Icing Characteristics of a Wing Behind a Propeller Wake

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Propeller-generated wakes create complex aerodynamic interactions that influence ice accretion on aircraft wings, consequently affecting aerodynamic performance. However, the effect of the propeller wake on wing icing characteristics is not well understood. This study clarifies the mechanisms and extent of propeller wake effects on wing icing by comparing the icing characteristics with and without the propeller wake. Three-dimensional quasi-unsteady simulations are employed to capture temporal changes in the droplet field and ice accretion rates caused by local and unsteady propeller wake flows. The computational results provide insights into the icing characteristics induced by aerodynamic interactions. Higher axial velocities enhance droplet impingement and heat convection on the wing. Upwash and downwash change the local effective attack angle, altering droplet impingement limits and the size and intensity of heat convection. The rotation of tip vortices creates droplet voids and dense regions, enhancing heat convection on the inside of the wing tip and leading to noticeable differences in ice formation. Consequently, ice shapes behind the propeller wake are up to 80% thicker and more irregular, leading to twice as severe degradation in aerodynamic performance of the non-wake-induced iced wing. This study highlights the need to consider propeller wake effects in wing icing analysis.

Nomenclature

c	=	wing chord length, m
$c_{p,w}$	=	specific heat capacity, $\mathrm{J \cdot kg^{-1} \cdot K}$
E	=	total energy per unit mass, $\mathrm{J \cdot kg^{-1}}$
e	=	internal energy per unit mass, $\mathrm{J \cdot kg^{-1}}$
h_c	=	convective heat transfer coefficient, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$
h_f	=	water film thickness, m
h_{ice}	=	ice thickness, m
J	=	propeller advance ratio
K	=	droplet inertia parameter
L_{eva}	=	specific latent heat of evaporation, $\mathrm{J \cdot kg^{-1}}$
L_{fus}	=	specific latent heat of fusion, $\mathrm{J \cdot kg^{-1}}$
L_{sub}	=	specific latent heat of sublimation, $\mathrm{J \cdot kg^{-1}}$
LWC	=	liquid water content, $\mathrm{g \cdot m^{-3}}$
M	=	Mach number
MVD	=	median volumetric droplet diameter, μm
$\dot{m}_{\mathrm{ice}}$	=	ice accretion rate, $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$
$\dot{m}_{\mathrm{imp}}$	=	droplet impingement rate, $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$
$\dot{m}_{\mathrm{eva}}$	=	water film evaporation rate, $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$
p	=	pressure, Pa
q	=	heat flux, W m^2
R	=	propeller radius, m
Re_d	=	relative Reynolds number
t_{rotate}	=	time for one rotation of the propeller, s
t_{total}	=	icing exposure time, s
T_c	=	freezing point temperature, K
T_∞	=	freestream temperature, K
T_{sur}	=	surface temperature, K
$\boldsymbol{u}_a$	=	air velocity vector
$\boldsymbol{u}_d$	=	droplet velocity vector
U_f	=	water film velocity, $\mathrm{m \cdot s^{-1}}$
V_∞	=	freestream velocity, $\mathrm{m \cdot s^{-1}}$
α	=	angle of attack, deg
β	=	collection efficiency
Φ	=	droplet concentration, $\mathrm{kg \cdot m^{-3}}$
κ	=	thermal conductivity of air, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
μ_a	=	air viscosity, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
ρ_d	=	droplet density, $\mathrm{kg \cdot m^{-3}}$
ρ_a	=	air density, $\mathrm{kg \cdot m^{-3}}$
ρ_{ice}	=	ice density, $\mathrm{kg \cdot m^{-3}}$

I. Introduction

ATMOSPHERIC ice accretion is one of the primary hazards threatening the safety of rotary-wing devices, such as propeller-driven aircraft, rotorcraft, and wind turbines [1–4]. The formation of ice on aerodynamic surfaces disrupts the smooth flow of air, which is essential for lift and propulsion, and creates additional weight and drag [5,6]. For rotary-wing devices, icing is highly unpredictable because of the aerodynamic interactions between rotating surfaces (rotors and propellers) and other structural components (wings, fuselage, and turbine towers). The rotating blades generate a complex flow pattern characterized by a series of vortices, known as the wake. This wake alters the airflow and icing characteristics around trailing objects in several ways [7,8]. Therefore, to ensure the effective design of ice protection systems and the safety of rotary-wing devices, it is crucial to understand how the wake from rotating blades affects the icing characteristics of objects positioned behind them. This study focuses on the icing of propeller-driven aircraft.

Propeller-driven aircraft play a pivotal role in a wide range of applications, from commercial and military aviation to emerging fields such as urban air mobility (UAM) and uncrewed aerial

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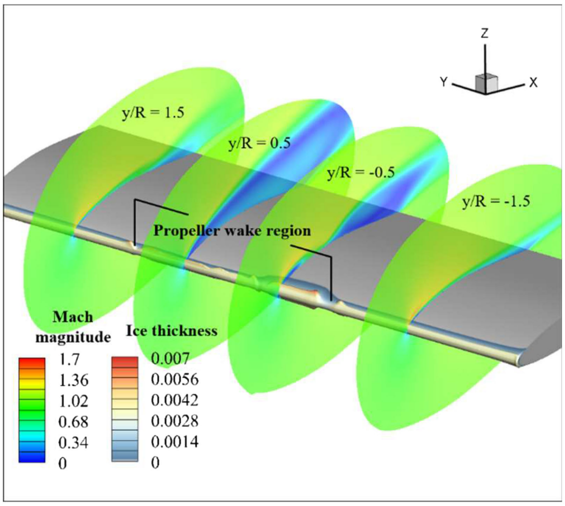

Fig. 30 Separation occurrence through velocity contours at sectional positions of the propeller wake-induced iced wing.

particular, the interaction between the propeller wake and wing icing must be factored into the design of Wing and Propeller Ice Protection Systems (IPS) to ensure effective ice mitigation. Addressing these interactions can help reduce aerodynamic performance losses and improve overall aircraft safety in icing environments.

V. Conclusions

This study has attempted to clarify the mechanisms and extent of propeller wake effects on wing icing, specifically focusing on the PROWIM configuration. By employing the 3D quasi-unsteady approach, which allows for detailed simulation of temporal variations in the droplet field, heat convection, and ice accretion due to unsteady changes in the flowfield, the study provides a more accurate representation of the complex effect of propeller wake. To enhance computational efficiency and ensure robust simulation, the droplet field was calculated using the DADI scheme embedded in ICEPAC. By comparing icing conditions with and without the influence of the propeller, several key insights were obtained regarding the aerodynamic interactions that significantly affect droplet impingement, heat transfer, and ice formation on the wings of propeller-driven aircraft. Additionally, the effects of varying the icing parameters and advance ratios were explored to determine their influence on these interactions. Finally, this study examined the aerodynamic performance degradation caused by the ice shapes formed under the influence of the propeller wake. The following conclusions were obtained:

1) The propeller wake significantly alters the droplet impingement and heat convection on the wing. The axial velocity of the propeller enhances droplet inertia, resulting in increased collection efficiency and increased heat convection due to the higher surface velocity, leading to an overall increase in the size of ice formations. Upwash and downwash change the effective AOA, altering the droplet impingement limits. Upwash increases the localized effective AOA, enhancing heat convection on the suction surface of the wing and producing a thicker ice horn. Conversely, downwash decreases the local effective AOA, reducing heat transfer. However, the higher collection efficiency through the axial velocity results in the ice horn developing farther back on the wing. Tip vortices create distinct void and dense regions through centrifugal forces, leading to fluctuations in the droplet collection efficiency. Void regions result in minimal droplet impingement, while dense regions significantly increase droplet collection. For dense concentrations of droplets near the inside of the propeller region, the velocity due to the sum of the rotation of the tip vortex and the axial velocity increases, leading to greater collection efficiency and heat convection, which in turn leads to partial but larger ice shape differences.

2) The icing parameters and advance ratio critically influence propeller wake effects on wing icing. A higher MVD reduces the airflow influence, while a lower MVD increases the impact of the propeller wake. Lower advance ratios amplify the propeller wake effects, enhancing droplet impingement and heat convection and significantly altering the ice shapes. As the influence of the propeller wake becomes stronger relative to the freestream, the differences in ice shapes become more pronounced. Thus, it is crucial to consider the propeller wake when attempting to obtain accurate wing icing predictions, especially at lower advance ratios.

3) The propeller wake-induced ice shape causes up to twice as great aerodynamic degradation compared with that of the non-wake-induced ice shape in the case of glazed ice. The ice shape formed under the influence of the propeller wake is up to 80% thicker and more irregular, especially in the formation of ice horns, which significantly reduces lift and increases drag. In the case of rime ice, the difference in performance degradation between the propeller wake-induced icing results and the non-wake-induced ice shape is not significant, because only the thickness of the ice is different and no ice horns are formed. However, as in the case of glaze ice, the propeller wake can change the wing icing geometry and the aerodynamic performance degradation, emphasizing the importance of considering propeller wake effects during the aircraft design and certification process for icing.

Further investigations could expand on these findings by considering other icing scenarios, such as those involving supercooled large droplets or different propeller configurations. Including the icing effects on the propeller itself and analyzing the interaction between propeller and wing icing could also provide a more comprehensive understanding of how these factors collectively influence aerodynamic performance. Efforts will also be directed toward incorporating transition models to better capture laminar-turbulent flow regions, further enhancing the accuracy and applicability of icing predictions. These future studies would be valuable in refining the design and certification process for aircraft operating in icing conditions.

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