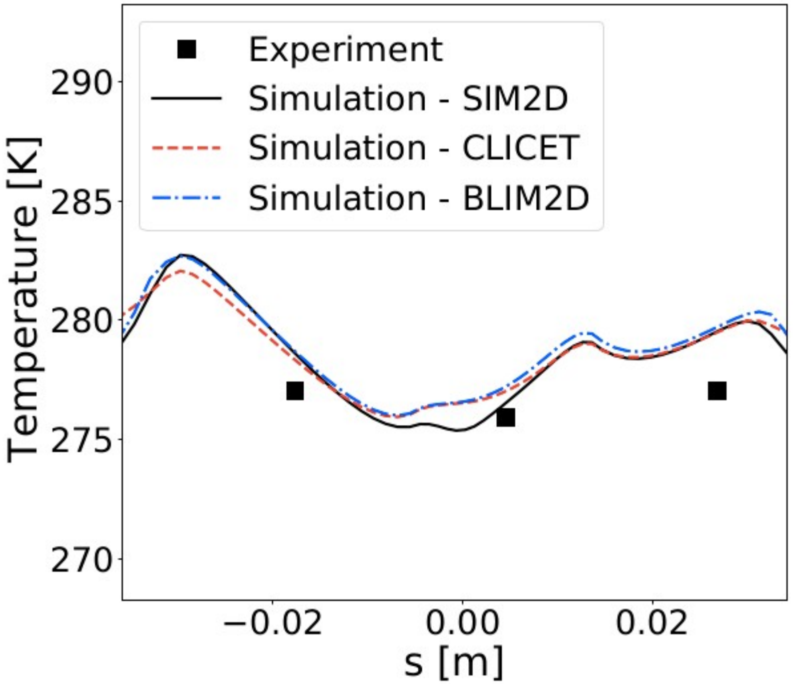
Electro-thermal ice protection system (ETIPS). Illustrative test cases.

Anti-icing mode

AoA [°]	M_∞	p_∞ **[Pa]**	T_∞ **[K]**	LWC **[g.m^{-3}]**	MVD **[μm]**
0	0.137	101,325	262.7	2	20

Heater nb	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Power density [W.m^{-2}]	3410	3875	5425	7130	4030	3875	3100





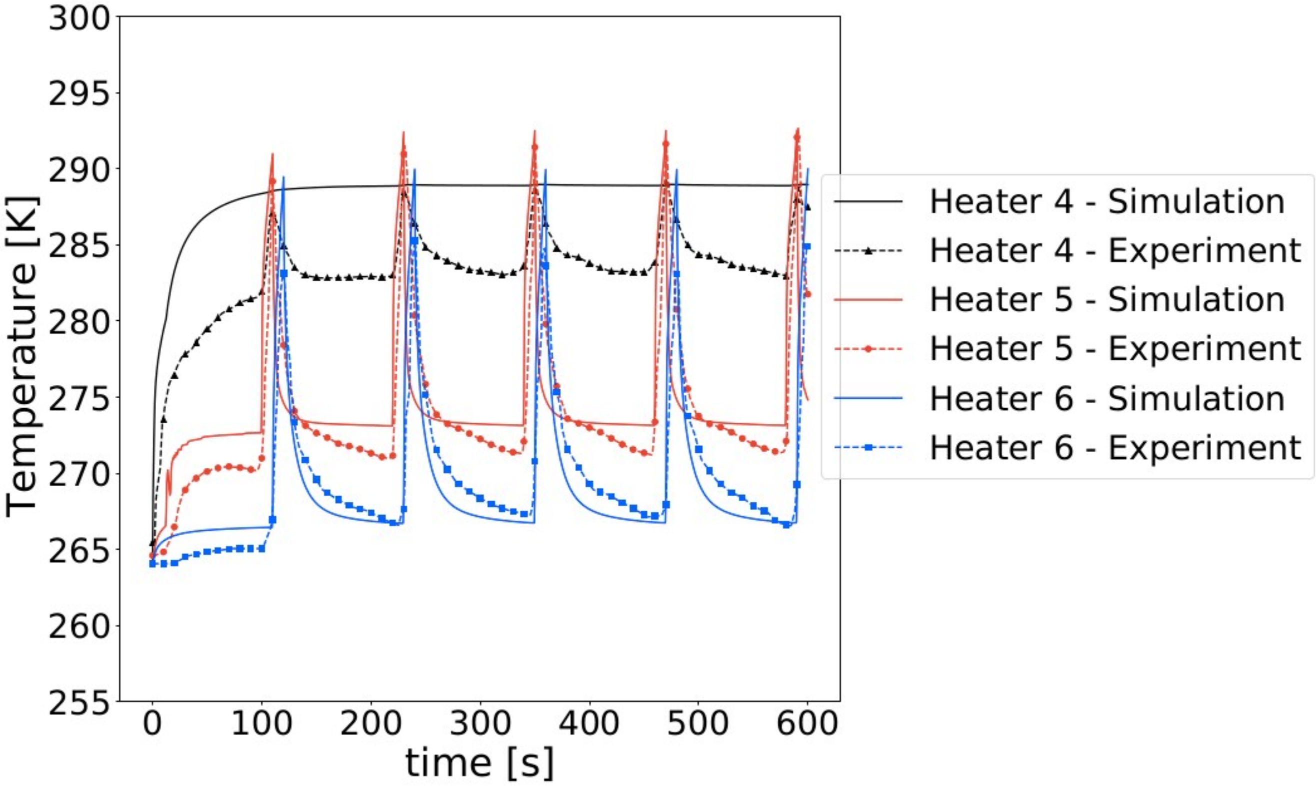
Bennani et al., Aerospace 2023

Electro-thermal ice protection system (ETIPS). Illustrative test cases.

De-icing mode

AoA [°]	M_∞	p_∞ **[Pa]**	T_∞ **[K]**	LWC **[g.m^{-3}]**	MVD **[μ m]**
0	0.137	101,325	265.5	0.78	20

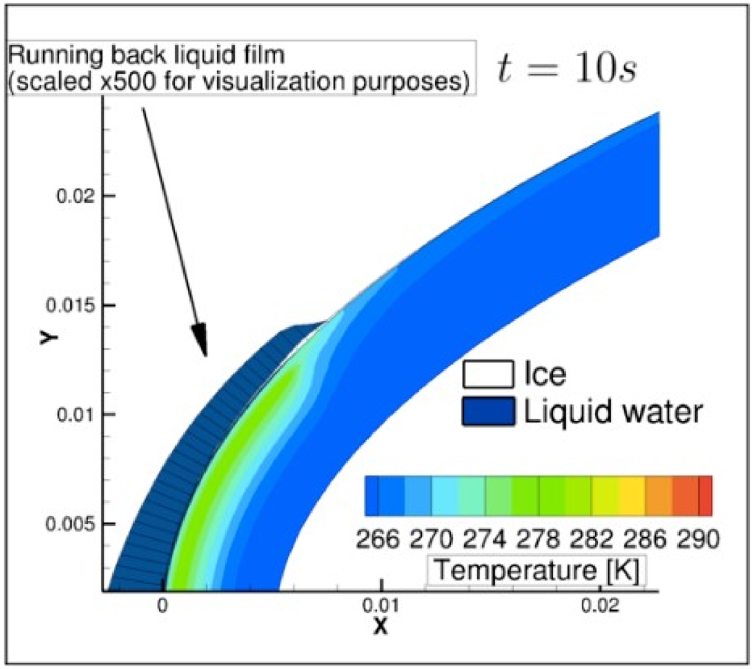
Heater nb	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Power density [W.m^{-2}]	12,400	12,400	15,500	7750	15,500	12,400	12,400

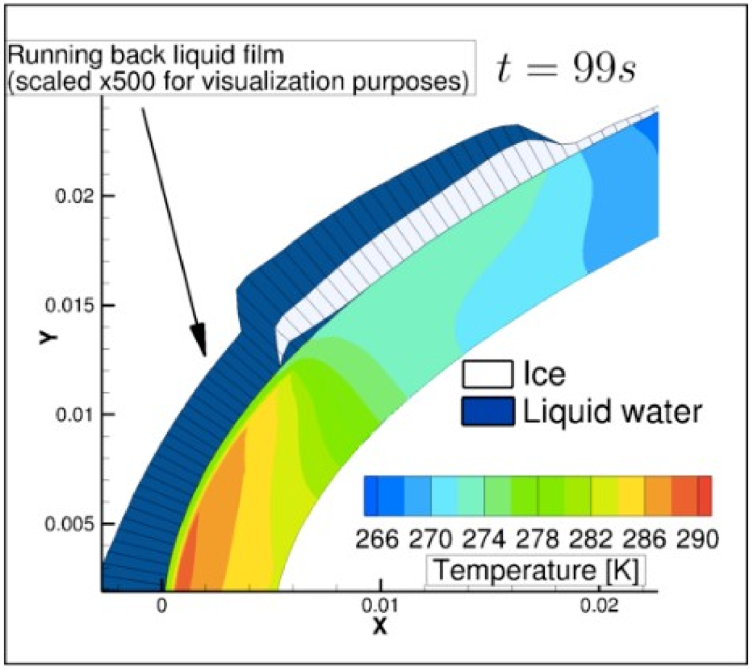


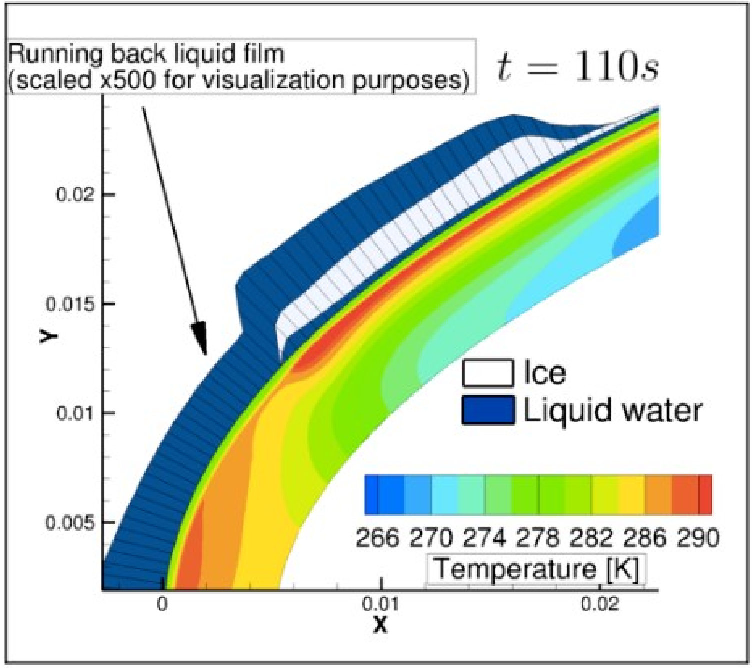
Bennani et al., Aerospace 2023

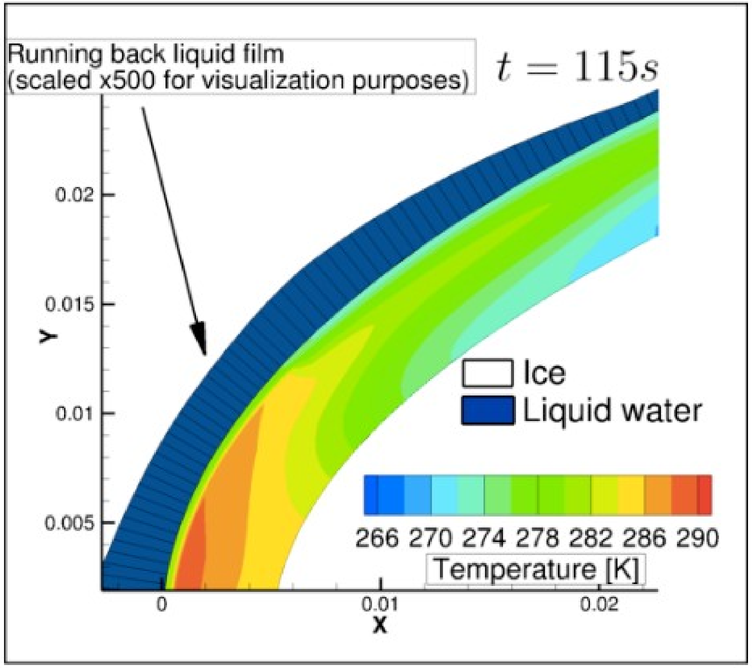
Electro-thermal ice protection system (ETIPS). Illustrative test cases.

De-icing mode



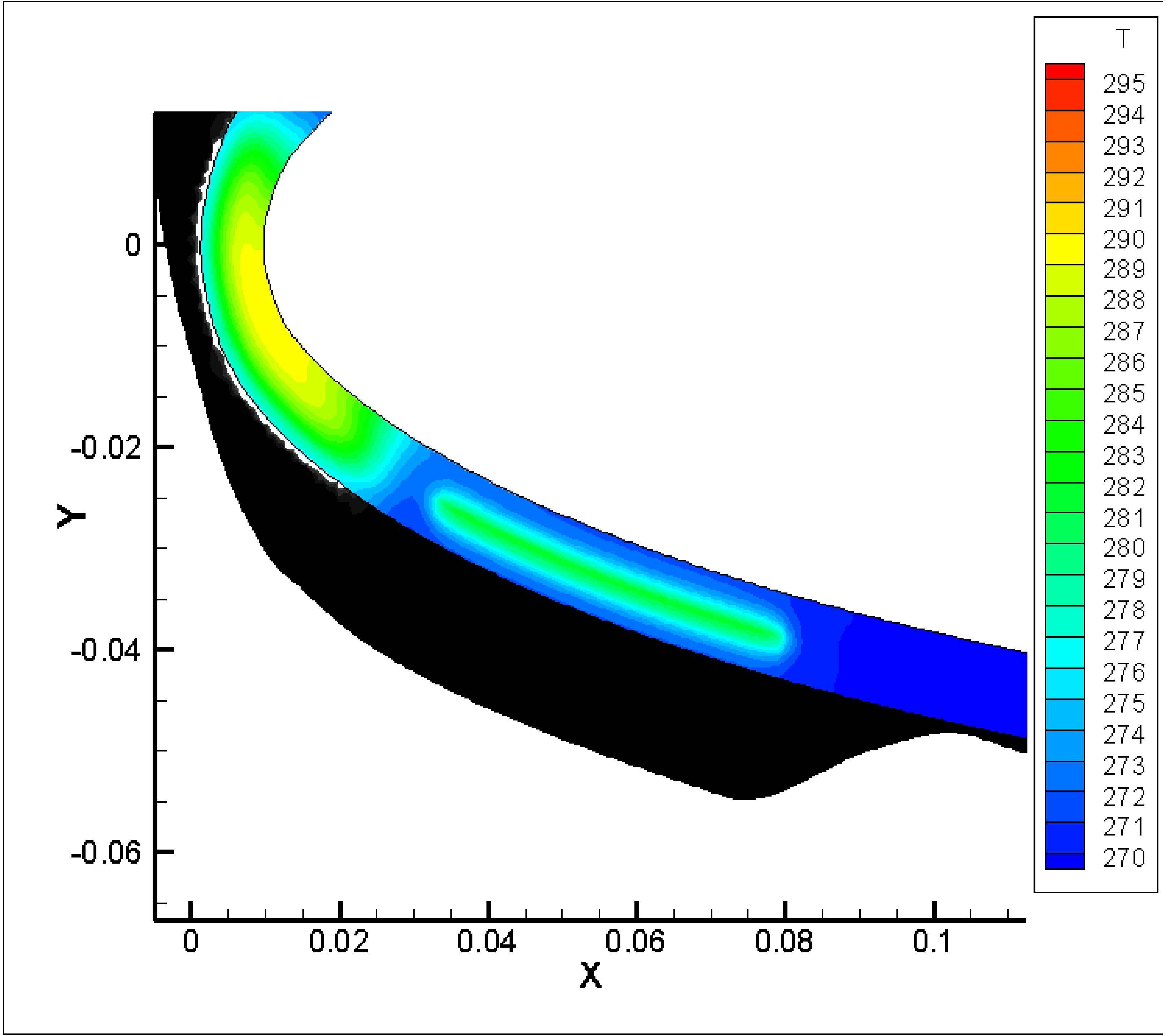






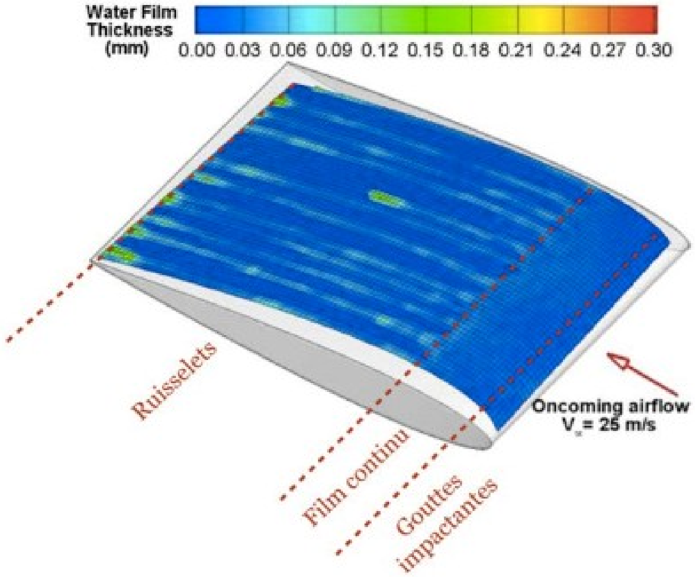
Bennani et al., Aerospace 2023

Electro-thermal ice protection system (ETIPS). Coupling between the ice accretion solver and the heat conduction solver.



Morphology of liquid water with ice protection systems : Partially wetting films and rivulets modeling

- **Rivulets formation**



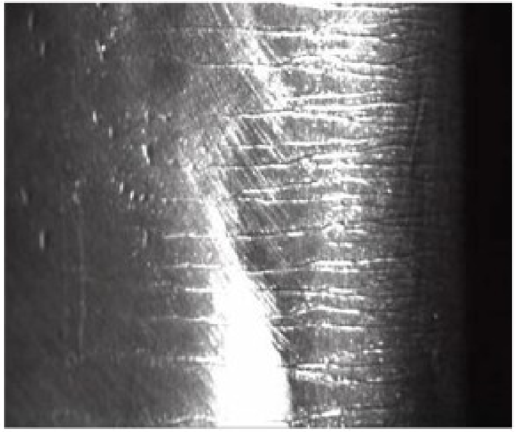


Fig. « Rivulets »

Fig. « Runback ice »

- **Isolated droplets**

- **Challenge: transition between continuous film/rivulets/isolated drolets**

PhD works of J. Lallement (2019)

Disjoining energy near the contact line

- **Film at equilibrium on an horizontal flat plate**

$$e_{film}(h,\vec{p}=\vec{\nabla}h) = \frac{\rho\, g_n\, h^2}{2} + \gamma_{lg}\sqrt{1+|\vec{p}|^2} + \gamma_{sl} + e_{disj}(h)$$

- $e_{disj}(h)$ **stands for partial wetting**

- Far from the contact line $(h \gg R)$
  $e_{disj}(h \gg R) = 0$

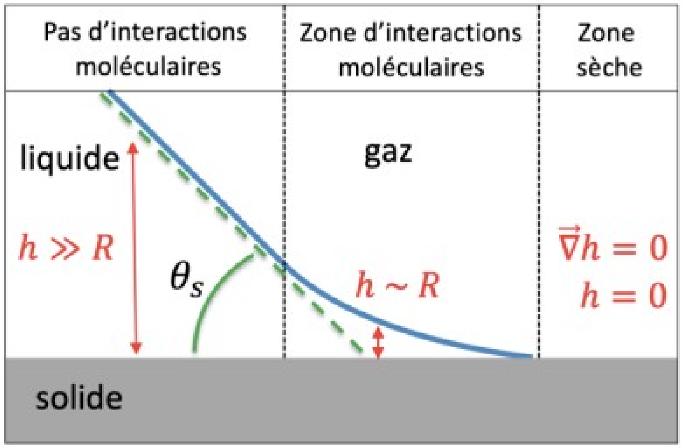
- For the dry area $(h = 0)$

$$\begin{cases} e_{film}(h=0) = \gamma_{sg} \\ e_{disj}(h=0) = \underbrace{\gamma_{sg}-\gamma_{sl}-\gamma_{lg}} \end{cases}$$

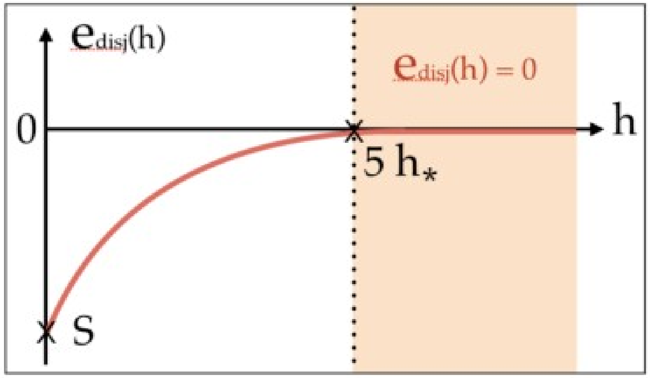
$$S = \gamma_{lg}\,[\cos(\theta_s) - 1]$$

$$e_{disj}(h) = \underbrace{\gamma_{lg}[cos(\theta_s) - 1]}_{S}\,\exp\left(-\frac{h}{h_*}\right)$$

➔ **Need to calibrate h_***



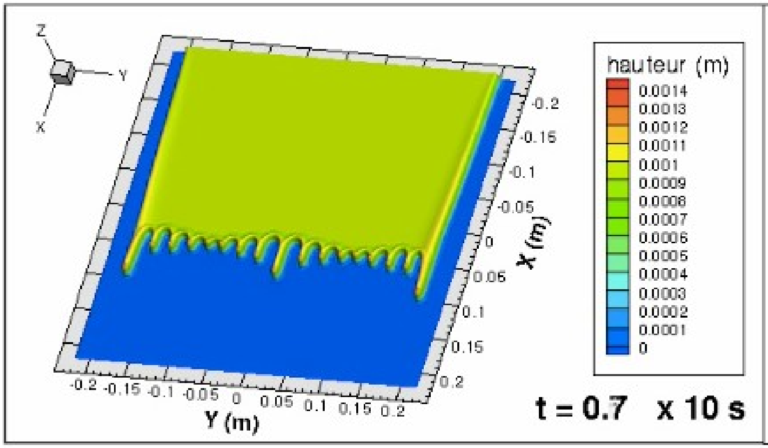
$R \equiv long - range\ \ forces\ scale$



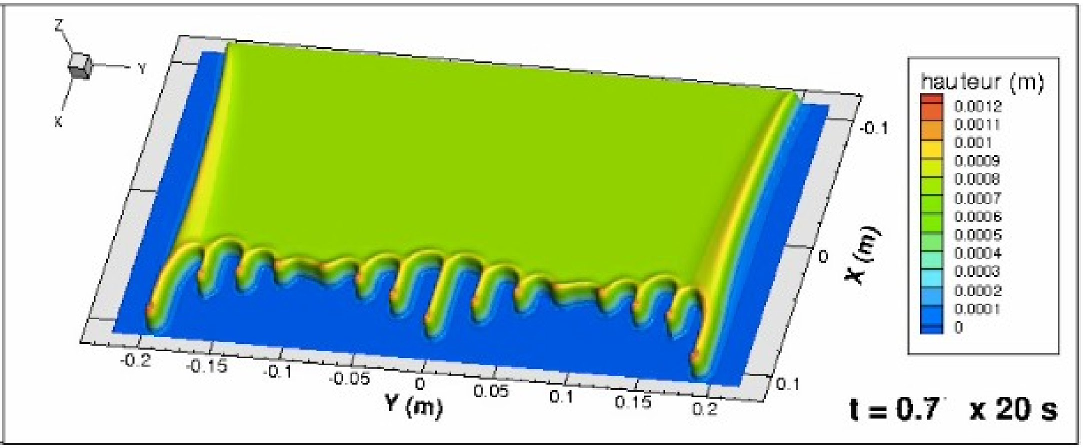
PhD works of J. Lallement (2019)

Transition to rivulets. Experiments from Johnson

Numerical simulations



$Re = 0{,}52$ et $\beta = 90°$



$Re = 0{,}13$ et $\beta = 27{,}9°$

- **Experiments from Johnson**
  - Falling film on an inclined flat plate
  - Water/glycerin mix, $\theta_s = 38°$
  - Change in injected mass rate (Re) and plane slope (β)

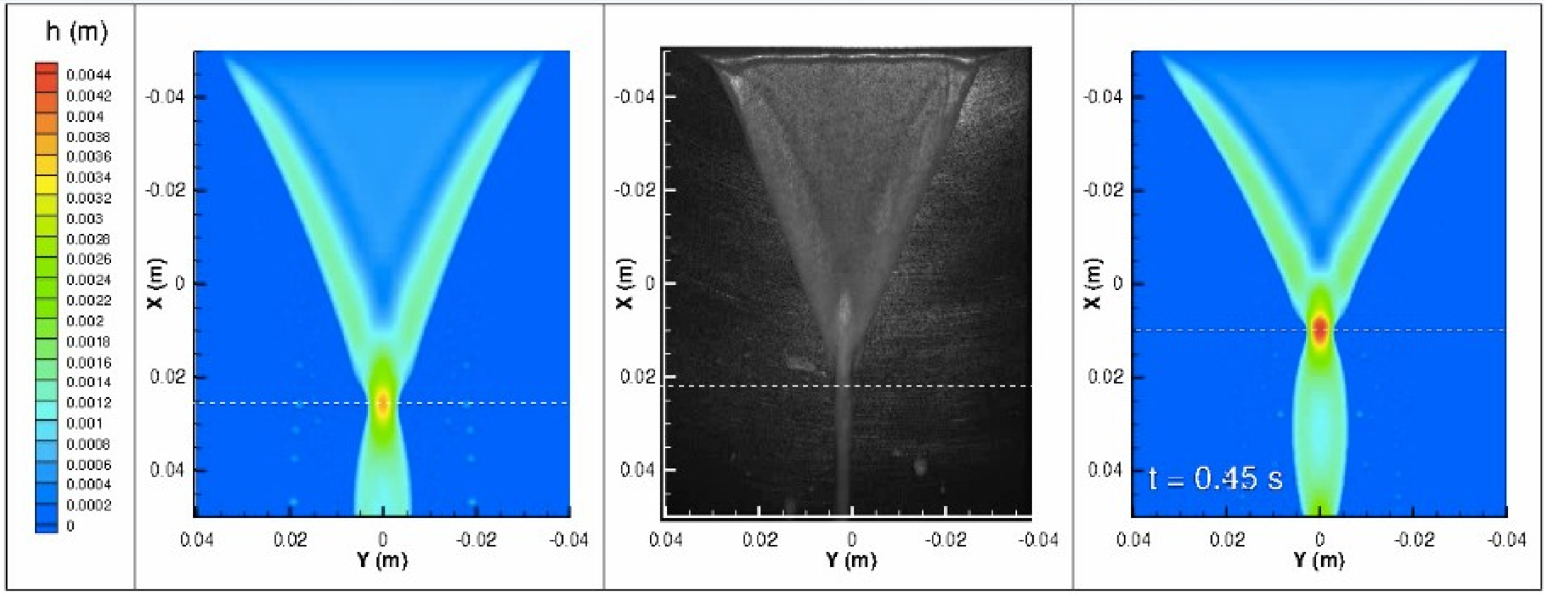
Comparison with the experiments

Re	β (°)	λ_{exp} (mm)	λ_{simu} (mm)	
0,13	90	21,5 $\mp$ 4	19,1	✓
	27,9	29,1 $\mp$ 4	28,5	✓
0,26	90	22 $\mp$ 4	21,1	✓
0,52	90	23,8 $\mp$ 4	23,5	✓
	27,9	31,5 $\mp$ 4	35	✓

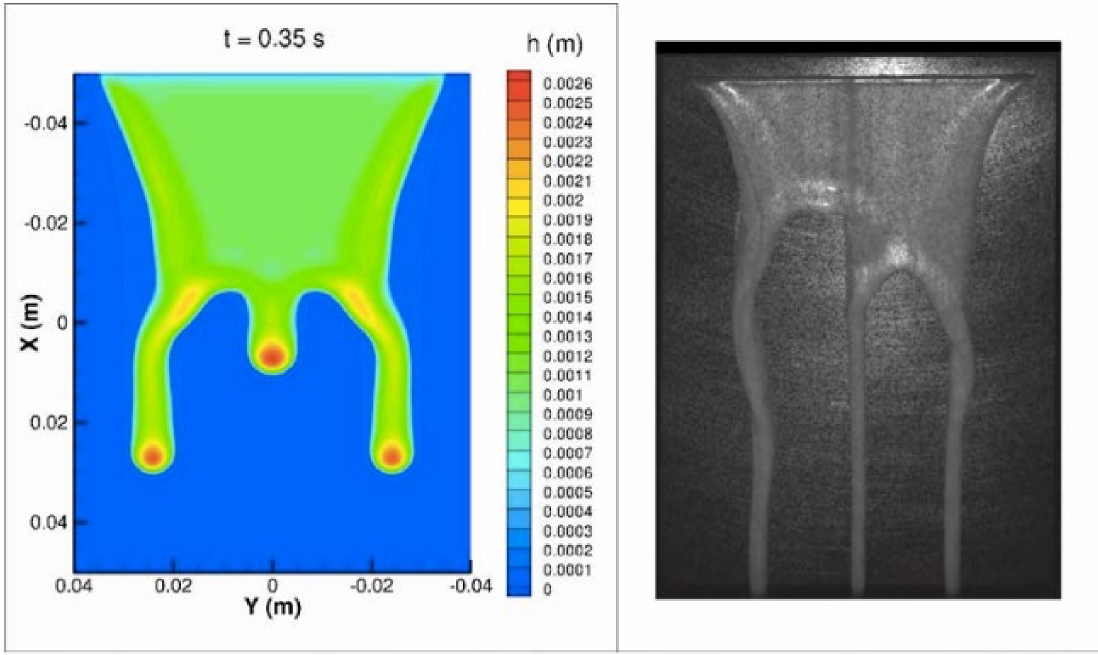
The gap between the rivulets is well found despite a poorly described bulk

PhD works of J. Lallement (2019)

Some examples of the effects near the contact line



- Pinching of a liquid film.
- Water/glycerin mix.
- $\theta_s \in [69°, 82°]$



- Liquid film falling on a vertical flat plate
- Water/glycerin mix at 20°C
- **Under-estimated bulk thickness**
- ➔ The speed at which rivulets appear is **slower** than in the experiment

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