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A comprehensive accretion model for glaciated icing conditions

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ABSTRACT

Icing has been identified as a major hazard for aviation safety since the beginning of aeronautical engineering. This paper is focused on ice crystal icing (ICI) which is related to ice accretion for an aircraft in flight in the presence of ice particles. Liquid water is necessary for the ice crystals to stick to the walls of the internal components of an aircraft engine. Emphasis is put on the glaciated conditions where the required liquid water comes from the melting of the ice crystals themselves when they enter a warm environment (the engine core). ICI represents an important concern for flight safety in addition to classical supercooled water icing where the accreted ice only derives from the instantaneous freezing of supercooled liquid droplets when they hit an obstacle. A semi-empirical model which accounts for the influence of the ice crystals on the mass and momentum balance equations is proposed. It accounts for the liquid transport in the porous ice layer and for the ice crystal sticking efficiency. The physics is extremely complicated and not completely understood. Therefore, several adjustable parameters are used in the model. However, the model predictions agree well with the existing experimental data. In particular, the model is able to predict typical conical accretion shapes that are never found in classical supercooled water icing conditions. Moreover, the influence of the ice crystal melting ratio on the accretion shapes is properly accounted for.

1. Introduction

Icing has been identified as a major hazard for aviation safety since the beginning of aeronautical engineering. Liquid water freezing may cause performance degradation such as loss of lift and increased drag due to local ice accumulation, erroneous flight parameters displayed inside the cockpit due to probe clogging or in the most severe cases loss of engine thrust, engine damage and even engine flame-out.

Among the possible causes of icing for aircraft in flight, supercooled water icing (SWI) where ice accretion is the result of the impact of supercooled droplets, can be considered as the primary hazard (Fluid Dynamics Panel Working Group 20, 1997; Civil Aviation Authority of New Zealand, 2000). Supercooling is a thermodynamically unstable state for liquid droplets where a phase change to solid state can be initiated when the droplets hit an obstacle like a wing, a probe or a blade inside an engine. Supercooled droplets appear in the atmosphere at low temperatures in the range of −40 °C–0 °C.

Icing may also be the result of impact and deposition of ice particles. Beside supercooled water icing, ice crystal icing (ICI) represents as well a severe threat for flight safety (Mason et al., 2006). Ice crystals are found in (sub)-tropical regions (Bravin et al., 2015) in the vicinity of convective clouds at the altitude of ∼7000 m where supercooled droplets usually do not exist. In these regions of deep convective systems, engine rollback, flameout or stall and damage to downstream compressors from shed ice have been observed. As reported by Mason et al. (2006), the power-loss incidents that have occured since 1990 result from atmospheric ice crystals entering the engine core.

With no liquid water, the ice particles do not adhere to cold airframe surfaces and bounce off. Regarding the presence of liquid water which is necessary for the ice crystals to stick, two origins are possible. On the one hand, the liquid water may come from supercooled liquid droplets mixed with the ice cores in mixed phase clouds at atmospheric temperatures above −40 °C. These atmospheric conditions are referred to “mixed phase conditions” and are encountered at temperatures below 0 °C. On the other hand, the liquid water may come from the melted part of the ice crystals themselves. This regime is referred to “glaciated conditions” and is often associated to engine conditions characterized by a wet bulb temperature above the freezing point. Both glaciated and mixed phase conditions occur in convective clouds and have been present during engine power-loss and damage events (Mason et al., 2006).

Among the experiments performed below 0 °C at mixed phase conditions, ice accretion tests have been performed at the COX ic-

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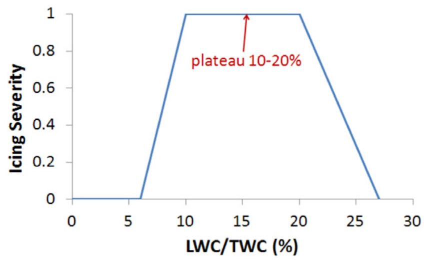

Fig. 1. "Plateau" effect: plateau of almost constant icing severity, which drastically decreases at its left and right limits. Reprinted from Currie and Fuleki (2015) with permission from SAE.

ing research tunnel (Al-Khalil et al., 2003; Miller et al., 1997) on a NACA0012 airfoil. Low total water contents (from 0.3 g.m^{-3} to 1.4 g.m^{-3}) have been investigated. Similarly to supercooled water icing, glaze and rime ice shapes have been observed. Since 1990 and due to the engine powerloss events (Mason et al., 2006), the NASA Propulsion System Laboratory (PSL) has been upgraded to have a capability for ice crystal generation for engine research activities under simulated altitude conditions (Goodwin and Dischinger, 2014). Ice particles are generated by the spray bar technique where the injected liquid droplets are forced to freeze to generate ice particles. The shaved ice method has been dropped since it appeared impractical for such a large facility (Griffin et al., 2014). Mixed phase conditions have been tested experimentally at RATFac from NRC with a hemispheric test model (Currie and Fuleki, 2016). For the coldest conditions, with a wet bulb temperature from $-8\,°$C to $-5.5\,°$C, the right end of the plateau (see below) has not been exhibited since accretion remains possible with supercooled liquid droplets only. For low melting ratios ($\sim$14.4%), accretion shapes with a constant cone angle of $\sim 90°$ has been observed (Currie and Fuleki, 2016). At higher melting ratios, the cone angle has become smaller as observed for past experiments where the wet bulb temperature was higher than the freezing point (glaciated conditions, see below). A detailed review dedicated to the experimental studies in mixed phase conditions can be found in Baumert et al. (2018).

Regarding the glaciated conditions, the melt ratio of the ice particles is driven by the local relative humidity or, which is equivalent, by the wet bulb temperature. The importance of the wet bulb temperature as primary scaling factor in matching accretion shapes has been demonstrated by Currie et al. (2013) at RATFac for two different pressures (34.5 kPa and 69 kPa). Both Mach number and total water content are being held constant. The wet bulb temperature has little influence on accretion growth beyond its effect on the particle melting (Currie et al., 2013). For the icing conditions where the melting ratio is adjusted by the addition of supplemental supercooled liquid water, similar ice accretions are obtained in comparison with conditions with natural melting of the ice crystals (Currie et al., 2013). For melting ratios ranging from 5 to 35 %, significant ice accretion rates have been reported by NASA and NRC studies at RATFac (Currie et al., 2012; 2013; 2014). This "plateau" (see Fig. 1) is characterized by a left and a right boundary where icing severity decreases strongly. At low melting ratios (left limit) the ice particles do not contain enough liquid water to stick to the model wall. On the other hand and for large melting ratios (right limit), the amount of liquid water is larger so that the ice particles do not stick and are washed off the surface (Currie et al., 2014). Moreover, erosion effects are strong enough to prevent ice accretion. For intermediate melting ratio, conical ice shapes are observed (Currie et al., 2013; 2014). The influence of the Mach number, total water content (TWC) and pressure (34.5 kPa and 69 kPa) on icing rates have been investigated (Currie et al., 2013; 2014; Currie and Fuleki, 2016). It is shown that the sticking efficiency is almost independent of the Mach number and TWC at normal incidence, near the stagnation point. On the other hand, they are strongly dependent on these parameters at oblique impingement angles (Currie et al., 2014). At the high Mach number of 0.65, ice accretion only occurs with the smallest ice particles with a diameter of 30 μm (Currie and Fuleki, 2016). Concerning the influence of total water content, icing severity is significantly increased with TWC at $M = 0.25$, but to a lesser extent at $M = 0.4$ (Currie et al., 2014). The very large accretions obtained at high TWC are subject to shedding and experimental works have been conducted at NRC on this topic (Currie et al., 2012; Mason et al., 2011). In Currie and Fuleki (2015), an instrument, denoted the Ice Properties Probe (IPP), has been developed to measure the volumetric liquid water content of a mixed phase deposit at 0 °C to quantify the erosion-related mechanical properties of ice-water mixtures.

The works discussed above are related to accretion tests. To feed the theoretical models, more fundamental studies have been performed, especially about ice crystal impingement. In Hauk et al. (2015), Hauk (2015) and Roisman and Tropea (2015), impingements on solid heated and unheated surfaces have been investigated, the surface being covered or not by a liquid layer. The modeling of the ice crystal melting process has been addressed in Hauk et al. (2014, 2016).

Regarding numerical simulation and modeling, previous works dedicated to ice crystal icing have been attempted. In Lozowski et al. (1979), all the impinging ice crystals (or at least a sufficient fraction to freeze all the existing water on the cylinder surface) are supposed to stick when the surface is fully wet. For dry surfaces, all the ice particles bounce off the wall. In Mazzawy (2007), the wall liquid film may splash due to ice crystal impingement. For the so called "zero net mass" model, the amount of liquid water which is splashed out of the wetted surface is equal to the amount of impinging ice crystal. Realistic configurations like partially melted ice particles which stick to the wall and add to the film height are out of the scope of this model. In Wright et al. (2010), modifications have been made to GlennICE for handling ice particles impacts. Improvements concern the solid ice particle trajectory equations (thermal and dynamic), mass loss prediction due to erosion and the extension of the Messinger's mass and energy balance equations (Messinger, 1953) to take into account the presence of ice crystals among the impinging particles. In Habashi and Nilamdeen (2011), the shallow-water icing model (SWIM) has been extended to ice crystal icing. In the rime region, it is assumed that all ice crystals bounce off the surface which is not realistic for partially melted ice particles. Erosion or film splashing are not considered. In Rios Pabon (2012), a multi-layer model is proposed. However, the classical Messinger's formulation is used to compute the runback mass fluxes without taking into account the porosity of the slushy ice deposit.

In Villedieu et al. (2014) the models for trajectory, impingement and accretion have been adapted to the ice crystal icing regime. However, the model for the ice crystal sticking efficiency is based on the presence of a liquid film on the wall which is not necessary for partially melted ice crystals. Erosion phenomena are not taken into account in Villedieu et al. (2014). Ice shedding phenomena, which are typically not predicted by the classical Messinger models but which are common in warm icing conditions, are taken into account in Bennani et al. (2014), Bennani (2014) or Kintea et al. (2016). The HAIC European project has been the opportunity for existing icing tools to be equipped with an ice crystal capability (Iuliano et al., 2015; Ayan et al., 2015).

The objective of this paper is to derive a comprehensive accretion model for glaciated conditions. The proposed model is based on three main features. Firstly, the classical Messinger model (Messinger, 1953) is extended to account for the presence