Discrete Particle Simulation for the Initial Stages of Ice Accretion in Aircraft Engines:

Initial Model Development

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Abstract—**Elements of a discrete particle model that might find application in aircraft engine icing studies are introduced in this paper. As it currently stands, the model is in an embryonic state but it does provides a framework from which further developments can easily proceed. It provides a convenient basis for assessment of aerodynamic particle drag, surface friction, heat transfer and other effects likely to be relevant in the engine icing problem. The model treats the initial stage of accretion, before the inviscid stagnation point flow field is measurably affected by the presence of the ice build-up. The intention is to provide an indication flow field and surface conditions that are likely to lead to stable accretion of ice prior to detectable changes in the aerodynamics of the stagnation point flow field. Preliminary results from the model are presented to demonstrate the current functionality of the model.**

Keywords – aircraft engine icing, ice particle, simulation

I. INTRODUCTION

Ice growth on engineered structures was originally studied in the context of marine applications [1], but power transmission lines and aircraft are also subjected to ice growth under certain conditions [2]. In aircraft, ice accretion can lead to serious loss of functionality, with possible aircraft destruction and consequent loss of life. Hence, the aircraft application of ice accretion has received the most attention [3].

Three modes of ice accretion are often considered and these modes are aligned with different temperature ranges: rime, glaze, and mixed rime/glaze icing. Rime ice accretion occurs for temperatures between about -40 and -10 ºC. It appears that the rate of rime ice accretion can be identified using mass conservation on the assumption that the supercooled liquid droplets solidify when hitting the freezing surface [4]. At temperatures between -15 to 0 ºC, glaze icing occurs. Droplets impacting on the chilled aircraft surface may add additional components of heat due to the kinetic energy of impinging droplets and the latent heat release from the freezing ice layer. Some of these droplets adhere close to the point of impact while others depart from the accreted ice mass. Glaze icing should be treated as a three phase flow problem since there is relative motion between the solid freezing surface, glaze ice, water film, and the air flow with droplets.

This paper focuses on the development of a model for solid ice accretion in aircraft engines. Solid ice accretion in aircraft engines appears to be the likely cause of a number of near disasters in the aviation industry [5]. It can occur when commercial or commuter aircraft traverse clouds systems at very low temperatures, less that -40 ºC [5]. At such temperatures the water cannot remain in a super-cooled state so the cloud moisture content is in the solid phase. Such conditions were previously considered benign from an aircraft icing perspective because the ice particles appeared to be deflected from the wings and other structures without observable accretion. However, recent evidence suggests ice accretion can occur in the compressor stages of certain engines and this can lead to a reduction or total loss of engine power [5, 6].

Although relatively few researchers have investigated the solid phase icing problem, there are numerous models for ice accretion under other conditions [7, 8, 9, 10, & 11]. Why introduce yet another simulation? There are a number of reasons. Solid phase ice accretion appears distinctly different from other ice accretion modes. Hence our understanding of the problem and how it should be controlled might be best served by problem-specific modeling. Furthermore, developing a model from first principles provides the opportunity to understand aspects of the problem that could easily be missed by a superficial ("black-box") application of another worker's model. By developing new models, we have complete access to the source code and complete control over the simulation process. Finally, by introducing another simulation tool, additional cross-checking between models is possible.

II. DISCRETE PARTICLE MODEL

A. Stagnation Point Flow Field

We are considering the initial stages of ice accretion in the vicinity of a stagnation point of a compressor stator, the arrangement illustrated in Fig. 1. The accreted ice layer is considered to be so thin that it does not affect the aerodynamics of the inviscid flow field.

The stator is considered to have a cylindrical leading edge. In the stagnation region, the flow speed external to the boundary layer (u_e) increases linearly with distance from the stagnation point as illustrated in Fig. 2. The velocity gradient of the flow external to the boundary layer is dependent on the diameter of the leading edge (*D*), the on-coming flow speed (*V*), and the Mach number. For low Mach numbers, the relationship can be approximated using [12]

$$\frac{du_e}{dx} \approx 4\frac{V}{D} \tag{1}$$

B. Initial Particle Conditions on the Surface

Small particles are likely to be carried by the flow around the stator, but large particles are likely to impact the blade with minimal change to their velocity. The dynamics of non-interacting particles of any given size suspended in the air stream can be estimated by integrating the equations of motion for the particles within the stagnation region flow field.

In the present work, we have simply assumed that particles are sufficiently large to be unaffected by the stagnation point flow field and that these particles impact on the surface from a direction perpendicular to the surface. Compete dissipation of the kinetic energy of the impacting particles is assumed. The particles on the surface are assumed to accelerate from rest under the action of the aerodynamic forces.

The simulation proceeds by assuming that particles appear on the surface at regular time intervals. The position of each new particle that appears on the surface is randomly selected within a certain region in the vicinity of the stagnation point.

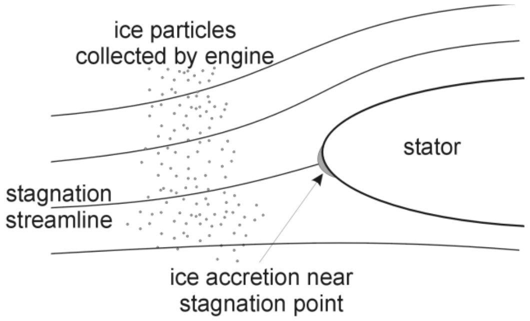

Figure 1. Illustration of icing problem.

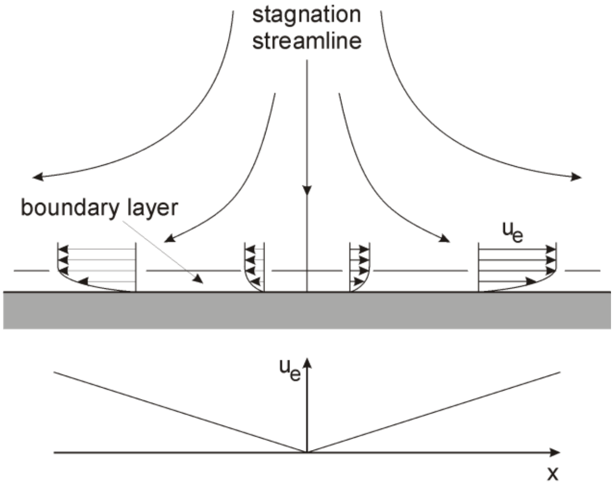

Figure 2. Illustration showing stagnation point flow field.

C. Particle Dynamics on the Surface

Once particles impact on the blade surface near the stagnation point, particles will be subjected to aerodynamic drag and surface friction forces, Fig. 3. The equations of motion for the particles can be integrated to give particle velocity and displacement along the surface as a function of time. If particles collide, a model for the collision process can be implemented and integration can continue. At present, the model we are using assumes that if two particles of mass m1 and m2 collide, Fig. 4, a merged particle is created with mass

$$m = m_1 + m_2 \tag{2}$$

and velocity from the conservation of momentum

$$u = \frac{m_1 u_1 + m_2 u_2}{m_1 + m_2} \tag{3}$$

At present, the merging of particles is based entirely on geometry: if particles are close enough to touch each other, a single merged particle is created. We are effectively assuming that conditions exits which support the agglomeration. In reality, agglomeration will only occur for certain surface and thermal conditions. Agglomeration ‘rules’ can be introduced into the model with relative ease; particles that touch but do not satisfy the requirements for agglomeration can continue to be tracked as individual particles.

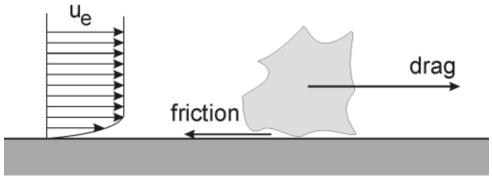

Figure 3. Illustration of ice particle subject to aerodynamic and friction forces due to surface interaction.

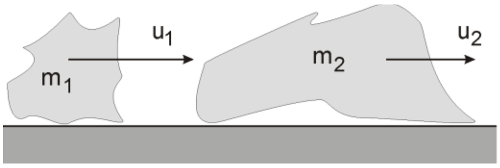

Figure 4. Illustration of impending collision between two ice particles on surface.

D. Implementation

The modeling was implemented in the Matlab environment. The nonlinear ordinary differential equations which govern the acceleration of the particles away from the stagnation point were integrated using the Matlab function ‘ode23’.

III. PRELIMINARY SIMULATION RESULTS

As a demonstration that the basic elements of the simulation are completed and are working reasonably well, simulation results from a number of trials are presented in this section.

A. *Time Stepping*

The equations of motion for the particles on the surface are integrated with respect to time, in between the times at which new particles arrive at the surface. In the present implementation, the largest time step that can be taken corresponds to the time between the arrival of successive particles. However, smaller time steps might be of some use in cases where large numbers of particle collisions occur on the surface. Figure 5 illustrates the effect of time step size on the development of ice mass in the vicinity of the stagnation point, for a particular spatial distribution of particles. Using shorter time stepping steepens the jumps in ice mass near the stagnation point, but essentially the same result is obtained, independent of time step size.

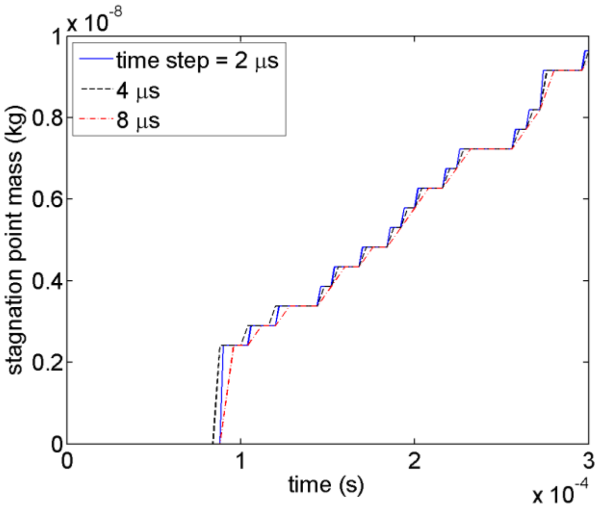

Figure 5. Increase in ice mass in the vicinity of the stagnation point as a function of time for 3 different simulation time steps. Ice particle diameter: 100 μm, density of ice particles in air: 2.4×10^{-5} g/m^3, flow speed: 200 m/s, cylinder diameter: 5 mm.

B. *Ice Particle Density Variations*

The present simulations are idealized in many respects. Stable stagnation point ice accretion is possible at very low values of ice particle density according to the simplistic models that we are currently using. Figure 6 illustrates the differences in ice accretion for 3 different ice particle densities in the air flow. At the lowest density, the development of mass at the stagnation point appears unstable: some mass develops but is swept away from the stagnation point by the aerodynamic forces. At the intermediate and highest densities, the stagnation point mass monotonically increases after relatively short delays.

C. *Initial Distribution of Particles*

Particles are assumed to arrive at the surface at regular intervals but the location at which they arrive is given by a random spatial distribution. This randomness leads to variability in the initial development of ice mass in the vicinity of the stagnation point. Figure 7 illustrated the effects of this variability for a particular case. Results from five different random distributions of particles are presented and each results in a different value for accumulated ice mass at the stagnation point at the end of the simulation. When averaged over the impact zone, the specified particle density in each of the simulations presented in Fig. 7 was identical. If the simulations are run for a sufficient period of time it is expected that *rate* of growth in the stagnation point ice mass in each of the simulations will be virtually identical, even if the total magnitude of ice mass is slightly different in each case.

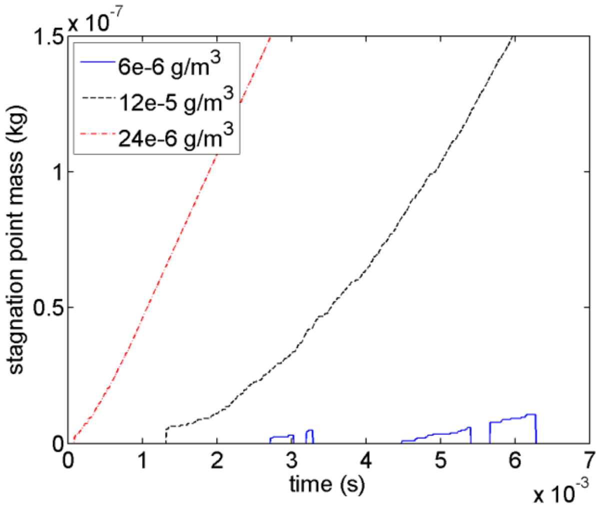

Figure 6. Increase in ice mass in the vicinity of the stagnation point as a function of time for 3 different densities of ice particles in air. Ice particle diameter: 100 μm, flow speed: 200 m/s, cylinder diameter: 5 mm.

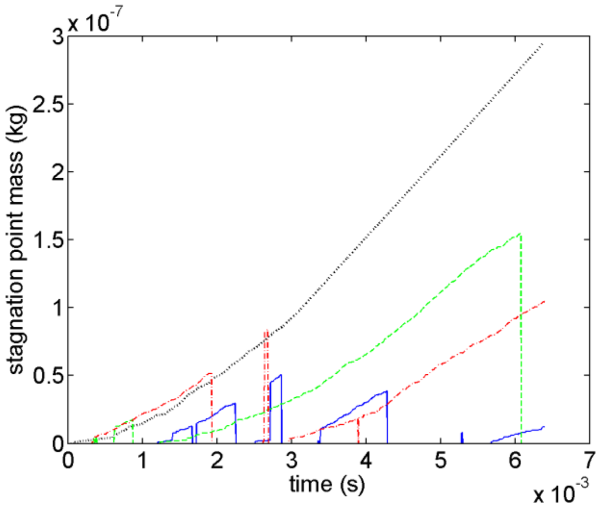

Figure 7. Increase in ice mass in the vicinity of the stagnation point as a function of time for 5 different random distributions of ice particles. Ice particle diameter: 100 μm, density of ice particles in air: 1.2×10^{-5} g/m^3, flow speed: 200 m/s, cylinder diameter: 5 mm.

IV. FUTURE DEVELOPMENTS

The modeling implemented in the current simulations is quite rudimentary. A number of important features need to be included to make the simulations more realistic.

Aerodynamic drag on the particles is currently based on the drag coefficient for spherical particles and the relative velocity difference between the particles and the air external to the boundary layer. This approach needs to be modified for small particles which fall within the stagnation point boundary layer. The approach also needs to be modified for elongated particles on the surface which are created via agglomeration. The aerodynamic drag on such particles is likely to be very different from that of a spherical particle.

Friction between the particles and the surface has not been modeled in the present simulations. It is an area of significant uncertainty. At conditions which lead to engine icing, the local temperature of compressor surfaces is likely to support the formation of a water film between the ice and the surface. Therefore, to adequately model the friction between the ice particles and the surface, it is likely that a thermal model for the development of liquid water from the ice will be needed.

The transverse momentum of particles is also an important issue that has not yet been addressed with the present approach. Even large particles which would normally be unaffected by the local stagnation point flow may impact near the stagnation point with some transverse momentum because of flow turning events within the compressor upstream. In future work, the particle dynamics at impact with the stagnation region should be characterized by integrating the equations of motion of the particles through the compressor flow field upstream of the stagnation point of interest.

Agglomeration modeling also needs to be considered. Conditions which favor the development of a water film between the ice particles and the surface are also likely to favor the agglomeration of the particles. Hence agglomeration models development may also be closely connected to thermal modeling.

The present simulations are one dimensional. Although the particles arrive on the surface at different distances from the stagnation point, the particles are assumed to arrive at the same span-wise location on the blade. This is obviously a simplification. However, the approach may yield adequate results if an effective density of particles in the suspended air stream can be identified which accurately relates the one dimensional simulation to the two dimensional reality.

V. CONCLUSIONS

The elements of a one dimensional simulation for the stagnation point accretion of ice particles have been described in this paper. Results from the simulations appear qualitatively correct. Higher particle densities result in a more certain and more rapid growth of the stagnation point mass. However, before quantitative agreement with experimental results can be achieved, a number of important additions need to be made to the modeling.

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