Icing effects on Airborne Wind Energy

Noel Ernsting Luz[1,2], Richard Hann[2,3], Thorsten Lutz[1], and Espen Oland[4]

[1]University of Stuttgart
[2]Norwegian University of Science and Technology
[3]Ubiq aerospace AS
[4]Kitemill AS

Abstract

Over the past twenty years, Airborne Wind Energy (AWE) has developed into an approach for harnessing high-altitude wind energy [1, 2]. Instead of being fixed on tall towers like conventional wind turbines, these systems operate at altitudes between 300 m to 500 m, where stronger and more continuous winds are found [3, 2]. The reduced structural mass of the airborne components offers a potential reduction in energy costs [1, 2], but operation in this altitude range also exposes the system to lower temperatures and variable humidity, which favours supercooled liquid water [3, 4]. In-flight icing changes the geometry, increases mass, degrades aerodynamics and has led to incidents in manned and unmanned aviation [4]. Since Airborne Wind Energy Systems (AWESs) operate at similar altitudes to Unmanned Aerial Vehicles (UAVs), they are subject to comparable icing risks [3, 2, 4].

This work quantifies the effect of in-flight icing on the aerodynamic power potential of a rigid-wing Airborne Wind Energy system under three FAA Appendix C Continuous Maximum icing cases: glaze at -2 °C, mixed at -4 °C, and rime at -10 °C. All cases are simulated over an icing exposure of about 54 minutes, under assumption of a quasi-stationary operation of ground-generation AWE systems. Mixed icing at -4 °C causes the most rapid and severe degradation. The available power is reduced to 50 % after about 7 minutes, to 25 % after about 11 minutes, and to 10 % after about 17 minutes, reaching a final reduction of roughly 99 %. Glaze icing at -2 °C shows a slightly slower progression, with power reduced to 50 % after about 5 minutes, to 25 % after about 13 minutes, and to 10 % after about 24 minutes, resulting in a final reduction of about 96 %. Rime icing at -10 °C leads to a more gradual loss: power is reduced to 50 % after about 22 minutes and to 25 % after about 32 minutes and a final reduction of about 78 %. These results show that, under sustained icing exposure, even moderate ice accretion can lead to rapid and substantial power losses, with mixed-ice conditions representing the most critical case for rigid-wing AWE operation [5].

The developed orchestration framework combines aerodynamic performance metrics from two-dimensional simulations with limited three-dimensional effects (2.5-D simulations) to derive key performance indicators for an AWE system. It is compatible with airfoils in Selig coordinate format and structured in modular blocks for geometry preparation, meshing, simulation and analysis, enabling application to other profiles and operating points. The results indicate that active or hybrid de-icing concepts, particularly along the leading edge, are effective levers to avoid the most severe efficiency losses and provide quantitative input for the aerodynamic and structural design of kites for cold and humid environments.

References

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