Thermo-Mechanical Expulsion Deicing System - TMEDS

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A new type of hybrid ice protection system was developed to protect leading edge regions of airfoils that can tolerate low levels of ice accumulation during flight. The system consists of an electro-thermal deicing subsystem and a low power expulsive deicing subsystem. They are co-located beneath a semi-rigid aircraft leading edge skin and operated in harmony to limit inter-cycle ice accumulation thickness to below a prescribed limit and to prevent the formation of ice ridges downstream.

Nomenclature

ARPA = Advanced Research Projects Agency
DCU = Deicing Control Unit
EIDI = Electro-Impulse De-Icing
EMEDS = Electro-Mechanical Expulsion Deicing System (Cox & Company, Inc.)
ESB = Energy Storage Bank
FAA = U.S. Federal Aviation Administration
FAR = U.S. Federal Aviation Regulations
LE = Leading Edge of an airfoil
LPDI = Low Power De-Icing
LWC = Liquid Water Content of droplets in a cloud (g/m^3)
MVD = Mean Volume Diameter of water droplets in a cloud (microns)
OAT = Outside Air Temperature, measured by an aircraft onboard instrument (°F)
SBIR = Small Business Innovation Research
TAT = Total Air Temperature (°F)
TMEDS = Thermo-Mechanical Expulsion Deicing System (Cox & Company, Inc.)

I. Introduction

WHEN flying through clouds or visible moisture under meteorological icing conditions, supercooled water droplets strike leading edges of aircraft surfaces. The impinging water droplets freeze and form a layer of ice that will continue to grow if the particular component is unprotected. The hazards associated with the existence of ice on a lifting or stabilizing surface have been extensively studied. They include reduction of lift and angle of attack margin-to-stall, increase in drag, and adverse effects on other control surfaces located downstream of unprotected or poorly protected leading edge surfaces as a result of flow disruption. The degree of degradation varies with the extent of coverage over the surface, the shape, size and texture of the ice growth, and the specific location on the surface of the airfoil.

It is also recognized that certain airfoils exhibit more or less sensitivity to ice accumulations. Certain aircraft can be quite sensitive to ice contamination on lifting surfaces (e.g., wings and horizontal tails). Consequently, evaporative ice protection systems using bleed air have been traditionally used to maintain a clean leading edge on the corresponding surfaces. However, the design of fuel-efficient high-bypass engines limits the amount of bleed air available for full evaporative anti-icing. The result has been the development of more electric aircraft using large generators to replace bleed air as an energy source. Even though the thermal efficiency of electrically powered systems is higher than that of bleed air systems, the amount of power required for a full evaporative anti-icing electrically powered system is still beyond the reach of available generators. The emphasis is therefore on the development of systems that offer still greater efficiencies. Such a system is presented and discussed in this manuscript. A review of other systems and comparison to the presented design is also presented.

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Methods by which a surface is protected from ice accumulations vary from energy intensive evaporative anti-icing systems that prevent the formation of ice to deicing systems that use substantially lesser amounts of energy. The system presented here addresses the ice accumulation limits of the surface to be protected. It combines two separate means of ice protection, electro-thermal and low power expulsive. The result is a combination that is highly efficient in its use of power and is capable of providing near-evaporative surface cleanliness during icing conditions.

Although many different types of ice protection systems are available to address a wide variety of applications for ice protection, one application category is particularly problematic. This is the case of an airfoil that is very sensitive to ice contamination when there is limited power.

II. Background

Ice protection system performance requirements vary widely. This is because different types of aircraft lifting surfaces have different sensitivities to ice contamination and, consequently, have different levels of ice protection requirements. For example, certain lifting surfaces may use airfoils that are more or less tolerant of the effects of ice contamination than are other airfoils; a quantity of accreted ice that might only imperceptibly degrade the performance of one type of airfoil section might degrade another type of airfoil significantly when operated at similar or different flight conditions.

Accordingly, ice protection systems can be optimized differently; energy available for ice protection is selectively applied to address the particular sensitivity of one airfoil section as opposed to another. On some airplanes, there may be sufficient electrical power to operate an ice protection system that relies on electrically generated heat (e.g., an electro-thermal deicing or anti-icing system), while on others, the available electrical power is insufficient for such a system. Such considerations necessarily affect the selection of the type of ice protection system to be used. For example, on an airplane having ample electrical power or bleed air, an energy intensive evaporative anti-icing system may be employed. For a power-limited application a deicing system may be used to shed ice only when the accumulation reaches a predetermined distributed thickness that has been shown to unacceptably degrade the performance of the airfoil.

The application of a particular type of ice protection system to an aircraft is the result of a trade-off or balance between the extent and quality of ice protection required and the available energy and cost of the ice protection system. TMEDS combines an electrically powered thermal system with a low power expulsive system, both of which operate in harmony as de-icing sub-systems. The background and operation of the various related individual systems is discussed below to illustrate the path leading to the development of TMEDS.

A. Electro-Thermal Deicing Systems

Deicing is typically used when the available power is limited. The preference is always to use a system that provides ice protection to the extent that no ice is permitted to form or reside on the protected surface. Typically, evaporative anti-icing systems using compressor-supplied bleed air on transport category aircraft are designed to achieve this level of performance. The power demand associated with fully evaporative systems (bleed air or electro-thermal) is very high and may not be readily available. In such cases, alternative systems are sought.

The aircraft performance should be compatible with the selected system, and the limitations of the selected ice protection performance must be taken into account. These include the levels of possible buildup of runback ice ridges, inter-cycle ice (ice buildup prior to each deicing cycle activation), and residual ice (ice remaining on the surface following a deicing cycle). An ice ridge disturbs the airflow over an airfoil, and can result in significant reductions of maximum lift and angle of attack margin-to-stall.

Conventional electro-thermal deicing systems use a resistive heater that is attached to the part of the leading edge to be protected, with particular emphasis on the limits of ice impingement, the so-called impingement zone. The heater applied to the airfoil is conventionally segmented into several sections. Each section consists of several individual heaters (typically 5) with a narrow side in the chordwise direction, and the long side along the spanwise direction. One of these heater strips, referred to as the "Parting Strip" heater, is positioned in such a way that it encompasses the aerodynamic stagnation zone on the leading edge. This parting strip operates continuously as a running-wet anti-icer. A parting strip is required on fixed-wing airfoils, but is not necessary on rotor blades where the centrifugal force helps to shed the ice from the leading edge.

This anti-icing parting strip heater is located at the aerodynamic attachment line where the incoming air stream splits between the upper and the lower surfaces. Its purpose is to maintain this surface free of ice. Typically, one or two heaters are positioned directly downstream of the parting strip, one on either side (upper and lower surface), and are activated individually on a de-icing schedule for a duration sufficient to melt a thin layer at the interface between the ice and the aircraft surface, thereby permitting aerodynamic forces to remove the corresponding ice accumulation.

Allowing the ice to build up at the aerodynamic attachment line would prevent the accreted ice from shedding since the aerodynamic forces tend to hold the ice layer within this region against the aircraft surface. This is true even during the melting of the ice at the cited interface where a warm water layer forms under the rigid ice cap. This phenomenon is referred to as ice capping, and its prevention is the main reason a parting strip is required.

The deicing heater segments are activated sequentially, as described above, in accordance with some scheme in order to remove the accumulated ice and to control to the best extent possible the water that flows back from the heated zones onto the unheated surfaces downstream of the segmented heaters. This may be problematic in the case of an inadvertent icing encounter in which the system not activated. The accumulated ice within the parting strip zone may overwhelm the corresponding heater and remain on the surface for the duration of the encounter. Consequently, ice accumulating on the adjacent deicing zones will also remain on the surface. Clearly, this complicates the operating procedure and can lead to undesirable aerodynamic effects.

Electro-thermal deicing systems suffer from several disadvantages besides the possible capping effects discussed above. First, they require substantial power as a result of the continuous operation of the parting strip over its relatively large area. As a general rule, the parting strip should be wide enough to encompass the range of movements of the aerodynamic attachment (stagnation) line under all possible operating flight conditions and aircraft configuration (angle of attack, flap settings, etc.), and extend along the entire span of the ice protected aircraft leading edges.

Another disadvantage of electro-thermal deicing systems is related to the difficulty in controlling runback water refreeze. Because thermal means are used to melt and debond the accreted ice, a small amount of runback water results. This water flows downstream past the last heated segment and eventually freezes. Subsequent deicing cycles produce more of the frozen runback that could build up substantially over time with little to no control. The rate of ice growth in those regions is accelerated by the fact that water droplets in the cloud are able to impinge directly on the ice ridge due to its growth into the freestream. This might be acceptable as long as the resulting buildup is below a stated limit and does not pose an un-controlled hazardous condition. Since it is difficult to predict the amount and shape of such runback ice refreeze, a limitation can be imposed on the duration that an aircraft can still fly safely in icing conditions. Other possible restrictions include limiting the operation of flaps, which can result in increased landing speeds and restrictions on available landing sites.

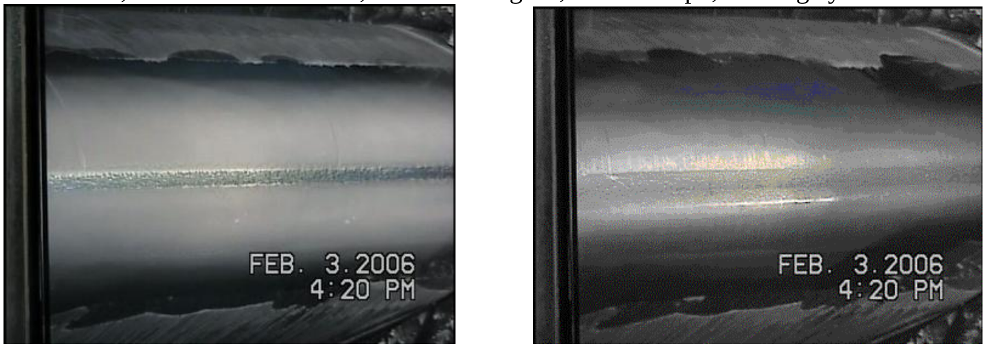
Another type of ice ridge that is not often discussed is the one that forms on the downstream edge of the parting strip of an electro-thermal deicing system. Being close to the stagnation line where the rate of impingement is high, a large amount of runback water is produced by the parting strip. This water flows downstream and freezes on the adjacent heater strip prior to its periodic activation. The rate of growth is extremely high and is enhanced by the direct impingement of supercooled water droplets from the cloud. This growth negates the use of such a system on aircraft with low limits of acceptable ice thickness.

The overall buildup of ice between deicing cycles can be minimized with short times between deicing cycles to protect the entire aircraft. However, this requires very careful design of the heated structure and use of available power to reduce the thermal lag of the heated aircraft skin.

Figure 1 illustrates an example of an electro-thermal deicing system for which utmost care has been taken to minimize runback ice. Here, the ridge height was below 0.125” and 0.25” on the upper and the lower surfaces, respectively, following approximately 30 minutes of icing exposure. This performance can be accomplished by using a heater that has high power density per zone for deicing, construction that provides low thermal lag, and a system that provides proper control.

By comparison, Figures 2a and 2b show that similar performance, except for the larger inter-cycle ice ridge adjacent to the parting strip, was obtained after 22 minutes of icing exposure at higher LWC with a longer deicing cycle time. The skin in this case is 0.032” thick aluminum versus 0.011” in the previous case of Figure 1. However, when icing exposure is extended to 44 minutes, the downstream ridge clearly is larger as shown in Figures 2c and 2d. This is a result of runback and direct impingement on the ridge. A shorter deicing cycle time reduces the size of the inter-cycle ridge next to the parting strip, while the downstream ridge increases. On the other hand, increasing the cycle time has the opposite effect. Clearly, controlling runback ice with a deicing thermal system can be challenging.

TAT = -4°F, *MVD* = 22.5 microns, *LWC* = 0.28 g/m^3, *V* = 200 mph, Deicing cycle = 15 min



(a) Pre-deicing (b) Post deicing

Figure 1: Performance of a properly designed and controlled electro-thermal deicing system.

TAT = 21°F, *MVD* = 20 microns, *LWC* ~ 0.7 g/m^3, *V* = 200 mph, Deicing cycle = 2 min

(a) Pre-deicing (22 minutes in icing) (b) Post deicing (22 minutes in icing)

(c) Pre-deicing (44 minutes in icing) (d) Post deicing (44 minutes in icing)

Figure 2: Possible performance of a typical electro-thermal deicing system.

In summary, an electro-thermal deicing system can provide good deicing performance, but the design and operation must be carefully executed. The following points should be taken into account when an electro-thermal deicing system is under consideration:

1. Downstream runback is difficult to control, and, once it has formed, cannot be removed
2. The ON time (dwell time) per deicing heater is usually a function of OAT. An incorrect dwell time can generate significant runback, particularly at temperatures near the freezing point
3. A small inter-cycle ice ridge will build at the edge of the parting strip. This is the point at which most high performance airfoils can be most sensitive to ice ridges. Reducing the deicing cycle time minimizes this inter-cycle ice ridge. However, this would require higher overall power that may not be available to permit de-icing of all segmented zones within this reduced cycle time. Also, as a

result of more frequent deicing, the downstream runback ridge will grow faster and may exceed the acceptable limit. Usually, this limit is larger than what could be tolerated at an upstream location, such as near the parting strip region.

4. The fact that the parting strip is required along the entire span of regions to be protected can absorb a significant amount of the total electrical power available.

B. Low Power Expulsive Deicing Systems

So called "Alternative Low Power" ice protection systems have been studied and developed over the years in an attempt to reduce the power required to protect aircraft from the effects of flight into icing conditions. These systems have been the subject of numerous patents. One of the earliest Low Power De-Icing (LPDI) systems was based on electro-impulse technology. The history goes back to the year 1939 when a patent was granted to Goldschmidt[1]. The first general documentation on Electro-Impulse De-Icing (EIDI) systems technology was reported by Levin[2,3]. In the early 1980's, the technology attracted interest by the US government and industry, which led to the development of several variations in LPDI systems[4]. Subsequently, Innovative Dynamics, Inc. under NASA SBIR and ARPA sponsorship developed the Electro-Magnetic Expulsion Deicing System[5] (EMEDS). Cox and Company obtained exclusive worldwide manufacturing and marketing rights to this system.

In spite of the number of such patents and development effort, only EMEDS has evolved, to date, into a system certificated by the FAA in the U.S. for use on aircraft for flight into known icing conditions.

In its first application, EMEDS is combined with a running-wet anti-icing sub-system[6,7]. In addition, EMEDS, without an electro-thermal subsystem, have been installed on a business jet for which FAA certification is imminent, on a smaller business jet and on a transport category size aircraft, for which icing development and demonstration tests have been concluded in the Cox Icing Wind Tunnel[8].

Regardless of the LPDI system used, Shin and Bond[9] demonstrated that minimum levels of ice thickness accumulations exist before a particular system can fully clean the surface during a de-icing cycle. The minimum "critical ice thickness" varied among the different systems studied by Shin and Bond, and depended on the type of ice on the surface (rime or glaze) and the location of ice (LE or downstream). This work emphasizes the fact that the use of any of the low power systems requires an assessment of the level of residual ice that can be tolerated on the surface to be protected.

Typical LPDI systems are capable of removing ice buildup as thin as 0.06 in, depending upon the temperature and LWC. Thicker ice accumulations are generally more easily removed by most LPDI systems, certainly by EMEDS. An important feature to be recognized in the use of these systems is that inter-cycle ice thickness can be controlled and maintained within certain acceptable levels by varying the de-icing cycle time.

EMEDS, in particular, is non-intrusive to the flow since expulsive actuators are mounted on either a composite substructure or metal tray beneath a semi-rigid metallic or composite aircraft skin. Consequently, the airflow is not disturbed in non-icing environments, as is the case with externally mounted systems. EMEDS has been demonstrated on surfaces having 0.016" stainless steel skins, as well as aluminum skins chemically milled down to 0.040" or thinner in the region of ice protection.

As presently configured, EMEDS consists of a De-icing Control Unit (DCU), an Energy Storage Bank (ESB) that contains capacitors, and the electro-mechanical actuators. An EMEDS actuator, shown in Figure 3, measures approximately 15" in length and consists of copper strips coiled into a tubular form with an elliptical cross section.

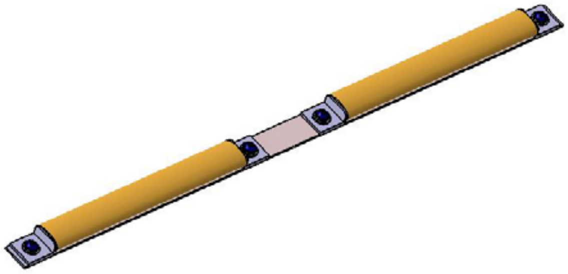


Figure 3: Production EMEDS actuator (15" long)

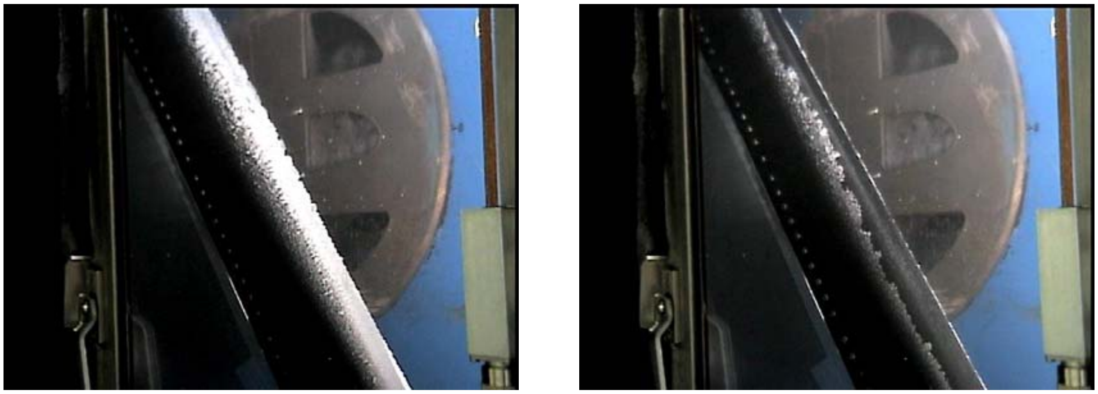
The DCU charges the ESB's and controls the sequencing of actuator firings in a prescribed order, rate, and deicing cycle time. When an electrical charge is released from an ESB to an actuator, a magnetic field forces the actuator cross-section to change shape rapidly from elliptical to near circular. Because of its proximity to the inside of the aircraft skin, this action imparts a force that results in high acceleration, and low deflection of the aircraft skin. Subsequently, the accreted ice is shattered and removed.

Two rows of actuators are typically installed beneath the skin in rigid channels, and local actuators are fired alternately between the upper and lower surfaces. Normally, each actuator is fired three times in a deicing cycle. The DCU also operates and controls the heater power output in combined electro-thermal and EMEDS (hybrid) systems discussed later.

Energy discharged from the ESB each time an actuator is fired is about 45 joules (550 volts and 300µF capacitance). Power consumption can be less than 500 Watts for an entire aircraft. The skin accelerates and deflects approximately 0.025” to 0.040” in less than 0.005 sec. Typically, ice as thin as 0.060” can be shed (see Figures 4 and 5 for two different EMEDS examples). However, like most mechanical deicing systems, it leaves residual ice on the surface following activation during the deicing cycle period. It does not remove very low levels of ice accretions effectively or consistently, especially near the impingement limits where the ice structure consists of individual feathers. Consequently, this system is not suitable for high performance wings that cannot tolerate accumulations and residual ice thicker than about 0.050”. Thus, two different types of hybrid systems were developed. These are discussed in the following sections.

(a) Pre-firing (b) post-firing

Figure 4:Typical EMEDS performance on 0.040” aluminum skin (200 mph, 13°F, 0.7 g/m3, 20 microns)



(a) Pre-firing (b) post-firing

Figure 5:Typical EMEDS performance on painted 0.025” aluminum skin (same conditions as above)

Other than the demonstrated deicing capability, EMEDS has the following advantages:

- The airfoil contour and aerodynamic smoothness are maintained. A polished exterior surface is used in applications to date.
- There is no erosion or deterioration over time.
- EMEDS applications are designed for the life of the aircraft
- EMEDS provides equivalent or superior deicing performance than either pneumatic or other mechanically based deicing systems

C. Hybrid Running-Wet Anti-icing System

This hybrid ice protection system was developed to provide an economical alternative to conventional anti-icing systems on roughness sensitive airfoils where high power is either impractical or unavailable[6,7]. It consists of a thermal subsystem operating in a running-wet mode that partially or fully covers a roughness sensitive zone located within the impingement zone at the leading edge, and a low power deicing subsystem just downstream. The thermal system maintains a clean leading edge in the roughness sensitive zone by preventing the impinging supercooled water droplets from freezing. Minimal power is used because the surface temperature is held just above freezing. The goal is not to evaporate the impinging water since, in which case, substantially power is required due to the high latent heat of vaporization.

The water runs downstream beyond the heated zone and freezes there. This is the location at which EMEDS actuators are installed beneath the skin. Periodic actuation at these locations removes the frozen runback ice. The size of the accumulation is controlled by the frequency of actuation. Shorter deicing cycle times produce smaller accumulations. It should be noted that the LPDI requires some minimum ice thickness, typically of the order of 0.060” to properly deice the surface. Consequently, residual and inter-cycle ice will always exist at these downstream locations. However, because EMEDS can remove small ice thicknesses without the creation of water, the possibility of downstream ice ridge formation is eliminated. One significant advantage is that no time limit is imposed on the aircraft’s exposure to an icing environment since no ice ridge forms.

The total power consumption of the EMEDS hybrid system just described is a fraction of that required to achieve total evaporation.

The anti-icing component should not be confused with the span-wise parting strip used in electro-thermal deicing systems, which is usually very narrow, comparatively. The wrap-wise heater coverage in the EMEDS hybrid is determined by the relative sensitivity of the airfoil to ice accumulations downstream of the LE and, consequently, the running-wet hybrid system provides much better aerodynamic performance than electro-thermal deicing systems described earlier. This advantage comes at the expense of a higher electrical power budget as a result of the larger heated surface. The EMEDS running-wet hybrid system was developed by Cox under a NASA SBIR award. The system underwent development tests at the NASA Glenn Icing Research Tunnel (IRT) before commercialization and system certification was achieved. Figure 6 illustrates the system pictorially and in operation at the NASA IRT. Note the performance difference between the upper half of the model fitted with the hybrid running-wet anti-icing system, and the lower half fitted with the EMEDS low power system only. In the case of the hybrid system, most of the sensitive LE is maintained ice free, while in the case of EMEDS, surface accumulations and residuals, albeit small, exist within the entire impingement zone most of the time.

Although the power requirement of the running-wet hybrid configuration is much lower than that required by an evaporative system, it could be considered substantial for certain aircraft if this type if ice protection is applied to all lifting surfaces. Consequently, a new type of hybrid system has been developed for which electro-thermal deicing, as opposed to running-wet anti-icing, is combined with EMEDS to provide superior ice protection performance at an even lower power. This system called TMEDS is discussed and presented in detail in the following section.

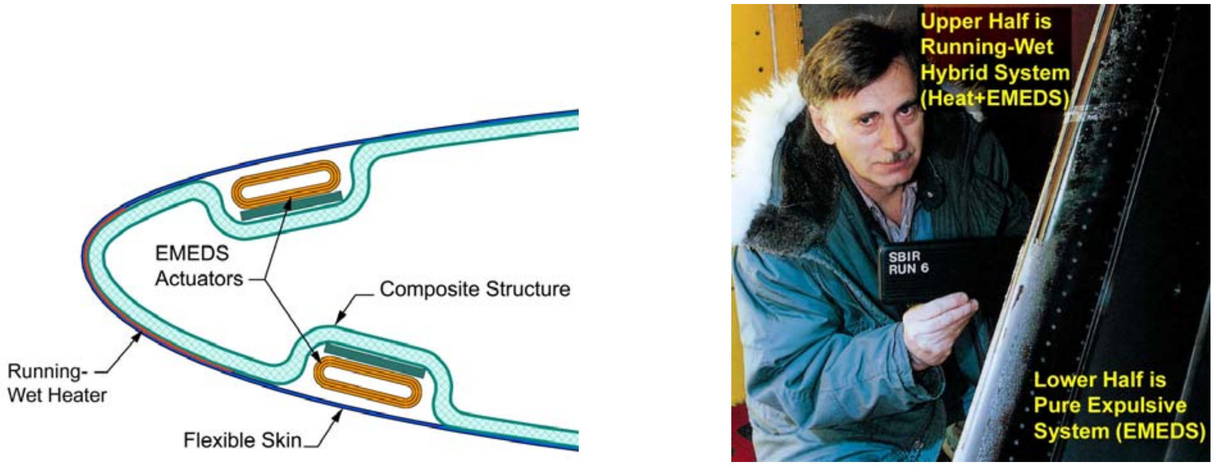


Figure 6: Hybrid system (running-wet anti-icing on LE and EMEDS expulsive deicing downstream)

III. TMEDS Hybrid Deicing System

While it is generally agreed that ice is detrimental to the aerodynamic characteristics of a lifting surface, it is nonetheless recognized that the existence of some level of ice accumulation or residual is permissible. Were this not the case, then all ice protection systems would be required to prevent the formation of ice at any point on the aircraft, and no "deicing" system would be acceptable. In most cases, an aircraft is also required to fly safely following a 2-minute inadvertent icing encounter when the ice protection system is not powered, either as the result of flight crew's failure to recognize an icing condition or a failed ice detector. The accumulated or residual ice may be in the form of a generally smooth layer or in accumulations and growths positioned sufficiently aft on the surface that its existence does not constitute a flight hazard, provided it does not continue to grow uncontrollably.

For purposes of discussion, it may be postulated that the admissible levels of accumulation of ice on the protected surface can be presented as the acceptable height, surface condition or structure of ice accumulation at specific locations, presented as a function of wrap distance measured chordwise along the airfoil surface from the highlight.

Consider the case for which the level of ice accretion permissible within the so-called roughness sensitive zone, located at the foremost leading edge, is greater than zero but less than some value set by aerodynamic considerations. This specification of the permissible level of ice accumulation, residual or accretion, is a function of the aerodynamic requirements of the surface to be protected, and defines the limits of ice accretion in terms of its effect on aerodynamic parameters such as lift, moment, and drag. Whereas the acceptable level of ice accumulation addressed by Al-Khalil[6,7] is zero at the critical zone of the roughness sensitive region, other airfoils might not exhibit such sensitivity and the acceptable level of ice may be greater than zero at that point and increase as the ice extends back over the surface of the wing measured chordwise (or spanwise, as the case may be).

Consider the case for which ice accumulation maintained at or below a defined level (e.g. 0.050") within the roughness sensitive region is considered as an acceptable limit. The use of a conventional electro-thermal deicing system would not meet this criteria for several reasons related to the buildup of runback ice, ice ridges, and overall accumulation prior to each deicing cycle. The criteria could be met with the use of a thermal system (hot air or electro-thermal) that operates in a fully evaporative anti-icing mode, but this requires a substantial amount of power, and may not be viable.

On the other hand, the use of a conventional expulsive system such as EMEDS could be sufficient since the expulsive system is capable of removing low levels of ice accretions. However, this would not be acceptable if the allowable ice accumulation and accretion are near the limits of the expulsive system's capability of consistent ice shedding.

TMEDS addresses and resolves this condition by the strategic combination of electro-thermal and EMEDS deicing in much the same manner as the hybrid running-wet anti-icing system described earlier [6,7]. However, instead of operating the heater continuously as a running-wet anti-icer, a very thin layer of ice is allowed to form within the direct impingement zone before it is removed by a coordinated sequencing of the thermal and EMEDS sub-systems. The result is a system that provides an ice protection system optimized for power and tailored to the allowable levels of ice accretion over the leading edge of the surface. TMEDS operates with substantially less power than an evaporative anti-icing system (hot air or electro-thermal), and also operates at significantly lower power than an electro-thermal de-icing system. This is because TMEDS eliminates the continuously operating parting strip along the entire span of a protected wing or tail. TMEDS also provides an improved level of surface cleanliness over that which is provided by conventional expulsive systems. As is the case of the anti-icing hybrid system, TMEDS also prevents the buildup of runback ice ridges, thereby allowing very long and unrestricted exposure to icing.

As indicated above, power consumption is greatly reduced by the elimination of the electro-thermal de-icing system requirement for a parting strip. In a TMEDS configuration, the parting strip is not required. Instead, the electro-thermal deicing heater is powered for a short time within each deicing cycle, only enough to melt a thin layer of ice and weaken the bond at the interface with the heated skin. At this point, the local EMEDS actuators are fired to remove the ice.

Tests have demonstrated that TMEDS can maintain worst-case distributed ice accretions to within critical limitations (typically less than 0.050") while consuming only a fraction of the power that would conventionally be expected for such an application. This power is equal to that required to deice each segment, or the sum of powers of all segments deiced simultaneously. Very small amounts of runback are produced, but are removed promptly by the mechanical deicing means downstream, preventing continuous growth that is typical of thermal deicing systems.

A cross section of a typical TMEDS installation is illustrated in Figure 7. A heater is vulcanized directly to the non-breeze side of the leading edge skin. Generally, the extent of the heater covers the entire direct impingement zone. In some specific cases, the heater can be limited to regions of sensitivity for which adequate protection cannot be provided by the use of EMEDS alone. Alternatively, the heater can cover the stagnation region and the upper surface impingement zone, while protection of the lower surface could be accomplished by the use of EMEDS only.

In this construction, the EMEDS actuators are contained in a tray assembly mounted to chordwise ribs that are set back from the LE area to be protected. The composite sub-structure as shown in Figure 6 for the anti-icing hybrid system configuration could also be used.

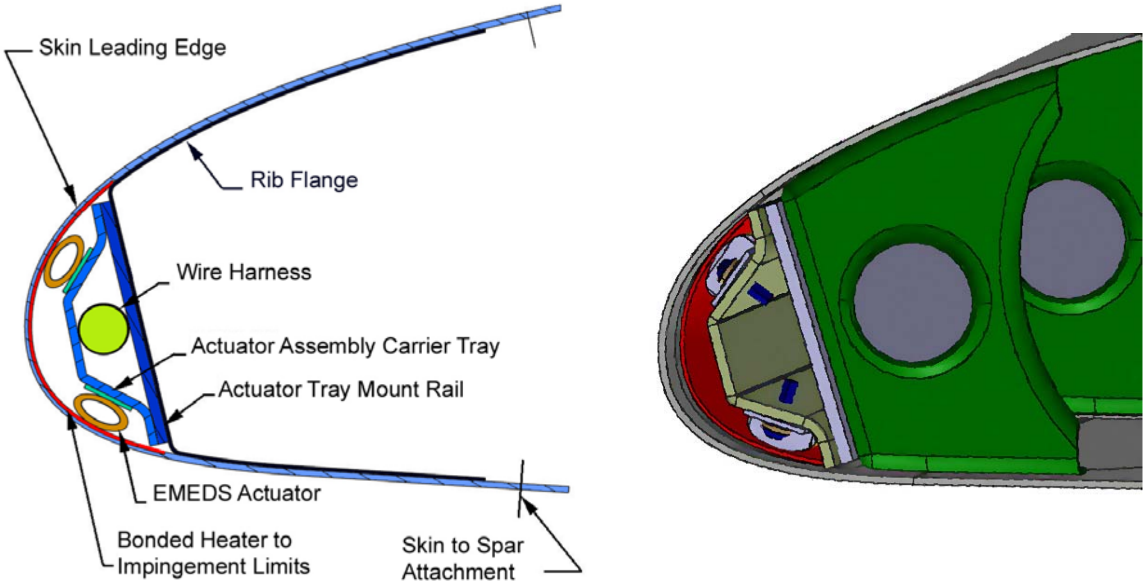


Figure 7: TMEDS hybrid deicing system configuration

The heating and flexing of the leading edge skin are applied in a coordinated fashion locally. Heat is used only to increase the temperature of the ice/skin interface, so as to reduce the level of adhesion between the ice layer and the subjacent skin and thereby weaken the bond between the skin and ice. Once this bond has been weakened, the heat is turned off and the actuators are used to flex the skin and shed the accumulated ice.

D. Tunnel Demonstration Tests

A TMEDS prototype was fabricated using a NACA0012 airfoil and tested in the Cox icing wind tunnel. The TMEDS effectiveness was demonstrated at different ambient temperatures and icing conditions. Results of four runs from these tests are illustrated in Figures 8(a) through 8(d). These figures show the surface conditions after continuous operation for about 45 minutes in icing. For each run, the airfoil LE is shown with the inter-cycle ice accumulation just prior to the last system firing, and the surface condition following the last deicing cycle event.

The four runs demonstrate TMEDS system deicing performance at the warmest temperature (Figure 8a) through the coldest temperature as specified in the FAR icing envelope (Part 25 Appendix C). Despite the long icing encounter (45 minutes), in each run, the performance of the last deicing cycle was identical to each of the previous cycles. The runback ice was measured and shown to be less than 0.030” height in every case.

The results show a smoothly textured inter-cycle ice accretion at total ambient temperature colder that 20°F. The ice cap forms a continuous ice layer over the leading edge of the airfoil section (wing or tail) and the accumulated inter-cycle ice conforms closely to the outer contour of the airfoil. Since the inter-cycle and residual ice thicknesses are very small, the resulting change in the outer contour of the airfoil is negligible. No forward or aft-facing steps are produced on the leading edge such as those formed on the downstream edge of the parting strip of an electro-thermal deicing system. Also, no residual ice remains on the protected surface following each deicing cycle.

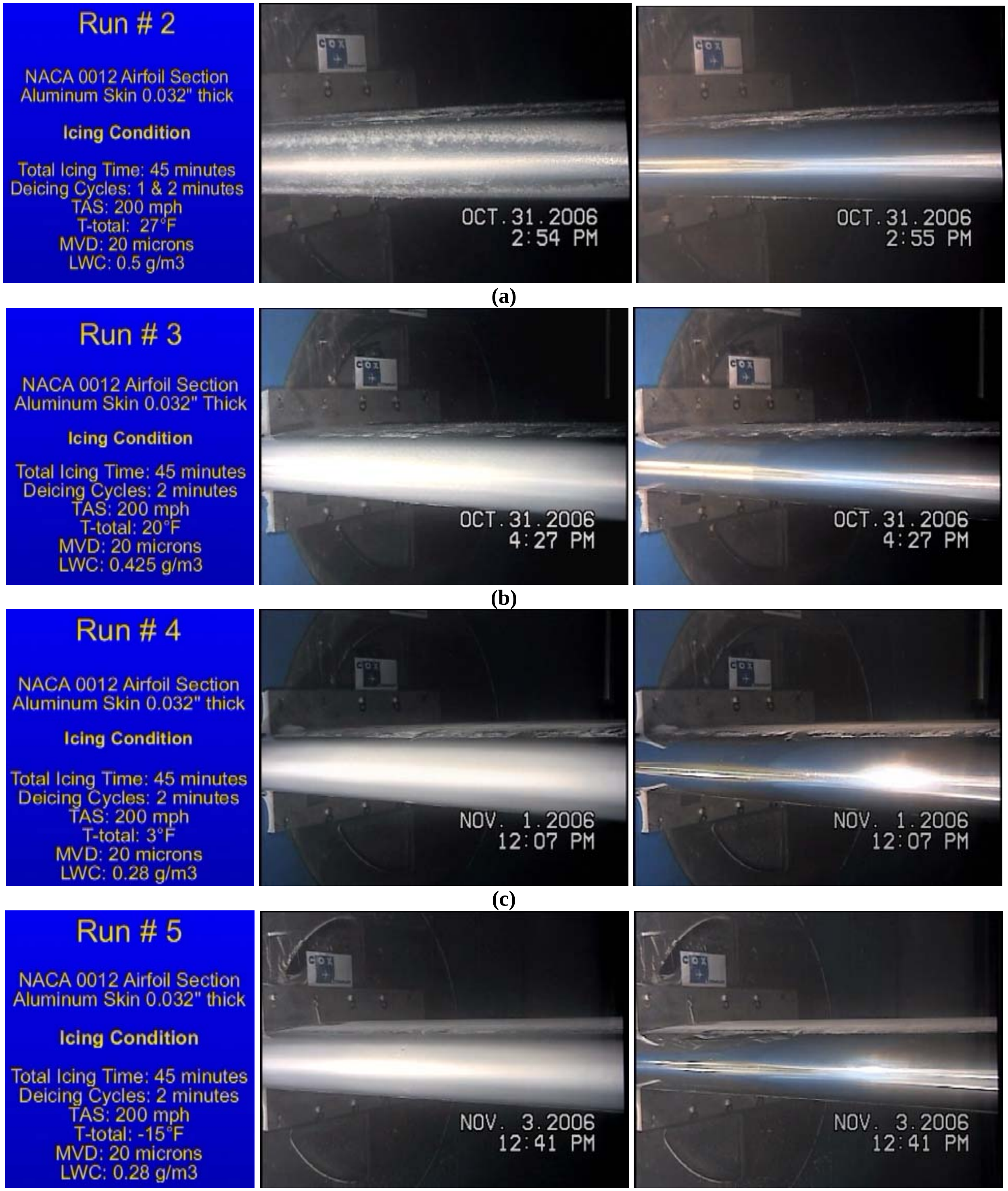


Figure 8: TMEDS Icing Tunnel Demonstration Tests

In the warmest cases, the inter-cycle ice may have a slightly rough texture. This is slightly exaggerated in the view captured from the high contrast video (Figure 8a). In reality, the actual accreted thickness is less than 0.020” because of the low freezing fraction at these warm temperatures. The runback ice on the upper surface of the airfoil following the 45-minute icing exposure is shown in Figure 9. These accumulations are localized and average 0.010” thickness with peak values near 0.020”. Any runback that might form a continuous ridge downstream of the heated surface is removed by the periodic operation of the EMEDS actuators.

The heater’s power density was about 35 W/in^2. This level insures fast deicing response consistent with the least possible amount of runback ice. It is important to accomplish a rapid deicing cycle in order to deice the entire protected aircraft lifting surfaces in a time sufficiently short to keep local accumulations below the specified limits.

System implementation to a full wingspan and sequencing of deicing segments is discussed in the following section.

E. Implementation and Operation of TMEDS on a Full Span Wing

An example will be presented to illustrate the integration of TMEDS into a leading edge consisting of segmented deicing zones and the order in which the deicing system is sequenced in these zones. The example shown in Figure 10 is for a system in which protection is to be provided to an aircraft full wingspan consisting of four slats per wing. Each slat is about 140” long. Since each actuator measures about 15” long, each slat could be protected with nine actuators on the upper surface and nine actuators on the lower surface. Thus, each slat is segmented into nine deicing zones.

One EMEDS ESB is used to power actuators individually on two adjacent slats. The slat is located centrally between the corresponding slats to limit the length of power cables to each actuator. This is done for weight reduction as well as to reduce resistive losses through the electrical cables.

Figure 9: Top view of airfoil following a 45-min icing exposure with the TMEDS
Few frozen runback downstream less than 0.030” thick

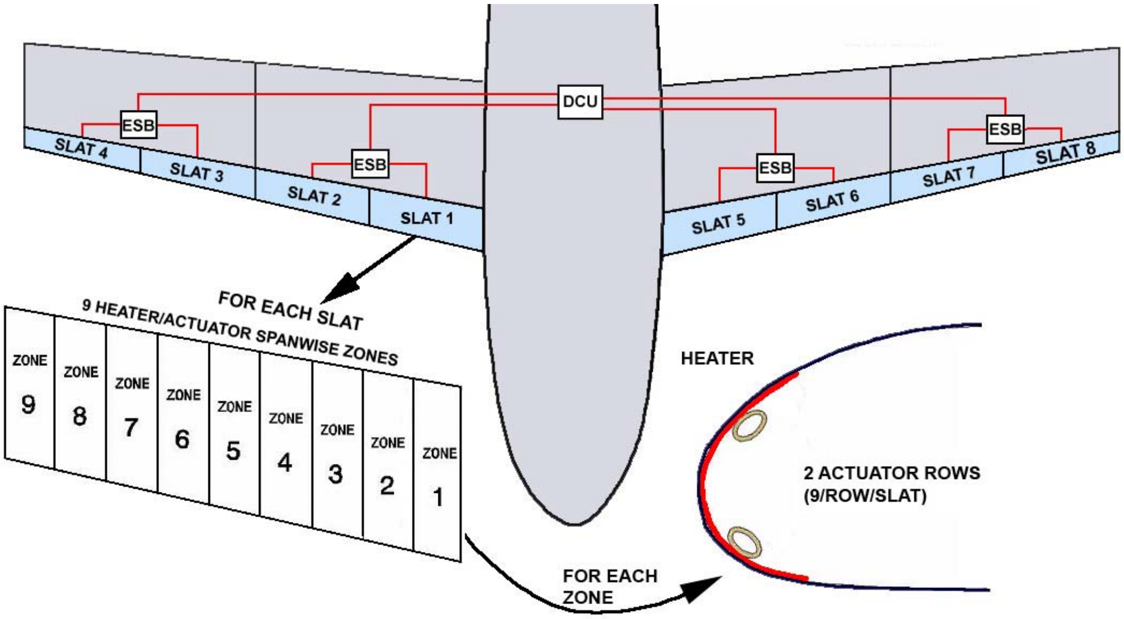


Figure 10: Typical TMEDS layout of spanwise deicing segments

The EMEDS DCU is equipped with circuitry to supply high voltage (500 to 550 volts) to charge the capacitors within the ESB’s. If desired, four ESB’s could be charged simultaneously, and the energy delivered through four actuators simultaneously. This may be required to reduce the deicing cycle time and, consequently, minimize the accreted inter-cycle ice. The deicing sequence is as follows:

1. Heaters on Zone 1 of slats 1, 3, 5 and 7 are powered simultaneously until the heater or wing surface reaches a specified temperature. This will insure the interface ice has melted.
2. The corresponding top and bottom EMEDS actuators within these zones are fired sequentially (top, and then bottom) to remove the accreted ice. Normally, EMEDS actuation occurs after the ice interface has melted. Each actuation requires a total of about 0.25 sec per hit. Each of the two actuators is fired typically 3 times per cycle. Thus, EMEDS actuation of each zone requires 1.5 seconds.
3. The deicing sequence continues from Zone 2 through Zone 9 on slats 1, 3, 5, and 7.
4. Deicing follows starting on Zones 1 of slats 2, 4, 6, and 8.
5. The deicing sequence continues from Zone 2 through Zone 9 on slats 2, 4, 6, and 8.
6. The above steps may be repeated at each deicing cycle without pausing.

At near-freezing ambient temperatures, each zone requires 1.5 seconds of heating as well as 1.5 seconds of EMEDS actuation. At very cold conditions (near -22°F from FAR 25-C), each zone requires about five seconds of heating to melt the interface ice. Thus, the minimum deicing cycle time with simultaneous deicing of zones from four slats is near 30 seconds at warm temperatures and 1.5 minutes at cold temperatures. The LWC at cold temperatures is very low. Besides, the ice accumulation at these temperatures is of the rime type that conforms very well to the airfoil contour and has a relatively smooth texture. Consequently, the longer deicing cycle time at cold temperatures is equivalent to the shorter cycle times at warm temperatures. Advantages and Power Consideration

TMEDS has several advantages over conventional thermal deicing systems: (1) the anti-icing parting strip and its associated high power is no longer required on the leading edge, (2) the ice ridge generated near the parting strip is prevented, (3) The ice ridges at the trailing edge of the heated zones are controlled by the EMEDS expulsive system, (4) there is no remaining residual ice following each TMEDS cycle.

The EMEDS portion of TMEDS requires just about 1 kW of power to operate one zone on four slats simultaneously. For a heater power density of 35 W/in^2 per zone and an area of 124 in^2 (15.5” span x 8” chord), the power per zone is 4.3 kW. In this example, the total ice protection power of TMEDS for this example is 18.4 kW if four zones are operated simultaneously.

By comparison, the following are rough predictions of power required for different systems for the same example case considered:

- Electro-thermal evaporative anti-icing: 160 kW
- Hybrid running-wet anti-icing and EMEDS: 55 kW (4” heated chordwise and entire span)
- Electro-thermal deicing (same simultaneous zones as TMEDS): 27 kW
- EMEDS: <1 kW

It is worth mentioning that failure of a heated zone in a TMEDS configuration might be tolerated since the EMEDS subsystem provides a certain level of protection. The degraded ice protection performance is localized and limited to that zone. The permissible number of failed zones that do not affect aircraft dispatch rate and continued operation in icing environments must be determined on a case-by-case basis.

IV. Conclusion

A high performance ice protection system was developed and demonstrated for use on airfoils for which only low levels of ice accumulation are permissible. It combines the coordinated use of an electro-thermal deicing system with a low power expulsive deicing system. They are both collocated beneath the aircraft skin and operated in harmony to limit inter-cycle ice accumulation thickness below a prescribed low limit and to prevent the formation of ice ridges downstream. The result is a combination that is highly efficient in its use of power and its capability to provide near-evaporative surface conditions during icing conditions.

A patent application has been filed for this system.

Acknowledgments

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