Lagrangian Droplet Impingement Analysis and Validation for an Axisymmtric Engine Inlet Nacelle and a Swept Wing

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In the current study, continued efforts to improve a computational in-flight icing prediction tool are introduced together with the obtained results. Emphasis is on the droplet trajectory computations and the resulting impingement efficiencies.

In an in-flight icing prediction tool there are four main modules; flow field computation, calculation of the droplet trajectories and subsequently the impingement or collection efficiencies, thermodynamical analysis and finally the computation of the ice accretion rates and the final ice shapes.

The most important step is the impingement evaluation due to its fundamental role in designing an effective ice protection system. The importance of droplet trajectories and impingement has increased with the recent amendment of CS 25 to better protect large airplanes certified for flight in icing conditions. The new icing environment would include Supercooled Large Drops (Appendix O), Mixed Phase and Ice Crystals (Appendix P) in addition to already existing Supercooled Drops (Appendix C) [1, 2]. In connection with this an amendment of CS-E to update turbine engine certification is proposed [3, 4].

It is clear that any computational tool to be used as a means of compliance must be capable of computing particle trajectories in a wide range of icing cloud conditions. These conditions include the liquid water content (LWC) or the total water content (TWC) of the cloud, ambient temperature (T_a), exposure time (t_{exp}) or distance (HE), flight velocity (V_∞), median volume diameter (MVD) or mass median diameter (MMD) of the cloud particles.

Lagrangian approach is used in the current method for computing particle trajectories. It is assumed that the presence of the droplets do not affect the flow field. Gravity and aerodynamic drag are the only forces acting on the droplets. Non-spherical particles are accounted for through an appropriate drag law, which becomes important for large droplets. The droplet trajectories are computed using the following equations:

$$m\ddot{x}_p = \cos\gamma_1, \tag{1}$$

$$m\ddot{y}_p = \cos\gamma_2, \tag{2}$$

$$m\ddot{z}_p = -(D\cos\gamma_3 + mg), \tag{3}$$

with

$$\gamma_1 = \tan^{-1}\frac{\dot{x}_p - V_x}{V_{rel}}, \quad \gamma_2 = \tan^{-1}\frac{\dot{y}_p - V_y}{V_{rel}}, \quad \gamma_3 = \tan^{-1}\frac{\dot{z}_p - V_z}{V_{rel}}, \tag{4}$$

$$D = \tfrac{1}{2}\rho\, V_{rel}^2 C_D A_p, \tag{5}$$

$$V_{rel} = \sqrt{(\dot{x}_p - V_x)^2 + (\dot{y}_p - V_y)^2 + (\dot{z}_p - V_z)^2}. \tag{6}$$

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In the above equations, V_x, V_y and V_z are the components of the flow velocity at the droplet location, while $\dot{x}_p, \dot{y}_p, \dot{z}_p, \ddot{x}_p, \ddot{y}_p$ and $\ddot{z}_p$ are the components of the droplet velocity and acceleration. The symbols ρ and A_p denote the atmospheric density and cross-sectional area of the droplet. C_D denotes the droplet drag coefficient.

Trajectory calculations start from an upstream location far away from the wing leading edge so that air flow velocity components are sufficiently close to their freestream values. The initial droplet velocity is taken to be the terminal velocity [5]:

$$V_{term}^2 = \frac{4}{3}\frac{(\rho_w - \rho)}{\rho}\frac{g d_p}{C_D}. \quad (7)$$

The droplet trajectories are obtained by integrating equations (1-3) over time until the droplet impacts the geometry. The trajectory calculations are undertaken using parallel computation in order to reduce the CPU time [6]. The droplet impact pattern on the section determines the amount of water that impinges on the surface and the region subject to icing. The local collection efficiency is defined as the ratio, of the area of impingement to the area through which water passes at some distance upstream of the section, $\beta = A_o/A$.

If the droplet size and velocity is high enough, the droplet can breakup into smaller droplets due to shear forces acting on its surface. After a droplet impacts the surface, part of its mass will impinge on the surface, while the remaining mass will bounce and reimpinge on the surface downstream of the initial impact point (droplet splash). These two phenomena are taken into account by appropriate models [5].

In the current paper, results of the droplet trajectory calculations like those shown in Figure 1 below will be presented together with the droplet impingement efficiency distributions (similar to those shown in Figure 2) obtained for an axisymmetric engine nacelle and a swept wing. The results will be validated using experimental and numerical data reported in the literature.

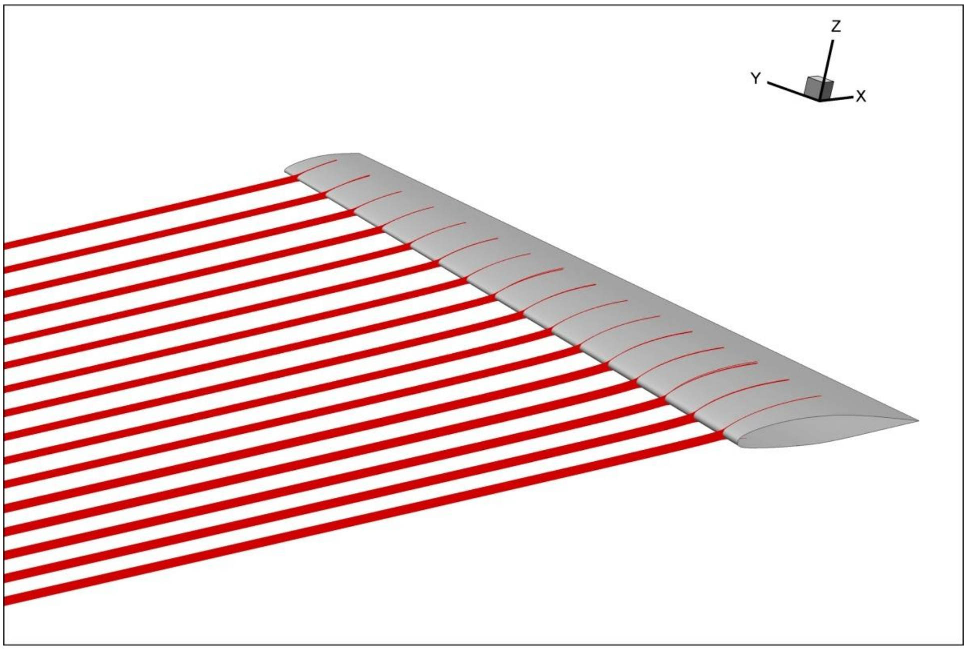

Fig. 1. Droplet trajectories for a swept wing.

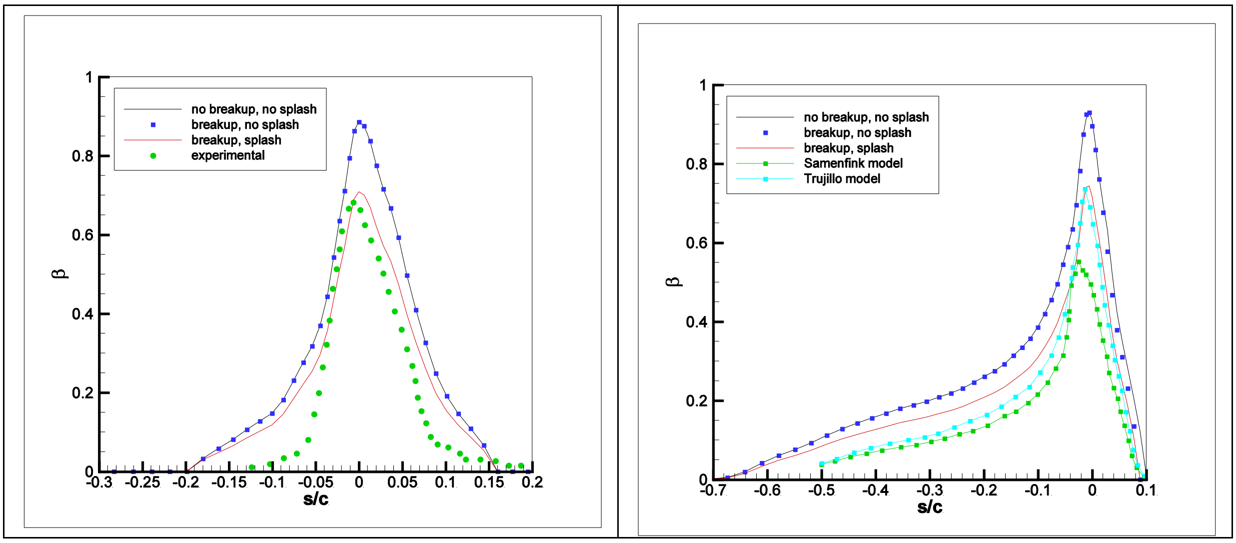

Fig. 2. Droplet impingement (collection) efficiencies for a MS317 profile at V_∞=78 m/s. MVD=92 μm, $\alpha=0^o$ (left), MVD=236 μm, $\alpha=8^o$ (right) [5].

References:

[1] European Aviation Safety Agency, Notice of Proposed Amendment (NPA) No 2011-03, 2011.

[2] European Aviation Safety Agency, Notice of Proposed Amendment (NPA) No 2012-22, 2012.

[3] European Aviation Safety Agency, Notice of Proposed Amendment (NPA) No 2011-04, 2011.

[4] European Aviation Safety Agency, Notice of Proposed Amendment (NPA) No 2012-23, 2012.

[5] Özgen, S. and Canıbek, M., In flight icing simulation with supercooled large droplet effects, *in 7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT 2010), Antalya, Turkey,* 2010.

[6] Özgen, S, Tarhan, E. And Canıbek, M., Parallel computing applied to three-dimensional droplet trajectory simulation in Lagrangian approach, *in International Conference on Aircraft and Engine Icing and Ground De-Icing, Chicago, Illinois, USA*, 2011.