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Blockage and three-dimensional effects in wind tunnel testing of ice accretion over aircraft wings

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Wind tunnel testing of ice accretion over aircraft wings is simulated numerically to investigate the effects of tunnel blockage and of the wall-wing interference at the wall-model juncture. The open source OpenFOAM software is used to compute the flow-field and the trajectories of water droplets. The PoliMIce ice prediction software is applied to solve the multi-phase flow around the body surface and to compute the thickness of the iced layer. Blockage effects are investigated for diverse operating conditions. Similarly to dry testing, wind tunnel blockage is found to produce a variation of the apparent angle of attack of the airfoil with respect to the free-stream. However, differently from dry testing, the blockage correction is found to be a function of time, due to the continuous modification of the airfoil shape in time resulting from ice accretion. The wall-wing interference results in the occurrence of a shadow region where water droplets do not impinge. In the rime ice regime, the shadow region is therefore free of ice. In the glaze ice regime instead, the liquid film over the wing moves towards the end-wall and ice is formed also in the shadow region.

Nomenclature

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t_{ice} = Total icing exposure time [s]
$\vec{V}_\infty$ = Free-stream velocity, [m/s]
T_∞ = Free-stream temperature, [K]
P_∞ = Free-stream static pressure, [Pa]
β = Collection Efficiency
MVD = Median Volume Diameter, mean droplets diameter, [μm]
LWC = Liquid Water Content, [g/m^3]
α = Angle of attack, [deg]
c = Airfoil chord [m]
h = Wind tunnel test-section height [m]
c/h = Wind tunnel blockage
$\Delta t_{\text{flow-field}}$ = Time interval between aerodynamic flow-field computations [s]
FC = Flight conditions (free-stream flow)
WT = Wind tunnel flow (confined flow)

I. Introduction

Aircraft flying through a cloud containing super-cooled water droplets or encountering precipitations such as freezing rain or drizzle are likely to experience a moderate to severe ice build-up on aerodynamically critical surfaces [1]. In-flight ice accretion poses a key safety issue because of its detrimental effect on the performance of several components of the aircraft. Ice accumulating on an aerodynamic surface modifies the shape of the airfoil sections, thus determining substantial maximum lift penalty, stall angle reduction and parasite drag increase [2]. Moreover, the accreted ice alters the weight distribution on the aircraft, reduces the efficiency of the control surfaces and contaminates the external sensors, thereby severely compromising the stability and controllability of the aircraft [3]. The presence of ice on the engine nacelle alters the airflow in the air-intake region. Unsteady aerodynamic and structural loads arise from ice formation over rotating devices such as the blades of the first stage of the compressor in a turbofan engine or the blades of a propeller. Icing on rotating devices may possibly result in dangerous ice shedding phenomena, which can eventually cause severe mechanical damages [4]. Ice accretion is also relevant in engineering applications not directly linked to the aerospace field, including the design and operation of wind turbines, and also to power cables and antennas installed in a cold environment, due to the possible activation of destructive aeroelastic phenomena [5, 6].

An accurate prediction of ice accretion and related performance degradation is mandatory for the design of aircraft, including ice protection systems, in order to guarantee safe all-weather operations, to increase power efficiency and to reduce operational costs. Over the years, complementary approaches have been adopted, including flight and wind tunnel tests and numerical simulations. From the numerical standpoint, several ice-prediction codes have been developed by diverse research agencies and serve as valuable design and certification tools for the aircraft industry, including among others NASA LEWICE [7], FENSAP-ICE [8, 9], ICECREMO [10], CIRA Multi-ICE [11, 12], ONERA [13] and PoliMIce [14, 15] icing prediction codes.

Icing conditions involving the complete aircraft configuration or some of its components are reproduced experimentally by observing an aircraft flying in natural icing conditions or in the wake of a tanker dispensing water droplets. In dedicated ground facilities, namely refrigerated wind tunnels equipped with a spray system for the generation of a cloud of super-cooled droplets, the same task is performed on subscale models under controlled conditions. Wind tunnel tests play a key role in the assessment of performance penalties associated to ice accretion, as well as in the phenomenological study of the flow around iced aerodynamic surfaces. However, the flow conditions in a wind tunnel are not the same encountered in the free-stream: scaling issues arise from the use of subscale models, the droplet seeding process and the presence of the tunnel walls. Moreover, in wing testing, the interaction between the boundary layer on the tunnel sidewalls and the wing boundary layer strongly affects the maximum lift achievable and the spanwise distribution of stall initiation on the wing. All these departures from the real oprating conditions have been widely studied since the early years of aviation in standard, dry testing [16, 17] and corrections to wind tunnel data have been devised [18]. On the contrary, the correction of wind tunnel effects in an icing experiment is complicated by the fact that the geometry of the model—and hence the flow-field—varies over time due to the accreted ice.

In order to predict the performance penalties affecting an aircraft in full-scale icing conditions from sub-scale testing, the dependence on the test Mach and Reynolds number on the aerodynamics of iced airfoils is to be assessed first. Compressibility effects begin to affect force measurements on iced airfoils at Mach numbers of about $0.10 \div 0.20$, a range where only minor compressibility effects can be observed on clean airfoils. However, Mach number effects on force coefficients are smaller than the performance degradation due to ice accretion, as documented in [19].

Differently from flow separation on clean airfoils, Reynolds number only exerts a minor influence on the behavior of the flow over iced airfoils: in the presence of an ice layer, flow separation, transition and potential reattachment are mainly governed by the size and location of the ice layer itself [19]. Therefore, the maximum lift coefficient—and hence the performance penalties due to ice accretion—can be obtained directly from the low-Reynolds data measured in wind tunnel tests, with acceptable accuracy [19]. That said, quantification of wind tunnel wall effects assumes a key role in the assessment of iced airfoil performance degradation. On the contrary, the test Reynolds number strongly influences the shear stress distribution and the convective heat transfer coefficient at the model surface. The former drives the flow of the liquid film over the surface of the model, whereas the latter affects the convective heat exchanges involved in the icing process. Therefore, the measured ice shape and the iced-airfoil drag coefficient are expected to show more significant variations if the test Reynolds number is changed.

Due to scaling issues and to hardware limitations associated with wind tunnel tests, numerical simulations are often a more suitable tool to simulate ice shapes in real operating conditions. The goal of the present work is to investigate wind-tunnel effects on ice-accretion over airfoils and wing. To this purpose, the PoliMIce ice accretion software [14, 15] is applied to the simulation of exemplary two-dimensional and three-dimensional geometry in icing conditions. In particular, the influence of the wind-tunnel blockage, namely, of the ratio of the airfoil chord to the test section height is investigated by considering two-dimensional geometries. The accreted ice in flight conditions is compared to the shape obtained for different blockage parameters. Force coefficients are compared to determine the wind-tunnel correction to be applied to experimental results. Numerical simulations of three-dimensional geometries are carried out to quantify the relevance of wing-wall interference

Fig. 1 Flowchart of calculation procedure within the PoliMIce framework.

Fig. 2 Exemplary computational grid for the three-dimensional simulations of the wind-tunnel setup. The three-dimensional grid is obtained by extruding the two-dimensional surface mesh along the span-wise direction. The flow is from left to right.

at the tunnel side walls.

The present paper is structured as follows. In Sec. II, the procedure for numerical simulation of wind tunnel icing tests within the simulation framework PoliMIce is overviewed. In Sec. III, numerical results are presented and compared to available experimental data. The blockage effects in two-dimensional airfoil tests and the wing-wall interference at the tunnel sidewall in three-dimensional testing are discussed. Sec. IV provides concluding remarks.

II. Numerical simulation of ice accretion

The simulation framework PoliMIce of the Department of Aerospace Science and Technology of Politecnico di Milano [14, 15], is applied to the simulation of wind tunnel tests of ice accretion. In PoliMIce, an ice accretion model is implemented and coupled to diverse CFD engines, including both open-source and commercial solvers. In this section, the calculation procedure is summarized for the reader convenience.

The simulation procedure implemented in PoliMIce follows a well-established pattern usually found in ice prediction codes, see e.g. [8]. With reference to the flowchart presented in Fig. 1, input to the problem are the total icing exposure time t_{ice}, the freestream velocity vector $\vec{V}_\infty$, temperature T_∞ and pressure P_∞, the liquid water content (LWC) of the cloud (grams of water contained in a cubic meter of air), the droplet median volume diameter (MVD) [1, 20] and the baseline un-iced or clean geometry. Firstly, the flow-field around the body is calculated. Secondly, the water distribution over the surface is determined from the cloud droplet trajectories. All the aerodynamic and thermodynamic parameters influencing ice accretion, namely the collection efficiency β, the convective heat transfer coefficient and recovery factor are calculated. Finally, the thermal analysis needed to determine the thickness of the iced layer is carried out.

To compute the flow-field, the steady-state solver for incompressible flows simpleFoam, distributed within the open source CFD software OpenFOAM [21], is adopted. In the present preliminary study, the qualitative evaluation of the effects of confinement in wind tunnel testing is limited to mildly separated flows around simple iced shapes. These flows are modeled using the Spalart-Allmaras turbulence model [22, 23].

The turbulence intensity at the inflow boundary (free-stream or wind tunnel inlet) is assumed to be 0.1% in all simulations. This value that is consistent with free-stream simulations, whereas turbulence intensity levels in icing wind tunnels are usually higher. For example, the reported intensity for the NASA IRT facility is 0.5%. The Spalart-Allmaras model boundary conditions are initialized from the value of the free-stream turbulence intensity according to the procedure reported in [24].

A Lagrangian approach is used to compute droplet trajectories. The impact point of each water droplet on the surface of the airfoil/wing is required to compute the shape and the thickness of the ice layer on the surface of the body.

Droplets are released from the inlet boundary from a plane within the computational domain, 5 -7 airfoil chords upstream of the body. The droplets are equally spaced and the droplet spacing and size depend on the study case. The initial droplet velocity is equal to the local flow velocity. Droplet trajectories are computed by time integration of a force balance in differential form involving inertia, aerodynamic drag, gravity and buoyancy [1]. No drop-drop interaction is modeled, assuming a fully uncoupled droplet motion, according to reference [1]. Droplets stick to the solid wall at the point of impact and no re-bouncing is modeled.

Particle tracking is accomplished by the OpenFOAM Lagrangian solver uncoupledKinematicParcelFoam [21]. Starting from these results, a C++ interface between OpenFOAM and the ice accretion module determines the fraction of the free-stream water concentration impacting on each surface cell: this parameter is called collection efficiency and it is referred to as β in the following.

Among the droplets hitting the surface of the wing, those which freeze immediately upon impact originate a layer of so-called rime ice: this occurs in cold and dry environments, namely at low temperatures (below about -10 °C) and low LWC. At temperatures near the freezing point of water and/or higher LWC, or after the rime ice layer has reached a critical thickness [25], the freezing of the impinging droplets is not instantaneous. As a result, a thin film of unfrozen water driven by aerodynamic and gravitational forces lies on top of a previously accreted iced layer. The occurrence of a liquid layer, which either flows downstream or sheds off the body, is the distinguishing feature of the so-called glaze ice. Both kinds of ice accretion can be simulated within PoliMIce, where a modified version of the extended Messinger model [26] for aircraft icing is implemented, as detailed in Ref. [14, 15]. In the model, the mass and energy exchanges governing the phenomenon of ice accretion include the mass entering as super-cooled droplets or leaving the system by evaporation, aerodynamic heating, convective heat transfer at the water surface, release of kinetic energy and latent heat of the incoming droplets, latent heats of fusion, freezing, evaporation and sublimation. These complex interactions are accounted for in the so-called Stefan problem, namely, a set of four partial differential equations expressing mass conservation, heat transfer in ice and water and the energy balance relating all the heat fluxes involved in the phase changes. The Stefan problem is solved on each surface element, where elementary control volumes containing a film of liquid water lying on top of an ice layer are defined. Ice is assumed to accrete perpendicularly to the body surface, with a distribution of thickness and temperature of the ice and water layer defined by the local solution of the set of equations. A complete analytic formulation of the problem can be found in the original paper by Myers [25] and the details of the model implemented in PoliMIce are introduced and discussed in [14, 15].

Ice accretion alters the geometry of the body, thereby modifying the flow-field, the droplet trajectories and the accretion parameters, namely the collection efficiency, the convective heat transfer coefficient and the recovery factor. To account for these effects, an iterative procedure is implemented: until the total icing exposure time is reached, the iced geometry is periodically updated and the aerodynamic flow-field is computed. This is known as a multistep procedure [27]. The major drawback of this kind of procedure lies in its iterative nature: recomputing the flow-field, the droplet trajectories and the accretion parameters at each step can turn out to be burdensome in terms of CPU-time. On the other hand, in a single-step procedure, the accretion parameters are evaluated only on the baseline clean configuration: this in turn causes a loss of accuracy for increasing exposure time and for increasing thickness of the ice layer.

Fig. 3 Picture of a Cessna Tail Wing Section installed in the test section of the NASA Icing Research Tunnel (IRT). Picture reproduced from Ref. [28].

III. Numerical simulation of ice accretion in wind tunnel testing

In Sec. III A and III B, the interactions between the tunnel walls and the model wing are analyzed by means of the numerical simulation of icing experiments described in public-domain literature. Specifically, three experiments taken from three different experimental campaigns conducted at the NASA Icing Research Tunnel [28] are considered.

The NASA Icing Research Tunnel (IRT) [28] is a closed-loop and closed-test-section refrigerated wind tunnel. The test section is 6.10 m long, 1.83 m high and 2.74 m wide. The facility is capable of guaranteeing continuous operations at air speeds up to 192 m/s and temperatures up to $-40°$C in the test section. Spray bars placed upstream of the test section can simulate a 1.22 m high and 1.83 m wide cloud of super-cooled droplets. MVDs range from 15 to 50 μm and LWCs from 0.2 to 2.5 g/m^3. In all cases, the models are mounted vertically within the test section and connected to an external balance for the measurement of lift, drag, and pitching moment. An exemplary setup is given in Fig. 3.

The first experimental campaign from IRT considered here includes tests carried out in the early 1990s on NACA 0012 airfoils to assess the repeatability of the observed ice shapes and the drag penalties associated to ice accretion [29]. One of these tests is taken in Sec. III A as the reference case for the study of wall blockage effects on ice shapes and lift coefficients. The second and third experimental campaigns took place between the end of the 1990s and in the early 2000s, when databases of ice shapes and performance degradation on currently used airfoils [30] and three-dimensional swept wings [31, 32] were draft. During wind-tunnel testing, peculiar ice shapes were observed at the wall-model juncture, possibly due to the interference between the model and the upper and lower walls of Fig. 3 and to the incomplete droplet seeding that is usually attained in the close proximity of the wind tunnel walls. The analysis of these three-dimensional flow features is carried out in Sec. III B, where the case of a straight wing and a swept wing are simulated numerically.

c [m]	α [deg]	V_∞ [m/s]	T_∞ [K]	P_∞ [Pa]	MVD [μm]	LWC [g/m^3]	t_{ice} [s]	$\Delta t_{\text{flow-field}}$ [s]
0.533	4	67	262.04	10^5	20	1	360	10

Table 1 Mixed rime-glaze icing conditions for the study of wind tunnel wall blockage on a constant-chord model of a NACA-0012 airfoil [29].

A. Wind tunnel blockage

A mixed rime-glaze ice accretion test over a constant-chord NACA 0012 airfoil is taken here as the reference case for the study of wind tunnel blockage. Test conditions are given in [29] and reported here in Tab. 1, see the Nomenclature for the definitions.

Consistently with the available literature about wind tunnel corrections [18], the ratio of the chord of the airfoil c to the height of the test section h is adopted here to quantify the relevance of wall blockage. More properly, the ratio c/h is, in this case, the ratio of the chord of the model to the width of the test section, being the model installed vertically within the wind tunnel, as shown in Fig. 3. For the test conditions given in Tab. 1, the ratio c/h is 0.2. At $c/h = 0.2$, the simulation domain closely reproduces the test section of the NASA IRT.

Wind tunnel walls confine the airflow, resulting in an increased velocity in the vicinity of the model with respect to free airflow conditions. If a model were placed in a wind tunnel at a given attitude, and if an identical model were placed in a free airflow at the same angle of attack, force measurements ideally carried out on both models would give different force coefficients: higher values of force coefficients are expected from the wind tunnel test. To correct this effect, it is common practice to associate the force coefficients measured in a wind tunnel test to a higher angle of attack, the so-called corrected angle of attack [18].

In order to identify the net effect of wall blockage, the input parameters, including grid refinement in the boundary layer region and boundary values of turbulence variables, are kept constant in all simulations. In addition to the boundary layer over the airfoil, a wind tunnel simulation has to deal with the boundary layer developing over the upper and lower walls of the wind tunnel. A number of solutions usually devised in the design and construction of a wind tunnel test section—e.g. the upper and lower walls are often slightly divergent in the direction of the flow—help minimizing

(a) Free-stream

(b) Wind tunnel ($c/h = 0.2$)

Fig. 4 Collection efficiency β over the airfoil surface from two-dimensional simulations of rime ice accretion on a GLC 305 airfoil ($c = 0.9144$ m, $\alpha = 6$ deg, $V_\infty = 90$ m/s, $P_\infty = 10^5$ Pa, $T_\infty = 263.15$ K, MVD $= 20$ μm, LWC $= 0.43$ g/m^3, $t_{\text{ice}} = 120$ s, $\Delta t_{\text{flow-field}} = 5$ s) on the reference and the fine grid. Left: free-stream case. Right: wind-tunnel case for $c/h = 0.2$.

the influence of the wall boundary layer on the flow within the test section. An inviscid-like slip boundary condition is imposed in the simulations over the upper and lower walls of the wind tunnel: this is equivalent to assuming that the layout of the test section accommodates the thickening of the boundary layer and that the flow within the test section is ideally uniform in transverse direction.

The analysis of wall blockage effects in two-dimensional airfoil testing requires an accurate representation of the flow and the ice shape at the middle section of the wind tunnel. Fig. 6 summarizes the results of a two-dimensional and a three-dimensional simulation of a GLC 305 airfoil at an angle of attack of 6 degrees in rime ice conditions. Three-dimensional simulation were carried out on the multi-block computational grid in Fig. 2, made of 2 005 632 hexahedral elements and 2 070 937 nodes. Two-dimensional results are obtained from a grid made of 27 856 quadrilateral elements and 28 369 nodes (the surfacial grid in Fig. 6). Numerical integration in the pseudo-time is iterated until a relative difference of 0.001% is achieved in the lift coefficient between two successive iterations. The agreement between the two ice shapes Fig. 6 is apparent. Therefore, two-dimensional simulations have been considered accurate enough to grasp wall blockage effects in icing tests; all the results shown in this section are obtained from two-dimensional simulations.

Fig. 4 reports the collection efficiency β over the airfoil surface from two-dimensional simulations of rime ice accretion on a GLC 305 airfoil, for different grid resolution and for the free-steam (Fig. 4a) and the wind tunnel (Fig. 4b) cases. In both conditions, β is found to be independent from the grid resolution.

Fig. 5 Numerical simulation of wind tunnel flow at $c/h = 0.2$ on three different computational grids and experimental ice shape. Test conditions are given in Tab. 1.

Fig. 6 Two-dimensional and three-dimensional results of a rime ice simulation on a GLC 305 airfoil, $c = 0.9144$ m, $\alpha = 6$ deg, $V_\infty = 90$ m/s, $P_\infty = 10^5$ Pa, $T_\infty = 263.15$ K, MVD $= 20$ μm, LWC $= 0.43$ g/m^3, $t_{\text{ice}} = 120$ s, $\Delta t_{\text{flow-field}} = 5$ s.

A grid dependence study on the final ice shape obtained under the test conditions reported in Tab. 1 is shown in figure 5. The ice shapes are computed using three different computational grids of the wind-tunnel for $c/h = 0.2$ and compared to the experimental results. The three grids are made of 15 248 elements and 15 560 nodes (coarse grid), 31 034 elements and 31 586 nodes (medium grid) and 124 136 elements and 125 240 nodes (fine grid), respectively. The medium grid is generated using the spacing of the coarser grids in Fig. 4 (a) and (b). The three grids correctly capture the overall shape of the ice profile, with differences on secondary ice shapes away from the stagnation point. The differences in the fine mesh computation are due to numerical errors during the update of the surface mesh, which impose a lower limit to the element size. In the following, the medium mesh size will be used in all computations.

In Fig. 7, the ice shape obtained from the simulation of the wind tunnel flow with $c/h = 0.2$ is compared to the corresponding IRT data from [29]. Only the leading edge region is shown, because the area around the stagnation point, where the free-stream flow that approaches the airfoil slows down and reaches rest, is the one in which ice is more likely to accrete.

The evaluation of the influence of wind tunnel walls on measured ice shapes is now addressed by simulating the test conditions given in Tab. 1 considering a number of different domains: a free air flow representing flight conditions (FC) and wind tunnel flows (WT) at four different values of the ratio c/h, namely $c/h = 0.2$, 0.3, 0.5, 0.7. The simulation domains are obtained by varying the height of the test section of the NASA IRT, while the airfoil chord is held constant.

In Fig. 8, the collection efficiency β for the clean airfoil (a) and for the iced airfoil (b) are plotted

Fig. 7 Numerical simulation of wind tunnel flow at $c/h = 0.2$ compared to the experimental ice shape. Test conditions are given in Tab. 1.

(a)(b)

Fig. 8 Collection efficiency versus non-dimensional curvilinear abscissa along the airfoil: clean airfoil (a) and iced airfoil (b). The origin is placed at the leading edge.

Fig. 9 Ice shapes resulting from the simulation of wind tunnel flows at varying blockage coefficient c/h.

against the non-dimensional curvilinear abscissa along the airfoil. The origin of the curvilinear coordinate s ($s/c = 0$) is the leading edge. On each graph, the collection efficiency obtained from the same flight and environmental conditions in a wind tunnel at $c/h = 0.2$ and in flight conditions are compared. In the case of the clean airfoil, there is no significant difference between the two curves, while for the iced airfoil a non negligible deviation occurs only away from the stagnation region. A comparison between the ice shapes obtained for four different values of the blockage coefficient is given in Fig. 9. The four ice shapes overlap in the stagnation region and show little deviations from each other immediately downstream.

A more detailed analysis is required for the study of blockage effects on the performances of the iced airfoils. In icing tests, the geometry of the model changes over time due to ice growth. Therefore, the corrected angle of attack is expected to be a function of time.

In the following, the corrected angle of attack is evaluated on the baseline un-iced configuration

	α [deg]		
	Flight	Wind tunnel	
h/c	conditions	Present	Ref. [18]
0.2	4.0	4.0956	4.0325
0.3	4.0	4.2527	4.0927
0.5	4.0	4.5576	4.2177
0.7	4.0	5.0269	4.4563

Table 2 Corrected angle of attack for the NACA 0012 test case in Table 1. The correction obtained from the procedure described in [18] are also reported. The free-stream angle of attack is $\alpha = 4$ deg.

(a)(b)

(c)(d)

Fig. 10 Lift coefficients and relative correction errors (y-axis) as function of the duration of the experiment (x-axis) for four values of c/h: 0.2 (a), 0.3 (b), 0.5 (c), 0.7 (d). Dashed lines: wind tunnel flows at the reference angle of attack. Continuous lines: flight conditions at the corrected angles of attack. Dotted lines: correction errors.

and then it is held constant over the entire duration of the test. To assess the accuracy of such correction, the value of the lift coefficient over time is monitored. Four free-air-flow additional simulations are carried out, namely those reproducing flight conditions at the corrected angles of attack associated to the four different blockage coefficients. The corrected angles of attack are determined as follows: the lift coefficient resulting from the wind tunnel flow simulation is determined first. Then, a piecewise linear approximation of the lift coefficient versus angle of attack curve referred to flight conditions is constructed. The corrected angle of attack, namely the free-air-flow angle of attack associated to the wind-tunnel lift coefficient, is retrieved by interpolation of the piecewise linear lift curve. The values of the corrected angles of attack for each blockage coefficient are reported in Tab. 2, together with the corresponding value obtained from the reference procedure in Ref. [18]. Note that the procedure in Ref. [18] requires one to specify the value of the momentum coefficient, whose accuracy in the present simulation is possibly not sufficient for producing the appropriate correction to the angle of attack.

For each value of the blockage coefficient c/h, the results of the wind-tunnel-flow simulation at the reference angle of attack and that of the free-air-flow at the corrected angle of attack are summarized in Fig. 10.

In Fig. 10 (a)-(d), the lift coefficient, on y-axis, is given as function of the duration of the experiment, on x-axis. The dashed lines refer to the wind tunnel flow simulations, while the continuous lines represent flight conditions at the corrected angles of attack. In all cases, a sensible deviation between the two $C_l(t)$ curves for increasing time is observed. This behavior is common to all the examined blockage coefficients, from 0.2 to 0.7, confirming the expectation of a time dependence of

c	α	V_∞	T_∞	P_∞	MVD	LWC	t_{ice}	$\Delta t_{\text{flow}-\text{field}}$
[m]	[deg]	[m/s]	[K]	[Pa]	[μm]	[g/m^3]	[s]	[s]
0.9144	6	90	263.15	10^5	20	0.43	120	120

Table 3 Mixed rime-glaze icing conditions for the study of wall-wing interference effects on a constant-chord model of a GLC 305 airfoil [30].

Fig. 11 Collection efficiency and resulting ice shape on the surface of a constant-chord model of a GLC 305 airfoil.

blockage correction angle due to ice build-up.

The percentage difference between the wind-tunnel and the corrected lift coefficients is also given on y-axis in Fig. 10 (a)-(d). As expected, the wind tunnel correction retrieved from the analysis of the clean-airfoil configuration well represents the iced airfoil performances only at the first stages of ice accretion. For longer exposure times, the shape variation caused by ice accretion worsens the estimate of the iced-airfoil lift coefficient, leading to errors up to about 10%. A well-defined trend of the lift coefficients versus time is not observed, neither for each single value of blockage, nor at varying blockage coefficient. Moreover, the relative error associated to the lowest value of blockage coefficient, $c/h = 0.2$, reveals that, counter-intuitively, a low blockage does not necessarily imply small errors in iced-airfoil lift coefficient estimation.

B. Wall-wing interference

In wind tunnel testing, the interaction between the boundary layer on the tunnel sidewalls and the one on the wing affects both the maximum lift achievable and the spanwise stall initiation. In flight conditions, similar phenomena take place at the wing-fuselage junction. Simulating the behavior of the flow at a wall-wing juncture and the resulting ice accretion is therefore of paramount importance when assessing maximum lift penalties caused by ice accretions.

Difficulties arising from both the droplet insemination of the flow and the control of the side-

Fig. 12 Ice accretion at the wall-model juncture on a constant-chord model of a GLC-305 airfoil.

wall boundary layer led to a substantial lack of qualitative and quantitative experimental data documenting ice shapes at a wall-wing juncture. A comprehensive evaluation of performances is not carried out in this paper. Instead, three-dimensional simulations aimed at capturing the peculiar ice geometries at the wall-wing juncture are carried out.

In particular, wind tunnel tests of a constant-chord model [30] and a swept wing [32] in rime ice conditions are simulated within the experimental setup shown in Fig. 3. The test conditions are given in Tab. 3 and 4, where t_{ice} represents the total icing exposure time and $\Delta t_{\text{flow-field}}$ the flow-field update interval. In these two cases, a single-step procedure is adopted and the flow-field is evaluated only on the clean configuration.

The case of the constant-chord model is analyzed first. Numerical simulations show that the flow at the leading edge of the model, near the juncture between the model and the tunnel wall, is characterized by a velocity component directed from the middle section of the wind tunnel towards the sidewall. Indeed, the streamlines clearly show that at the wall-model juncture there is a region of separated flow that originates from the interaction between the boundary layer at the sidewall and the model boundary layer. This results in the occurrence of a shadow zone in which water droplets do not impinge. The shadow zone is evident from Fig. 11, where a view of the ice accreted on the model is superposed to the collection efficiency distribution. In Fig. 12, the ice shape at the wall-model juncture is reported. The ice formation is due both to the particular behavior of the flow at the juncture between the wall and the model, and to the fact that the motion of droplets of small diameter, such as those considered in this simulation, is affected more by aerodynamic forces than by buoyancy and inertia. Indeed, droplet aerodynamic drag is proportional to the square of its radius, whereas inertia forces vary as the cube of the radius. Therefore, the trajectories of small droplets closely resemble streamlines. The opposite applies to droplets with larger diameters, such as the so-called super-cooled Large Droplets (SLD).

The test conditions correspond to rime ice conditions. However, in Fig. 11, ice is observed even where the collection efficiency is zero. According to the icing model implemented in PoliMIce, the very first accretion is indeed of the rime type, because the wing temperature is below water freezing temperature and incoming droplets freeze upon impact. Liquid water develops only in a second

α	V_∞	T_∞	P_∞	MVD	LWC	t_{ice}	$\Delta t_{\text{flow}-\text{field}}$
[deg]	[m/s]	[K]	[Pa]	[μm]	[g/m^3]	[s]	[s]
6	90	261.87	10^5	20	0.51	120	120

Table 4 Mixed rime-glaze icing conditions for the study of wall-wing interference effects on a swept wing model [32].

Fig. 13 Collection efficiency and resulting ice shape on the surface of a GLC 305 swept wing model.

stage of the icing process. The liquid film is driven by the shear stresses at the wall; therefore, ice is observed both downstream of the region of non-zero collection efficiency and at the model-wall juncture. Ice accreted at the juncture is mostly of glaze type, because it results from the freezing of liquid water driven towards the root of the model by shear stresses acting on the surface of the model itself.

Different but equally prominent three-dimensional effects are observed in the case of the swept wing. As in the case of the constant-chord model discussed above, a sensible variation in the ice shape along the span is observed, especially at the wall-wing juncture, where a strong interaction between the boundary layer on the wall and that on the wing exists. The simulation reproduces also in this case the experimental setup presented in Fig. 3, but the model is now a swept wing with root choord of 25.2 in, tip chord of 10.08 in and swept angle $\Lambda = 28°$. Planform details are given in [32].

Similarly to the case of the constant-chord model, inspection of the streamlines and of the z-component of the shear stress at the wing surface suggest the presence of a region of separated flow on the suction side of the wing, close to the juncture to the tunnel sidewall. Flow separation in this region affects droplet impingement, leading to an irregular distribution of the collection efficiency at the wall-wing juncture, as shown in Fig. 13.

The simulated test conditions are expected to produce an ice accretion of the rime type. Indeed, numerical results confirm that, outside the separated flow region, ice build-ups of the so-called

Fig. 14 Ice accretion at the wall-model juncture on a GLC-305 swept wing model.

(a)(b)

Fig. 15 Ice accretion at the wall-model juncture on a GLC-305 swept wing model: suction side (left) and pressure side (right) of the wing.

streamwise type [19] are observed. In the near-wall region, instead, a larger amount of ice of the glaze type accumulates due to shear stresses driving liquid water towards the root of the model (cf. Fig. 14 and 15). Moreover, on the pressure side of the wing, the module of the shear stresses is larger than its suction-side counterpart and a large spanwise variation in the ice shape is observed (Fig. 15). Differently from the case of the constant-chord model, only a smooth decrease in the ice thickness is observed at the wall-wing juncture, instead of a larger shadow zone where ice does not accumulate.

IV. Conclusions

Wind tunnel tests of ice accretion over airfoils and wings were reproduced numerically using the simulation framework PoliMIce [14, 15] to study the effects of wall blockage and of wall-wing boundary layer interaction on ice accretion.

Two-dimensional simulations—carried out in free air flows and in wind tunnels at varying blockage coefficient—exposed for the first time a dependence of the blockage correction angle on time and showed that a standard blockage correction could lead up to a 10% error on the estimation of the lift coefficient of the iced airfoil. This suggests the need to reassess all the experimental results obtained so far, in order to evaluate their dependence on wind tunnel blockage and test time. The assessment can be done by numerical simulations or by recording the time variation of the lift coefficient during the experimental runs.

The ice build-up at the juncture between a model wing and the adjacent wind tunnel wall was analyzed by means of three-dimensional simulations. A shadow zone where droplets do not impinge and ice does not accrete was observed to occur in rime ice conditions, at the juncture between a constant-chord model and the tunnel sidewall. At later times, glaze ice is formed within the shadow region. Similar environmental conditions were taken as reference for the study of ice accretion at the wall-wing juncture of a swept-wing model. Also in this case, shear stresses driving the liquid film towards the root of the model prevented the occurrence of an ice-free region even in the shadow zone and led to a mixed rime-glaze ice build-up at the wall-wing juncture. So-called streamwise ice formations are observed along the wing span.

To improve the performance estimation of basic two-dimensional airfoils and of modern highly twisted and tapered swept wings, further research on wall-wing interference effects is required. Numerical simulations are a valuable tool to achieve a complete understanding of the flow physics. From the phenomenological standpoint, diverse geometrical configurations and environmental conditions can be simulated and the resulting ice accretions analyzed and classified. As far as performance degradation is concerned, comparing the force coefficient obtained from a simulated flight conditions to a wind-tunnel flow simulation allows both to devise suitable blockage corrections and to isolate the effect of boundary layer interaction at the sidewalls. Numerical simulation of wind tunnel flows could also help identifying issues in the insemination of water droplets, especially water droplets of large diameters such as the super-cooled large droplets (SLD). Indeed, in a wind tunnel test, the flow is seeded with water droplets upstream of the test section and water droplets move towards the model, driven by the airflow; the opposite happens in real operating conditions. Large droplets may experience unrealistic deformation or aggregation before reaching the model, thus testing conditions can significantly depart from those encountered in flight.

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