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UAV Icing: Challenges for computational fluid dynamic (CFD) tools

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Abstract: Atmospheric in-flight icing imposes a significant hazard for the operation of unmanned aircraft. The objective of this study is to highlight current challenges for simulating icing with the computational fluid dynamic (CFD) methods on unmanned aerial vehicles (UAVs). In particular, the focus is on the gaps that exist between models and icing CFD tools that were originally developed for icing in manned aviation. Several key challenges are identified. UAV icing occurs at low Reynolds numbers where low Reynolds effects like laminar separation bubbles and laminar-turbulent transition are more prominent compared to manned aircraft. Also, many empirical or semi-empirical models from manned aviation are not validated or applicable for typical UAV conditions and geometries. Last but not least, there is a lack of suitable experimental datasets to validate icing CFD methods and models. Overcoming these gaps is required to unlock the full potential of digital twin methods for unmanned aircraft development.

Keywords: Unmanned aircraft, UAV, icing, CFD, aerodynamics, UAS, RPAS

1. Introduction

Unmanned aerial vehicles (UAVs), also called uncrewed aerial systems (UAS), remotely piloted aircraft systems (RPAS), or drones, are a technology that is currently growing rapidly. In addition to the established use of UAVs for military purposes, more and more civil applications are emerging [1]. Also, many urban air mobility (UAM) and advanced air mobility (AAM) concepts utilize unmanned aircraft. Many of these new applications rely on beyond visual line of sight (BVLOS) operations, e.g. package deliveries, search and rescue, pipeline inspections, passenger transport, or remote operations. During such missions, there is a risk that the aircraft encounters meteorological conditions that lead to icing on the airframe [2]. This hazard is called atmospheric in-flight icing and occurs in conditions where supercooled liquid droplets exist. Such droplets consist of liquid water with a temperature below freezing, that exists inside clouds or in form of freezing precipitation (i.e. freezing rain or drizzle) [3]. When an aircraft flies into such conditions, the supercooled liquid droplets collide with the airframe and freeze. The resulting ice shapes typically accumulate on the leading-edge of lifting surfaces and propellers. These ice accretions change the airflow over the surfaces and can severely degrade their aerodynamic performance. Icing on airfoils decreases lift, increases drag, degrades maximum stall angles, and decreases stability [4,5]. Icing on propellers rapidly reduces thrust, increases torque, and induces vibrations [6]. Consequently, icing is a severe hazard for UAVs, that needs to be addressed adequately to expand the operational envelope of unmanned aircraft into cold weather conditions and safe BVLOS operations. It should be noted, that the icing risk is global and year-round [7,8] and not limited to high latitudes or especially cold regions.

The ability to accurately model and predict icing processes with simulation tools is an important aspect of the design of aircraft that are designed to fly in icing conditions. There are three main objectives when it comes to the modeling and prediction of icing on UAVs [9]:

1. Simulation of ice accretions and ice shapes;
2. Simulation of aerodynamic performance degradations originating from ice accretions;
3. Simulation of ice protection systems (IPS) that mitigate icing.

The prediction of ice accretions and its subsequent aerodynamic performance penalties is relevant for the analysis of the vulnerability of aircraft systems in icing conditions. This type of input is relevant for the design of flight envelopes and assessing the risk of flight in inadvertent icing conditions [10,11]. The simulation of ice protection systems covers interactions of ice accretion with mitigation technologies (e.g. thermal or mechanical IPS). For UAVs, it is mostly electrothermal IPS which are typically used [12–14]. The ability to accurately model and simulate these objectives adds significant benefits and value to the design of UAV systems in icing conditions by reducing the need for wind tunnel and flight tests and thus increasing development cycles and reducing costs.

Computational fluid dynamic (CFD) icing methods are a suitable tool to achieve the three aforementioned objectives. Today, a wide variety of CFD icing tools exist, most of which have their origin in manned aviation. The first icing codes emerged in the 1970-80s and were based on panel methods that were able to predict 2D ice shapes and IPS heat requirements [15]. In recent years, Navier-Stokes solvers have replaced the panel methods and thus added more fidelity to the simulation of the involved aerodynamics and thermodynamic processes [16].

Ice accretions are simulated with special icing CFD tools, for recent examples see [16]. These icing CFD tools typically model the ice accretion process in several time-discrete steps (though other approaches exist as well, e.g. morphogenetic methods). For each step the following actions are performed, see Fig 1. The first step is to generate a mesh of the clean, uniced, geometry. Second, a flow solution using regular CFD flow solver – usually Reynolds-averaged Navier-Stokes (RANS) – is generated. Based on the flowfield, a droplet solution is generated that describes the impingement areas on the geometry. Droplet impingement is computed either with Eularian methods by simulating droplet trajectories, or Lagrangian. In a third step, the energy and mass balance on the surface is solved to calculate the amount of freezing water. This depends on the previously calculated droplet impingement solution and the length of the time step. Ice growth is computed by solving the Messinger equation [17]. The result of these three steps is an iced geometry. This iced geometry is then used as the input geometry to repeat the simulation cycle until the final timesteps have been reached, see Fig. 2.

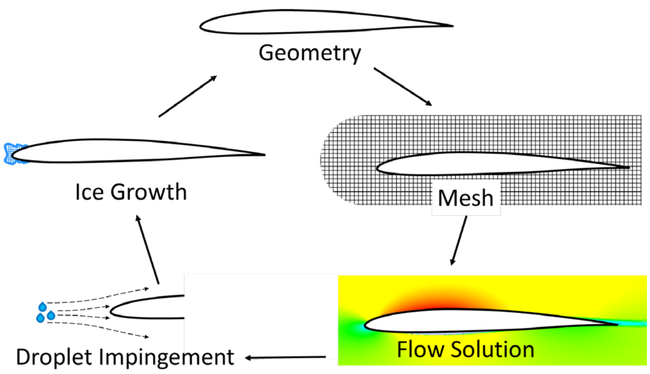

Figure 1: Typical iterative icing CFD process.

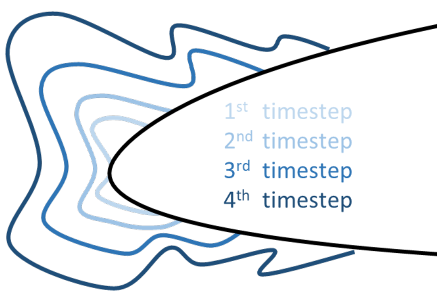

Figure 2: Iterative simulation of ice growth on an airfoil.

Simulations of aerodynamic performance degradation induced from ice shapes can be typically calculated with any CFD tool. Input geometries are either simulation results from ice accretion simulations or experimental ice shapes that are obtained from icing wind tunnel tests or natural icing flights. Ice shapes can be very complex and highly 3D geometries that can be challenging to capture and simulate, see Fig. 3. Often, 2D simulations are used instead to reduce the computational requirements for analysis, Fig. 4. Simulations of ice protection systems require the modeling of the energy and mass balances, especially heat convection to the ambient air, heat convection into the airframe, and latent heat release from the impinging droplets, solving the Messinger equation. This is typically included in icing CFD tools and requires coupling with conjugate heat transfer models.

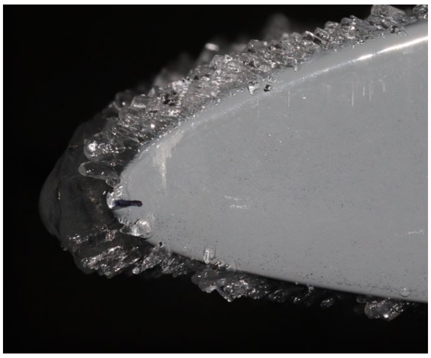

Figure 3: Clear ice accretion on a UAV airfoil from icing wind tunnel experiments.

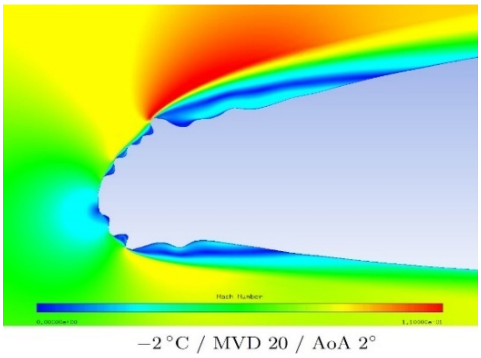

Figure 4: Simulated flow field around an iced UAV airfoil.

2. Problem statement and objective

Most existing numerical tools for icing simulations have been developed for manned aircraft applications. Codes and methods were designed with a certain problem setting and range of conditions in mind. The three biggest areas of interest in manned aviation are icing on lifting surfaces, icing on helicopter rotors, and icing on jet engines. Consequently, the developed models, tools, and validation datasets focus on these specific areas typical to these manned aviation applications and are designed to perform well under specific conditions. Applying these tools to unmanned aircraft generally pushes them outside of their area of validation. This means, that the established models and tools cannot be applied confidently for UAV applications as they introduce substantial uncertainty to the results. Practically, this means that developing solutions that enable safe and continuous operations of UAVs in icing conditions is facing a substantial barrier. With the current speed at which new applications for UAVs, UAM, and AAM are proposed, it is essential to address the icing issue with rigor as otherwise, icing may become a key barrier preventing these technologies from succeeding in the near future.

3. Gap analysis

In the following, the main challenges of icing CFD tools for simulating icing on unmanned aircraft are outlined. The objective is to highlight the key gaps and differences in manned aviation and the challenges that arise from them with respect to simulating icing on typical UAVs.

3.1. Reynolds number

The Reynolds number is a dimensionless number describing the ratio of viscosity to inertia (momentum) in the fluid. The Reynolds number is used to characterize flow with regard to laminar and turbulent effects. There is a large difference in the typical Reynolds number regimes between manned aviation (Re=10^7-10^9) and unmanned aircraft (Re=10^4-10^7) [18]. This large difference in Reynolds number is related to the smaller size and lower flight speeds of unmanned aircraft compared to manned aircraft. The lower Reynolds number implies that laminar flow effects are more prominent for unmanned aircraft. Icing at low Reynolds numbers poses several special challenges for icing CFD codes that typically do not occur – or occur only to a lower degree – at high Reynolds numbers of manned aviation. The difference in Reynolds number itself is a gap that needs to be considered, but several effects deserve close investigation, which will be discussed in the following.

3.2. Lamiar-turbulent transition

Airfoils used for unmanned aircraft typically exhibit laminar flow for significant parts of the airfoil. The laminar flow regions are often over 80% or more of the chord on the pressure and suction side. Predicting the location of the laminar-transition point is a formidable challenge for CFD methods, even without the presence of icing [19]. For icing, the accurate prediction of the transition point is important as the flow state (laminar/turbulent) is having a driving influence on convective heat transfer. The convective heat transfer is a significant element for the energy balance in icing conditions and has thus a significant impact on the ice accretion process and resulting ice shapes [20,21]. In the early stages of icing, a thin roughness layer is forming on the leading-edge of airfoils. This initial surface roughness is suited to trigger laminar-turbulent transition and for manned aviation, it is typically assumed that flow turns fully-turbulent instantly upon the onset of icing [4]. At lower Reynolds numbers, boundary-layer thicknesses are greater and can therefore resist roughness-related perturbances more readily. As consequence, there may be laminar flow present in the early stages of icing when thin surface ice roughnesses form. Consequently, the typical assumption that flow turns fully-turbulent immediately after the onset of icing does not necessarily hold up for unmanned aircraft applications. There is currently a lack of models that can suitably predict the interactions between surface roughness, boundary-layer transition, and heat transfer, which constitutes a major gap for icing CFD models.

3.3. Surface roughness modeling

Surface roughness has an impact on transition, but also affects the heat transfer – which consequently affects ice accretion and ice shapes [22]. Historically, the modeling of ice surface roughness heights was conducted at high Reynolds numbers. For example, the often-used model proposed by Shin [23], which is based on experimental wind tunnel data, had the lowest Reynolds numbers conditions at 0.53m chord length and 67m/s airspeed. This results in Reynolds numbers of approximately $2 \cdot 10^6$, which is still higher than many smaller UAV applications. While it has been attempted to model the ice roughness in more detail (e.g. [22,24]), there is a lack of experimental data suitable for the validation of such models at low Reynolds numbers [25]. One potential way forward is an analytical model that estimates roughness height directly via a beading model [26], however, it remains unvalidated for low Reynolds numbers. In addition, roughness leads to a substantial increase in viscous drag.

3.4. Laminar separation bubbles

Another low Reynolds number effect that has a larger prominence for icing on unmanned aircraft are laminar separation bubbles (LSBs). This flow phenomenon occurs in the presence of adverse pressure gradients in laminar flow, which leads to separation and subsequent turbulent reattachment [27]. Whereas LSBs are not commonly encountered at icing for manned aviation, they are similar to the turbulent separation bubbles forming on horn ice shapes [4]. However, iced-induced laminar separation bubbles have been shown to occur on UAV airfoils at low Reynolds numbers [28,29]. Simulation thereof, using Large Eddy Simulation (LES) methods were reported to be challenging and not able to capture LSBs in all cases [30]. The ability to capture LSB is essential for predicting the airflow around the leading edge – which thus influences ice accretion, heat transfer, and performance losses.

3.5. Turbulence models

The current standard for icing CFD tools are RANS solvers with one or two-equation turbulence models [16]. In manned aviation, most codes use steady-state Spalart-Allmeras [31] or Menter's k-ω SST [32] turbulent models. For performance analysis of iced airfoils, typically higher-order turbulence models can be used, although good results have been documented with the Spalart-Allmeras model. These simple turbulence models typically perform acceptable for low Reynolds numbers (e.g. [33]), but capturing the aforementioned low Reynolds number effects is limited. Furthermore, the steady-state assumption may not be applicable at low Reynolds numbers. In addition to flow effects like LSB, unsteady vortex-shedding may be an effect that can be induced by ice horns [34], and is more likely to occur at low Reynolds numbers [35]. Consequently, the most suitable settings for turbulence models for icing at low Reynolds numbers need to be investigated in more detail and typical assumptions from manned aviation need to be verified.

3.6. Propeller and rotor icing

When icing occurs on rotating surfaces, such as propellers (Fig. 5), ice shedding is an important process to model. Ice shedding occurs when the accumulated ice mass exceeds a critical value where the centrifugal forces become larger than the adhesion forces. As a result, the ice fractures, and fragments of ice are shed from the rotating surface, see Fig. 6. This process is inherently stochastic which makes it very challenging to model accurately. In manned aviation, usually empirical or semi-empirical models are used to estimate performance losses, e.g. [36]. There are substantial differences in diameters and rotational speeds between manned and unmanned aircraft rotors and propellers. Manned aviation focuses either on larger helicopter rotors, while unmanned aircraft favor multiple smaller rotors. Propellers for unmanned aircraft are also typically substantially smaller and operate at lower rotational velocities. Due to the lack of experimental data on ice shedding for typical UAV propellers and rotors, it is currently only possible to propose very simple icing performance models, e.g. [37]. Developing more holistic ice shedding tools would benefit both the unmanned and manned icing development.

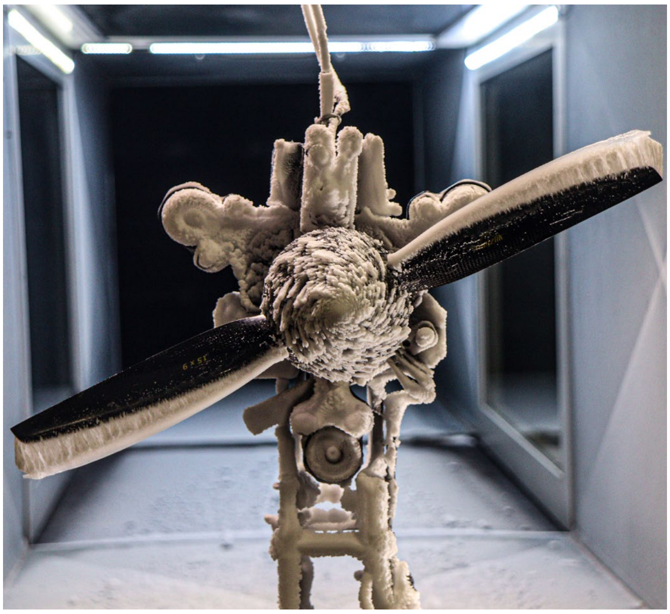

Figure 4: Ice accretion on a UAV propeller in an icing wind tunnel.

Figure 5: Ice shedding removed ice on the outer span of the propeller.

3.7. Electrothermal ice protection systems

Most mature UAV ice protection systems for small to medium-sized aircraft are electrothermal [2]. Electrothermal systems utilize the Joule effect to generate heat in critical areas of the airframe which mitigates icing performance losses. Such systems either operate continuously (anti-icing) or periodically (de-icing). Simulating and predicting the required heat fluxes for ice protection is a key engineering skill for developing energy-efficient protection systems for UAVs [13,14]. Generally, anti-icing simulations are easier, as the condition for anti-icing is to generate sufficient heat to prevent freezing on the surface. This can easily be implemented in the energy and mass balance equations. De-icing, however, is more complicated as it involves the accumulation of a certain amount of intercycle ice (ice that is uncritical to the aircraft's performance) which is then shed periodically. The key challenge in simulation here is the coupling of convective and conductive heat transfer. Also, the criterion for ice shedding is a challenge, which requires estimating the adhesion forces of the melting ice layers and aerodynamic forces acting on the intercycle ice.

3.8. Validation data

Validation is a key part of using any simulation model. Any assessment of the confidence of simulation data can only be performed by comparing the model results with real-world data. For icing CFD, the main validation data types are:

- Ice shapes for validation of ice accretion. Ideally, this includes high-resolution scans of the ice shapes with weight and density measurements;
- Lift, drag, moment curves, and pressure distributions for validation of aerodynamic performance degradation. Ideally, this includes a large sweep of angles of attack at multiple Reynolds numbers;
- Impingement distributions for validation of droplet trajectories. Ideally for known and very narrow droplet size distributions;
- Heat transfer measurements for validation of the energy and mass balance models.

A good overview of available datasets is given in [38]. While there are a (relatively) larger number of validation datasets available for manned aviation applications, few datasets exist for low Reynolds number applications. The lack of suitable validation data is one of the main barriers to resolving the aforementioned challenges for icing CFD simulations. Without experimental data, it is challenging to develop new models or validate existing tools and methods. Consequently, there is a large need for the community to generate high-quality and open datasets that are designed specifically to meet the needs of the UAV and UAM community.

3.9. Other challenges

There are other challenges and gaps in icing CFD. These topics are not specific to unmanned aircraft or low Reynolds number icing and also apply to icing in manned aviation – thus they will be only briefly mentioned.

Ice density is an important parameter for ice accretion modeling. The ice density determines the resulting ice volume resulting from a specific amount of freezing water. Ice densities can vary significantly, depending on the ice accretion conditions [39]. The main parameters that affect ice density are temperature and velocity. Recent studies have shown that accurate ice density models may be critical for ice accretion modeling, even in manned aviation [16]. There is a need to verify experimental findings on ice density at low Reynolds numbers.

Icing with supercooled large droplets (SLD) is a special case of atmospheric icing that occurs in presence of freezing precipitation (freezing drizzle or freezing rain) [40]. These are characterized by substantially larger droplet sizes (up to 2mm) compared to in-cloud icing (15-40µm). Modeling of SLD icing requires advanced models for large droplet behavior, e.g. for break up, splash, rebound, re-impingement. SLD icing is considered an ongoing challenge for the manned aviation industry, in particular when it comes to modeling.

Another current topic in manned aviation is ice crystal icing. Ice crystals can become an issue when ingested in large numbers by jet engines [41]. Since most UAVs utilize fuel or electric engines, this is a lesser issue. However, slow-flying aircraft (e.g. multirotor UAVs), may be subject to ice accumulation by wet snow. Ongoing research is mainly focussing on ice crystal icing in engines and to this date and no in-depth studies have been conducted on UAVs.

4. Conclusion

The objective of this study was to highlight current challenges for icing CFD on unmanned aircraft, especially the gaps between icing in manned aviation. The main focus was on small to medium-sized UAVs that are operating at relatively low flight velocities. Existing icing codes have been developed for manned aviation and are not easily transferable to unmanned aircraft due to a number of reasons. From a CFD simulation point of view, the main gaps are related to the substantially lower Reynolds numbers. As a result, several low Reynolds effects become (more) relevant. The most important is the modeling of laminar-turbulent transition, effects of surface roughness, and laminar separation bubbles. Furthermore, there are several aspects of icing which manned aviation addresses with empirical or semi-empirical models, most importantly for rotors and propellers. These models are based on experiments that do not represent geometries or conditions that are typical for UAVs. Last but not least, there is a pressing lack of validation data from wind tunnel or flight tests. Without validation data or further studies it is difficult to make any assessments about which of the discussed the has the biggest impact and relevance. Most likely, gaps that have an direct effect on heat transfer may be most relevant – this is because they would directly affect ice accretion and ice protection system heat requirements.

Finally, the following steps are recommended to further advance icing CFD on unmanned aircraft and to unlock the full potential of digital twin development methods:

- Apply advanced turbulence models in existing icing CFD codes to improve the capabilities to capture low Reynolds number flow effects. In particular, LSB, laminar-turbulent transition, and surface roughness interactions.
- Generate validation datasets from experiments with conditions and geometries specifically for unmanned aircraft. Conduct validation of existing icing CFD tools for ice accretion, aerodynamic performance degradation, and ice protection systems.
- Develop or adapt existing models for ice shedding, surface roughness, and ice density that are valid at low Reynolds numbers.

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