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REQUIREMENTS FOR UAV OPERATIONS IN COLD CLIMATES AND ICING CONDITIONS

RICHARD HANN, LEAD AERODYNAMICS ENGINEER
KASPER TROLLE BORUP, CHIEF TECHNOLOGY OFFICER
UBIQ AEROSPACE
Krambugata 2, Trondheim Norway

Requirements for UAV operations in cold climates and icing conditions

Richard Hann, Kasper Trolle Borup
UBIQ Aerospace, Trondheim, Norway,
Contact: reqs@ubiqaerospace.com

Introduction

Uncrewed aerial vehicles (UAVs)[1] have become increasingly important for commercial and defense sectors. A major concern for these aircraft is atmospheric in-flight icing, a hazard found in environments with supercooled clouds or freezing precipitation. Flight in icing conditions presents a substantial safety hazard that limits the operational availability, flyability, range, and function of UAVs in cold weather [1].

The objective of this document is to give an overview of the physical and meteorological processes related to atmospheric in-flight icing while also describing the effects of icing on UAVs. Further, this document suggests comprehensive operational and technical requirements for ice protection systems that enable safe operations of UAVs in icing conditions. This holistic approach is designed to inform and guide UAV designers, operators, and policymakers in addressing the challenges posed by icing in uncrewed aerial operations.

Atmospheric in-flight icing

Atmospheric in-flight icing is a meteorological phenomenon critical to flight safety. It occurs when aircraft encounter supercooled liquid water in the atmosphere. This supercooled water, present as cloud droplets or liquid precipitation, remains liquid even below the freezing point. Upon colliding with an aircraft, these supercooled droplets freeze upon impingement (impact). This leads to ice accretion on the aircraft's surfaces, building into various ice shapes. Atmospheric icing can happen globally and at any time of the year – but is substantially more frequent at higher latitudes, in cold climate regions, and cold seasons [2,3].

Ice accretion rate

The ice accretion rate, i.e., the speed at which ice accumulates on an aircraft, is linked to icing severity and is an important aspect in evaluating icing risks. It is influenced by several factors, in order of importance:

- **Liquid water content (LWC):** The amount of liquid water in the atmosphere contributes directly to the icing rate.
- **Air temperature:** The ambient temperature is linked to altitude and plays a crucial role in the shape of ice accretions and the related performance impact. Cold temperatures typically lead to more severe effects, especially on the propulsion system.
- **Aircraft velocity:** The aircraft's speed affects how droplets collide with its surface. High speeds lead to higher accretion rates but also higher aerodynamic friction.
- **Droplet size:** Often quantified by the median volume diameter (MVD), larger droplets can lead to larger icing impingement areas than smaller ones.

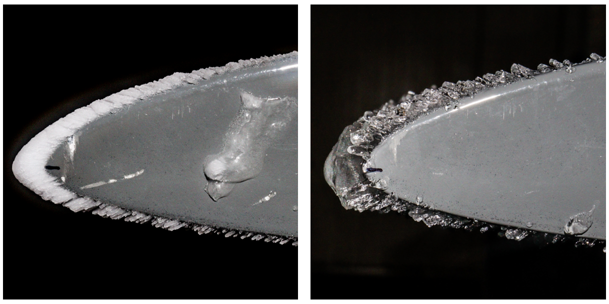

Figure 1: Rime ice (left) and glaze ice (right) ice shapes on a UAV wing from icing wind tunnel experiments.

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[1] Also called, uncrewed aerial vehicles, unmanned aerial systems (UAS), remotely piloted aircraft systems (RPAS), and drones.

Ice shape morphology

The accumulated ice can take several different ice shapes or ice morphologies; see the example in Fig. 1.

- **Rime ice:** Occurs at lower temperatures when droplets freeze instantly upon impact, trapping small air pockets and giving it a white, rough appearance with small ice feathers. Rime ice usually forms streamlined shapes with high adhesion to the surface. They are responsible for severe performance degradation, especially on propellers.
- **Glaze ice:** Forms in temperatures near freezing, where not all droplets freeze immediately. This leads to a thin, liquid film that gradually freezes, creating translucent ice (also called clear ice). Glaze ice can form irregular shapes, like large ice horns, significantly impacting aerodynamics, especially on lifting surfaces.
- **Mixed ice:** A combination of glaze and rime ice resulting from partial freezing of droplets and the formation of a liquid film. Mixed ice can form various shapes, including horn-like structures that degrade aerodynamic performance significantly.

Special icing conditions

In addition to in-cloud icing, there are some special icing conditions that require additional attention:

- **Supercooled large droplets (SLDs):** These occur primarily in precipitation (freezing rain or freezing drizzle) with droplets larger than 40-50 microns, potentially reaching drop sizes of several millimetres. SLD icing is hazardous due to high accretion rates and extensive surface coverage and is a severe threat to all aircraft.
- **Snow and ice crystals:** Generally, snow is less threatening to aircraft due to its inability to stick to surfaces at high speeds. However, ingestion of ice crystals can adversely affect combustion engines. Snow is more relevant for ground structures or rotary-wing UAVs hovering stationarily in wet snow conditions.
- **Cold soaking:** This phenomenon occurs when cold fuel in aircraft wings leads to the freezing of precipitation on the wings, even in above-freezing air temperatures. This is particularly relevant for high-altitude, long-endurance UAVs during descend and landing.

Icing effects

A growing body of research proves that icing has significant negative effects on UAVs. Ice affects a larger number of components and, without suitable ice protection systems, can lead to a loss of the aircraft within minutes [4].

Critical effects

The following represents an assessment of negative icing effects on critical components, ranked by sensitiveness.

1. **Airspeed sensor/pitot tube:** Ice accretion on the pitot tube lead to blocked airspeed readings, resulting in erroneous data being fed to the autopilot. This could cause inappropriate autopilot responses such as stalls or nose-diving. Because of the exposed location and small size of the pressure holes, airspeed sensors are extremely sensitive to icing and can get blocked within seconds, see Fig. 2.
2. **Propellers:** Icing on propellers rapidly and severely reduces thrust and increases power requirements. Experiments have shown a reduction of thrust by 75% percent and a power increase by 250% percent after only 100 seconds in moderate icing conditions [5]. Ice shedding due to centrifugal forces, see Fig. 3, can cause excessive vibrations and imbalances exceeding 10G, which can damage the propulsion system.

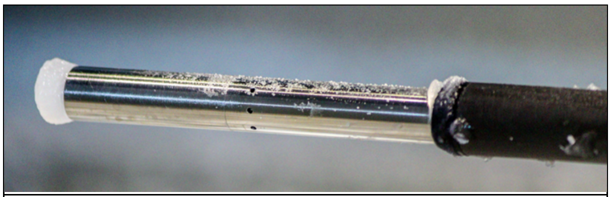

Figure 2: Ice accretion on a UAV pitot tube.

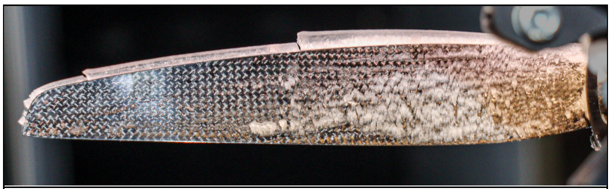

Figure 3: Ice accretion on a UAV propeller after several ice-shedding events, creating “steps” on the leading edge.

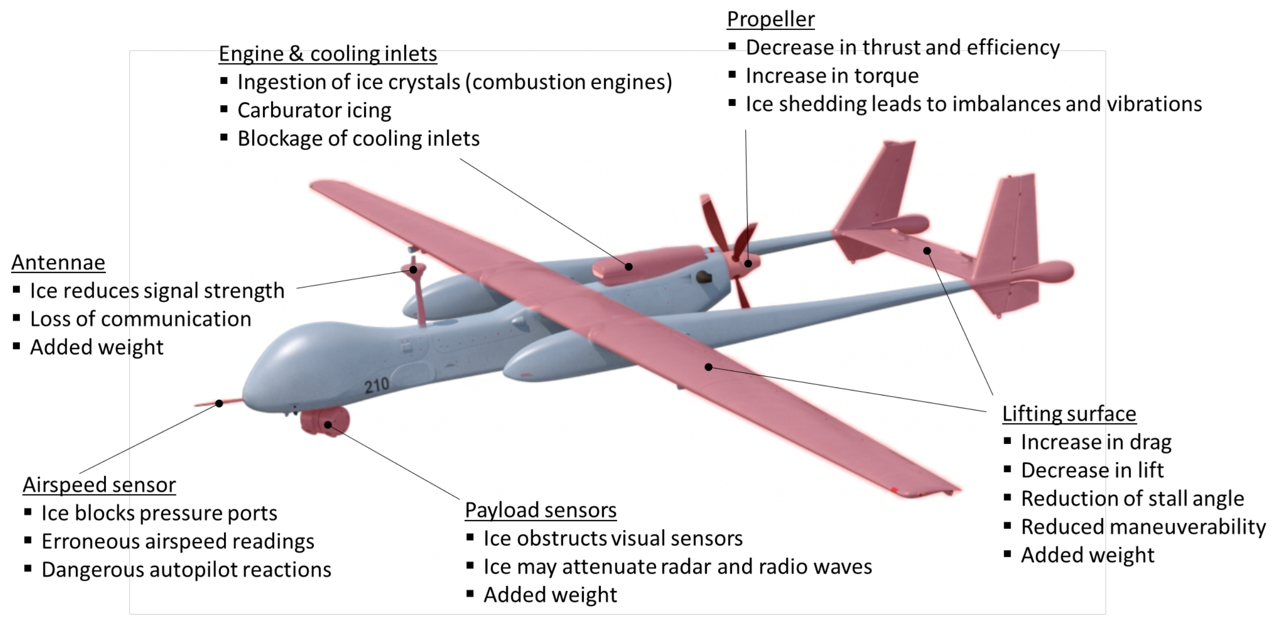

Figure 4: An overview of icing effects on different components of a typical tactical fixed-wing UAV.

3. **Lifting surfaces:** Ice accretion on wings and vertical/horizontal stabilizers alters the airfoil geometry and profile. This substantially increases drag, decreases lift, and reduces the stall margins. Simulations have shown a reduction of lift by 37%, an increase in drag by 107%, and a stall angle reduction of 4 degrees in severe icing conditions [6]. Also, ice reduces the effectiveness of control surfaces and thereby reduces maneuverability.
4. **Autopilot:** Atmospheric icing can mislead the autopilot by altering the UAV's flight performance, stability, and control. The autopilot system may struggle to accurately identify and adapt to these changes, increasing the risk of flight errors.
5. **Antennae:** Icing on antennae can attenuate electromagnetic signals, degrade signal quality, and lead to communication loss. This is particularly critical for remotely piloted UAVs, where reliable communication is essential for safe operation.

Secondary effects

Furthermore, icing also affects other systems that are not critical for safe operations but affect the operational effectiveness and functionality of the UAV. A visual overview is given in Fig. 4.

- **Carburetor icing:** In UAVs with piston engines, the carburetor can experience icing as the vaporization of fuel causes a drop in temperature, which, combined with high humidity, leads to ice formation inside the engine. This can obstruct the fuel/air mixture, resulting in engine power loss or shutdown.
- **Engine & cooling inlets:** Ice accretion on the engine and cooling inlets can restrict critical airflow, leading to reduced combustion efficiency, potential engine stall, or mechanical failure due to overheating from inadequate heat dissipation.
- **Payload sensors:** Icing on payload sensors, such as cameras or radar domes, can obscure lenses and surfaces, leading to compromised data quality and reduced sensor accuracy.

Ice protection systems

Ice protection systems (IPS) in aviation are categorized as anti-icing or de-icing systems. Anti-icing systems continuously prevent any ice accretion on critical aircraft surfaces. De-icing systems allow for an uncritical amount of ice to accumulate, which is then removed periodically. Today, several concepts can be used for ice protection [1]; the most common are **electro-thermal** systems, which use electrical heat; **pneumatic boots** that mechanically break the ice through inflatable membranes (e.g., rubber); freezing point depressant systems ("weeping wings") that disperse a de-icing fluid; and **piccolo tubes** that channel hot, high-pressure engine bleed air into critical areas (most commonly found on airliners). Furthermore, there are more advanced ice protection concepts that have low maturity but may be promising in the future, such as **icephobic coatings,** which passively change material properties such that ice cannot form on surfaces or reduce its adhesion and **electro-mechanical systems** which induce mechanical force generated by electric motors to break and shed ice from aircraft with low energy requirements.

For UAVs, the absence of a pilot necessitates reliable **ice detection** systems to activate and deactivate ice protection systems as needed. It is crucial that these systems are lightweight, energy-efficient, and rapid at detecting an icing encounter. In addition, for continuous flight in icing conditions, detection systems need to be able to indicate the severity of icing and when the aircraft exists in icing conditions.

Icing environments

Icing environments describe icing conditions that aircraft can expect to encounter and which are used to design ice protection systems. Icing environments describe expected combinations of liquid water content, droplet sizes, and exposure times. In manned aviation, the civil aviation authorities have developed icing environments to be used for certification [7,8]. These icing envelopes are described in several appendices of the certification standards. For UAVs, typically, the following envelopes are considered relevant.

- **Appendix C, in-cloud icing:** There are two envelopes that describe typical icing conditions in two different types of clouds, see Fig. 5. The continuous maximum (CM) envelope describes icing in stratus clouds with liquid water contents 0.2-0.8 g/m³ and droplet sizes 15-40 microns over a 17.4 nm (32.2 km) extent. The intermittent maximum (IM) envelope describes icing in isolated cumulus clouds with liquid water contents 1.1-2.9 g/m³ and droplet sizes 15-50 microns in diameter over a 2.6 nm (4.8 km) extent.
- **Appendix O, SLD icing:** More recently, two envelopes have been developed to account for supercooled large droplet icing (freezing precipitation), a very severe form of icing. There are two envelopes that describe freezing drizzle (FZDZ) and freezing rain (FZRA). These conditions are typically very severe and challenging to design for.

Note that these envelopes represent averages over a set distance, and actual conditions may fall outside these predefined ranges. Further research is essential to determine the most appropriate icing envelopes suited for different UAVs, tailored to their specific operational needs.

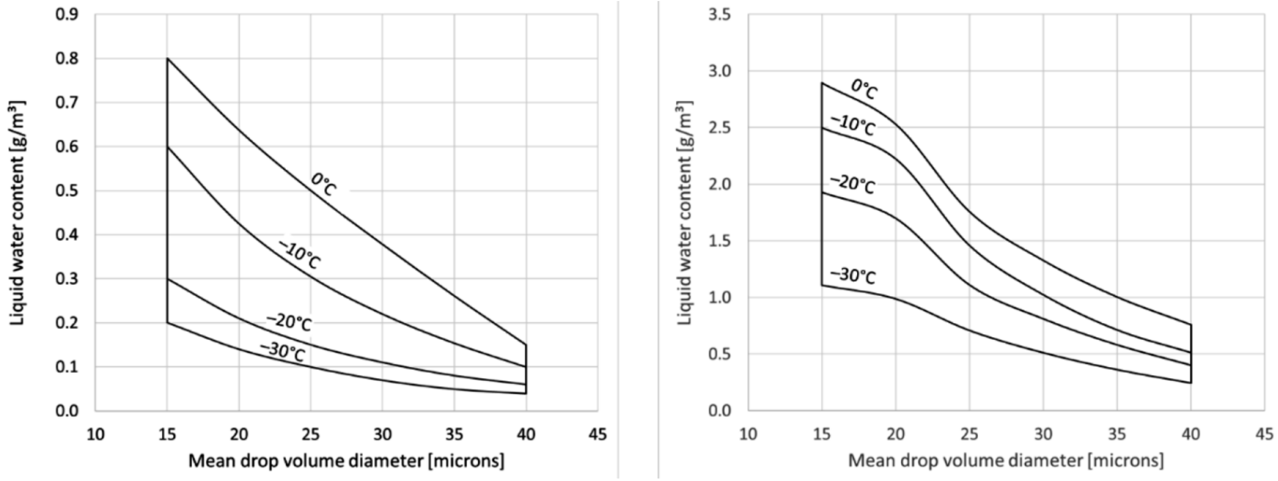

Figure 5: Meteorological icing environments as defined by the civil aviation authorities for Appendix C in-cloud icing. Continuous maximum icing in stratus clouds (left) and intermittent maximum icing in cumulus clouds (right).

Component	Criticality	Effects	Duration till critical effects
Airspeed sensor	Very high	Ice blocks the sensor, leading to erroneous airspeed readings and dangerous autopilot responses.	< 1 min
Propeller	High	Ice accretion leads to rapid and significant performance degradation. Thrust reduction and power requirement increases. Ice shedding causes vibrations exceeding 10G.	< 4 min
Lifting surfaces (wings, & stabilizers)	Moderate to high	Ice changes wing geometry, leading to decreased lift, increased drag, and reduced stall angles. Also, adds weight and reduces maneuverability.	< 10 min
Autopilot	Moderate	Autopilots must adapt to icing-induced changes in flight performance, stability, and control. This includes identifying icing conditions and adjusting flight parameters accordingly.	< 10 min
Antennae	Low to moderate	Ice accumulating on antennae increases weight and drag. Ice can decrease signal strength and lead to communication loss.	< 10 min

Table 1: Overview of component criticality and duration till effects reach a critical level.

Technical requirements

When addressing the technical requirements for UAV operation in icing conditions, it is important to consider three distinct scenarios based on the aircraft's ice protection capabilities:

- **No ice protection system:** Aircraft without ice protection system cannot operate in icing conditions, as ice accretions quickly compromises performance and system integrity, potentially leading to loss of the aircraft. Operations must strictly avoid areas with any forecasted icing and avoid flight into visible moisture (e.g. clouds, fog, rain) in cold weather. This essentially translates to no flight beyond visual line of sight (BVLOS) in cold weather.
- **Inadvertent icing:** Aircraft are equipped with basic ice protection systems to handle unexpected, short-term icing. These systems provide a safety margin for exiting icing conditions inadvertently (unintentionally) encountered, but are not intended for prolonged exposure to such environments.
- **Flight into known icing (FIKI):** Aircraft equipped with advanced ice protection systems, allowing for safe and continuous operations in known (forecasted) icing conditions. These sophisticated systems enable the UAV to handle a wide range of icing situations, thereby significantly broadening their operational capabilities and flexibility. Some severe icing conditions may be still outside the envelope for continuous operation.

In the following, two tables offer an overview of requirements for UAVs operating in these three icing scenarios. The first, Tab. 2, outlines the risks, operational implications, and required ice protection system components for each case. The second, Tab. 3, translates these aspects into recommendations on high-level technical requirements, guiding the necessary specifications for safe UAV operation in these environments.

Summary

For UAV operations in cold weather environments, the importance of adequate operational and related technical requirements to ensure safe operation cannot be overstated. Suitable ice protection systems are crucial for guaranteeing the operational readiness and effectiveness of UAVs in diverse and challenging conditions.

- **Mission readiness and safety:** Operations often require UAVs to operate in harsh, cold-weather environments where icing is a common hazard. Suitable ice protection systems ensures that aircraft can perform their missions in any cold weather without the risk of ice-related failures, which can compromise mission objectives and safety.
- **Operational flexibility and extended range:** Robust ice protection systems allow to operate across a wider range of environments and weather conditions. This flexibility allows for greater strategic and tactical options, ensuring that critical missions can be carried out under

various circumstances without being limited by weather constraints.

- **Enhanced performance and reliability:** Advanced IPS ensure that UAVs maintain optimal aerodynamic performance and system functionality even in icy conditions. This reliability is essential for critical missions where performance can directly impact mission success and the safety of ground forces relying on UAVs support.
- **Autonomy in operations:** Given the uncrewed nature of UAVs, autonomous ice detection and protection capabilities are crucial. They enable UAVs to independently manage icing threats, reducing the need for ground intervention and allowing for more autonomous operation profiles.

In summary, the integration of effective ice protection systems in UAVs is a key factor in enhancing their operational effectiveness, safety, and reliability in cold weather conditions. This capability is essential not only for the successful execution of operations but also for maintaining the integrity and longevity of these valuable aircraft.

	No ice protection system	Inadvertent icing	Flight into known icing
Description	Aircraft has no ice protection capabilities and cannot operate in conditions with any risk of icing. Any icing encounter has a high likelihood to lead to a loss of aircraft.	Aircraft has limited ice protection systems that allow the aircraft to safely escape unforecasted icing with a safety margin.	Aircraft has full ice protection systems that allow safe continuous flight in known icing conditions.
Risk of icing to aircraft	High	Moderate	Low
Operational implications	▪ No flight beyond visual line of sight (BVLOS) when static ground air temperatures are below +5°C. ▪ Aircraft must avoid icing conditions entirely. ▪ Flight planning relies heavily on weather forecasts. ▪ Restrictions on operating in certain climates or seasons.	▪ No continuous flight in clouds at static air temperatures below 5°C. ▪ Aircraft must immediately exit icing conditions if encountered. ▪ No sustained operations in icing environments.	▪ Continuous operations in a wide range of icing conditions, including moderate to severe icing. ▪ Limited operations into most severe conditions like freezing rain/drizzle (SLD).
Required ice protection equipment	▪ None	▪ Ice detection system ▪ Protected pitot tube ▪ Protected propeller	▪ Ice detection system ▪ Protected pitot tube ▪ Protected propeller ▪ Protected lifting surfaces (wings, empennage) ▪ Protected antennae (optional) ▪ Protected payloads (optional)

Table 2: Summary of operational limitations of UAVs operating in icing environments depending on their ice protection system capabilities.

Topic	Technical requirement	Scenario
General	The UAV shall maintain performance and safety for the duration of an icing encounters. This duration is defined as the time from initial ice accumulation to the point where the UAV successfully exits the icing conditions.	All
General	The duration of an inadvertent icing encounter should be at least 5 min.	Inadvertent icing
General	The duration of an flight into known icing encounter should be at least 20 min.	Flight into known icing
General	The effectiveness of the ice protection system shall be demonstrated during flight tests into natural icing conditions.	All
General	The performance of an ice protection system (propeller or airframe) shall be demonstrated for critical design cases in icing wind tunnel tests.	All
General	Critical icing design cases should be identified from Appendix C (continuous maximum and intermittent maximum) for the airframe and propeller separately by means of simulation	All
Ice detection	The UAV shall be able to accurately detect the onset and presence of icing conditions. The time between entering icing conditions and detection shall be sufficient to allow the UAV to safely exit the icing conditions. Detection duration should be less than 1 minute.	Inadvertent icing
Ice detection	The UAV shall be able to accurately detect the onset and presence of icing conditions. The time between entering icing conditions and detection shall be sufficient to allow the UAV to activate suitable ice protection systems. The detection duration should be less than 1 minute. In addition, the UAV shall detect when icing conditions have been exited and estimate icing severity (ice accretion rate).	Flight into known icing
Airspeed sensor	The static pressure port shall always provide a data reading not affected by ice or air moisture condensation, which can form even flying outside clouds.	All
Airspeed sensor	Pitot tubes, which provide airspeed indication through the total pressure reading, shall be heated.	All
Propulsion	Ice accretions on propeller or rotor shall not result in hazardous vibrations, which can damage the propulsion system.	All
Propulsion	The propulsion system shall be protected against excessive performance loss due to icing for the duration of the icing encounter. Sufficient thrust and torque shall be are maintained to keep the UAV airborne and manoeuvrable.	All
Propulsion	Ice shedding from an heated or unheated propeller shall not lead to excessive vibrations to damage the propulsion system.	All
Airframe	Ice accretions on the airframe shall not results in hazardous aerodynamic performance degradation during the duration of the icing encounter. This includes effects on lift, drag, moment, stall, and control surface effectiveness.	All
Airframe	For a de-icing system, it shall be shown that intercycle ice shapes are not resulting in hazardous aerodynamic performance degradation.	Flight into known icing
Airframe	The total weight of ice accretions accumulated during an icing encounter shall not result in hazardous weight changes.	All

Table 3: Recommendations for technical requirements of UAVs operating in icing conditions.

Literature

[1] Hann, R., Johansen, T.A. (2020). Unsettled Topics in Unmanned Aerial Vehicle Icing. SAE International, SAE EDGE Research Report EPR2020008. doi.org/10.4271/EPR2020008.6

[2] Sørensen, K.L., Borup, K.T., Hann, R., Bernstein, B., Hansbø, M. (2021). UAV Atmospheric Icing Limitations: Climate Report for Norway and Surrounding Regions. Report. UBIQ Aerospace.

[3] Bernstein, B. C., Le Bot, C. (2009). An inferred climatology of icing conditions aloft, including supercooled large drops. Part II: Europe, Asia, and the globe. Journal of applied meteorology and climatology, 48(8), 1503-1526.

[4] Hann, R. (2020). Atmospheric Ice Accretions, Aerodynamic Icing Penalties, and Ice Protection Systems on Unmanned Aerial Vehicles. PhD Thesis NTNU2020:200, Norwegian University of Science and Technology.

[5] Müller, N.C., Løw-Hansen, B., Borup, K.T., Hann, R. (2023). UAV icing: Development of an ice protection system for the propeller of a small UAV. Cold Regions Science and Technology, 213, 103938. doi.org/ 10.1016/j.coldregions.2023.103938.

[6] Lindner, M., Wallisch, J., Hann, R. (2023). UAV Icing: Numerical Simulation of Icing Effects on Wing and Empennage. SAE International Conference on Icing of Aircraft, Engines, and Structures. doi.org/10.4271/2023-01-1384.

[7] Federal Aviation Administration FAA (2002), 14 CFR Parts 25 and 29, Appendix C, Icing Design Envelopes, DOT/FAA/AR-00/30.

[8] European Union Aviation Safety Agency EASA (2007). CS-25 Certification Specifications for Large Aeroplanes