Proceedings of the 10th World Congress on Momentum, Heat and Mass Transfer (MHMT 2025)
Barcelona, Spain - April, 2025
Paper No. ENFHT 169
DOI: 10.11159/enfht25.169

Numerical Modeling of Anti-Icing Operations Over Super-Hydrophobic Surfaces

Giulio Croce[1], Nicola Suzzi[1]
[1]DPIA, University of Udine Via delle Scienze 206, 33100 Udine
giulio.croce@uniud.it; nicola.suzzi@uniud.it

Extended Abstract

Hydrophobic and super-hydrophobic coatings are currently considered promising tools to enhance the performances of thermal devices for in-flight icing protection. Icing protection is mostly obtained via heating of the critical surfaces: the simulation is quite complex, including the need for CFD solution of the flow around the wing, including the tracking of the cloud supercooled droplet, the simulation of the evolution of the interaction between droplets and airfoil (including coalescence into rivulets and continuous film, evaporation due to the de-icing heat flux, freezing on impact or later…). However, current commercial numerical prediction tools for in-flight icing simulation are based on the Messinger model [1], although extended to 3-D arbitrary surfaces [2], coupled with Lagrangian or Eulerian [3] droplet flow field analysis. Messinger's model assumes that the runback water layer is a continuous film driven by the shear stress and provides reliable and accurate results in several applications. Unfortunately, it intrinsically neglects any wettability effect and thus cannot assess hydrophobic coating performances.

The main difficulty in the simulation of such coatings is that it involves an inherently multi-scale problem: wettability operates at a small scale, at most of the order of the single impinging droplet, but the local impinging mass flow, shear stresses, and heat transfer convective coefficients require state-of-the-art CFD computation around a whole wing or a whole aircraft. Since it is not practical to manage the large-scale computations with a grid fine enough to resolve the single droplet evolution (e.g., via VOF approach), a kind of intermediate bridge is required to derive average integral corrections from the small scale and transfer them to a coarser grid for the standard CFD solution of the large scale thermal and flow field.

Here, a hierarchical approach is followed: first, a high-fidelity, small-scale model defines statistical distributions of relevant properties (rebounding droplet fractions, average runback water velocities, wet area fractions, coalesced droplet diameter distribution, including heat transfer and phase changes) as a function of the local fluid dynamic conditions; as a second step, statistical correlations are extracted by this small-scale computation campaign, providing integral corrections to the larger-scale CFD simulation.

The high-fidelity simulation tool, an individual-based droplet phenomenological model, was described and validated in [4], and here is improved with regard to the phase change modeling (for both the ice beads freezing and the droplet evaporation due to de-icing system heat flux). The present work is then focused on the statistical models derived by the high- fidelity results, with special attention to the distribution of the small scale droplets (i.e., below the radius where coalescences become the main growth effect), following the approach described in [5] under different conditions. Such small droplets are of special interest for the anti-icing devices, which ideally should operate mostly under such regime, allowing for quick evaporation and minimization of runback water rivulets.

The statistical model is coupled with a CFD simulation of the heat and fluid flow around an airfoil under icing condition and a lagrangian droplet tracing code, allowing for thoughtful final validation versus literature experimental data provided in [6]. Finally, a parametrical analysis is conducted commenting on the usefulness of hydrophobic coatings of different properties for anti-icing operations under various environmental conditions. It demonstrates that it may offer a valuable aid in obtaining dry clean surfaces with no or little runback water with a relatively low energy consumption.

References

[1] B.L. Messinger, “Equilibrium Temperature of an Unheated Icing Surface as a Function of Air Speed”, *J Aero. Sciences*, Jann. 1953 pp. 29–42.

[2] Y. Bourgault, H. Beaugendre, W.G. Habashi, “Development of a shallow-water icing model in FENSAP-ICE”, In *Journal of Aircraft*, Vol. 37, pp. 640-646, 2000.
[3] Y. Bourgault, Z. Boutanios, W.G. Habashi, “Three-dimensional Eulerian approach to droplet impingement simulation using FENSAP-ICE, Part 1: Model, algorithm, and validation”, *Journal of Aircraft*, Vol. 37, pp. 95-103, 2000.
[4] G. Croce, N. Suzzi, M. Pretto, P. Giannattasio, Numerical Modelling of Droplets and Beads Behavior over Super-Hydrophobic and Hydrophilic Coatings under in-Flight Icing Conditions”, *Applied Sciences*, Vol.12 n.5, 2022.
[5] G. Croce, N. Suzzi, “Effect of hydrophobic coating on optimization of dropwise condensation of steam on hybrid surfaces”, *Journal of Physics: Conference Series*, Volume 2766 n. 12024, 2024
[6] L. Gao, Y. Liu, L. Ma, H. Hu, “A hybrid strategy combining minimized leading edge electricheating and superhydro-/ice-phobic surface coating for wind turbine icing mitigation”, *Renewable Energy,* Vol. 140, pp. 943-956, 2019.