The 14th International Workshop on Atmospheric Icing of Structures, Chongqing, China, May 8 - May 13, 2011

Cross-fertilizing the technologies of atmospheric icing on structures and in-flight structural icing

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Abstract— **Almost 15 years ago, through relentless prodding by aircraft pilots who were concerned that not enough science was being used for In-Flight Icing, sometimes called In-Flight Structural Icing, protection systems, the first author decided to gear his research toward studying that problem. Today, with the encouragement and collaboration of colleagues in the Atmospheric Icing on the Structures side, such as the second author, we are taking a joint look about how we could bring technologies developed on both sides of the fence, to cross-fertilize our respective disciplines. The lecture will highlight the advances of in-flight icing CFD simulation of the last decade, in a field that was mired in correlations, and where CFD had been long limited to two-dimensional, inviscid, incompressible Panel Method flows, to, today's modular systemic approach. The presentation will also highlight the budding research ideas between the two disciplines, recent progress on overhead line research projects and what can be accomplished in the not so distant future.**

Keywords: Computational fluid dynamics, ice accretion simulations, ice shedding simulations, wind-structure interactions.

I. INTRODUCTION

Since its inception in 1982 in Hanover, New Hampshire, USA, this international workshop has fostered an impressive amount of research and encouraged sharing of good industrial practices for the mitigation of atmospheric icing on structures, with a particular focus on transmission line engineering applications. In preparation for this lecture, we have perused the list of 40 technical presentations made during the four sessions of this 1st IWAIS. During Session 1, titled basic research, “Simulation and Modeling” appeared as a sub-topic with five presentations. There was also (only) one presentation on “Aircraft icing research at NASA by J.J. Reinmann, R.J. Shaw, and W.A. Olsen, Jr. Successive workshops have all provided a prominent place for discussion of numerical modeling aspects and the aerodynamics of ice-covered structures. This was almost 30 years ago, and progress in computational mechanics research has been fulgurant since then. Those of you who were there from the start with a keen interest in the field of computational fluid dynamics and/or structural dynamics can appreciate that what we were dreaming then of what is actually feasible today. Coincidently, it was after a presentation in Montreal close to 20 years ago by none other than J.J. Rienmann, that the first author was able to identify the huge chasm that separates in-flight icing experts from CFD practitioners. Icing research has certainly been a very interdisciplinary discipline since, but when it comes to its numerous engineering applications, it is somewhat unfortunate that this interdisciplinarity is lost. A direct consequence of this “specialized” approach is that there is a tremendous waste of resources and effort. Many scientific developments and engineering solutions exist in the various disciplines that could benefit the icing-on-structures community at large, and vice versa. In the spirit of sharing expertise and ideas, we present here recent computational developments in relation to in-flight icing. With a few variants related to flow conditions, the reader interested in power line icing problems will appreciate that the physics is there to explain many phenomena that we still do not understand and that computational mechanics, in good hands, is the way of the future for sustainable engineering of complex structures and systems.

II. MOTIVATION FOR RECENT ADVANCES IN COMPUTATIONAL IN-FLIGHT ICING

When an aircraft hits supercooled liquid water droplets present in a cloud, the droplets reject the heat of fusion either immediately upon impact, or slightly thereafter, forming ice whose shape, location, roughness and dimension can lead to substantial distortions in the aerodynamic profiles of lifting surfaces, control surfaces, air intakes, fan blades, rotors and propellers. Performance degradation can then occur from a combination of increased drag as a result of roughness and flow separation, a reduced stall angle of attack, with higher and shifted weight being additional issues of secondary and often trivial significance. Additionally, ice can distort flow or block engine inlets and internal ducts and, if ingested or released, damage components, causing power fluctuations, thrust loss, rollback, flameout, and loss of transient capability. Asymmetric ice distribution can also cause significant stability and control problems, compounding already reduced aircraft performance. While changes in pitching moment or hinge moment may cause some of these adverse effects, aerodynamic flow separation (stall), singly or in combination with other effects, is most often the killer. Current stall protection systems cannot alert the pilot that the margin between stall warning and actual stall is significantly reduced and perhaps completely eliminated in icing situations. To further underscore the widespread consequences of ignoring or ineffectively addressing the adverse effects of icing and its impact, even current crew training for stall recovery has been inappropriate for airplanes degraded by ice contamination [1].

In-flight ice accretion can be prevented or removed. It can be prevented by adding energy in the form of heat (thermal anti-icing: preventing water droplets from rejecting heat of fusion, or evaporating the droplets) or by chemically depressing the freezing point. It can be cyclically removed after accretion by intermittent heating or mechanical de-icing using pneumatically inflated de-icing boots or other mechanical devices that distort the leading edge of the airfoil, break the ice-surface bond and fracture the ice allowing the ice particles to be swept away in the airflow.

Unfortunately, the total prevention of ice formation, or its complete removal, is not, and likely will never be, economically feasible because of the large amount of thermal or electrothermal energy required, the problems inherent in mechanical removal, and the weight penalties of freezing point depressant fluids. Moreover, the controlled amount of anti-icing or de-icing hot air bled from the engines is often needed during climb, especially for smaller airplanes and may be insufficient during descent, approach and landing because of reduced engine power settings. In practice therefore, while some areas of the aircraft are anti-iced, others can only be de-iced and large areas are left unprotected. Such unprotected areas must be precisely determined and the aircraft tested in an icing tunnel, with artificial ice shapes, behind an icing tanker, or through flight in natural icing conditions, before being certificated for ‘flying into known icing’.

An ironclad solution against icing is further prevented by two shortcomings: the difficulty of detecting and/or measuring ice accretion and the necessarily cyclic nature of de-icing an aircraft in flight. Ice detection systems are installed on only a fraction of the airplanes operating today and are subject to limitations in reliable and accurate detection of the entire icing spectrum. Pilots are often skeptical about relying on ice detection systems and may simply monitor places where ice collection is more efficient due to geometry and visibility: “If I have ice on the windshield wiper bolt,” they reason, “I must have ice on the wings.” In the case of airplanes with mechanical systems, the pilot must wait for some ice to accrete before activating the de-icing system. One would think that the precise amount of ice safely permitted to accrete, as specified in an Airplane Flight Manual, would be based on aerodynamic analysis, but it turns out to be no more than a rule of thumb (quarter inch to half an inch, varying with temperature) usually based on the percentage of ice that is removed in the first cycle of the system. In flight, half an inch of ice could have vastly different aerodynamic effects on different aircraft, and, furthermore, can a pilot really sense half an inch of ice on portions of the wing hidden from his line of sight, especially at night? In some accidents it has been shown that the character of the ice was such that it caused severe adverse effects at dimensions less than those recommended for operation of the ice protection system. What is truly required and has been elusive is not an ice detector, but rather a means of determining in real-time the aerodynamic state of the aircraft as it degrades with ice accretion

Figure 1. Ice accretion on wing during natural flight tests

A second shortcoming is that available power dictates that in-flight de-icing operations are cycled serially - say wing, tail, empennage, and thus repeating - with blackout periods for each component. It only makes sense for the wing to be designed to sustain aerodynamically the severe inter-cycle ice load that accretes during the wing de-icing blackout period [2], but this has only recently started being studied [3], mostly experimentally, and only because of recent accidents. This raises the question of whether any turboprop booted aircraft may thus be flying today without having been properly assessed for the effect of intercycle ice, residual ice or ice that accretes before the ice protection system is actuated (delayed turn-on)?

With major aircraft manufacturers, certification agencies, and research agencies seemingly globally linked with research in the area of in-flight icing, it is only natural for the public to assume that this aspect of flying has been mastered. While these entities are certainly trying their best, the fact is that aircraft and system design and operational procedures still have not totally conquered the in-flight icing problem. Flying in icing conditions continues to result in incidents and accidents, with no aircraft type, size, or configuration being immune. A May 2006 article in Aerospace America entitled “Icing Research Heats Up” [4] reconfirms the fact that adverse weather conditions contribute to 30% of all aircraft accidents. As notable is the fact that this article does not mention CFD simulation even once, reflecting again the conservatism that controls the official icing research community, but from which, interestingly enough, industry is slowly breaking free.

Another example is the two-year study of CFD methods by the AC-9C Committee of the SAE [5], in which the author participated, which was lukewarm in its recommendation of the use of even 2D codes for aid-to-certification purposes, leaving little or no approval room for 3D codes.

III. SECOND-GENERATION ICING CODES

This section will present a general overview of so-called second-generation icing codes, typified by FENSAP-ICE. More details can be found in review articles on in-flight icing [2] and on computational aspects [2], as space does not allow this. Verification and validation aspects have been individually presented in a number of other papers, [2], but results will be interspersed to illustrate what is presented in each section.

A. *A Comprehensive 3D CFD Approach in FENSAP-ICE*

Ice accretion simulations have traditionally been based on 2D and quasi-3D inviscid Panel method or Euler flow computations for the air [6], on Lagrangian tracking techniques [7] for droplet impingement, and on a 1-D control volume analysis of the mass and heat transfer for ice accretion [8]. Existing ice shape prediction codes are unable to faithfully model ice in the entire envelope, and particularly troubling is the fact that some of these areas are those in which the greatest hazards are often found. More up-to-date truly computational fluid dynamics (CFD) technologies could easily overcome many of the self-imposed limitations of these approaches such as limited ability to handle compressibility, three-dimensionality and flow recirculation and/or separation. There is a price to pay, however, in doing so: it is only at the cost of solving models based on partial differential equations that a comprehensive 3D approach to icing simulation becomes possible. The high cost of a 3D simulation, however, pales in comparison to a test flight or, worse, to that of an incident or an accident. One must also realize how spotty the nature of icing testing for certification can be, as not all regulation conditions (FAR 25 and others) can be icing tunnel-tested, or flight-tested, nor encountered in natural icing testing, with only CFD making it possible to explore all possible corners or nonlinear combinations of the icing and flight envelopes. To test possible dangerous scenarios it is safer to crash the computer than the plane but, unfortunately, 3D simulations were up to quite recently used more at accident investigation time than at design and prevention time.

In addition, one of the greatest difficulties of icing tunnel testing is the need for simultaneous scaling of geometric, aerodynamic and droplet characteristics, still a wide-open research area with serious limitations that cast doubt on the quantitative value of the experimental results, as well as the applicability of data obtained from limited scaled down partial geometries due to the smallness of tunnels. It is thus not difficult to imagine that a CFD-based approach is favored because it:

- Requires no scaling, is multi-disciplinary, reproducible, traceable, upgradeable, and continuously decreasing in cost,
- Harmonizes the technology of aerodynamics and icing groups,
- Highlights misconceptions, for example, that worst impingement-ice accretion and worst performance do not coincide and must be analyzed separately,
- Provides a practical tool and methodology to evaluate areas of the icing envelope that may be difficult to model, and
- Facilitates analyzing a gamut of situations difficult or not possible to test.

At the McGill University Computational Fluid Dynamics Laboratory, we are developing a numerical icing simulation and aid-to-certification tool, FENSAP-ICE [9] that can accurately predict ice accretion on an entire aircraft, rotorcraft or tiltrotor, engine or UAV, under all atmospheric conditions. It facilitates the prediction of water impingement, the determination of the limits of impingement, the ice accretion shapes, the melted ice runback, as well as the iced aircraft's degraded performance characteristics. This holistic approach views icing simulation as the solution of the compressible Navier-Stokes equations (here with FENSAP [10]: Finite Element Navier-Stokes Analysis Package), the computation of the collection efficiency distribution by an Eulerian method with DROP3D [11,12], the prediction of the 3D ice accretion shape by ICE3D [13,14], and the prediction of the heat loads by a conjugate heat transfer approach CHT3D [15,16], all four being Partial Differential Equations (PDE)-based. Figure 2 illustrates the concept map of FENSAP-ICE with its four modules.

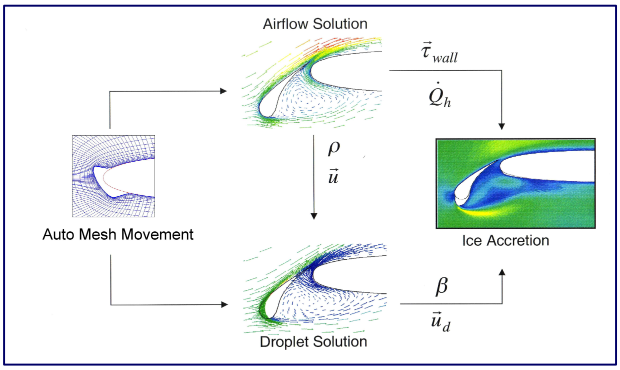


Figure 2. Four interactive modules of FENSAP-ICE, a second-generation in-flight icing simulation code

1) *Turbulent air flow solver*

The airflow solver of FENSAP-ICE, FENSAP, can act in an inviscid (Euler) or viscous (Navier-Stokes) mode, as necessitated by the application at hand. Spatial discretization is carried out by FEM and the equations are linearized by a Newton method. The time integration employed is a second-order accurate implicit Gear scheme, along with a generalized minimal residual procedure (Galerkin-type) to iteratively solve the resulting matrix system.

For ice accretion, accurate turbulent heat fluxes at walls are essential to the simulation and, currently, one-equation turbulence models such as Spalart-Allmaras [17,18], and two-equation models such as low-Reynolds and high-Reynolds k-ε and k- ω, have been implemented.

2) Water Concentration Solver

The Eulerian droplet impingement model is essentially a two-fluid model consisting of the Euler or Navier-Stokes set of equations for dry air, augmented by the droplet-specific continuity and momentum equations. An empirical correlation is used for the drag coefficient of the droplets. The two-fluid model assumes spherical monochromatic droplets, at the median volumetric diameter of the sample size distribution. The spherical droplet approximation is valid for droplet Reynolds numbers below 500. No collision or mixing between the droplets is accounted for, as these are not significant in regular in-flight icing situations.

3) Ice Accretion Solver

The widely used 2.5D control volume equilibrium model introduced in [8] has been further improved, by reformulating it as partial differential equations, to predict the ice accretion and water runback on the entire surface [13,14].

As shown in Figure 3, the velocity $\mathbf{u}_f$ of the water in the film is a function of coordinates $\mathbf{x} = (x_1, x_2)$ on the surface and y normal to the surface. A simplifying assumption consists of taking a linear profile for $\mathbf{u}_f(\mathbf{x}, y)$, with a zero velocity imposed at the wall, i.e.:

$$\mathbf{u}_f(\mathbf{x}, y) = \frac{y}{\mu_w} \tau_{wall}(\mathbf{x}, y) \tag{1}$$

where τ_{wall}, the shear stress from the air, is the main driving force for the water film.

By averaging across the thickness of the film, a mean velocity is obtained:

$$\bar{\mathbf{u}}_f(\mathbf{x}, y) = \frac{1}{h_f} \int_0^{h_f} \mathbf{u}_f(\mathbf{x}, y) dy = \frac{h_f}{2\mu_w} \tau_{wall}(\mathbf{x}, y) \tag{2}$$

The resulting system of partial differential equations is the following:

a) Mass conservation:

$$\rho_w \left[\frac{\partial h_f}{\partial t} + div(\bar{u}_f h_f) \right] = U_\infty LWCB - m_{evap} - m_{ice} \tag{3}$$

where the right-hand-side terms correspond to mass transfer by water droplet impingement (source for the film), the evaporation and the ice accretion (sinks for the film), respectively.

b) Energy conservation:

$$\begin{aligned} \rho_w \frac{\partial h_f C_w \tilde{T}_s}{\partial t} + div\left(\overline{\mathbf{u}_f} h_f C_w \tilde{T}\right) = \left[C_w \tilde{T}_{d,\infty} + \frac{\|\mathbf{u}_d\|^2}{2} \right] \times U_\infty LWC\beta \\ -0.5\left(L_{evap} + L_{subl}\right)\dot{m}_{evap} + \left(L_{fusion} - C_{ice}\tilde{T}\right)\dot{m}_{ice} + \varepsilon\sigma\left(T_\infty^4 - T_s^4\right) + \dot{Q}_h \end{aligned} \tag{4}$$

where the first three terms on the right-hand-side model, respectively, the heat transfer caused by the supercooled water droplets impingement, the evaporation and the ice accretion. The last two terms represent the radiative and convective heat transfer.

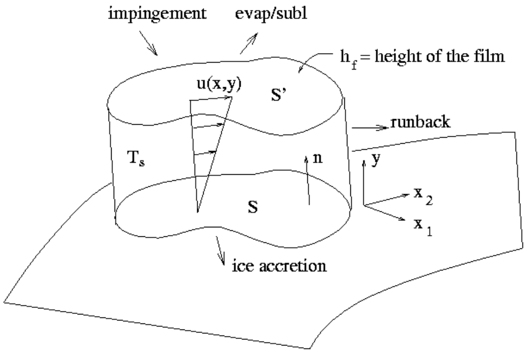


Figure 3. Heat and mass balance in a thin film

The coefficients ρ_w, C_w, C_{ice}, L_{evap}, L_{subl}, L_{fusion} represent physical properties of water, while $\tilde{T}_{d,\infty}$, U_∞, LWC, σ and T_∞ are airflow and droplet parameters specified by the user. The ambient icing conditions completely determine those values. The tilde symbol over *T*, i.e. $\tilde{T}$, stands for the temperature in Celsius, otherwise temperature is in Kelvin.

The Eulerian droplet module provides local values for the collection efficiency β and the droplet impact velocity $\mathbf{u}_d$. The flow solver provides the local wall shear stress τ_{wall} and the convective heat flux $\dot{Q}_h$. The evaporative mass flux is recovered from the convective heat flux using a parametric model [19]. There remain three unknowns: the film thickness h_f, the equilibrium temperature $\tilde{T}$ within the air/water film/ice/wall interface, and the instantaneous mass accumulation of ice, $\dot{m}_{ice}$. Compatibility relations are needed to close the system and one way to write them is the following:

$$h_f \geq 0 \tag{5}$$

$$\dot{m}_{ice} \geq 0 \tag{6}$$

$$h_f \tilde{T} \geq 0 \tag{7}$$

$$\dot{m}_{ice} \tilde{T} \leq 0 \tag{8}$$

The discretization of the equations is via finite-volume method (FVM). The hull of the three-dimensional mesh at the air-structure/ice shape interface is called the surface mesh. From the surface mesh, a dual surface mesh is obtained by connecting the centroids of the surface mesh cells to the mid-edges of the cells. The unknowns are computed at the center of each cell, thus corresponding one-to-one to the nodes of the FEM used for the air and droplet solutions.

4) CHT Solver

FENSAP-ICE comprises a conjugate heat transfer (CHT) module, CHT3D, which couples convection (FENSAP), conduction and phase change calculations (C3D). The coupling between the fluid and solid computations is obtained through an exchange of boundary conditions, across any number of interfaces. Example of interfaces would be between the internal flow in the wing from a piccolo tube, the wing's skin, and the external flow over the aircraft. A fixed temperature boundary condition is imposed to the Navier-Stokes solver along the interface and the heat flux at the interface is then computed from the flow solution and imposed as a boundary condition to the heat conduction/phase change solver. This provides a new temperature distribution along the interface to impose on the Navier-Stokes solver, and the procedure is repeated until convergence of both domains is achieved for temperatures and heat fluxes.

Figure 4 illustrates CHT calculations of the coupled external flow over the wing (the slat is shown), the internal piccolo flow inside the wing and the conduction across the wing's skin, whether sequentially or simultaneously.

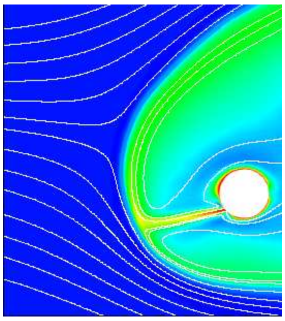
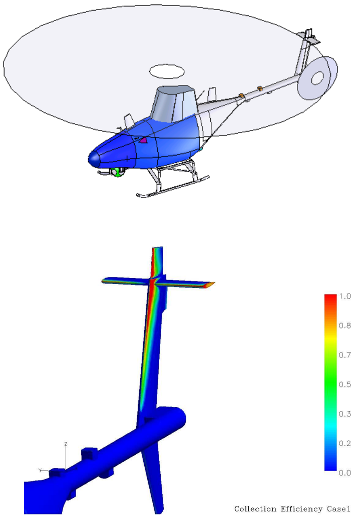


Figure 4. CHT (external+skin+internal) calculations of a piccolo tube within a leading edge slat

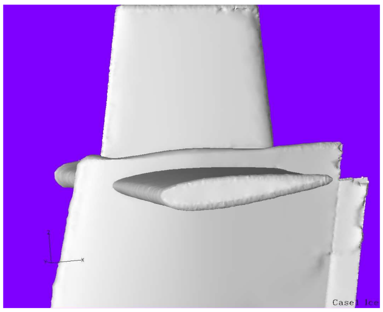
B. Example: In-Flight Icing on a Rotorcraft

Traditionally, very few rotorcrafts have been equipped and certified for flight into known icing. Most helicopters have operational limitations, which allow flight into inadvertent icing only, with demonstrated safe flight capabilities to exit icing conditions or to safely land. However, the advent of tiltrotor technology and the requirement for more helicopters with full icing capabilities have created a need for affordable all-weather operations. One of the major contributing factors to bring development costs down is to develop new in-flight icing prediction methods applicable to helicopters and tiltrotors or improve on existing ones. While undoubtedly aircraft and engine icing analysis can be complex, nothing approaches the complexities of helicopter icing in terms of geometries, attitudes, propeller/rotor interaction, engine intakes (side entrance, front entrance), etc.

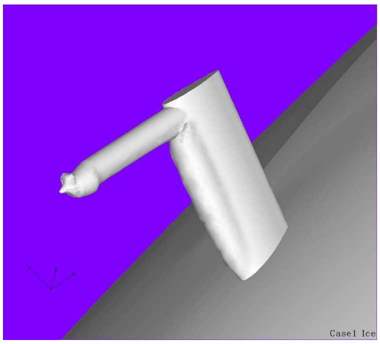


Fi Figure 5. (a) View of the rotorcraft UAV, (b) Collection efficiency on tail

Figures 5 and 6 show a synopsis of the detailed results of [20] for the Fire Scout, a rotorcraft type of UAV. Figure 5 shows the impingement pattern on the skid, payload, and Figure 6 shows the ice accretion on the tail (a) and on the Pitot tube (b).



(a)



(b)

Figure 6. Glaze ice shape (a) on rotorcraft tail and (b) on Pitot tube

C. Simulation of Supercooled Liquid Droplets (SLD)

Traditionally, the design of anti-icing measures is based on the impingement limits corresponding to droplet size distributions featuring mean volumetric diameters (MVD) of 40 to 50 μm or less, as currently defined in Appendix C of the Federal Aviation Regulations FAR 25 for continuous and intermittent icing certification, respectively. Ice accretions due to SLD may result in extremely severe aircraft performance degradation, including a reduction in stall angle accompanied by an increase in stall speed, a reduction in lift in excess of 60% and an increase in drag up to 200%. Due to the large size and inherently ballistic trajectories of SLD droplets, the corresponding ice accretions may be established downstream of the impingement regions protected by anti-icing measures leading to a potentially uncontrolled ice accretion process [21,22].

The importance of CFD for in-flight icing will increase in the future as the rarity of SLD encounters in nature is such that natural icing trials are nearly precluded, while icing tunnels will suffer severe limitations in producing SLD environments. In such limited natural and tunnel-testing atmosphere, numerical simulation will play an increasingly crucial role.

IV. FUTURE WORK ON IN-FLIGHT ICING

FENSAP-ICE is a complete in-flight icing CFD simulation package developed to tackle in a timely and cost-effective way problems involving complex flow over on in three-dimensional bodies. Because of the Eulerian formulation used, droplet impingement on 3D geometries is obtained for all surfaces at once and the computational cost is similar to solving the Euler equations on the same grid. The incremental cost of computing impingement is therefore small, since the much larger cost of generating mesh and solving inviscid or turbulent viscous airflow has been already incurred. Solving for ice shapes is computationally cheaper by several orders of magnitude as it involves a two-dimensional problem with two degrees of freedom per node and is therefore negligible in the overall process of producing a CAD, generating a mesh, solving airflow, computing droplet impingement and finally obtaining ice growth.

Progress towards full in-flight icing simulation of propeller driven and rotary winged aircraft has been achieved and solves problems of great geometric complexity. It is now possible to calculate droplet impingement and ice accretion conditions taking into account propellers' and rotors' effects, which are by no mean negligible. Thus through CFD, the asymmetric ice accretion in the flow field of the propeller or rotor can be modelled and the results can be considered in the design and operation of the vehicles ice protection system. Previous to this, such asymmetries have generally been ignored.

It is believed that the current airplane + rotorcraft + engine + unmanned aerial vehicle (UAV) analysis capability is a major step towards the objective of reducing the amount of testing required by demonstrating the severity, or lack thereof, of certain certification conditions in an accurate, scientific, repeatable and traceable manner. The use of such CFD-based approaches in support of aircraft icing certification offers enormous advantages such as:

- the elimination of the need for scaling or similitude studies;
- the exploration of a more complete icing envelope in a risk-free fashion;
- a synergy between the methods used to design the aircraft and those used to design ice protection systems;
- the elimination of experimental inaccuracies generally associated with icing tests (measurement and control of droplet size, relative humidity, ambient temperature, water flow rate, repeatability, start-up times).

All the preceding advantages translate into significant cost reductions, shortening of the certification process, and improving the safe operation of the air vehicle in service.

Although certain phenomena or interactions cannot be simulated at this moment, it is believed that advanced CFD technology, used hand-in-hand with tunnel or flight tests, can still considerably shorten the certification cycle time, mitigate the associated risks, reduce the associated costs, reduce post-certification issues and more importantly, increase flight safety in adverse atmospheric conditions. It represents another tool in the toolbox available to the icing analyst to design efficient ice protection schemes and ensure continued airworthiness of the craft in adverse environmental conditions.

FENSAP-ICE represents a platform over which more advances in CFD modeling and in physical modeling can be easily integrated. It is interesting, however, to say that advances in physical modeling are sometimes held back by the conservatism that exists in the icing community. One is often asked, for example, if FENSAP-ICE reproduces the results of other longer established codes such as LEWICE or ONERA, with no apparent interest in knowing to what the differences could be attributed, or what could a richer physical model produce. As an example of this are the sometimes-held symposia where the results of many codes are compared to experimental results [23]. From the scientific point of view, ice shapes are governed by airflow, impingement and ice accretion modeling. When calculated ice shapes are compared and found different, it becomes impossible to say what the culprit is. The differences could be due to one airflow being calculated by a panel method and the other by a Navier-Stokes solver or perhaps to an impingement calculated with a Lagrangian method with sparse seeding of particles as opposed to an Eulerian method with an extremely tight mesh, and similarly for differences in the ice accretion model. The only way to correctly compare ice shapes would be based on the same flow + impingement solvers, in order to isolate what the differences in ice accretion modelling can be. In addition, in most cases experimental results of icing are not accompanied by error bars and are taken as "sacrosanct": that is to say, if it is measured, it must be the truth. When one observes the way ice shapes are "traced" in an icing tunnel, using a cardboard and a pencil or how the collection coefficient is measured with blotting paper and a timer, and considers all the associated uncertainties including the position at which the ice was measured, the effect of tunnel walls, the start-up time of the tunnel, the uniformity of the droplets size and water content, the scaling parameters, etc. severe doubts can be cast on published experimental shapes that are not studied for uncertainties. Thus, comparison exercises held to compare in a brute force manner codes and experiments are what one can call "an exercise in creating a meeting" and will hopefully in the future be done on a more rigorous scientific basis.

Future work includes conducting similar analyses on helicopters in forward flight where the advancing and retreating regions of the main rotor induces additional complexities to the actuator disk implementation in finite-element.

It is also planned to improve the mesh movement algorithms based on ALE to avoid remeshing deformed iced surfaces. The new scheme will rely on technologies developed for solution-based anisotropic mesh adaptation [24]. It is believed that this will ensure increased robustness of the scheme, as well as the ability to grow ice on concave surfaces, which are currently found to be problematic because of the presence of different iced surfaces growing towards each other.

In terms of additional physical modeling work, it is proposed to bypass the traditional Messinger model [8] and develop a truly unsteady third-generation ice accretion approach, rather than the series of quasi-steady frames used now in all codes. Not only would that continuously account for the effect of the flow on droplet impingement and ice accretion, but it can be coupled with improvements in all physical and numerical models of all phenomena taking place during ice accretion, such as increasing the accuracy of both flow and droplet solutions for shear stresses (driving force on the film of water), heat fluxes (acting on the thermodynamics of the ice layer), turbulence, roughness and transition and hence vastly improve on the thermodynamic balance within the ice layer.

Glaze ice scalloping [25] is another problem that needs to be addressed with simulation methods more sophisticated than currently available.

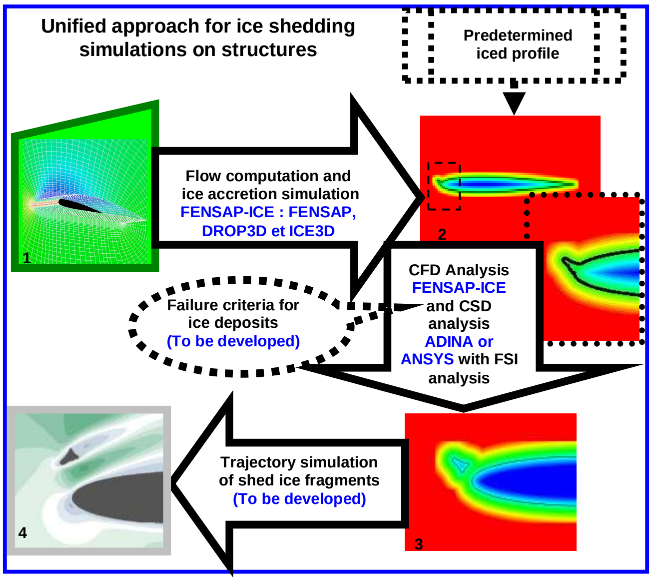


Figure 7. Unified approach for ice shedding simulations
Source of Illustration 1 :
http://www.tafsm.org/INTERNSHIP/1997/wibben/

Finally, the recently recognized jet engine power loss and damage at high altitudes due to the ingestion of ice crystals [26] is also a current subject that will require further developments in simulation capabilities, including ice accretion in multi-stage engine cores.

Figure 7 is a schematic representation of a unified approach envisioned by the writers to simulate ice shedding effects on structures. Although the illustration represents an aircraft in-flight icing application, a similar approach is applicable to most engineering applications (on ground or offshore). Of particular interest is the simulation of ice shedding effects on overhead line conductors. Some developments are still necessary to address this complex problem which requires computational solid dynamics and due consideration of fluid-structure interactions.

V. SHOULD WE TRUST COMPUTATIONAL METHODS?

The question is not new. The interested reader is referred to the excellent 2001 review article by Lynch and Khodadoust [27] on icing, which contains the following as the only passing reference to CFD: "*Incidentally, CFD* *methods have not been utilized in this review to either correlate or expand the existing experimental database on the aerodynamic effects of various ice accretions. This is because even the most advanced of these methods such as Reynolds Averaged Navier-Stokes (RANS) have not yet been demonstrated to be reliable for this purpose, especially relative to determining whether a flow is separated or not (even on an uncontaminated surface). Claims of good agreement between CFD and experimental results involving separation onset/progression characteristics typically involve post-test computations wherein a number of adjustments (turbulence model, grid characteristics, dissipation, constants, etc.) can be made to facilitate the agreement. For example, having one turbulence model work best for one ice shape and another one for a different ice shape is not unusual. Also, obtaining ''good'' predictions of global (integrated) forces without agreement in pressure distributions (i.e., indicating that the real flow physics are not being properly modeled) has also been seen."*

The conservatism of the icing community is well reflected in this paragraph, and is still very present today. This is contrary to aerodynamicists and turbomachinery specialists who have long understood two things: first, CFD can and must be used hand in hand with testing, and second, if you understand the region of applicability of your tool you can use it judiciously especially in situations where nothing else can be used (can one imagine even for a minute testing in detail every stage of a turbomachine design?). In icing, similarly, knowing something about the behavior of the combined aero and icing envelopes, even if in error around its fringes, is better than not knowing anything.

There are two types of errors possible using CFD exclusively as an aid to understanding the aerodynamics. The first type and the most hazardous is that the result underestimates the full adverse consequences of icing. Diametrically opposed is the opposite extreme that overestimates the full adverse consequences. In the former, the risk involves the potential for accident and death. In the latter, the design is overly conservative and may have lesser attractiveness in the marketplace; it is economic risk. Accordingly, it appears that a rational and reasonable approach would involve methodical and sequential examination of the design using CFD, followed by use of the remaining tools to examine and verify results of the CFD analysis and so avoid either extreme. There are also strategies for use of CFD to avoid pitfalls that may result from regimes where the ice accretion model may have less accuracy.

CFD has reached a degree of sophistication that can no longer be ignored. So our answer to the question is: Trust but Verify. C***rashing the computer is a hell of a lot preferable to crashing an airplane***.

VI. CONCLUSION

This lecture has presented an overview of recent computational fluid dynamics developments for the simulation of in-flight icing effects. Several of the issues and challenges discussed also apply to the study of icing effects on overhead power lines, and cross-fertilization of technologies developed in the two domains should be encouraged. On-going collaborative work also presented in this Workshop includes FENSAP-ICE applications to galloping modeling of twin-bundled conductors (by Borna *et al.*) and conductor response to wind and ice loadings (by Keyhan *et al*.). Realistic simulation of mechanical ice shedding under turbulent wind and galloping motion is the next challenge.

ACKNOWLEDGMENTS

The research collaboration between the co-authors is funded by the *Fonds québécois de la recherche sur la nature et les technologies* (FQRNT) under research team grant no. PR-128866.

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