UAV Icing: A Unified Icing Severity Index Derived from Performance Degradation

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A problem that unmanned aerial vehicles (UAV) operators face when dealing with in-flight icing conditions is a reliable way to assess icing severity risk. This paper aims to develop an icing severity index that looks at the combined effect of icing performance degradation on wings and propellers for a specific UAV. The index developed in this paper will provide UAV operators with an easier way to assess icing risk. Icing severity indices for the wings and propeller are computed separately to highlight the individual contributions of power increase. Combining them yields the unified icing severity index. To develop the unified icing severity index, a focus is put on the power consumption increase resulting from aerodynamics performance degradation that is due to ice. The wings and propeller will be subject to different icing conditions specified by median volume diameter (MVD), and temperature. Two propeller rotation rates are also tested for each of these icing conditions. The tests are performed through computer simulations using a pre-existing simulation framework. Each condition will yield the power consumption from these simulations, where the UAV will fly the same straight path. These parameters are compared against the baseline, clean condition, to yield an index. Results from a case-study show significant differences in power consumption between different icing conditions. The ice affects performance degradation on the wing and propeller differently depending on ice type. The propeller degradation is the least severe for glaze ice and the worst for the rime ice case. The wing degradation is the least severe for rime ice case and worst for the glaze ice case. Combining the wing and propeller degradation show 8 times increase in power consumption for rime ice compared to clean condition in the worst case.

I. Introduction

Atmospheric icing is a limiting factor for operating unmanned aerial vehicles (UAVs) to their full extent [1]. Ice degrades the performance of UAVs by decreasing lift, increasing drag, and reducing stall angle by disturbing airflow around the airfoil shapes of the wing and propeller as the ice changes the shape of these surfaces [2]. There are three main ice types relevant for aircraft icing: glaze, rime, and mixed ice. Glaze ice occurs at temperatures closer to the freezing point of water. Liquid water freezes slowly and leads to an uneven surface, and in some cases, ice horns forms on the ice structure detrimental to performance. Rime ice occurs at lower temperatures, freezing quickly, and entrapping air. This

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preserves the airfoil shape better, leading to less performance degradation. Mixed ice is as the name suggest a mix between the two conditions [2]. For propeller performance degradation, rime ice has been reported to degrade propeller performance the most [3]. While glaze ice has been the most detrimental to performance for the wing [4]. Mixed ice is the second worst case for both the wing and propeller. Figure 1 shows the different ice types on an airfoil, showing how rime ice (top left) preserves the airfoil shape better, while glaze ice (top right) is more horn-like. Figure 2 shows different ice types on a propeller. As it was not possible to take photos when the propeller was rotating, all photos were taken post-experiment. For all experiments, glaze ice shed completely and hence there are no photos of glaze ice on a propeller. For an example on glaze ice, the closest thing is what is shown in Fig. 1. It can be observed in Fig. 2, as temperature decreases, more ice is left on the propeller by the end of the experiment. At −5 °C, there is not much ice left, but show mixed ice. For −10 °C and −20 °C they both show rime ice. Further details will be discussed in the methods section.

The performance degrades differently between the wing and propeller due to the difference in how they operate. The propeller rotates at significant speeds such that it can shed ice naturally, through centripetal forces. Additionally, aerodynamic friction of the propeller prevents ice-formation in temperatures close to freezing. This is due to the heat generated on the propeller blade surfaces from high relative airspeed resulting from the rotating propeller [5]. For the wings this does not occur due to low relative airspeed [6]. While ice can shed naturally, there is still performance degradation occurring [7]. The wing does not experience similar forces compared to the propeller; hence, wing ice requires help from an ice protection system (IPS) to shed ice. Why then do different ice types affect performance of the propeller and wings differently? Rime ice has higher adhesion force with the propeller surface and the ice rarely sheds completely [3]. Rime ice also have less cohesion, due to its porosity, than on the propeller surface. Hence, as the ice thickness increases, the outer layer of the ice sheds more easily. The ice will tend to shed at the tips as the rotational speed is faster than at the hub. This leads to uneven shedding and hence more performance degradation. Glaze ice, in combination with aerodynamic friction, more readily sheds from the propeller, sometimes completely, which makes it less dangerous [3].

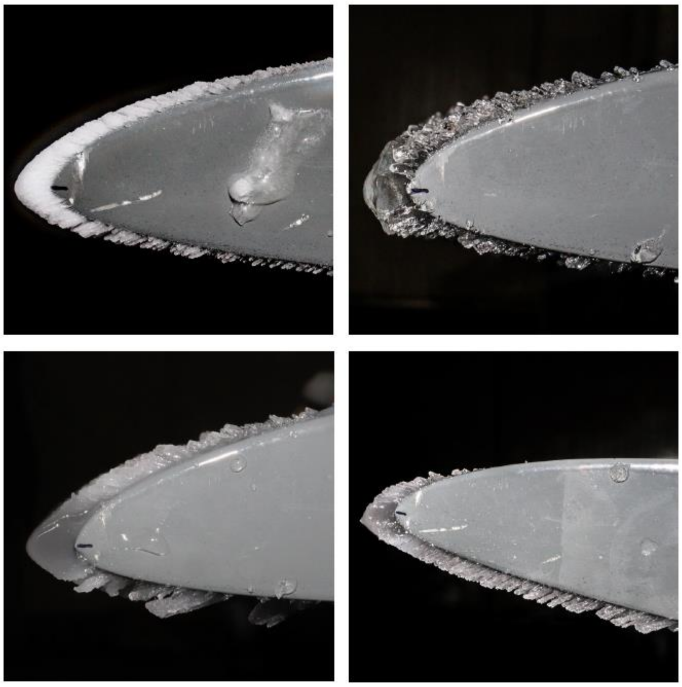

Figure 1 Different ice types on an airfoil. Rime ice (top left), glaze ice (top right), mixed ice (bottom left and right) [8]. Photo: Richard Hann.

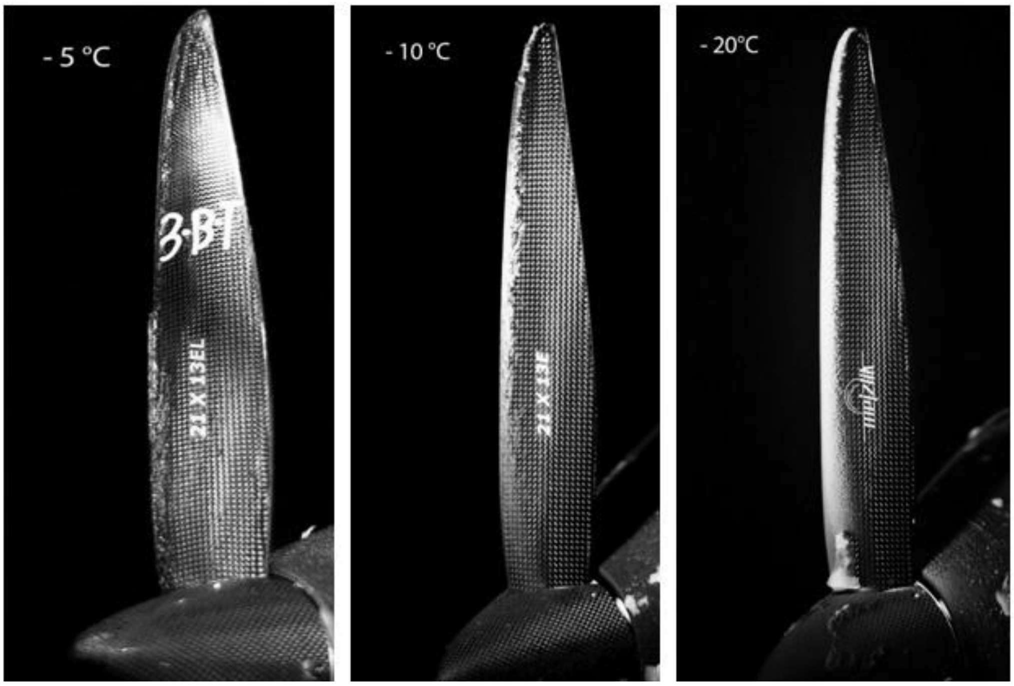

Figure 2 Different ice types on propeller blades. Mixed ice (left), rime ice at different temperatures (middle and right). The photos were all taken post experiment and all experiments with glaze ice completely shed, which is why no photos are included. Photo: Nicolas Müller.

Ice increases power consumption of the aircraft as drag increases [8]. To counteract the drag, the engine needs to output more power to meet thrust requirements. In the worst case, icing can lead to loss of the aircraft when drag exceeds what the engine can provide in thrust [9]. The power consumption increase due to ice can be a challenge, as it can hinder the UAV from completing its mission as fuel depletes quicker. Icing is well understood in manned aviation, with mature ice protection systems [10]. However, there is still a lack of knowledge in the case of UAVs because it is only recently the UAV market has grown large enough to warrant investigation [1]. UAVs are generally smaller, restricting resources such as less fuel and smaller batteries, hence less power capacity is available to deal with the ice [6]. UAVs are also more susceptible to ice as the accumulated ice mass is of higher relative percentage of the UAV mass [11]. Ice protection systems for UAVs are currently under development, but are not in a mature state yet [12]. There are many reasons an IPS for UAVs are yet to be mature. One reason is that it requires more efficient operation as to not strain the already restricted resources of the UAV, which is currently being investigated by Wallisch and Hann [13]. UAVs thus still lack the means to properly deal with ice that does not strain its resources and hence UAVs still experience significant risk even with IPS.

Weather forecasters divides icing into four categories, trace, light, moderate, and heavy, and looks at how fast ice thickness accretes 25% of the airfoil chord length, as defined by NOAA in [14]. Trace is 1 hour, light is 15-60 minutes, moderate between 5-15 minutes, while heavy is less than 5 minutes. However, the index only looks at ice accretion rate and does not consider ice type, which degrades performance differently as explained above. It has also been shown that icing behaves differently depending on the size and type of aircraft, and it is not clear how well ice shapes translate from one aircraft size to another [1,6]. As outlined by Jeck [15], different organizations use different definitions and the descriptions make it difficult to distinguish between categories and is often subjective.

There has been previous work in developing icing indices such as [16–18]. The work by Lamraoui et al. [16] and Morcrette et al. [17] focus on prediction and forecasting of atmospheric icing. Morcrette et al. [17] mention that pre-existing icing indices are, from anecdotal evidence, unreliable but that they improve it. The method in the paper by Morcrette et al. [17] improve the reliability of the pre-existing icing index computed by the UK MET office. Morcrette et al. does this by redefining the index by comparing hindcasts and ground-based sensors, which is validated through satellite-based observations. The papers by Lamraoui et al. [16] and Morcrette et al. [17] focus on quantifying ice in the atmosphere and is not directly related to aircraft icing. The study by Politovich [18] is the closest approach to what is being attempted in this paper, by using a commercial research aircraft to directly test icing indices. A combination of liquid water content (LWC) (>0.2 g/m^3), median volume diameter (MVD) (>30 µm) and temperature (between −2 and −10 °C) was found to yield the largest performance degradation. It was, however, noted that it most likely only applied to their research aircraft. Politovich [18] analyzed the performance degradation through the decrease of lift and climb rate, and increase in drag rather than power consumption. However, Politovich [18] tests icing indices by exposing the aircraft directly to ice, which can be time consuming.

To summarize, previous severity indices have been shown to be unreliable. This is because it can be difficult to differentiate between icing categories or does not differentiate between different icing conditions nor aircraft size and type. Additionally, some icing indices are not directly related to aircraft icing, and it has been difficult for pilots to evaluate different icing conditions. By developing a method that directly uses aircraft specific data will allow a more robust approach when calculating icing severity. By gaining access to a reliable method, will enable UAV operators and manufacturers to use the index as reference for either mission planning or in developing efficient IPS. To have a unified metric for icing, where propeller and wing performance degradation is combined, can simplify the evaluation process on mission risk and to plan for preventative measures depending on the ice conditions.

This paper aims to develop a unified icing severity index (ISI) based on the aerodynamic performance degradation experienced due to ice on both the wings and the propeller. The aerodynamic performance is quantified through lift and drag in the case of the wing and propeller efficiency in the case of the propeller. As the UAV gets exposed to ice, the clean wing lift and drag curves changes in response to the change in wing shape and yields new iced lift and drag curves. The propeller gets a decrease in efficiency in response to ice exposure affecting thrust generation. These data are used directly to compute an iced power consumption. The icing conditions investigated are the three icing types, glaze, rime, and mixed ice (corresponding to three different temperatures) at different median volume diameter (MVD). The ISI will be developed through using computer simulations, by using a pre-existing simulation algorithm.

The ISI can then be used to develop a map over a mission area showing icing risks, granting a better overview of the conditions in the area. To define how to interpret the ISI, the ISI values are compared against the clean case, where for example a value of 5 mean it sees 5 times increase in power consumption. Think of a mission length of, for example, 100 km, with just enough battery for an UAV flying through clear conditions. If ice occurs, the length the UAV can fly will depend on the ISI. If the ISI is 5 means the UAV will decrease the endurance of the UAV by 5 times, then the UAV would only be able to fly 20 km. The ISI is required to mark the boundaries of the icing risk on a map of the mission area that will be created from the simulator detailed in the methods section. This will benefit UAV operators where operational uptime is important, rescuers during hazardous weather or operators with critical deliveries where no other option is possible. By using the ISI, UAV operators will be able to map the risks and prepare their equipment to operate as efficiently as possible and hence maximize mission success rate.

The outline of the paper is as follows: The methods section will be presented next, presenting the general method of calculating the ISI before showcasing the method by using data from a case-study. The case-study will be introduced with the data for the propeller and wing in table format. From the methods, results are then presented and highlights noteworthy findings. This is followed with a discussion on the results and other interesting findings from the tests not directly related to the ISI. The paper then concludes with some comments on future work.

II. Methods

This section presents the simulation framework used to calculate the power consumption and how the ISI is computed. It also presents a case study, the PX-31 Falk, a 3.2-meter fixed wing UAV developed by Maritime Robotics. The propeller and wing data comes from experiments made on the same propeller and airfoil shape as on the Falk. The data and its usage are explained as there are some caveats in the data. First, the simulator is presented, followed by ISI calculation procedure. The propeller and the wing data are then presented respectively.

A. Simulation Algorithm

A particle swarm optimization (PSO) path planner developed by Hovenburg et al. [19], and refined by Narum et al. [20] and Tiller [21], will be used to compute the ISI. It considers UAV specifications and environmental data over the mission area. A general path planner generates a viable path by defining obstacles, UAV specifications, weather data and terrain data that it needs to consider while flying. A start and end point are user specified, which defines the mission area. A viable path generated by the planner is in general not the only path available but satisfies some specified criteria by the user and the capabilities of the specific UAV. The weather data contains wind data and icing parameters used to determine whether there is ice present at certain locations of the mission area. The path planner also incorporates an IPS model that removes ice. This enables the planner to evaluate whether it will be optimal to fly through an area with ice while activating the IPS or to try to find a path around it. The frame of reference, kinematics, and flight mechanics are also implemented as specified in [22]. The PSO is not directly used in this paper, but the interested reader can refer to the paper by Tiller [21] for the full details on the algorithm.

To develop the ISI, an ISI module will be implemented into the path planner. The ISI module is separate from the path planning process. To ensure that the power consumption differences in the simulation are based purely on different icing conditions, the following assumptions are made for all scenarios:

1) straight path;
2) no weather is simulated, such as wind;
3) same cruise speed;
4) same operating weight;
5) constant air density.

The only difference between the simulations is the usage of different lift/drag curves and propeller efficiency corresponding to the different icing conditions. The ISI is then derived from comparing the power consumption differences between different icing conditions and the baseline clean condition. To fulfil the lift and drag equations, the required parameters are air density, lift and drag coefficient, airspeed, and area of the wing surface.

The general code framework will be used as there are modules, such as flight mechanics module, that are necessary to compute power consumption. It is also helpful to have the path planner compute the ISI, as it would be possible to directly use the ISI in the planner later for optimization, path planning and mapping of ice. The ISI module can also be extended later to include time-dependencies to make it more accurate. The flight mechanics module solves a series of equations that yield power consumed and is detailed below.

B. Estimation of Icing Severity Index

To calculate the power consumption, the thrust needs to be calculated. The aircraft is assumed to be at steady-state, and hence, thrust will equal drag of the aircraft. The lift L will equal the aircraft weight and the lift coefficient C_L will be calculated from the lift equation as detailed in Eq. 1-2:

$$L = mg \tag{1}$$

$$C_L = \frac{2L}{\rho V^2 A_{wing}} \tag{2}$$

Here, m is aircraft mass, g is earth's gravity, ρ is air density, V is aircraft airspeed and A_{wing} is wing surface area. The corresponding AOA will be found from the lift curve with a linear fit on the lift data points. The AOA will then be used to find the drag coefficient C_D from a polynomial fit on the data points in the drag curve. The drag D is found from the drag equation:

$$D = \frac{1}{2}\rho V^2 C_D A_{ref} \tag{3}$$

where A_{ref} is the aircraft reference area (surface area of entire aircraft). Since the aircraft has a non-zero angle of attack, its lift will have a component backwards that contribute to the drag. This induced drag due to lift can be calculated by Eq. 4:

$$D_{ind} = L \cdot \sin(AOA) \tag{4}$$

The thrust T and power P can then be calculated with Eqs. 5-6 respectively:

$$T = D_{ind} + D \tag{5}$$

$$P = TV \tag{6}$$

The theoretical energy requirement can then be calculated by multiplying with the time the aircraft takes to complete the path. This is the energy required to complete the path, without considering the losses in delivering it. The actual energy drawn from the motor is calculated by dividing with the engine efficiency and propeller efficiency to yield energy consumed for the path. The index is finally calculated by dividing the energy consumption of the icing conditions with the clean baseline energy consumption as shown in the Eq. 7 below. The power consumption ratio can be used in the case where flight time is the same for all test scenarios, which for this paper, is true.

$$ISI = \frac{E_{iced}}{E_{clean}} = \frac{P_{iced}}{P_{clean}} \tag{7}$$

The following sections will present the PX-31 Falk specifications that will be used to compute a UAV specific index. The next section will present the propeller performance data and how it is used.

C. Case Study of Falk PX-31: Propeller Performance Degradation

The degree of degradation can vary depending on the UAV, as different airfoil and airframe shapes have different sensitivities to ice. Hence, as a case study, the PX-31 Falk is presented. It is developed by Maritime Robotics, a company specializing in providing unmanned vehicles for maritime use, and is used as a case study in this paper [23]. By replacing the PX-31 data as presented in Tables 1-2 with other UAV specific data will allow you to calculate indices for other UAVs. In the next sub-section, the propeller performance degradation will be presented. This section reviews the work by Müller and Hann [3]. The findings will be summarized and the justification on how the data is used will be presented.

The propeller performance is quantified by propeller efficiency. However, propeller efficiency is a parameter that fluctuates and depends on the advance ratio. The advance ratio is the ratio between freestream velocity and propeller tip speed. With a constant freestream velocity through airspeed, adjusting the speed or revolutions per minute (RPM) of the propeller changes the advance ratio and hence efficiency. The change in RPM requires re-calculating the aircraft parameters such as thrust, power, efficiency, and torque coefficients. A simplifying assumption is made here: For the UAV to maintain the specified cruise speed, the thrust requirements need to be met. It is assumed that the rotation rate of the propeller does not change from 4200 RPM during icing condition. In reality, the RPM will increase as to meet the required thrust requirements. With ice accretion on the propeller blades, the propeller needs to rotate faster to generate more thrust to overcome additional drag from ice. The test RPMs were chosen to be 4200 and 5000 RPM because 4200 RPM is the RPM required to maintain cruise speed of 25 m/s. Increasing it to 5000 RPM is a realistic increase to maintain the same cruise speed with icing.

Table 1 Propeller efficiencies used for each icing condition.

Efficiency	Clean	Iced Average	Iced Maximum	Iced Minimum
−2°C (4000 RPM)	0.63	0.63	0.67	0.51
−2°C (5000 RPM)	0.71	0.67	0.72	0.65
−5°C (4200 RPM)	0.77	0.63	0.68	0.57
−5°C (5000 RPM)	0.78	0.69	0.72	0.67
−15°C (4200 RPM)	0.70	0.13	0.36	−0.038
−15°C (5000 RPM)	0.72	0.39	0.48	0.14

Table 1 shows the efficiencies for different atmospheric conditions and RPMs. Ice accretion on a propeller is complex due to the forces on a spinning object that makes the ice shed. The propeller undergoes a cycle of ice accretion and ice shedding. The data in Table 1 is obtained from icing wind tunnel (IWT) tests, tested at two RPMs, at different temperatures −2 °C (glaze), −5 °C (mixed), and −15 °C (rime) [3]. The nature of ice accretion and shedding for a propeller, can be random and difficult to predict. Hence, the average, maximum and minimum efficiency were each used to illustrate average, best and worst case, respectively, and grants a range of possible power consumption values for each ice condition. It is important to note that the maximum and minimum propeller efficiency only occurs for a short period. Hence, it is assumed that using the average efficiency will be more representative of actual conditions, but the maximum and minimum are included for completeness. The minimum efficiency is negative for one of the test runs, which is automatically given an index of infinity, as the simulation is not able to process negative efficiency. Another key observation is how RPM affects efficiency. By comparing the values in Table 1 it can be observed that the faster rotational rate gives increased efficiency. It is important to note that the values in Table 1 are extrapolated to 20 minutes to match the ice sensitivity of the wing. A detailed explanation is presented in the discussion.

Table 1 shows the clean efficiencies of the propeller. This is dependent on the freestream velocity used in the IWT experiments and may have changed between experiments, hence there is some variation. In the −2 °C case, the max efficiency is higher than the clean case. When the first shedding occurs, there will be an instantaneous moment when the ice sheds, reducing drag and mass. The speed controller requires a moment to adjust to this new condition, hence, there is a moment where the propeller rotates faster, allowing the efficiency to exceed the clean efficiency.

D. Case Study of Falk PX-31: Wing Performance Degradation

Table 2 PX-31 Falk Specifications.

Specifications	Value
Max take-off weight	25 kg
Standard operating weight	18 kg
Cruise speed	25 m/s
Max speed	40 m/s
Wing surface area	0.6 m²
Aircraft reference area	1 m²
Wingspan	3.2 m
Engine efficiency	0.8

Table 3 Meteorological Conditions for Icing used in simulations.

Variable	Glaze	Rime	Mixed
Temperature	−2 °C	−15 °C	−5 °C
MVD	15/20/30/40 μm	15/20/30/40 μm	15/20/30/40 μm
Air Density	1.05 kg/ m³		

The lift and drag curves are derived from ANSYS FENSAP-ICE, a state-of-the-art tool for numerical modelling of icing effects on aircrafts, with the simulations performed by Fajt et.al. [4]. The lift and drag data of the airfoils from FENSAP-ICE assumes 20 minutes of the UAV being exposed to ice. The wing performance degradation is not as complex as propeller performance degradation but does in general follow the same aerodynamic principles. Glaze ice leads to a more uneven surface or ice horns which might trip the airflow into turbulence. Rime preserves the shape better and hence degradation is less. Table 3 shows the meteorological icing conditions that are used to get the lift and drag curves. These conditions are chosen with regards to CFR 14, which is used by the federal aviation administration (FAA) to certify manned aircraft [24]. The aircraft specifications are summarized in Table 2. The airfoil of the PX-31 Falk is the RG-15 which is designed for lower Reynolds numbers that smaller UAVs usually operate in [13]. The wing degradation only scenario uses the iced lift and drag curves combined with the clean efficiency of the propeller. Because there is not any propeller degradation, there is no reason to use the 5000 RPM values. Hence, only the 4200 RPM efficiency values are used when computing wing degradation only indices. With the method and data explained, the results computed from these methods will be presented next.

III. Results

In this section, the results are presented. The results for propeller degradation only will be presented first, followed by wing degradation only. This section ends with the unified ISI results.

A. Propeller degradation only

Figure 3 shows the ice severity index for propeller degradation only. It shows the variation between the different ice types, RPM and maximum, average, and minimum efficiency as indicated in Table 1. It is assumed that a change in LWC or MVD only affects how fast the propeller degrades and not how much degradation occurs [3][§]. Glaze ice has the interesting result of having an ISI lower than 1 for the maximum efficiency case. Having an ISI below 1 is different for the propeller and the wing. For the propeller, it indicates that the maximum efficiency is higher than the clean efficiency. How this can occur is explained under section II.C. It is also interesting to note that the average efficiency index for the same case is 1. This means that glaze ice averages out to have no effect on the propeller and hence no effect on power consumption. This does not mean that it will occur every time due to test variation, also explained under section II.C.

[§] This statement is not highlighted in the Müller paper [3], but the experiments performed do show signs of this trend in the post-processing of the results. Additional experiments are required to validate this claim in the future, but in this paper, it is an assumption.

An example on test variation is seen when comparing between the glaze ice cases with different RPMs. Although both have the instance where the ISI is below 1, the ISI of average efficiency is above 1 for the 5000 RPM case. It is known that the efficiency in the 5000 RPM case is generally higher and the difference between the two cases is small. This can be explained by experimental variation. The minimum efficiency exhibit, as expected, the highest ISI. Mixed ice shows slightly higher ISI compared to glaze ice for both RPMs, meaning it is slightly worse than glaze. The mixed ice ISI for the 5000 RPM case is lower than for 4200 RPM, but not by a large margin. The rime ice case exhibits a significant increase in ISI compared to glaze and mixed ice. The ISI for maximum efficiency for rime is higher than minimum efficiency ISI for both the glaze and mixed ice. This shows the severity that rime ice has on propellers. For the 4200 RPM case, the minimum efficiency ISI gives a failed run due to negative efficiency. What is remarkable is that the average efficiency ISI for 4200 RPM is higher than the minimum efficiency ISI for the 5000 RPM case. It is difficult to have a precise explanation but is most likely a combination of test variation and that rime ice sheds easier at higher rotation rates. The average efficiency ISI for 5000 RPM is below 2, which is low when compared against 4200 RPM case. The highest ISI is 5.4 for rime ice, which means the power consumption is 5.4 times higher than the clean power consumption. The next section will present the results for the wing.

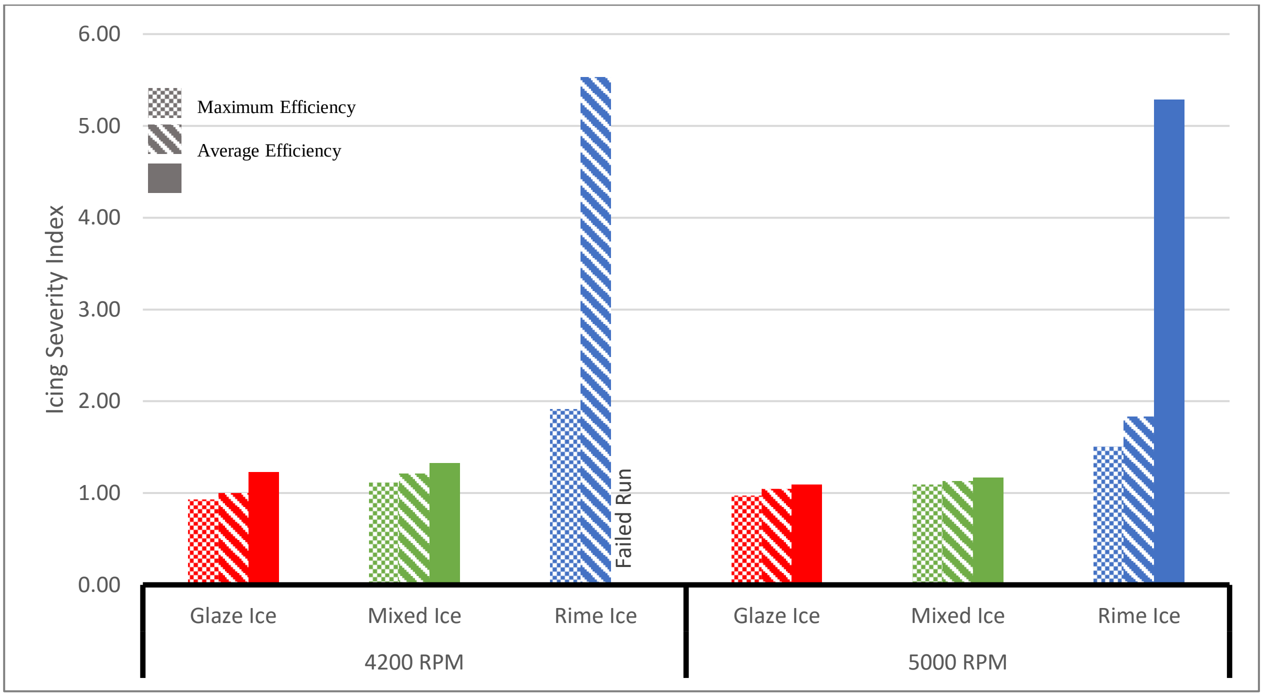

Figure 3 Ice Severity Index for Propeller Degradation Only.

B. Wing degradation only

Figure 4 shows results for wing degradation only. Here, glaze ice gives the worst performance degradation across all MVDs. This is followed by mixed and glaze ice respectively. Glaze ice ISI peaks when MVD is 20 µm, while for mixed and rime ice the ISI peaks when MVD is 15 µm. There is not much difference when comparing ice severity when the MVDs are 30 and 40 µm except for the glaze ice case where the ISI is relatively higher in the 30 µm compared to the 40 µm case. Glaze ice gives the highest degradation due to the uneven surface associated with glaze ice formation. The performance degradation is not as severe as the propeller case, with the largest ISI only being half as high. The reason why degradation is less for the 30 and 40 µm cases is because the LWC reaches much lower values compared to the 15 and 20 µm cases. For the wings, it is the LWC that determines how much degradation can occur. While MVD is a metric on droplet size, LWC is the metric on the amount of liquid water in the atmosphere. The more water is present, the higher the ice accretion, given that the droplets are not too small. For smaller MVD the droplets follow the streamline around the airfoil better and hence avoid collision with the aircraft. Larger droplets lead to more splashing and, hence, more downstream icing. This is supported by the findings in the work by Fajt et al. [4].

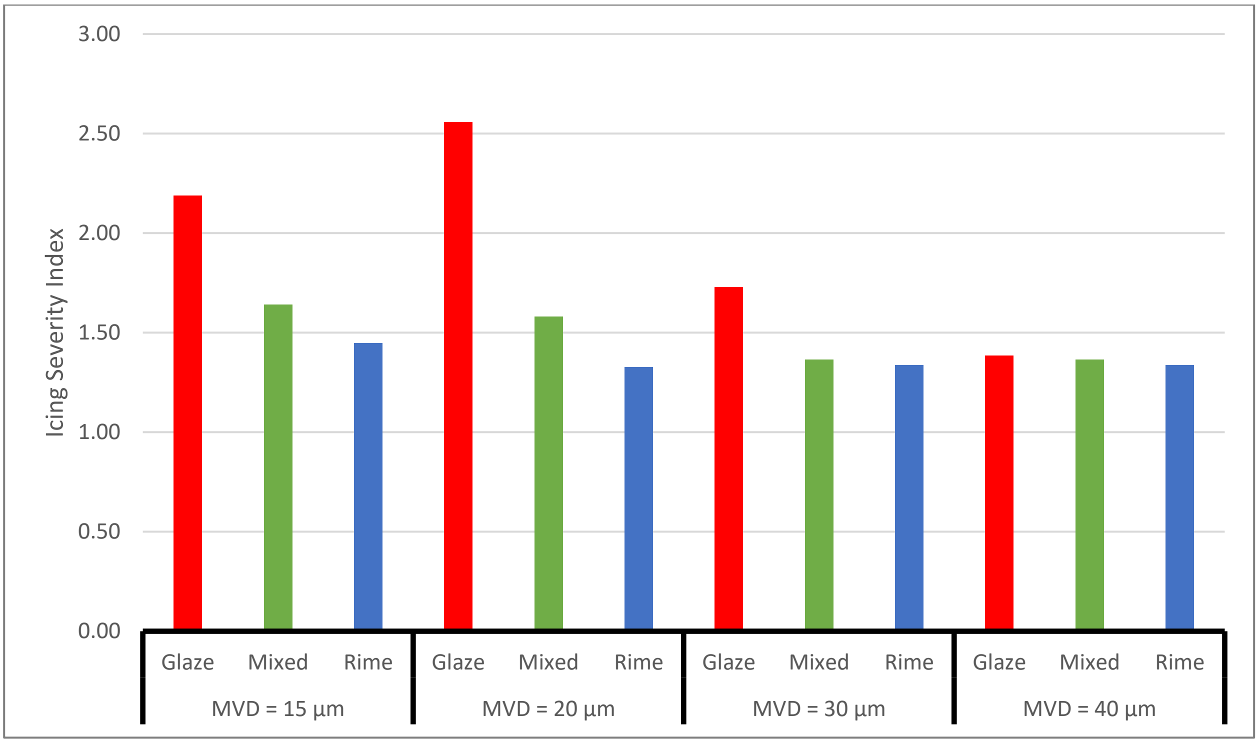

Figure 4 Ice Severity Index for Wing Degradation Only.

C. Unified icing severity index

Although the results presented in the figures include three efficiencies, it is only to show how severe it can get it in the worst case, or how "well" the UAV can survive in the best case. As explained in section II.C, the propellers only experience maximum or minimum efficiency for a short moment. Hence, when comparing the ISI, the focus should be on the average efficiency. The figures presented in this section will still include all three efficiencies for completeness. Figures 5 and 6 combines the wing and propeller degradation for 4200 and 5000 RPM respectively. The figures show that for the 4200 RPM case, rime ice exhibit the largest ISI at average efficiency with an ISI of 8. This essentially means that the UAV performance is heavily degraded. Increasing the rotation rate of the propeller could be an effective short-term option as to decrease the ISI to more acceptable levels. As expected, the indices are lower for every condition in the 5000 RPM case due to an overall higher efficiency from more shedding, or due to a change in advance ratio. The general trend on ice type severity is, however, still preserved. The performance degradation is worse at lower MVD compared to higher MVD as discussed in the wing results.

A noteworthy result is the significant increase in ISI on glaze ice relative to mixed ice when combining the propeller and wing degradation. It is due to how propeller degradation "inflates" the power required due to how efficiency is used in the power equation. Wing degradation increases power requirement through an increase in drag, which is an indirect increase in required motor output to overcome the drag of the UAV. The propeller converts the power directly into required thrust. However, the power output from the motor is determined by engine efficiency and propeller efficiency. With the engine efficiency constant, the propeller efficiency influences what the engine needs to generate in terms of power to meet thrust requirements. As mentioned in section II.B, the propeller efficiency is divided by the required power to get actual engine power output. This means that as wing degradation increases, it will be additionally increased through the propeller degradation. This is the reason why the propeller has the most influence when considering degradation. It is possible, as the wing continues to degrade, that the most severe ice type will be glaze ice and the ISI will exceed rime ice ISI in the long term. In fact, for the 5000 RPM case, when MVD is 20 µm, glaze ice already has the highest average ISI. This shows that with proper solutions to remove ice on the propeller, glaze ice will degrade the performance the most. Ice mass is included in the simulation but is a small fraction of the UAV mass and does not significantly impact the results as it only accounts for 20 minutes of ice accumulation. In the next section, additional comments and findings will be discussed.

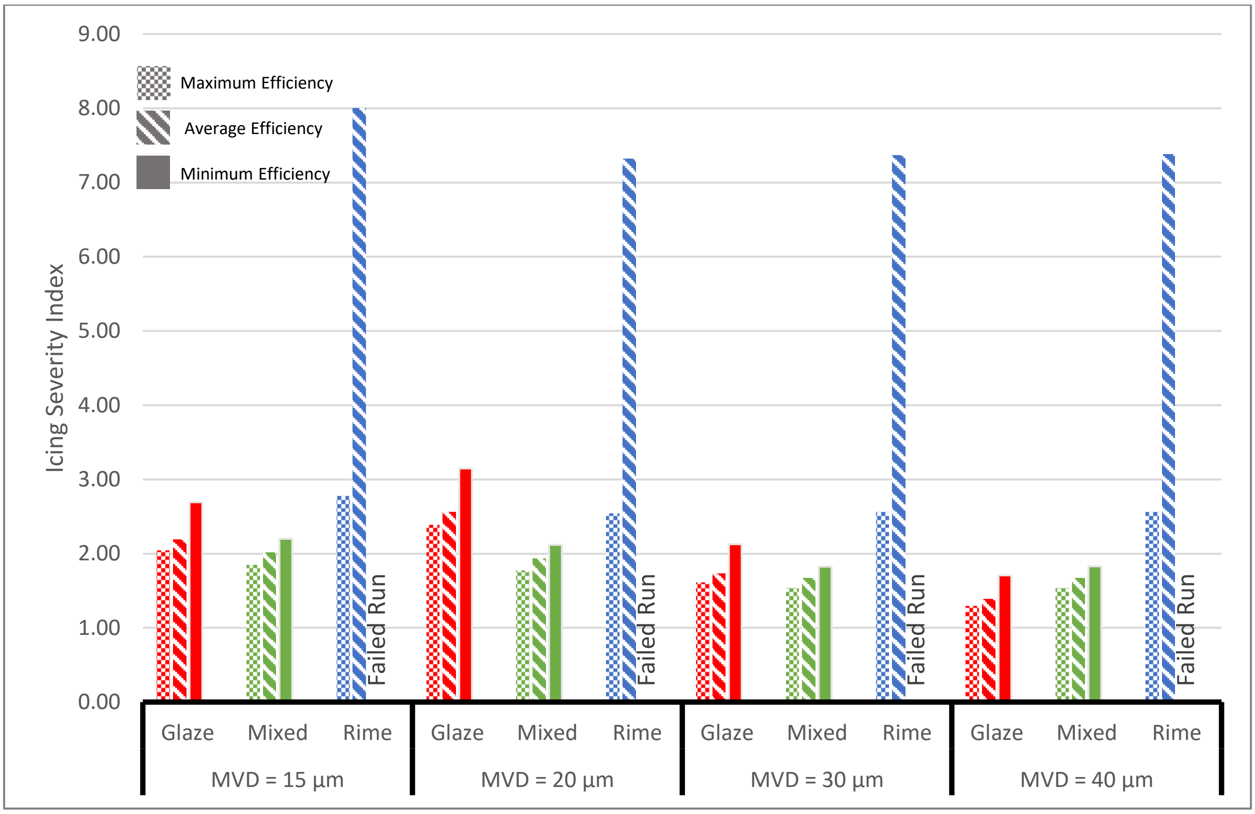

Figure 5 Ice Severity Index for combined wing and propeller degradation (4200 RPM).

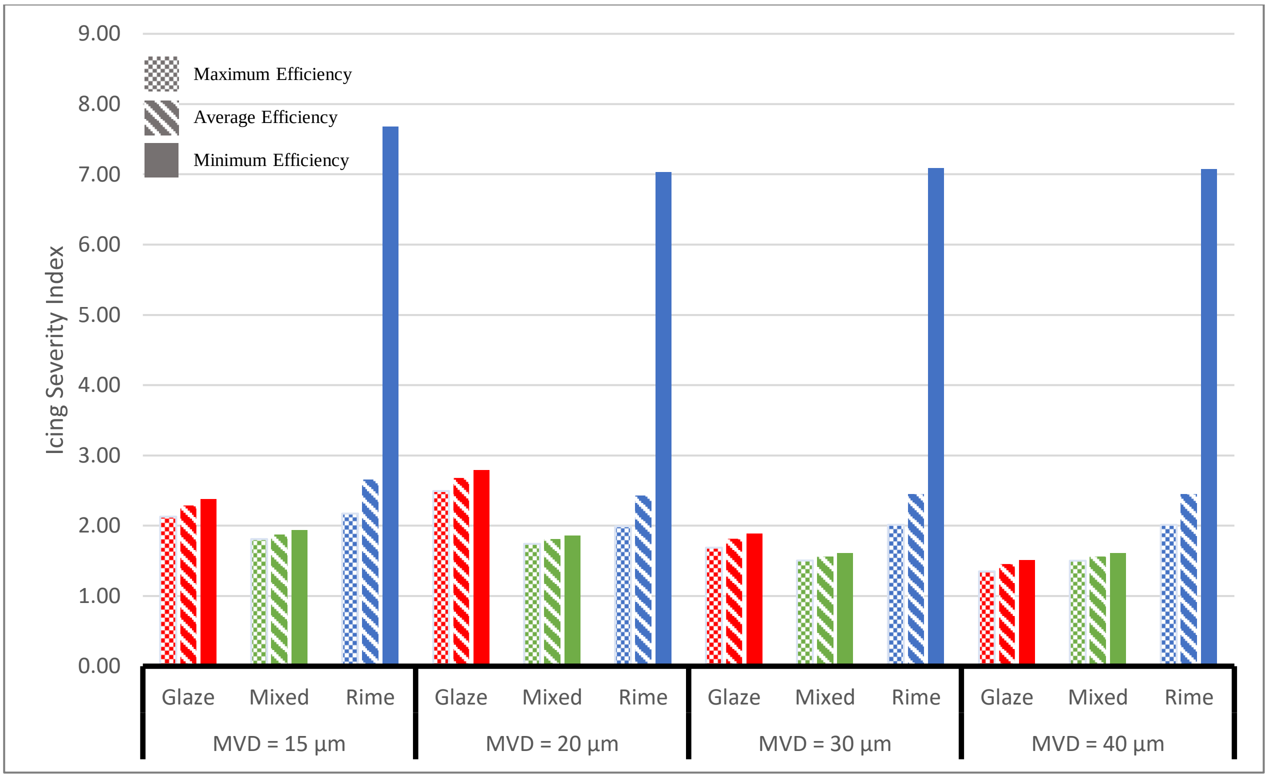

Figure 6 Ice Severity Index for combined wing and propeller degradation (5000 RPM).

IV. Discussion

In this section, additional noteworthy findings related to the case study are discussed. The presented results highlight what can be expected from developing the unified ISI. In this study, the unified ISI was one goal, and the second goal was to investigate it for a specific case study. When looking at the unified ISI, the best case gives 1.3 times increase in power consumption. For the worst case, the 8 times increase in power consumption can seem excessive and one can quickly conclude that the mission might as well have failed. However, whether the increase is dangerous is mission specific. Even with 8 times increase of power required, if the mission is short, it is possible for the UAV to complete its mission. A mission with a long duration is most likely to fail for every ice type. As mentioned earlier, ice continuously accumulates on the wing without the use of an IPS. There will eventually be a point where the wings will not be able to deliver enough lift as ice accumulates beyond a critical point and will fail either by accumulating enough ice mass or through increased drag. When and if it will fail widely depends on the conditions, battery capacity remaining, and mission duration left.

The loss of thrust from the propeller happens much quicker than the loss of lift of the wing in the rime ice case. Loss of thrust leads to a reduction of airspeed and hence higher lift coefficient is required, which can lead to stall with subsequent further loss in thrust. Hence, an IPS for the propellers is typically useful for glaze and mixed ice but is typically necessary for rime ice conditions. An IPS model can be implemented and is based on experimental results from IWT tests, similar to the approach used for the wings in the PhD thesis by Hann [8]. The IPS adds on a power consumption on top of the normal power consumption when the IPS is under operation.

There is a difference in icing sensitivity between the ice accretion of a propeller and the wings of a typical UAV. To calculate the ISI, it is assumed that the UAV undergoes 20 minutes of icing before flying the path. While the propeller typically sees noticeable degradation within one minute, noticeable wing degradation is usually observed after 20 minutes [4]. To account for the discrepancy in time sensitivity, it is assumed that the average, maximum and minimum efficiency is predicted to be constant up until the 20-minute mark. It is predicted because the longest propeller IWT experiments only ran for 10 minutes.

Under max take-off weight (MTOW) conditions when subject to glaze and mixed ice conditions, the aircraft wings fail to deliver sufficient lift at cruise speed of 25 m/s. This is easily checked with a simple lift calculation and comparing with the lift curves at glaze and mixed ice conditions. These conditions are assigned an index of infinity by default. The only way to operate under MTOW conditions is to increase aircraft speed to reduce required lift coefficient. However, it can be observed from the lift coefficient equation that increased airspeed increases drag. To increase airspeed also requires an increase in thrust and hence an increase in RPM. The potential RPM increase is not unlimited and there are other considerations that can limit motor speed. For example, the motor is limited by the heat generation and max power rating.

The RPMs investigated, particularly 5000 RPM is already seeing unacceptable heat generation that can damage the motor given enough runtime in the tests ran by Müller and Hann [3]. With additional cooling, the motor can be pushed further, but it is still not unlimited. The propeller blades can also only generate limited thrust and at some critical point further increase in RPM will lead to a decay in thrust generation [3]. To improve results, modelling the relationship between thrust and RPM is one possible solution, but is currently unavailable and is planned future work. The presented results focus on an operating weight of 18 kg, which is the usual operating condition. The MTOW discussion is to highlight that it is possible for the UAV to fail at maximum payload at nominal cruise speed or without intervention.

The choice to use two RPMs as two separate cases is to illustrate the effect of changing the RPM. The UAV attempts to compensate for the presence of ice by increasing the rotational rate of the propeller. If the UAV is allowed to compensate, it would not reflect the severity of the ice condition. However, by not including this adjustment, means not considering what the UAV would do to compensate for the ice. It remains difficult to separate these two effects, hence it would be interesting to include both RPMs to see their effects. It is then assumed that the efficiency alone encapsulates all this information in the computation of the ISI. Note that the rest of the UAV will also accumulate ice, which cannot shed ice without an IPS. In short, the UAV may crash in the long term if it does not land or have an IPS to remove ice.

At the start of this paper, it was mentioned that the ISI will help UAV operators to develop their equipment. One way for them to prepare is to design an IPS. Assuming the wing IPS as presented in the paper by Wallisch and Hann [13] is used, it has a parting strip heater on the wing. As discussed in the paper, by delaying turning on the parting strip will lose the benefit of exploiting aerodynamic forces to shed ice off the wing. The parting strip power depends on temperature, ranging from 8-70 W. At temperatures close to freezing point (−2 °C) it requires only 8 W. If the UAV operators know that there will be conditions with glaze ice in the mission area, it would be worth the trade-off to keep the parting strip on. This will allow more effective shedding of glaze ice and save energy in the long run. However, further investigation is required to identify the conditions worth doing this strategy. It is also ideal that the parting strip only require this low power for glaze ice since it degrades the performance of the wings the most.

V. Conclusion

In this paper, a unified ISI has been developed by combining the performance degradation of a wing and propeller by using a simulator. Propeller efficiency and lift and drag data were implemented into the simulator which then uses the data to compute a power consumption and ISI. The data used is UAV specific and result in an UAV specific ISI. To make the power consumption comparable, every flight needs to undergo the same conditions and path, with the main difference being the change in propeller efficiency and lift and drag curve for the specific atmospheric conditions. The propeller performance degradation was too complex to implement as is and some simplifying assumptions were required, such as using the efficiency to compensate thrust generation through the power generated. The results show that glaze ice is the worst for wing, and rime ice is worst for the propeller. Rime ice condition is the worst ice type combined due to how fast and how much the propeller degrades for that ice type. Its average for 4200 RPM can be up to 8 times increase in power consumption compared to clean condition. For 5000 RPM it is only around 2.5 times increase on average. The high increase in power consumption can seem excessive but is mission dependent. Failure depends on the conditions, battery remaining, and mission duration left. Any mission that has a long duration left will likely fail in many circumstances. The ISI is dependent on the mass and fails under MTOW if cruise speed is maintained. To account for increase in mass will require an increase in airspeed and hence thrust. This has its own issues in the presence of ice as the propeller will only be able to generate so much thrust before no more thrust generation is possible due to propeller limitations. The results in this paper will aid UAV operators in assessing potential icing risks and to prepare their equipment for optimal operation.

A. Future Work

How the ISI can benefit UAV operators as presented in the end of the discussion section is just one example of many. The end goal of this work is to automate the entire process. The UAV will be able to make decision on which path is best, and how to use the IPS optimally to maximize mission success. For future work, improvements of the path planner and ISI is achieved by implementing a more accurate propeller model [3]. The iced lift and drag curves of the wing can also be improved. It would have been preferable to include iced lift and drag curves for different LWC values during the writing of this paper, but data was not available. Hence, this is planned future work. Furthermore, it would be possible to extend the ISI by implementing an IPS model [13]. It will give a revised ISI and the severity will change depending on time the IPS needs to be turned on and in what condition. Finally, to automate the UAV will require an online path planner. The current path planner used in this paper is offline, which means it calculates the path before take-off. This means it has no abilities to deal with situations that are not predicted. The online planner will be able to make decisions while it is flying and will make decisions based on the information it currently has access to from onboard sensors. This will require a rigorous statistical model to best deal with uncertainty in weather data. An icing detector will be required to detect performance degradation and situations that are not planned for. It will work in conjunction with the IPS such that the IPS can operate optimally and know when to turn on and off [25].

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