Effect of Mixed Icing Conditions on Thermal Ice Protection Systems

By

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I. INTRODUCTION

The purpose of this presentation is to discuss the thermal effects of glaciated and mixed icing conditions on the ice accretion, and particularly on thermal ice protection systems. In order to understand the effect of frozen ice versus supercooled water droplets, the energy equation on the accreting aircraft surface will be explored and the different terms identified.

II. ENERGY BALANCE EQUATIONS

The heat flux required, $q_{A/I}$, to anti-ice the aircraft surface at a particular location can be expressed in its simplest form by the following equation:

$$q_{A/I} = q_{evap} + q_{convec} + q_{imp}$$

where,

q_{evap}	=	Evaporative heat loss = $m_{evap} * L_v$
m_{evap}	=	Rate of mass evaporated from the surface
L_v	=	Latent heat of vaporization of water or latent heat of sublimation of ice
q_{convec}	=	Convective Heat Loss = $h (T_{surface} - T_{ambient})$
q_{imp}	=	Heat transfer due to impinging water
	=	$q_{sensible} - q_{KE}$

and,

$q_{sensible}$	=	Heat required to raise the impinging droplet temperature from ambient to surface temperature
q_{KE}	=	Kinetic Heating due to droplets coming to rest when striking the surface

Impingement Heat Transfer Equations:

The kinetic and sensible heat terms in the previous equations can be expressed as follows:

$$q_{KE} = (m_{ice} + m_{liq}) * V^2 / 2$$

$$q_{sensible} = m_{ice} * (H_{surf} - H_{ice}) + m_{liq} * (H_{surf} - H_{liq})$$

where,

m_{ice}	=	mass flux of impinging frozen ice
m_{liq}	=	mass flux of impinging liquid water
V	=	aircraft speed
H_{surf}	=	enthalpy of ice/water on the aircraft surface at the local surface temperature
H_{liq}	=	enthalpy of supercooled liquid water at ambient air temperature
H_{ice}	=	enthalpy of frozen ice crystals at ambient air temperature

Regardless of the relative proportions of ice and water contents in the cloud, the total kinetic heating depends on the total mass that strikes the aircraft surface. However, the sensible cooling associated with the water/ice mass impinging on the surface is affected by the state (liquid/solid) and the individual content within the Total Water Content (TWC). Here, we define:

TWC = Liquid Water Content (LWC) + Ice Water Content (IWC)

Figures 1 and 2 illustrate the enthalpy of supercooled water and solid ice at temperatures ranging from –40 °F to 212 °F. It should be noted that since supercooled liquid water does not crystallize, it retains more heat than the frozen particles. The difference is the latent heat of fusion. Consequently, the anti-icing heat required to raise the surface temperature above freezing is higher in the case of frozen ice crystals.

III. EXAMPLE CALCULATIONS

There exist two modes of anti-icing of an aircraft surface: (1) fully evaporative, and (2) running-wet. In the first case, the surface is heated sufficiently to evaporate the impinging liquid water and ice crystals. This is the cleanest mode of anti-icing but it has the highest power requirements. In a running-wet system application, the surface is maintained a few degrees above the freezing point (generally, from 40 to 45 °F). However, since a running-wet system only partially evaporates the surface water, large amounts of runback water are normally observed flowing on the surface. Consequently, heat must be applied to the large surface area onto which runback flows. On the contrary, evaporative systems provide high power densities to smaller areas in the zones of direct impingement.

Evaporative systems are normally found on airfoil leading edges (e.g., wings and tails) where the impingement areas are well defined and restricted to a small percent of the chord. This assumes that the aircraft has enough power (electrical or bleed air) to anti-ice those surfaces. In regions of large curvatures as in "S" shaped ducts, the direct impingement areas are large although local collection efficiencies are usually low. In these cases, running wet systems are used.

Two example cases, evaporative and running-wet, will be considered to illustrate the effect of ice and water content on the heat required, $q_{A/I}$, to anti-ice the aircraft surface thermally. Table 1 summarizes the environmental conditions in these examples.

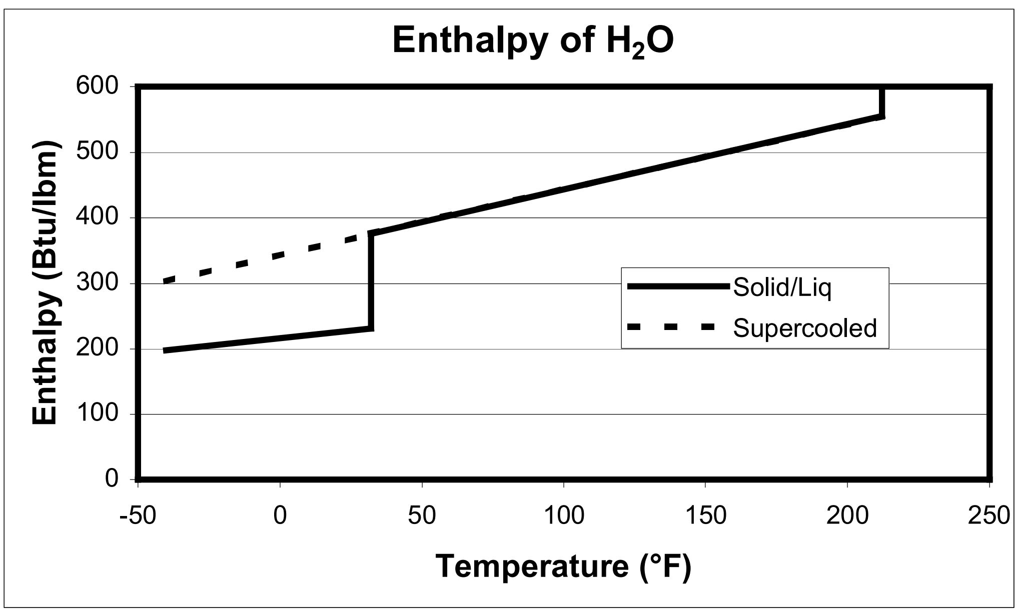

Figure 1: Enthalpy of Liquid Water, Solid Ice, and Mixed Phase

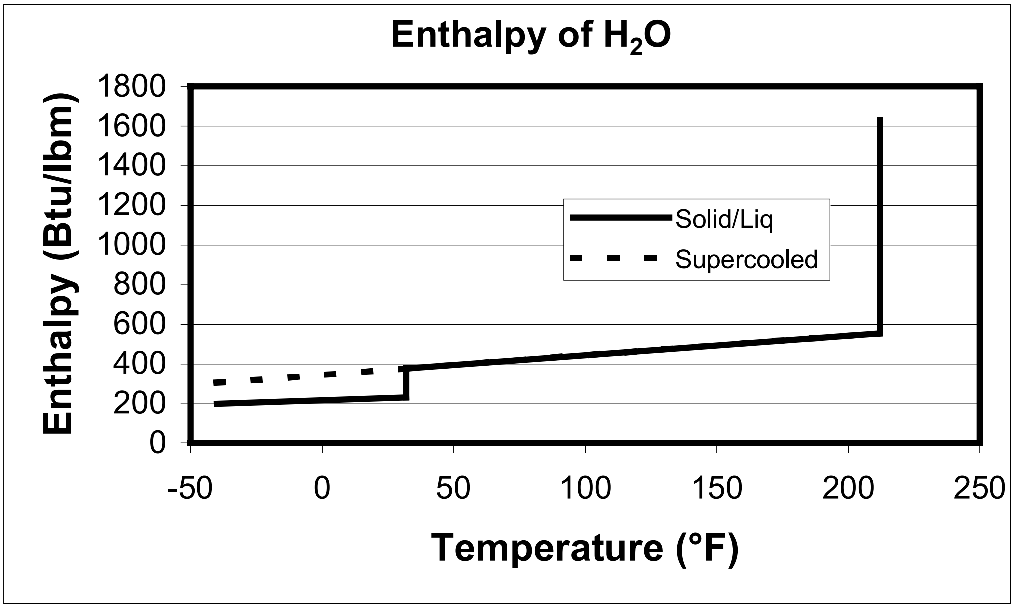

Figure 2: Enthalpy of Liquid Water, Solid Ice, and Mixed Phase

Table 1: Conditions for Example Calculations

PARAMETER	VALUE	UNITS
Airspeed	175	Kts
Altitude	5000	Ft
Convection Film Coefficient	70	$Btu/hr.ft^2.°F$
Average Collection Efficiency	0.3	
Relative Humidity	100	%
Minimum Surface Temperature (Running-Wet Anti-icing)	45	°F

These conditions are typical average values within the direct impingement region of a given geometry. In the running-wet example, a surface temperature of 45 °F was chosen. In evaporative systems, the surface temperature depends on the conditions and the heat required to evaporate the impinging water/ice. Typically, this is in the range of 80 °F (in cold ambient conditions) to 120 °F (in warm ambient conditions).

Figures 3 and 4 illustrate the fully evaporative power required to anti-ice the example surface in a warm (23 °F) and in a cold (4 °F) condition, respectively. In each case, a wide range of TWC (g/m^3) is considered. For each TWC, the power density is plotted versus the fraction of ice crystal content ("0" indicates all water, "0.5" indicates half water and half ice, and "1" indicates all ice).

The computed evaporative power densities are those that would be required to evaporate the impinging water upon impact. Numbers higher than 30 or 40 W/in^2 produce local high temperatures that are beyond the limits of typical aircraft construction materials. In practice, a lower power density spread over a wider surface area is used to remain within the material temperature limits.

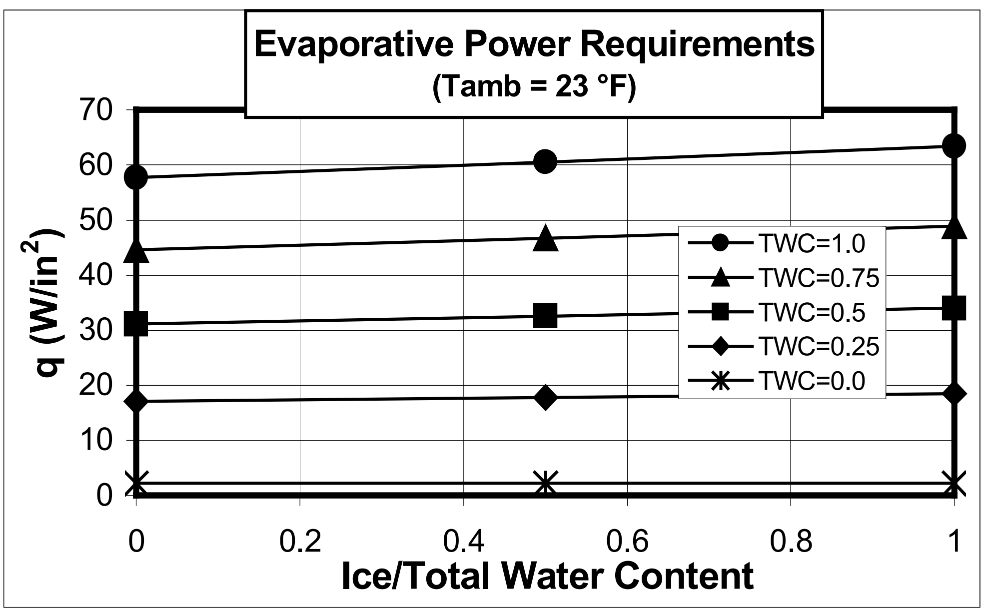

Figure 3: Evaporative power requirements in a warm condition

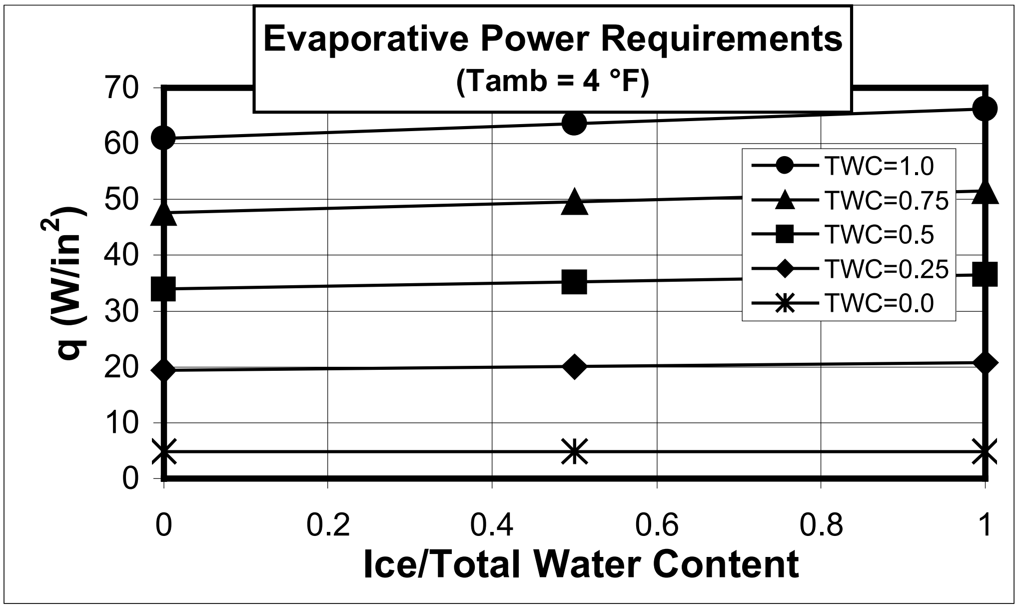

Figure 4: Evaporative power requirements in a cold condition

Comparison of the cold and warm cases reveals that the power required to achieve full evaporation is almost independent of ambient temperature for a given TWC. This is because of the dominant evaporation term in the energy balance equation due to the high latent heat of vaporization of water. Also, for a given TWC and ambient temperature, the total power required is almost independent of the ratio of water/ice content in the cloud. The true variable is the total water content.

In the next example, consider the case of a running-wet anti-icing system where the surface is heated and maintained at 45 °F. Figures 5 and 6 illustrate the running-wet power required to anti-ice the example surface in a warm (23 °F) and in a cold condition (4 °F), respectively. Clearly, there is a large dependency on the ice content for a given TWC. In the warm condition, the power required almost doubles for the no-ice to all-ice ratio in the case of TWC=1.0 g/m^3. For the same TWC, the power required increases from 10.6 to 16 W/in^2 going from the warmer to the colder temperature.

These examples illustrate the fact that evaporative anti-icing systems are not affected by frozen ice content in the cloud or the ambient air temperature. It is the total water content that determines the evaporative heat requirements. On the other hand, power required in running-wet systems is greatly dependent on the ambient temperature and on the frozen ice content of the cloud.

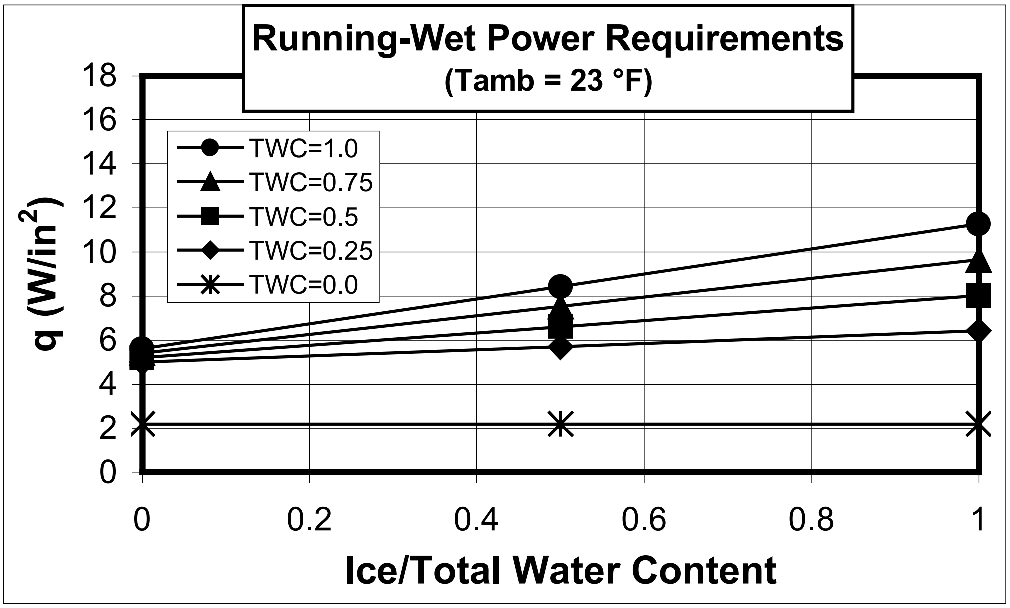

Figure 5: Running-wet power requirements in a warm condition

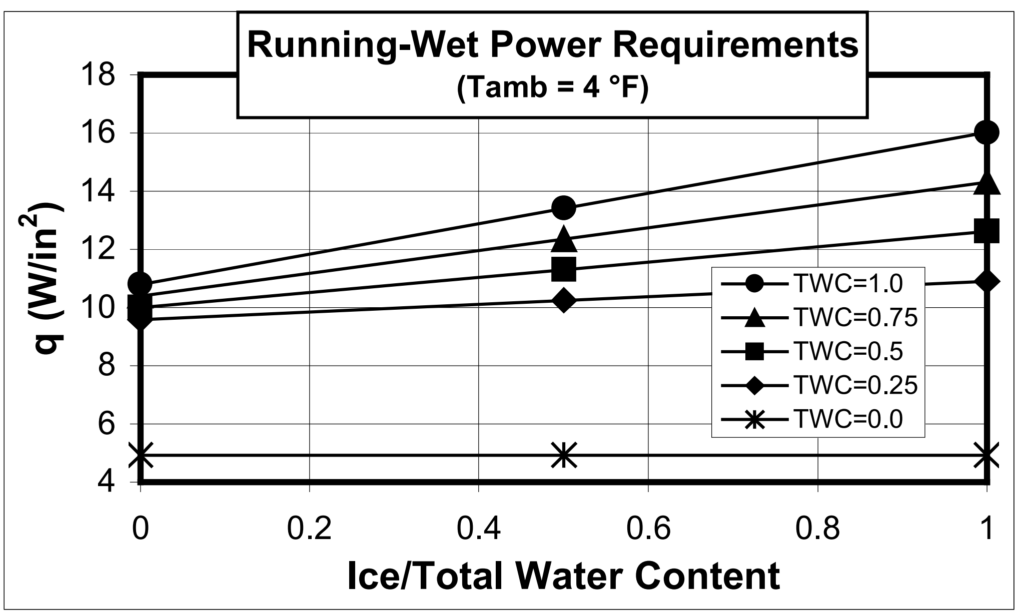

Figure 6: Running-wet power requirements in a cold condition

IV. CONCLUDING REMARKS

Example calculations were made to illustrate the effect of mixed icing conditions on the power required to anti-ice an aircraft surface using evaporative and running-wet modes of operation. The calculations neglect few physical phenomena such as erosion or ice crystals that strike but do not adhere to the aircraft surface after impact. This might be acceptable for leading edge regions of airfoil type surfaces.

It should also be noted that ice crystals do not stick to unheated aircraft surface in frozen ice clouds (with negligible liquid water). Flight test videos confirmed that "wet snow" will stick to the surface even if unheated. This tends to be the worse case because wet snow can exist at high TWC.

Other relevant conclusions are:

- Evaporative thermal systems are not significantly affected by the state of the water content but rather by its total content in the atmosphere.
- Running-wet thermal systems are significantly affected by the high ice content. This is typical of engine inlet ducts (example, helicopters and turboprops) and ECS scoops, especially where near stagnant regions may exist.
- A certain wetness (liquid content) has to exist in the atmosphere and/or on the surface for the ice crystals to stick, at least partially, on the impinging surface.
- The size of ice crystals will determine the collection efficiency, and the surface temperature and wetness conditions will determine whether ice will stick or bounce off the surface (more research needed in this area).
- Wet snow or mixed ice/water may be very severe as the thermal conductivity of collected snow is low. This reduces the efficiency of transferring the anti-ice heat to melt the accreted ice. "Capping" may then form where frozen ice exists over a hot melted layer of water. It becomes difficult to remove the frozen ice. The ice may be shed off the surface in these cases by aerodynamic forces and could cause FOD.