AN OVERVIEW OF THE DEICING AND ANTIICING TECHNOLOGIES WITH PROSPECTS FOR THE FUTURE

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Abstract

This paper reviews selected technologies devoted to anti-icing and de-icing. Among the discussed solutions there are Electro-Impulse System, Electro_Expulsive Separation Systems in a few versions, Weeping Wing Technology based on De-icing Fluid, Shape Memory Alloys Deicing Technology, Ultrasound Technology and Electrical Heating. Some of these technologies are qualitatively compared and their specific features, including power consumption, electromagnetic interference and environmental issues are discussed. Only a few of these anti-icing and de-icing technologies are commercially available to-day. Some of them are still immature and need further extensive investigation and testing in laboratories and in-flight. Other are commercially available and are certified on older type of small and medium size aircraft. Most of these technologies are patented. Their full comparison and a selection the most safe and in-flight reliable solution for a chosen class of aircraft would be possible if they are tested in the same laboratory under the same condition. Coming from this assumption an international research project was proposed, which would create objective means for independent assessment of the methods available on the market. Patent descriptions and different companies' websites are widely referred.

1 Introduction: Statistics and Goal

The need to improve all-weather flying safety is absolutely necessary and beyond of any discussion. Basing on statistics of US air carriers [1] in the period 1990-1999 for scheduled & nonscheduled airline service related to 89 716 000 departures & 139 027 000 aircraft hours flown one can figure out the following rates (per to 100 000 departures):

- Current accident rate due to icing: 0.00668
- General current accident rate: 0.37
- Percent of accidents due to icing to all accidents: 1.7%.

Modern scheduled aviation has developed through the years into a reliable economical & almost all-weather transport system. Through the use of ever-improving aerodynamics & engine technology, as well as the increasing use of light weight composite materials since 1970, the SFC has been reduced by more than 30%. Radio navigation & approach systems, inertial navigation systems, weather radar, ATC etc, in combination with ever-improving training and standardized procedures, allow relatively safe flight, also in reduced visibility conditions. However, in instrument meteorological conditions, the pilot's situational awareness is quite poor due to the nonexistence of outside visual altitude, navigation, weather (including icing conditions) & terrain information.

Traditional approach to coping with ice accretion problem can not be farther used efficiently, mainly due to the fact that ice is still a reason of fatal crashes (6 well documented crashes of big commercial airplanes in the last 15 years, including 3 fatal accidents with 110 people killed).

2 Worldwide accident's statistics

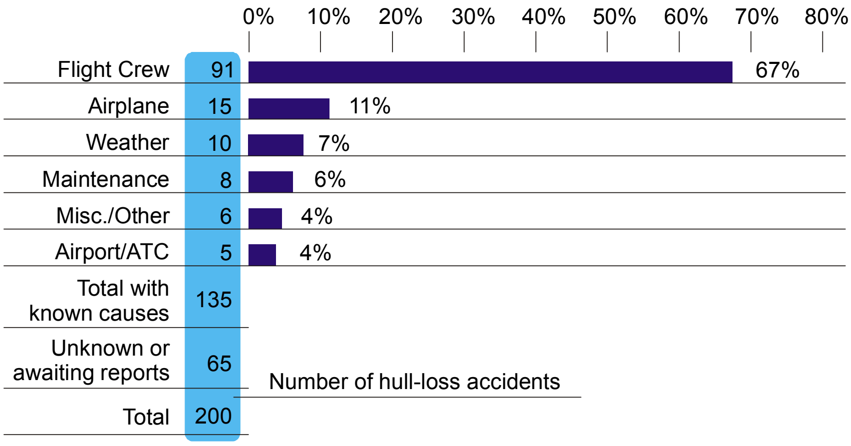

Fig.1 Primary cause factors in hull-loss accidents, all airplanes, worldwide commercial Jet fleet, 1990-1999, after Commercial Aviation Safety by Aviation Week, 2001 [1]

Generation	Controlled flight into terrain	Loss of control	Midair collision	In-flight fire	Fuel tank explosion	Landing				Gear collapse/fail/up	Ice/snow	Fuel management/exhaustion	Windshear	Takeoff configuration	Off side on takeoff	Runway incursion vehicle/poeple	Wing strike	Engine failure/separation	Ground collision	Ground crew injury	Boarding/deboarding	Turbulence fatality	Miscellaneous*	Fire on ground	Aircraft structure	Unknown	Refused takeoff - off end	Total
						Off end on landing	Off side on landing	Hard landing	Landed short																			
First	5	8		1		7	3	3	4	8		2		1	1		2	3					1	1		1	3	54
Second	17	7	1	2		17	20	15	9	8	3	4	1	1	1	5		2	2	3		1	2	2	2	3	6	134
Early widebody	3	2	1	1	1	3	3	5	1	2		1	1		3	1		4	2	2	2	1	2	3	2		3	49
Current	11	13		1	1	22	11	32	2	13	3		1	1	3	10		1	6	2	2	1	3	2	2	3	2	148
Total	36	30	2	5	2	49	37	55	16	31	6	7	3	3	8	16	2	10	10	7	4	3	8	8	6	7	14	385

where

First	Comet 4, 707/720, DC-8, CV-880/990, Caravelle
Second	727, Trident, VC-10, BAC 1-11, DC-9, 737-100/200, F-28
Early widebody	747-100/200/300/SP, DC-10, L-1011, A300
Current	MD-80, 767, 757, A310, Bae146, A300-600, 737-300/400/500, F-100, A320/319/321, 747-400, MD-11, A340, A330, MD-90, 777, 737NG, 717

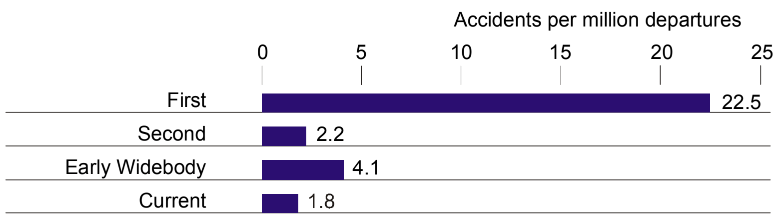

Fig.2 Accident categories by airplane generation, all accidents, worldwide commercial jet operations, 1990-1990 , after Commercial Aviation Safety by Aviation Week, 2001 [1]

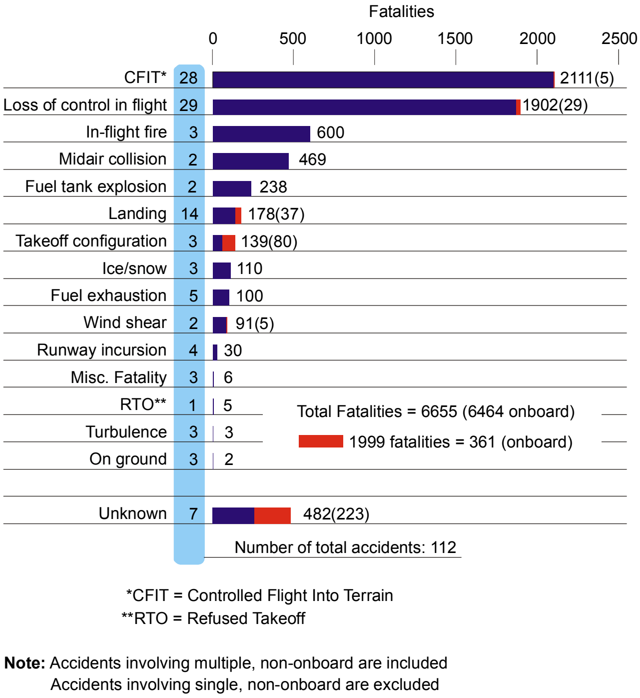

Fig.3. Fatalities by accident categories, fatal accidents, worldwide commercial jet fleet, 1990-1999, [1]

An example:

- ATR-72 accident, Roselawn, Indiana, Oct.31, 1994, all passengers (72) killed
- Embraer 120, Monroe, Michigan, Jan.9, 1997, 29 passengers & crew members killed.

3 State-of-the-art in aircraft ice protection

Anti-ice aircraft protection should be based on deep knowledge of flight physics, meteorology and icing phenomenon. In the relevant bibliography one can find a lot of books, papers and reports [2-39] describing the methodology of icing research and results obtained from measurements and numerical simulation.

A traditional approach to coping with ice includes pneumatic deicing boots (usually used on propeller–driven aircraft), thermal anti–icing systems (to de-ice wing leading edges & propeller leading edges & engine air intakes), glycol based fluid (usually used to protect wing surfaces & propeller leading edges). All these systems are highly complicated, need a lot of on–board power & demand very careful maintenance.

Reliability of such systems usually contradicts to the degree of their complexity. It is especially difficult to accommodate all these traditional systems on smaller commercial transport airplane, for example on business jet, where weight of additional equipment & its complexity can be a real obstacle to install these systems on–board. An example of the parametrical comparison is presented in Table 1.

Table 1 Some features of EMEDS technology [47] compared to traditional Pneumatic Boots

Parameter	modern technology: EMEDS	traditional technology: Pneumatic boots
erosion surface	metal	elastometric
surface life	life of aircraft	months, rather not years, depending on service
drag increment	no increase	measurable increase
deice performance	ice as thin as 0.12 cm & no upper limit	typically greater than 0.6 cm
Weight	equivalent	baseline
Cost	equivalent	baseline
electric power for 12 m span	25 amp* 28 V DC = 0.7 kW	zero

4 A review of modern technologies

4.1 SPEED - Sonic Pulse Electro-Expulsive Deicer

The Sonic Pulse Electro-Expulsive Deicer (SPEED) is an acceleration based deicer for aircraft ice protection [41]. The system was developed in collaboration with NASA Lewis and ARPA’s SBIR program. SPEED evolved from the Electro-Impulsive deicing (EIDI) concept with a major improvement in the actuator coil and electronics. This is due to a special multiple winding actuator that is seated in the leading edge substructure. As in EIDI, actuator coils are strategically placed behind the leading edge to apply impulsive loads directly to the aircraft skin or outer surface material. The rapid acceleration debonds and sheds ice into the airstream in a very efficient manner (ice layers can be shed as thin as 12 mm). SPEED represents the most technically advanced low power deicing system available. IDI's (Innovative Dynamics Inc.) Icing Onset Sensor (IOS) can be added to the basic system to provide an autonomous mode of operation. The IOS detects the initiation of ice accretion (icing onset) and continuously monitors the amount of accumulation. When the accumulation reaches a thickness threshold at which efficient clearing is possible, the sensor commands the deicer to fire. Because the sensor continuously monitors the accumulation, the sensor can determine if the ice was properly shed or if another clearing cycle is required. The sensor continues to monitor accretion and initiate deicing cycles as required. The IDI deicing technology has been extensively tested both in ice tunnels and in flight. It has been selected by Raytheon for use on the Premier I aircraft, scheduled for FAA certification in 2000. The design is protected by U.S. Patent Number 6,102,333. IDI company underlines the following features of the SPEED solution: Electrically operated; Very low power consumption; Erosion resistant; Low cost solid state design; Reliable and maintenance-free; Fault-tolerant operation and; Graceful degradation (of aircraft performance).

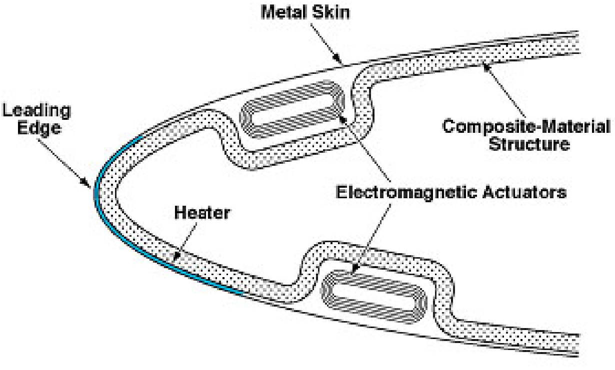

Fig.4 Electro-Expulsive Deicer located in the wing nose – a possible arrangement

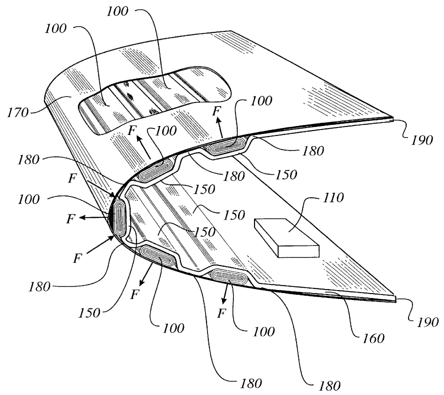

Fig.5 Original sketch from US Patent 6,102,333, Innovative Dynamics, Inc.

4.2 The electro-impulse method

The electro-impulse method was first patented in England in 1937 [62]. Wichita State University extensively tested this method both in wind tunnel and in flight using NASA Twin Otter aircraft, [18].

Fig.6 NASA Twin Otter used for the Electro-Impulse Method testing

When the high-voltage capacitors are rapidly discharged through the coils installed just inside the skin of the aircraft leading edge, the result is a sudden electromagnetic repulsive force in the skin which throws ice in all directions. The well known drawbacks of this method is an electromagnetic interference, structural fatigue and passenger response to the noise. Deicing system based on this method has been certified on only one airplane and only on its tail. No matter that this system is potentially applicable to many light airplanes, but most of them are no longer in production and product liability and following risk limits any further applications. This method could be also applicable to helicopter rotors and turbine engine inlets. As Dennis Newton [60] wrote, " … a properly designed electro-impulsive system could be reliable, effective, require very little power and be light in weight ..”.

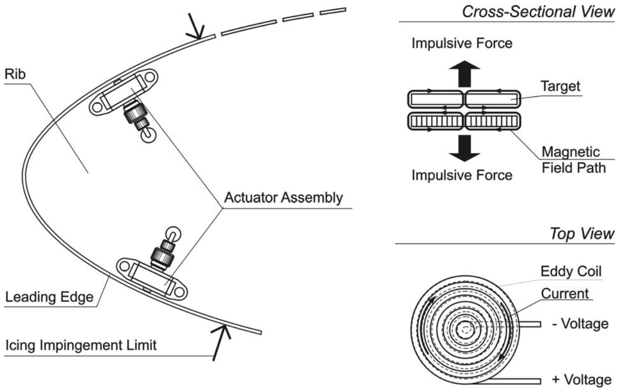

Fig.7 Impulsive coil in a leading edge (Eddy current)

4.3 EESS (Electro-Expulsive Separation System), Ice Management Systems, Inc.

The Electro-Expulsive Separation System (EESS) is innovative aircraft deicing system. It consists of two major components, the EESS Controller and the EESS Expulsive Boot. System is supplemented with ice sensors, electrical cabling, indicators and controls. When current is passing through two conductors, the magnetic fields are created about the conductors, producing either attractive or repulsive forces. These forces push the conductors apart. The bottom layer conductors are embedded in an elastomer material that is bonded directly to airframe surfaces where deicing is essential. The top conductor, also embedded in elastomer, is placed on top of the first layer. The two layers are bonded together at intervals to allow the layers to flex apart. When necessary, a very large pulse of current is passed through the embedded conductors. In a millisecond, the resultant magnetic fields repel each other, causing the upper conductor to jump less than a twenty-thousandth of an inch. This high acceleration motion breaks the ice bond, shattering the ice. According to Leonard Haslim of NASA’s Ames “it can remove layers of ice thin as frost or thick as an inch of glaze. The ice, shredded into small particles, is too small to harm aircraft components, including jet engines. It uses one-thousandth the power and is one-tenth the weight of Electro-Thermal Ice Removal Systems used to-day”.

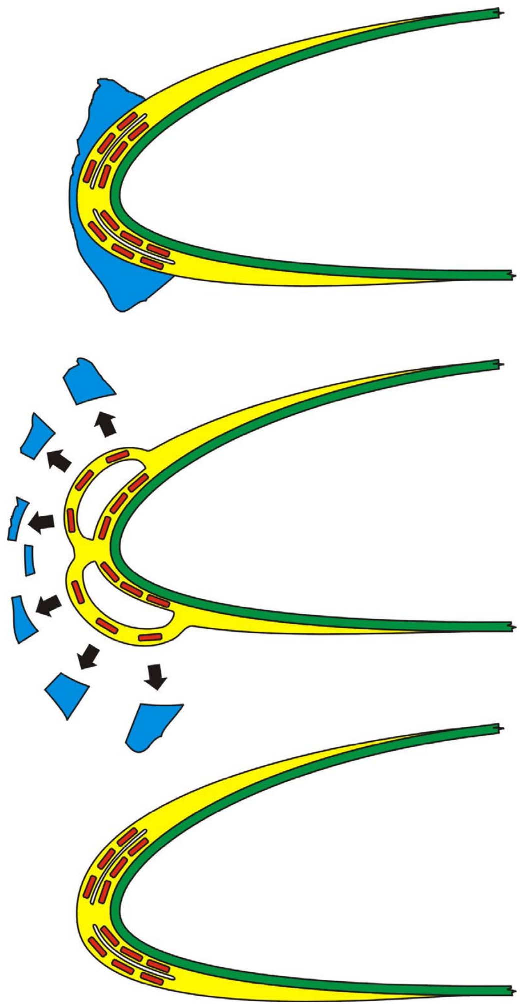

Fig.8 Ice shattering using the Electro-Expulsive Separation System

It can run continually during flight, acting once or twice a minute to keep surfaces free of ice, L.Haslim said. “Thermal deicers that melt ice use a lot of energy”. Melted ice can re-freeze elsewhere on the aircraft or large pieces of ice can cause a damage. Bleed Air System require high Energy levels and re-freezing is still a problem. Newer aircraft with high performance jet engines do not provide sufficient bleed air for deicing. Moreover, the traditional Pneumatic Boot Systems using the pressurization phenomenon work slow. According to Dick Nolan – the President of Ice Management

Systems, the task of converting the EESS patent in a commercial product has already taken over 5 years and $1.8 millions. The Ice Management Systems is the process of FAA certification of the Electro-Expulsive Separation System on the modified STOL Cessna Skymaster.

Fig.9 Cessna Skymaster – the platform used in the certification process of EESS

4.4 A Comparison between Electro-Impulsive and Electro-Expulsive systems

An advantage of Electro-Expulsive system is that it flexes a elastic boot and does not fatigue the aircraft structure and also is easier for installation and exchange. However, the boots in electro-expulsive version could be subject to damage and erosion just as current pneumatic boots are. As D.Newton [60] wrote “both systems use little power” and “all they need is an incentive to develop and certify them”.

4.5 EMEDS - Electro-Mechanical Expulsion Deicing System

Electro-Mechanical Expulsion Deicing System (EMEDS) is based on the latest technology in aircraft ice protection and was developed by COX Inc. “A microsecond duration high current electrical pulse delivered to the actuators in timed sequences generates opposing electro-magnetic fields that cause the actuators to change shape rapidly. This change of the actuator shape is transmitted to the erosion shield of the LEA causing it to flex and vibrate at a very high frequency. This rapid motion results in acceleration-based debonding of accumulated ice on the erosion shield”, [47]. Key features include: Erosion resistant metal surface; Efficient Ice Protection at weights and costs competitive with other deicing technologies; System Components designed to last the life of the aircraft; Automatic Ice Protection through operation with integral or independent ice detectors; Hybrid Protection Systems. The primary advantage of a Low Power Ice Protection System is to provide lifting surface ice protection at power levels much below those required by conventional means such as bleed air and electro-thermal. EMEDS lives up to its expectations in this regard in that it offers ice protection equivalent to those other systems at a fraction of the power they consume. In addition, EMEDS offers many advantages over pneumatic boot ice protection systems (see Tab.1).

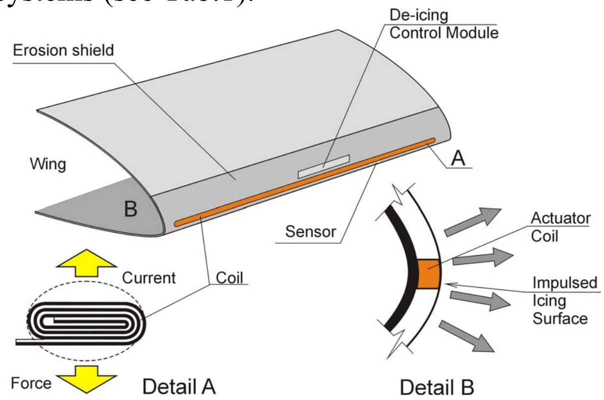

Fig.10 Innovative Dynamics, Inc.

4.6 Electrical heating

A very promising method to remove ice from aircraft surfaces is recently developed “graphite based heating element”. It can be heated very quickly and also cools very quickly. In this system small areas of of the graphite are strongly and suddenly heated, so the ice over that section dis-bonds and leaves with airflow, without melting. A complete deicing cycle does not take long, and very thin accretions of ice can be shed not damaging the aircraft. The system for small aircraft was tested in NASA and its weight is under 20 kg including its own alternator [60].

4.7 UT – Ultrasound Technology

Ultrasonic technology [58] being developed by the NASA Glenn Research Center can be used for automotive, marine and aeronautical industry that would like to break the adhesive bond between two materials. Some potential uses include: Airframe ice protection; Automobile windshield ice protection; Ice buildup protection for marine vessels; Refrigerator & freezer frost removal; Removal of mussels & other ocean life from marine vessels; Elimination of material buildup in crucibles. Among advantages there are cost-effective ice protection and environmental benefits of reduced use of anti-icing fluid. Sound waves create a stress field in a material. If this stress field is great enough at the interface of two materials, debonding begins. Current research is focused on debonding ice from aluminium, and future investigations will include composite, glass, and steel. It seems that this technology is still in the laboratory state of research and eventually could be mature for commercial application in the further future.

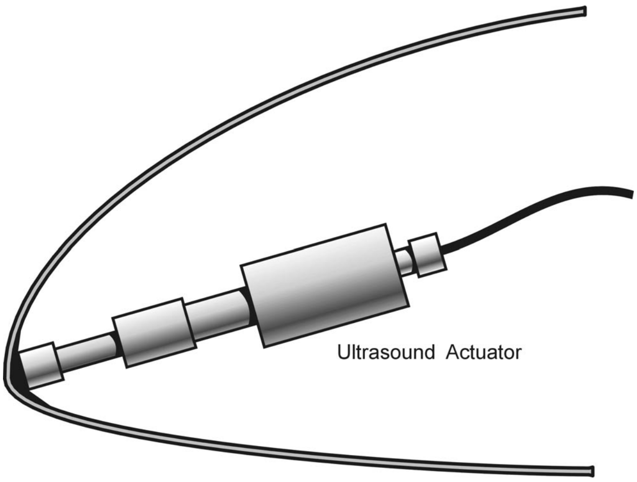

Fig.11 Ultrasound actuator placed inside the nose of leading edge

4.8 Ice Protection Systems Based on Fluid (Weeping wings)

The fluid ice protection method is based upon the freezing point depressant concept [63]. An antifreeze fluid is pumped from panels mounted on the leading edges of wings, horizontal and vertical stabilizers. The solution mixes with the super-cooled water in the cloud, depresses its freezing point, and allows the mixture to flow off of the aircraft without freezing. Fluid ice protection system started in the 1930's. The TKS Ice Protection Systems were developed during WWII, as an ice protection measure that was compatible with armoured leading edges, when a balloon cable could strike the leading edges of the wing and when a rubber boot on the leading edge was not acceptable. The first TKS systems developed were relatively crude, porous channel systems, partly made from porous, powdered metal. During next years the concept evolved and became mature. In the early 80's, laser-drilled panels were developed and first applied to the Cessna Citation SII as standard equipment. With the introduction of the system for the Beech Bonanza, the foundation for the development of several general aviation class systems was laid. As typical fluid the AL-5 is used. It consists of ethylene glycol (85%), isopropyl alcohol (5%) and de-ionized water (10% by volume). Since the 1987, the following systems have been certified in US and are available to customers: Beech (Raytheon), Mooney (M20J, M20K, M20M, M20R), Cessna (U206F, U206G, P210), Socata (TB20, TB21), Commander Aircraft (114B, 114TC) and many other [63].

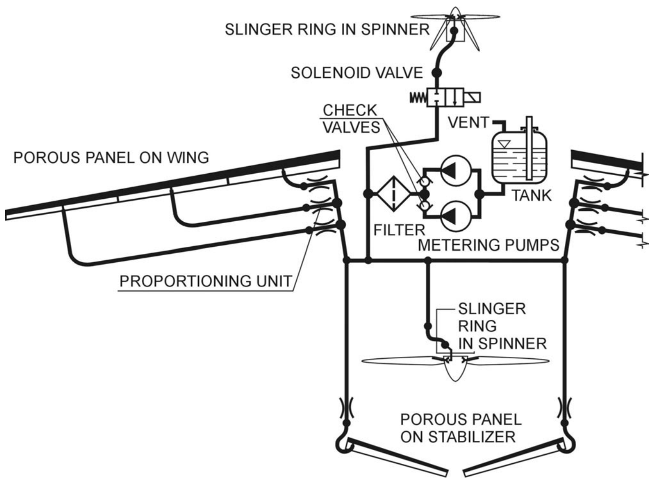

Fig.12 Ice Protection Fluid System proposed for MALE UAV, developed at Warsaw University of Technology

4.9 Shape Memory Alloys (SMA) deicing technology

Shape Memory Alloy (SMA) materials exhibit the ability to transform shape and create force through a martinsitic phase transformation following an appropriate amount of energy is delivered to the material. This energy is typically applied by external heating or direct resistive heating of the SMA material itself. This phenomenon can be utilized to mechanically manipulate a surface to remove ice through unique methods of surface bending, shearing, pealing or acceleration. In one version, a thin sheet of SMA material is mounted to the icing prone Leading Edge surface to perform the force and displacement combination that can debond ice [64]. After allowing a small amount of ice to build up, the SMA sheet is activated to shrink like a piece of rubber, shearing and peeling the ice off into the air stream. The following features and steps are important: Latent heat transfers from the ice to strips of SMAs at the LE; Heat activates the LE deicer & shed the ice; LE is rapidly cooled & SMA restores to its original shape and; Whole process goes autonomously.In another (preferred) version, the deicing system includes a SMA actuator and a SMA sheet. The SMA actuator stretches the SMA sheet to achieve the ice debonding action. The SMA actuator is located aft of the icing area and when it is activated by heating, it pulls on the SMA sheet. When the SMA sheet is under tension, it is forced over a ribbed underlay and grooved bands (riblets) which causes a complex strain field that severs the ice's adhesive bond. The riblets can be made to form in either the chordwise or the spanwise direction. The most common SMA material, a nickel-titanium (NiTi) alloy, possesses a high combination of corrosion, erosion, and abrasion resistance and is ideally suited for service as a Leading Edge erosion shield material. Transformation temperatures between -100^{o} and $+100^{o}$ C are possible and depend on the particular alloy composition. Every square foot of de-icer area (SMA sheet 310) will require a 0.03 m^2 of activated SMA actuator 300 for a SMA sheet. Detailed calculations have shown that if the SMA actuator is heated in 10 sec, 2.7 kW/m^2 are needed. This can be compared with 38.7 kW/m^2 typically required for electrothermal de-icers. Much more details is presented in US Patent no 5,686,003, the invention and property of Innovative Dynamics, Inc. (Ithaca, NY).

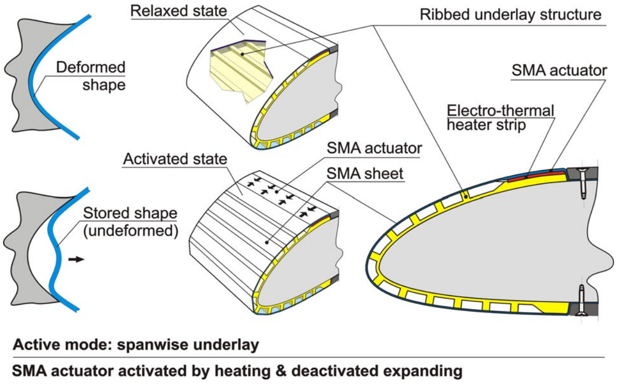

Fig.13 Ice Protection System based on Shape Memory Alloys, US Patent 5,686,003

4.10 Icing sensors

From safety point of view it is very important to have reliable information about the icing onset. Typically the system for icing monitoring uses of a thin film capacitivity-based sensor [43]. Sensor element consists of a copper electrode embedded in a polyimide laminate, which is bonded to the host airfoil. A small electric field is set up on the exposed surface of the sensor. The presence of ice on the sensor surface alters the field characteristics which are monitored by the sensor electrodes. The sensing region measures 1.5 inches chord-wise and 4.5 inches span-wise. Remotely located computer analyses and interprets the electric field signals. An example of a fully automated system for measuring the ambient temperature, thickness of ice and a freezing temperature of liquid, developed to be used together with the Ice Fluid Protection System by NASA Ames Research Center, is presented in Fig.14. Another useful devise is the so-called Ice Advisor, which uses an eyesafe laser to remotely determine the presence of ice on a surface. By sensing the absorption and reflection of laser light from the environment, the Ice Adviser is able to alert the crew of the existence of icing conditions.

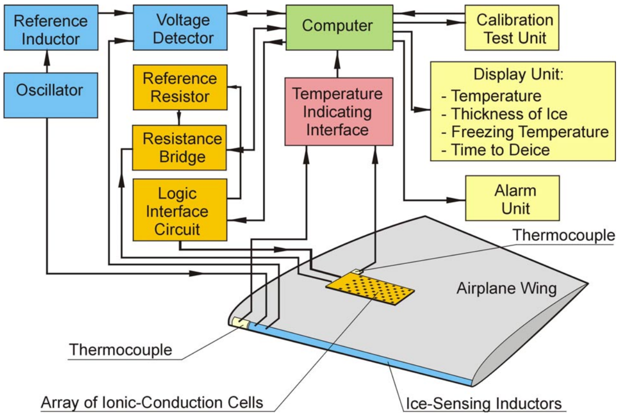

Fig.14 Ice thickness monitoring system developed at NASA Ames, US Patent No. 5,523,959

5 Research Project (DEICING) devoted to anti-icing / de-icing technology comparison and effectiveness

The idea of a such project was created on the forum of the UAV_NET consortium [61] and was elaborated by Warsaw University of Technology. Producers of key technologies might be asked to deliver a leading edge anti icing / deicing panels for testing of its efficiency. It is important to test original anti icing / deicing devices in the same laboratory and in the same conditions. To compare system's efficiency it is unnecessary to use any icing wind tunnel, an industrial refrigerator chamber will be sufficient to simulate the ice accretion.

In order to satisfy the future demands from industry, there is a pressing need to develop the anti-icing systems & the ice-selecting sensors that will be cost effective, reliable, almost maintenance-free, not interfering with other on-board systems & not decreasing the aerodynamic characteristics of wings.

The main objectives of the DEICING project are to: Identify the requirements for ice protection both for commuters, airliners & taxi-jet airplanes; Compare critical technologies currently available; Improve on the present-state-of-the-art and know-how; Select reliable, cost-effective, maintenance-easy, not interfering with other on-board systems & keeping undeteriorated aerodynamic characteristics.

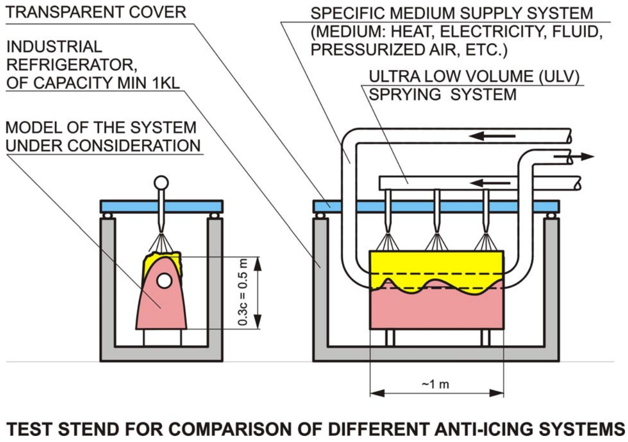

Fig.15 An industrial refrigerator to be used for testing

Important parameters and characteristics to be investigated and compared during research and testing could be: Power consumption; Effectiveness in different flight condition; Limitation in use; Safety issues; Environmental issues; In-flight diagnostics; Risk analysis; Cost analysis; Reliability; Weight analysis; Maturity assessment; Electromagnetic interference; Airworthiness; Certification issues.

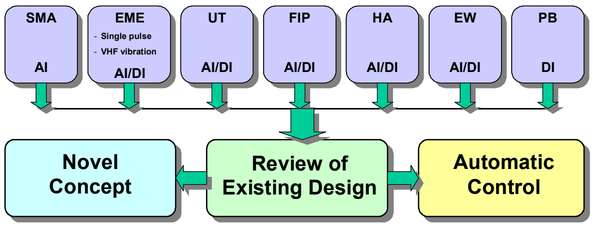

Fig.16 After an assessment a novel concept of antiicing technology will be proposed and a corresponding control will be elaborated

Table 2. Technologies to be compared within the proposed project

technology	leading company to be asked for LE panel delivery for testing
SMA (Shape Memory Alloys)	FOX
EESS (Electro-Expulsive Separation	NASA, Ice Management

System)	Systems, Inc.
SPEED (Sonic Pulse Electro-Expulsive Deicer)	IDI (Innovative Dynamics Inc.)
EMEDS (Electro-Mechanical Expulsion Deicing System), vabrations	COX & Company, Inc.
EME (Electro-Mechanical Expulsion)	Goodrich
UT (UltraSound Technology)	NASA, AIRTECH
FIP (Fluid Ice Protection)	TKS
EW (Electrical Wire)	B/E AEROSPACE
PB (Pneumatic Boot)	Goodrich, B/E AEROSPACE

6 Conclusion and recommendations

A number of anti-icing and de-icing technologies are available to-day. Some of them are still immature and need further extensive investigation and testing in laboratories and in-flight. Other are commercially available and are certified on older type small and medium size aircraft. However, there is still a big risk for producers of new model aircraft to adopt one of such modern technology. From the other side, both the European and American priority list for aeronautics includes safety and all-weather operation. It is only the matter of time when such a safe and reliable new anti-icing / de-icing technology will be widely used in aviation.

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