Aeronautics and Astronautics - AIDAA XXVII International Congress Materials Research Forum LLC
Materials Research Proceedings 37 (2023) 127-132 https://doi.org/10.21741/9781644902813-28

Effects of different drag laws on ice crystals impingement on probes mounted on a fuselage

A. Carozza[1*], P.L. Vitagliano[1], G. Mingione[1]

[1]Centro Italiano Ricerche Aerospaziali, Dipartimento di Meccanica dei Fluidi, via Maiorise snc, Capua, Italia

*a.carozza@cira.it

Abstract. In this work the effects of different drag laws regarding the ice crystals impingement on the fuselage of a regional aircraft are investigated. Different probes are considered on the surface of interest. Along each of these instrumentations the collection efficiency has been calculated by using a RANS structured solver named UZEN and an eulerian impingement code IMP3D, both developed internally at CIRA. The solvers are parallelized and well assessed. The computational grid has been generated with ICEM CFD. Results show the strong influence of the shape considered for the ice crystal particles. Results are shown in terms of collection efficiency and total ice mass collected.

Keywords: Impingement, Probes, Ice Crystals, Eulerian Scheme

Nomenclature

Latin symbols

A	surface area of the particle	[m^2]
d	particle diameter	[μm]
MVD	mean volume diameter	[μm]
X	x axis - coordinate of probe	[m]
Y	y axis - coordinate of probe	[m]
Z	z axis - coordinate of probe	[m]
V	ice crystals velocity	[m/s]

Greek symbols

β_{inst}	installation coefficient, ratio of the local particle concentration to the upstream particle concentration, is calculated along the direction normal to the fuselage	
y+	dimensionless wall distance	[m]
Φ	$\frac{\pi {d_p}^2}{A}$	[0,1]

Subscripts

p	particle

Introduction

Icing is a major hazard for aviation safety. In flight icing is caused by water droplets that froze after impacting on aircraft surface. Ice crystals were assumed to not be an hazard for in flight aircraft operations, nevertheless in the last decades an additional risk has been identified when flying in clouds with high concentrations of ice-crystals where ice accretion may occur on warm parts of the engine core, resulting in engine incidents such as loss of engine thrust, strong vibrations, blade damage, or even the inability to restart engines. Ice crystals can also accumulate on probe: on July 2029 an A320 from Paris to Rio de Janeiro had a fatal incident, investigators demonstrated that the main cause of the incident was ice formation on pitot tube due to a very strong concentration of ice crystals, that caused provision of false information on pilots instruments that caused the incident. Performing physical engine tests in icing wind tunnels is extremely challenging, expensive and currently limited to partial tests for engine components and in addition very few facilities are able to simulate ice crystals.

The need for the European aeronautics industry to use numerical simulation tools able to accurately predict ICI (Ice Crystal Icing) is therefore urgent and paramount, especially regarding the development of the new generation engines (UHBR, CROR, ATP) which are expected to be even more sensitive to the ICI threat than current in-service engines and for which comparative analysis methods will not be applicable any more.

MUSIC-HAIC research project is devoted to complete the development of ICI models, implement them in existing industrial 3D multidisciplinary tools, and perform extensive validation of the new ICI numerical capability through comparison of numerical results with both academic and industrial experimental data.

The resulting capability will allow the replacement of physical tests by cheaper virtual tests, which would be easier to configure and run, allowing substantial gains in development costs and more design choices to be explored and de-risked.

Most importantly, MUSIC-HAIC will provide the aeronautical sector with the confidence to move away from a step-by-step incremental evolution of engine design to a more radical breakthrough approach, because the ability to simulate the behaviour of ICI on these designs with a high degree of confidence will be available. This will reinforce the competitiveness of the European aircraft and engine manufacturers. MUSIC-HAIC will also enhance the expertise of the scientific and research community on ICI.

The scope of this work is to show the effects of the sphericity and deformation of a particle on the collection efficiency when ice crystals with high MVD are considered. At this aim different drag laws have been implemented in the Eulerian impingement code developed at CIRA IMP3D.

Methods

Since the end of the 1990s CIRA has invested in the study, development and application of numerical methods for the analysis of in flight icing conditions. Over the years, the presence of the in-house IWT facility has promoted the development of tools for supporting experiments as well as offering a viable and low-cost means to industrial customers. Besides, the participation in EU-funded projects has implied a continuous upgrade of in-house competences, allowing at the same time the monitoring of the most promising finds. Currently, almost all the project's proposals on the icing topic include, in addition to the experimental measurements, work packages dedicated to numerical analyses and/or the study of new simulation techniques.

For 2D ice accretion a very fast low-order model, was developed, the Multi-Ice tool, which solves two-dimensional potential flow. It is a classic panel method often used for the aerodynamic analysis of single- and multi-element airfoils, capable to compute impingement and ice accretion on each component. In case of 3D complex geometries two software have been developed at CIRA: UZEN and SIMBA [7][8]. They solve the compressible RANS equations on two- and three-dimensional block-structured (UZEN), and Cartesian meshes (SIMBA).

Water droplets trajectories can be calculated by using IMP3D and SIMBICE-ICE, respectively coupled to UZEN and SIMBA. They both solve the water phase by using a Eulerian approach.

For the objective of this study the in-house Eulerian solver named IMP3D is available to estimate the ice crystal impingement around 2D and 3D geometries. Several models can be used for the drag coefficient C_d of the ice crystals as a function of the particle sphericity [2] and the Reynolds number based on the particle equivalent diameter. It is crucial for the trajectories of ice crystals.

In this work the following drag correlations have been used:

1. Clift and Gauvin [1][3], with no sphericity (Φ=1)
2. Ganser et al. [4],
3. Haider and Levenspiel [5],
4. Hölzer and Sommerfeld [6],
5. Nakayama et al. with the effect of the surface tension (EXTICE) on Φ.

On the other hand, evaporation and melting processes have been simulated within an Eulerian formulation by means of source terms for mass and energy transfer.

Results and Discussion

A research configuration of fuselage has been considered with five probe locations. Indeed, the probe blockage represents a risk pilots face when they travel in icing conditions. In order to have a representative overview of what recent numerical tools can predict on these instrumentations in terms of ice impingement the effects of several drag correlations are shown.

Four probes were considered: a pitot probe, a total temperature probe and two angle of attack probes. In addition, it was decided to add a fifth location for post-processing at the nose of the fuselage.

The probes locations on the aircraft nose are provided in Table 1.

Table 1: Coordinates of the probes on the fuselage configuration for post-processing purposes

	X [m]	Y [m]	Z [m]
PT2	8.9195	1.2950	-1.1660
TAT2	9.5832	0.6389	-1.9203
AoA1	13.7037	2.6183	-0.6364
AoA2	13.6996	2.5187	-0.9685
Nose	6.3825	0	0.2925

The aircraft is assumed to be flying at Mach number 0.78 at altitude 34000 ft. corresponding to an atmospheric pressure of 25000 Pa. The angle of attack is 2.05 degree (Table 2).

Table 2: Flight conditions

Altitude [ft]	Angle of attack [°]	Mach	Pressure [Pa]	Temperature [K]
34000	2.05	0.78	25000.	233.15

The impingement has been computed considering the MMD and the IWC indicated in Table 3 without considering droplets but only ice crystals.

Table 3: Ice crystal characteristics

Mean Mass Diameter [μm]	Ice Water Content [g/m^3]
336.5	1.15

Only half of the configuration is meshed and a symmetry plane condition is used. The geometry shown in the Figure 1 is meshed using ANSYS/ICEMCFD. The limits of the computational domain surrounding the geometry are located at a distance of 30 times the length of the nose. The ratio between two adjacent cells is equal or lower than 1.2. The height of the first cell at the vicinity of the wall is 0.006 mm. 50 cells have been used to capture the boundary layer characteristics near the wall and in direction perpendicular to it. A Navier-Stokes multiblock structured mesh of about 18 Million of cells and 26 blocks has been generated.

Materials Research Proceedings 37 (2023) 127-132 https://doi.org/10.21741/9781644902813-28

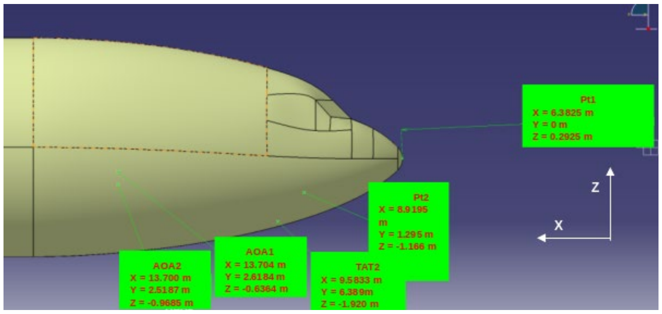


Figure 1: nose fuselage configuration

Results show that the wall y+ lies between 0.5 and 1.0, Figure 2. Pressure coefficient is shown in Figure 3 while a collection efficiency distribution is plotted in Figure 4.

The computation of the aerodynamic flow field around the geometry made of nose and fuselage is realized using the in house UZEN Multi-block CFD simulation software. The Reynold number based on the length of the geometry nose is 5.9×10^6. The aerodynamic flow field is computed using RANS modelling with TNT k-ω turbulence model in fully turbulent approach.

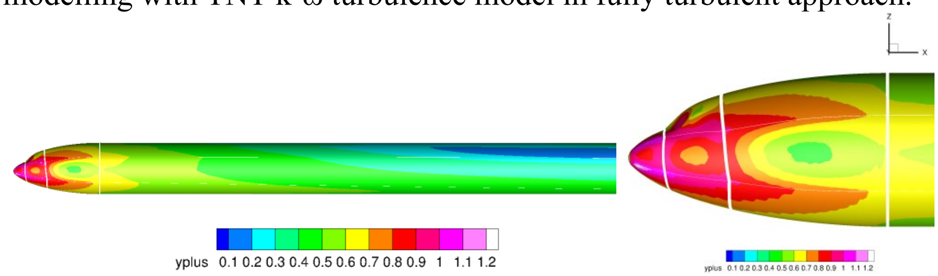


Figure 2 y+ contours

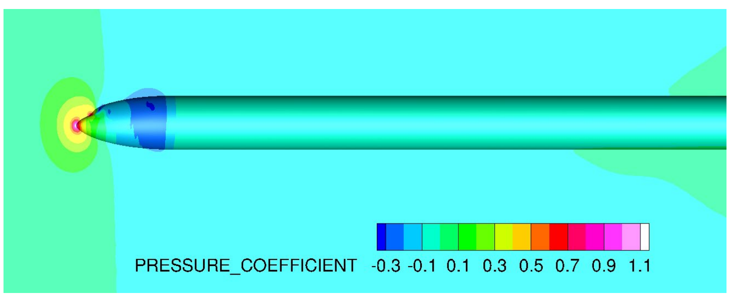
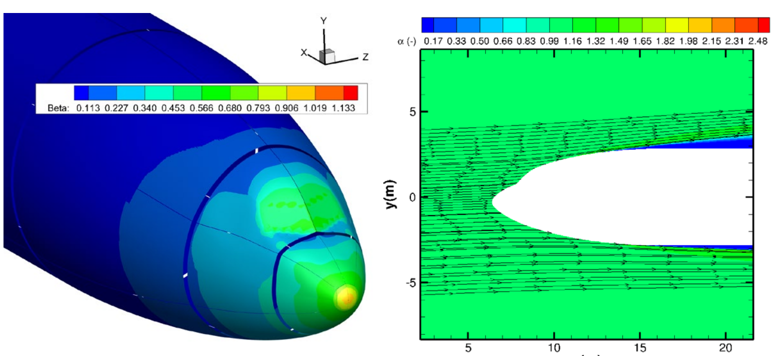


Figure 3 Pressure coefficient C_p contours

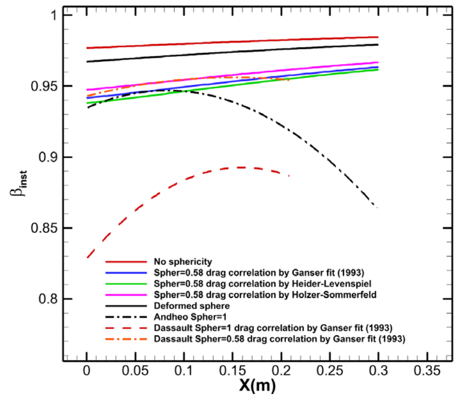


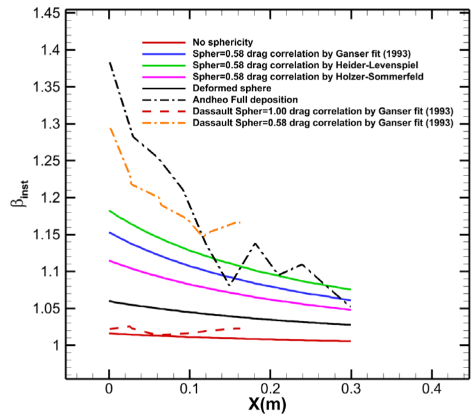
Bucknell (with fragmentation threshold)

Figure 4 Ice crystals collection efficiency using the Bucknell impact model

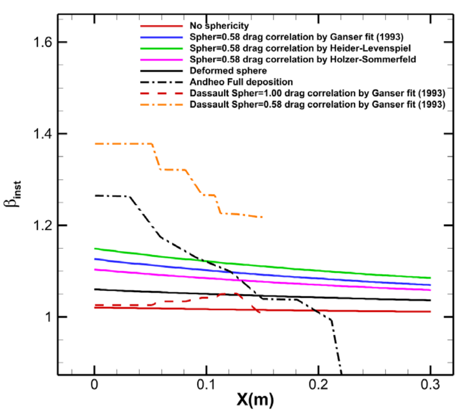
Materials Research Proceedings 37 (2023) 127-132 https://doi.org/10.21741/9781644902813-28

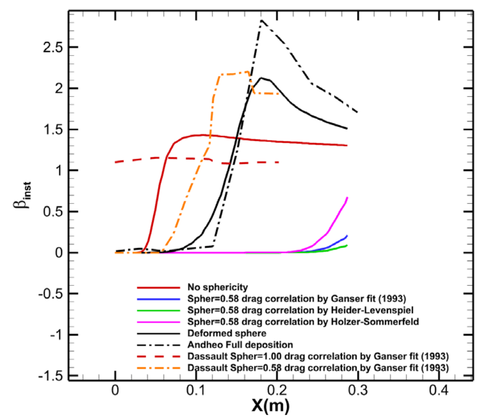
Observing the collection efficiency contours, see Figure 4, it is possible to state that the two zones mainly affected by the problem of ice crystals impact are the nose and the glass in front of the cabin. The maximum value of the collection efficiency does not go over 1.15 also for this simulation, while the total mass flux deposited on the surface is about 2.12 kg/s on the whole surface. In the Figure 5 the installation coefficient β_{inst}, ratio of the local particle concentration to the upstream particle concentration, IWC, is calculated along the direction normal to the fuselage, calculated by using the Bucknell model [9] including the fragmentation without re-emission are shown.



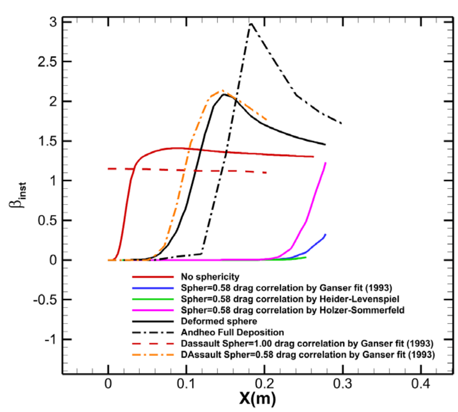


PT1 PT2





TAT2 AOA1



AOA2

Figure 5 Installation coefficient for different shapes of ice crystals along the probes axis

The installation coefficients can be looked at. Probes AoA1 and AoA2, that are the furthest ones from the nose, show the more relevant impact of the ice crystals shapes and related correlations on the installation coefficient and mass deposition along the probes. The ice crystals current is subjected to fragmentation with a larger mass loss when compared to the case with ice crystals modelled like simple spheres. Moreover, it has to be noticed that there are strong over concentrations of ice crystal particles on the probes AoA1 and AoA2 without considering the effect of particle shape. This behaviour is inverted when probes Nose, PT2 and TAT2 are considered.

Some comparisons have also been added in the installation coefficient plots, considering data coming from Andheo or Dassault companies. They are in agreement with data computed by the authors.

Conclusions

An impingement study has been carried out on some probes installed on a fuselage. At this aim a RANS finite difference code and a Eulerian scheme impingement 3D code have been used on the same computational grid generated around a fuselage. Different drag laws related to the ice crystals injected in the domain have been adopted in order to assess the sphericity importance in the collection efficiency of a specific geometry of aeronautical interest. The main conclusions are:

1. Sphericity has a relevant rule into determining the impingement values and the shadow zones
2. It generates a variable water concentration of ice crystals along the probes axis

Acknowledgments

Authors would thank Andheo and Dassault for their support and permission to use the data collected in the Eu project Music-haic.

References

[1] Clift R, Grace JR, Weber ME. Bubbles, drops, and particles. New York: Academic Press 1978.

[2] E. Loth, Drag of non-spherical solid particles of regular and irregular shape, Powder Technology 182 (2008) 342–353

[3] Clift, R., and Gauvin, W.H., The motion of particles in turbulent gas streams, Proceedings CHEMECA 1970, Butterworth, Melbourne, 1, 14-28, 1970.

[4] G.H. Ganser, A rational approach to drag prediction of spherical and nonspherical particles, Powder Technol. 77 (1993) 143.

[5] A. Haider, O. Levenspiel, Drag coefficient and terminal velocity of spherical and non-spherical particles, Powder Technol. 58 (1989) 63–70.

[6] A. Hölzer, M. Sommerfeld, New simple correlation formula for the drag coefficient of non-spherical particles, Powder Technology 184 (2008) 361–365

[7] C. Marongiu, P. Catalano, M. Amato, G. Iaccarino, U-ZEN : A computational tool solving U-RANS equations for industrial unsteady applications, 34th AIAA FluidDynamics Conference, Portland (Or), June 28 -July 1 2004, AIAA Paper 2004–2345.

[8] Capizzano et al., CIRA contribution to the first AIAA Ice Prediction Workshop, AIAA AVIATION 2022 Forum, https://doi.org/10.2514/6.2022-3400

[9] Bucknell, A., McGilvray, M., Gillespie, D., Yang, X. et al., "ICICLE: A Model for Glaciated & Mixed Phase Icing for Application to Aircraft Engines," SAE Technical Paper 2019-01-1969, 2019, https://doi.org/10.4271/2019-01-1969.