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Experimental and numerical investigations on aircraft icing at mixed phase conditions

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A B S T R A C T

Since the beginning of civil aviation, icing is a severe weather hazard for aircraft operation. In this context, the phenomenon of ice crystal icing has been identified as a risk for flight safety in the recent past. Ice crystals can accrete on warm components such as heated stagnation pressure probes and engine compressor blades. Liquid melt water or additional liquid droplets in the icing cloud enable the ice particles to stick to the component surface and to form a cohesive ice accretion layer. In this paper, we present results of comprehensive icing wind tunnel tests on ice crystal ice accretion together with results of complementary simulations by means of the ONERA icing code IGLOO2D. The experiments show a strong influence of ambient temperature on the icing process. In agreement with literature findings, ice particle sticking ability can be correlated with the ice cloud composition. Correlations between accretion shape and growth rate have been identified. IGLOO2D separates accretion abrasion by particle impact from the efficiency with which those particles stick to the deposit. Comparisons of computational and experimental results indicate that this sticking efficiency has the greatest effect on ice shapes at low Mach numbers, at least for the particle sizes and conditions used in the experiments. The experimental and numerical findings of this study can be considered as complementary to existing knowledge on ice crystal icing. Therefore, the experimental results are provided to an international benchmark of test cases for icing code validation.

1. Introduction

Since the beginning of aeronautical engineering, aircraft icing has been a great issue to flight safety. Consequently, research on this topic is ongoing for decades. Most of these research activities are dedicated to supercooled droplet icing which can be addressed as the primary icing hazard for aircraft in flight [1,2]. Supercooled droplets appear in the earth atmosphere at temperatures in the range of 0 to −40 °C. These liquid droplets can be considered as thermodynamically metastable, a phase change to solid state can be initiated by local mechanical disturbances, for example by collision with an aircraft passing a cloud of supercooled droplets. Droplet freezing on the aircraft fuselage, wings and engine intakes causes a great reduction of flight performance. Additional weight and increased drag go along with lift losses and result in severe danger for aircraft operation.

Beside supercooled droplet icing (SDI), another icing mechanism called ice crystal icing (ICI) has to be considered as a severe risk for flight safety [3]. Dense clouds of fully frozen ice crystals can be found in the vicinity of mesoscale convective cloud systems (MCS), mostly in tropical regions [4]. At flight altitude, high concentrations of particular small ice crystals are found which can rarely be detected by current on-board radar technology. Ice crystal concentrations are quantified by the ice water content (IWC) similar to the liquid water content (LWC) of supercooled droplet clouds. The liquid water content is defined as the ratio of cumulative liquid droplet mass to the surrounding volume of air. At atmospheric temperatures above −40 °C, mixed phase clouds consisting of solid ice particles and liquid droplets can appear. The overall water mass of these clouds is quantified by the total water content TWC which is the sum of LWC and IWC and water vapor.

This paper is dedicated to mixed phase icing. Mixed phase clouds generally appear below the flight level of civil aircraft and

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Nomenclature

α_0	accretion efficiency
β_0	stagnation point collection efficiency
ϵ_s	ice particle sticking efficiency
ρ_{acc}	density [kg/m^3]
φ_0	accretion tip angle [°]
f_l	accretion surface total liquid fraction
$\dot{m}_f$	freezing mass rate [kg/(s · m^2)]
$\dot{m}_{dep}$	deposition mass flux [kg/(s · m^2)]
$\dot{m}_{imp}$	impinging mass flux [kg/(s · m^2)]
m_r	melting ratio
M	Mach number
t_L	accretion leading edge thickness [mm]
$\dot{t}_L$	accretion growth rate [mm/s]
T_∞	static temperature [°C]
T_{wb}	wet bulb temperature [°C]
U_∞	free stream velocity [m/s]
y_l	accretion surface liquid mass fraction
CIRA	Centralo Italiano Ricerche Aerospaziali
HAIC	High Altitude Ice Crystals
ICI	Ice Crystal Icing

IGLOO2D	ONERA 2D icing suite
IGS	Ice Crystal Generation and Conveyance System
IKP	Isokinetic Probe
IWC	Ice Water Content
IWT	Icing Wind Tunnel
LWC	Liquid Water Content
MCS	Mesoscale Convective System
MVD	Medium Volume Diameter
MMD	Medium Mass Diameter
NASA	National Aeronautics and Space Administration
NRC	National Research Council of Canada
ONERA	Office National d'Etudes et de Recherches Aerospatiales
PSL	Propulsion System Laboratory
RATFac	Research Altitude Test Facility
SDI	Supercooled Droplet Icing
SLD	Supercooled Large Droplet
TUBS	Technische Universität Braunschweig
TWC	Total Water Content

are strongly avoided because of increased icing severity. However, they might be unavoidable to pass during climb or descend.

Beside atmospheric clouds, mixed phase conditions can also occur around warm aircraft assemblies, such as heated stagnation pressure probes and engine compressor blades. Convective heating and particle impact on heated surfaces can cause the ice crystals to partially melt. The liquid phase enables the particles to stick on probes or engine stator blades, as soon as the concerned component has cooled down to freezing temperature upon particle impact. The amount of liquid that is involved in ice crystal icing is characterized by the melting ratio m_r, which is defined as the ratio of liquid to total water content:

$$m_r = \frac{\eta_m \cdot IWC + LWC}{TWC} \tag{1}$$

η_m is the ice crystal melting ratio which quantifies the melt water of initially solid ice crystals. The term 'melting ratio' is also used in the present study, even if the liquid phase does origin from supplemental water supply and not from ice particle melting ($\eta_m = 0$). In contrast to mixed phase conditions, solid ice particles bounce off cold surfaces which is why glaciated clouds cause no danger of wing or fuselage icing.

Icing of aircraft probes can cause false flight parameters displayed inside the cockpit. In case of aircraft engines, ice accretion related to ice crystal icing is observed to appear at the outer regions of the low pressure compressor stator blades [5]. Ice accretion inside the compressor causes flow blockage, forcing the compressor to operate towards stall conditions. The compressor encounters a decay in rotational speed resulting in significant thrust losses (rollback event) [6]. Moreover, total engine flame out may appear if great masses of accumulated ice are shed into the combustor. Atmospheric mixed phase clouds can cause icing of the outer aircraft surface similar to supercooled droplet icing but usually of enhanced severity.

Recent flight campaigns conducted in the course of the HAIC project have yielded total water contents up to 4 g/m^3 in MCSs at flight altitude [7]. TWCs up to 4 g/m^3 are reasonable for mixed phase clouds at atmospheric temperatures between −40 and 0 °C [8]. Atmospheric ice crystal clouds have been observed to feature median mass diameters in the range of 300–800 μm [9]. Inside the engine, ice particles are expected to be significantly smaller (MMD of 20–40 μm) because the particles get fragmented inside the fan and first compressor stages [10]. Centrifuging increases the particle concentration (TWC) near the compressor outer casing. Total water contents four times higher than the atmospheric TWC are expected to cause local ice accretion around the stator blade roots [10].

Fundamental research on ice crystal icing has been sparked by the comprehensive paper of Mason et al. on engine icing from 2006 [3]. Most of these research activities have been performed from an experimental point of view by the National Research Council of Canada (NRC) and NASA [11–13]. A great variety of experiments has been performed at the NRC Research Altitude Test Facility (RATFac) [14,15]. In the following, selected research findings of NRC studies are presented and compared to the results of this study in subsequent chapters.

At current state, the NRC studies at RATFac have focused on investigations of ice accretion behaviour of generic test articles depending on aerothermal and icing cloud conditions. The NRC studies have shown that ice crystal icing inside an engine is limited to a characteristic range of melting ratios. Significant ice accretions have been observed for melting ratios ranging from 5 to 35 percent. A plateau of constant icing severity has been reported which drastically decreases at its left and right boundary, see Fig. 1. It has been concluded that at low melting ratios not enough liquid water is present to enable the ice particles to effectively stick to the model surface. At the right boundary of the plateau, the amount

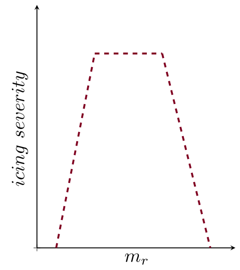

Fig. 1. Mixed phase icing: Icing severity vs. melting ratio.