CAV ICE PROTECTION LTD

Electrothermal-FPD Hybrid System

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SYMBOLS AND DEFINITIONS

Symbol or Abbreviation	Definition
AOA	Angle of Attack
CNT	Carbon Nanotubes
ET	Electrothermal
FPD	Freezing Point Depressant
IPS	Ice Protection System
KTAS	True Airspeed (Knots)
LWC	Liquid Water Content
MVD	Mean Volumetric Diameter
OAT	Outside Air Temperature
TAS	True Airspeed
g	Grams
kW	Kilowatts
ml	Milliliters
m	Meters
µm	Micrometre (Micron)
min	Minute
in	Inches
psi	Pounds per square inch
s	Seconds
^{o}F	Degrees Fahrenheit
^{o}C	Degrees Celsius
^{o}	Degrees

1. INTRODUCTION

As large commercial aircraft continue to attempt to decrease their bleed air demands and smaller aircraft look for more efficient and higher performing ice protection systems (IPS) the industry must look at new solutions. One method used to improve upon current system IPS is to combine the strengths of multiple ice protection methods to create a hybrid system which offsets the disadvantages of the various system types. This paper looks at the creation of a hybrid system by combining a freezing point depressant (FPD) system with an electrothermal de-ice system.

The use of freezing-point depressant and electrothermal ice protection systems have been well established in the aviation industry. Both types of systems have been certified on Part 23 and Part 25 aircraft and are in use today. One of the major challenges for an electrothermal IPS is the power generation required to achieve certifiable performance over the entire FAR Part 25 Appendix C Icing Envelope. This is especially critical in the coldest temperature areas of the Icing Envelope. For an FPD system one of the perceived challenges is the weight of the fluid required to be carried to meet regulatory requirements and ensure appropriate system endurance.

The goal of the hybrid system was to maintain or improve upon the established electrothermal de-ice IPS performance while minimizing power usage and fluid consumption. This would result in a lower power generation requirement for the aircraft while lowering the amount of fluid required to be carried to meet regulatory requirements.

2. FREEZING-POINT DEPRESSANT SYSTEMS

In aircraft icing, freezing-point depression occurs when the mixture of two or more materials leads to a decreased freezing point of the original material. Traditional CAV ice protection systems utilize this phenomenon by excreting glycol-based fluids through the leading edges of the protected areas where it mixes with airborne water droplets to prevent or remove airframe icing.

Figure 1: FPD Fluid Flowing from a Porous Panel

2.1 POROUS PANELS

FPD ice protection systems are fluid-based systems whereby a fluid that acts as a freezing point depressant is delivered via a pipeline system to the leading edges of a protected surface via porous panels. The porous panels primarily consist of a titanium outer skin (frontplate) and inner skin (backplate) as well as a porous membrane. The frontplate contains a porous area termed the active area which is created by laser drilling holes 0.0025 inches in diameter with a pitch that provides 800 holes per square inch. The backplate is formed such that when it is laser welded to the frontplate it forms a reservoir that allows fluid to be supplied to the entire porous area of the frontplate. The porous membrane is located within this reservoir and it assures even flow distribution of the FPD fluid across the entire active area. Figure 2 shows a cross section of a typical porous panel. These panels can be designed as an integral part of the aircraft structure or fit over an existing leading edge as an “overshoe”

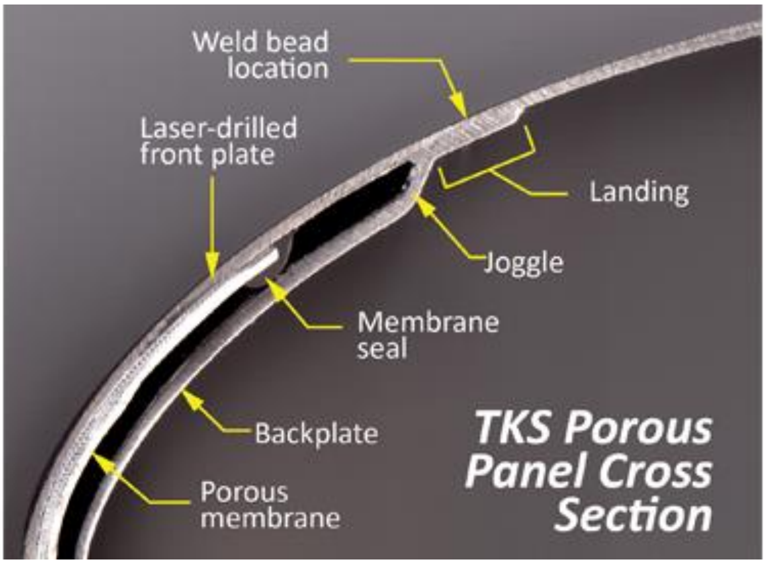

Figure 2: Cross Section of a Typical Porous Panel

2.2 SYSTEM DESIGN FUNDAMENTALS

When supercooled water impinges on the surfaces protected by the porous panels they combine with the FPD fluid to form a mixture. The temperature and ratio of the mixture determines the performance of the system.

If enough FPD fluid is provided at the point of maximum water catch, the freezing point of the fluid mixture will fall below the ambient air temperature, preventing any ice from forming. In this instance the system is said to be performing in an “anti-icing” mode.

If the icing conditions were to worsen and the volume of FPD fluid being supplied became insufficient to handle the increased water catch, then the result would be a process of periodic building and shedding of ice accretion on the protected surface. In this instance the system is said to be performing in a “natural de-icing” mode.

After “natural de-ice” mode, as the water catch becomes more intense, the local ice accumulation will become larger prior to departure from the airframe. The upper limit of natural de-icing is reached when a continuous strip of ice accretes on a protected surface before it sheds.

If system start-up occurs after ice has already accreted, the exuding FPD fluid will melt the interface so that the ice can be shed under aerodynamic forces, in this instance the system is said to be performing in a “de-icing” mode.

Under ideal circumstances the required volume of FPD fluid would be matched to the icing condition resulting in anti-icing. This approach is used for the continuous maximum envelope but is impractical and unnecessary for the maximum intermittent envelope because of the de-ice capability of the system and the short intercept time of an intermittent maximum encounter.

2.3 DESIGN POINT DETERMINATION

FPD ice protection systems are designed with the capability to provide freezing point depression over the FAA continuous maximum icing envelope for the protected surfaces. This approach provides a pure anti-icing capability for all flight conditions within the envelope. It is also capable of providing de-ice capability during and after encounters with ice defined by the intermittent maximum envelope.

Freezing point depression is achieved when the amount of ice protection fluid mixing with the water catch reaches a critical ratio which results in the freezing point of the fluid mixture becoming lower than the ambient temperature. When the correct mixture is achieved, pure anti-icing will occur. Since this is the basic design principle of the FPD system, the first objective is to identify the condition within the continuous maximum icing envelope, as defined Part 25 Appendix C where the maximum water catch occurs. This first design step may be accomplished with no regard to the fundamental geometry of the aircraft.

First, the Continuous Maximum envelope is cross-plotted versus temperature at constant droplet diameters as shown in Figure 3.

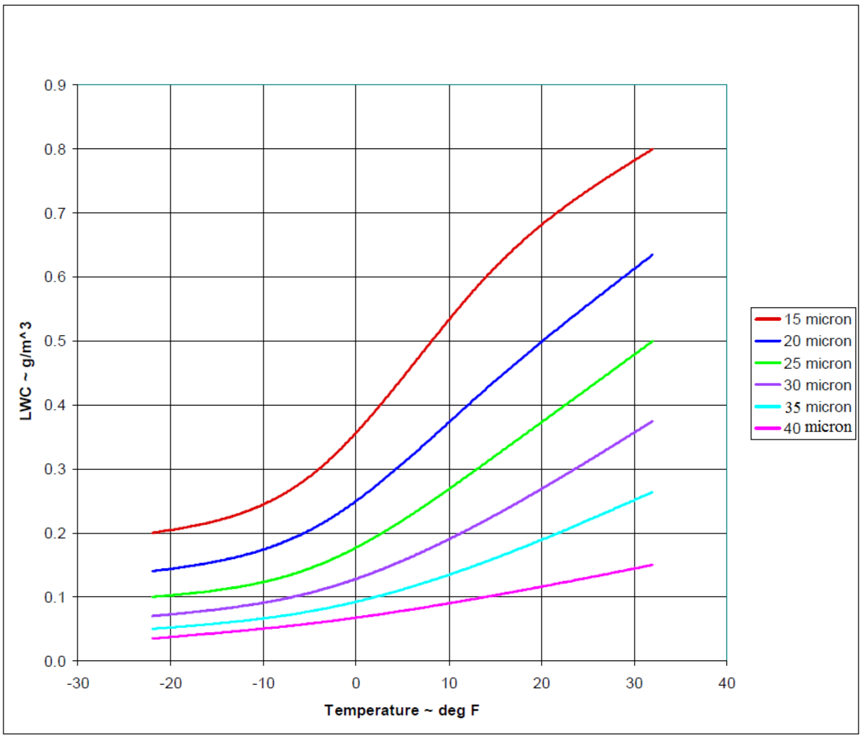

Figure 3: Continuous Maximum Icing Envelope as a Function of Temperature

The next element of the process is to apply the fluid requirement to the water content of the envelope. Figure 4 presents the mass fraction of FPD fluid required for anti-icing. The information for this figure can be found both in the Aircraft Icing Handbook and ADS-4, though the plot is inverted in this document. The amount of fluid required for a given volume of water may be found from the following equation:

$$V_F = \frac{V_W \, . FPD}{(1 - FPD)} \tag{1}$$

Where:

V_F = Volume of FPD fluid

V_W = Volume of water

FPD = mass fraction value from Figure 4

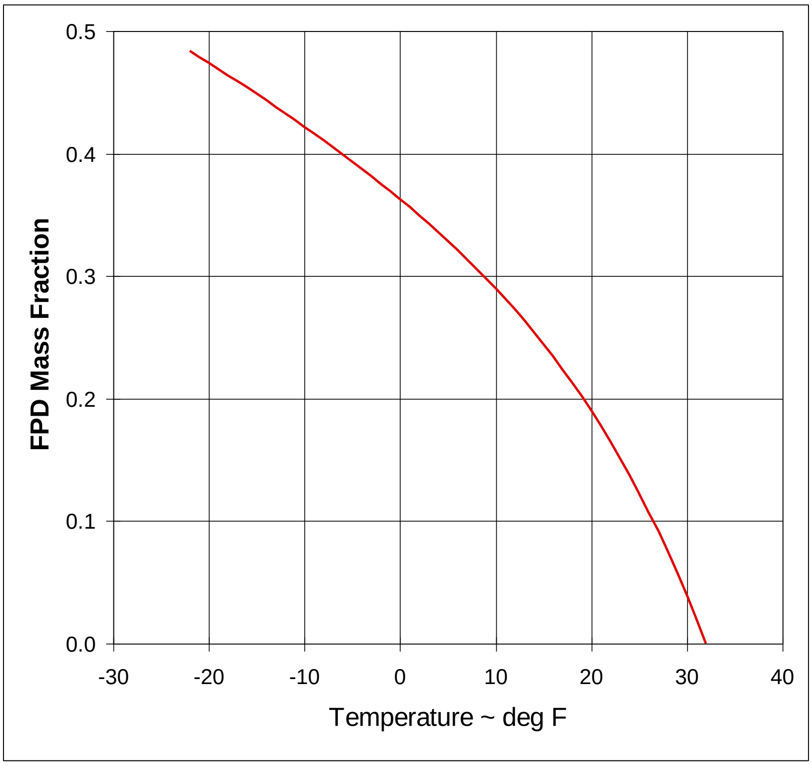

Figure 4: Ice Protection Fluid Mass Fraction Characteristics

The equation above allows the volume of fluid required across the icing envelope to be calculated by inserting data from Figure 3 in place of the V_W term and data from Figure 4 in place of the *FPD* term. The results of this exercise appear in Figure 5. The figure illustrates a characteristic that is fundamental to the design of a FPD system for freezing point depression. The peaks of each curve identify the critical temperature for each droplet size, i.e. the point that requires the maximum volume of FPD fluid.

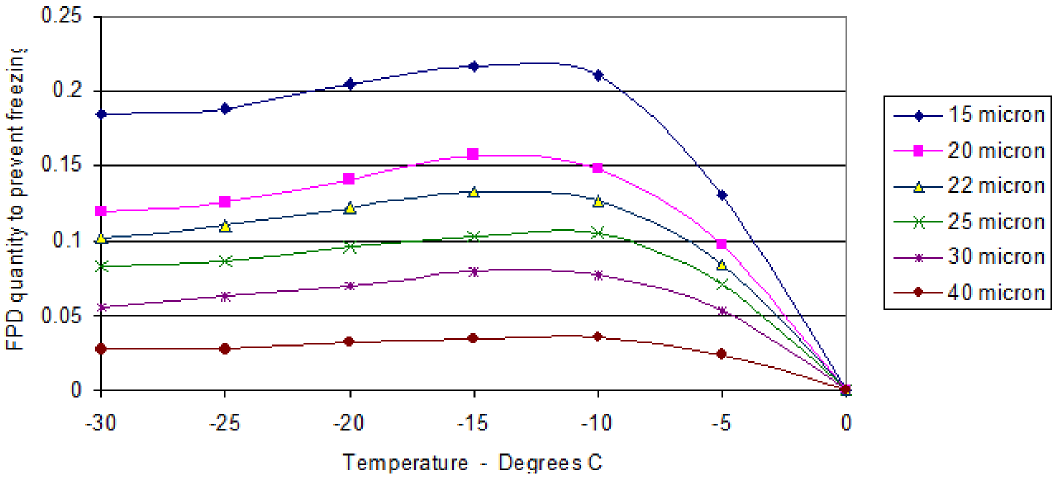

Figure 5: Continuous Maximum Critical Temperature

Although Figure 5 has been developed without reference to catch efficiency, it shows that regardless of cloud Median Volumetric Diameter (MVD), the temperature at which most FPD fluid is required is -12.5° C (9.5°F). The figure also suggests that the 15-micron droplet size condition results in the critical amount of required FPD fluid. As discussed previously, these data points consider only the relationship between the Appendix C continuous maximum envelope and the freezing fraction curve of the FPD fluid. The final critical conditions for a given aircraft are influenced by the flight conditions, and the size and shape of the airfoils.

For reference purposes, the identification of the critical temperature within the Intermittent Maximum envelope is also determined. The envelope development and analysis follow the same process used in determining critical temperature for the Continuous Maximum envelope. The results of this development appear in Figure 6, indicating a critical temperature of -20 °C for the 15-micron case. Typical FPD systems are not designed to provide anti-ice protection for the Intermittent Maximum envelope; however, identifying the critical temperature in this envelope is beneficial as it allows for estimation of de-icing performance during these severe encounters.

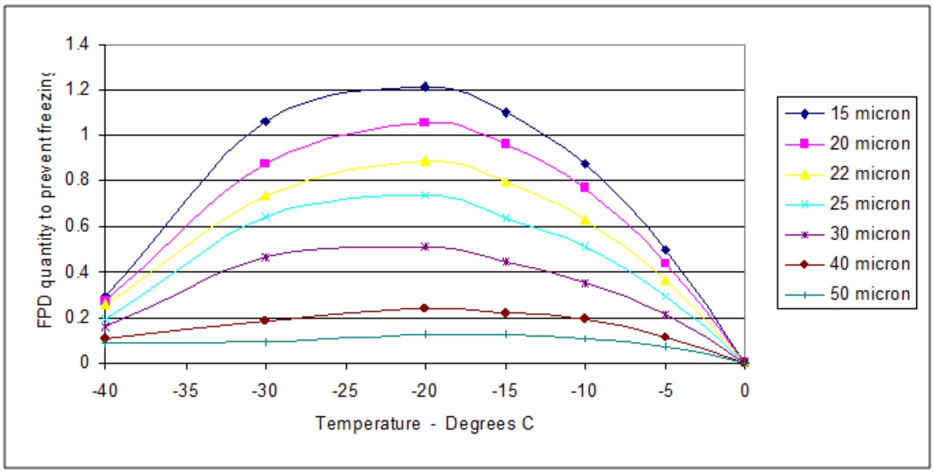

Figure 6: Intermittent Maximum Critical Temperature

2.4 PANEL DESIGN PHILOSOPHY

Following identification of the design points, an impingement analysis is performed for the appropriate sections of the aircraft. The analysis is performed using the LEWICE icing analysis program developed by NASA to determine the location and volume of water impinging on the airfoil at the root and tip locations of the panel.

FPD, fluid-based systems are sensitive to the location of the airflow stagnation point on the airfoil as it influences the water catch distribution and the FPD fluid dispersion to the upper and lower surfaces. Any factor that contributes to the location of the stagnation point (e.g. climb/cruise speed, MGW, etc.) needs to be considered in the design, and ideally, the stagnation point is determined through flight tests at the critical configurations such as heavy climb and light cruise. An illustration of the effects stagnation point has on fluid and water distribution on an airfoil is shown in Figure 7. After determining the flight envelope, a catch efficiency and impingement analysis is performed, as discussed above, and used to define the porous area of each panel and the flow rate per unit area.

The computer software, LEWICE, contains an analytical ice accretion model that evaluates the thermodynamics of the freezing process that occur when supercooled droplets impinge on a body. The atmospheric parameters of temperature, pressure, and velocity, as well as the meteorological parameters of liquid water content (LWC), droplet diameter, and relative humidity are specified and used to determine the shape of the ice accretion. The software consists of four major modules. They are the flow field calculation, the particle trajectory and impingement calculation, the thermodynamic and ice growth calculation, and the modification of the airfoil geometry due to ice accretion. For porous panel design, only the first two major modules are required.

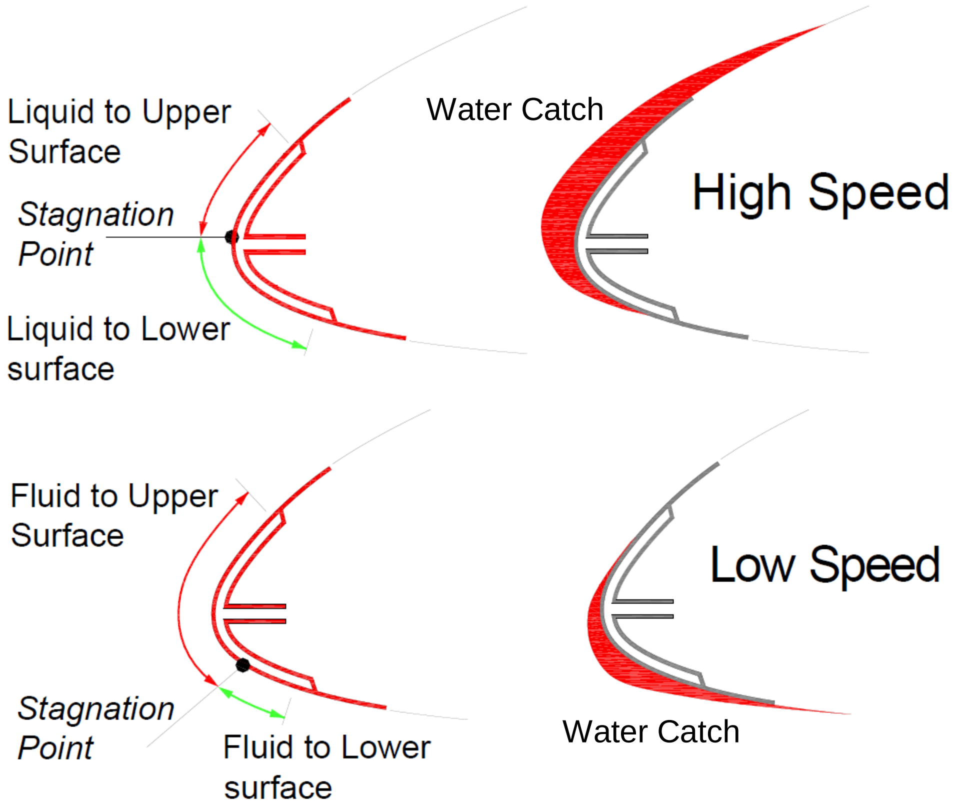

Figure 7: Effects of Stagnation Point on Water and Fluid Distribution

The specific flow rate (i.e. flow per unit area) of a porous panel cannot be varied across its span and is defined by the critical local water catch across the panel. The highest local water catch for any panel will occur at the region of greatest catch efficiency and at the highest true airspeed. For tapered surfaces the section with the smallest leading-edge radius (typically the outboard section) has the highest catch efficiency and the highest true airspeed occurs during the high-speed condition. Under these conditions the specific flow rate of FPD fluid is calculated so that it balances with the critical water catch.

Because the specific flow rate is invariant across the panel and is defined by the critical water catch, the panel will produce excess fluid in all areas where the water catch is less then critical. This excess fluid is moved aft along the surface by the airflow and helps keep the airfoil ice-free from impinging droplets and runback. By determining the extents of droplet impingement and the available excess fluid, the panel active area can be optimized (i.e. decreased) to the point where the amount of excess FPD fluid is zero at the impingement limits. This results in an efficient panel that will protect the aircraft surface throughout the prescribed icing-flight envelope. The typical workflow for a panel design is shown in Figure 8.

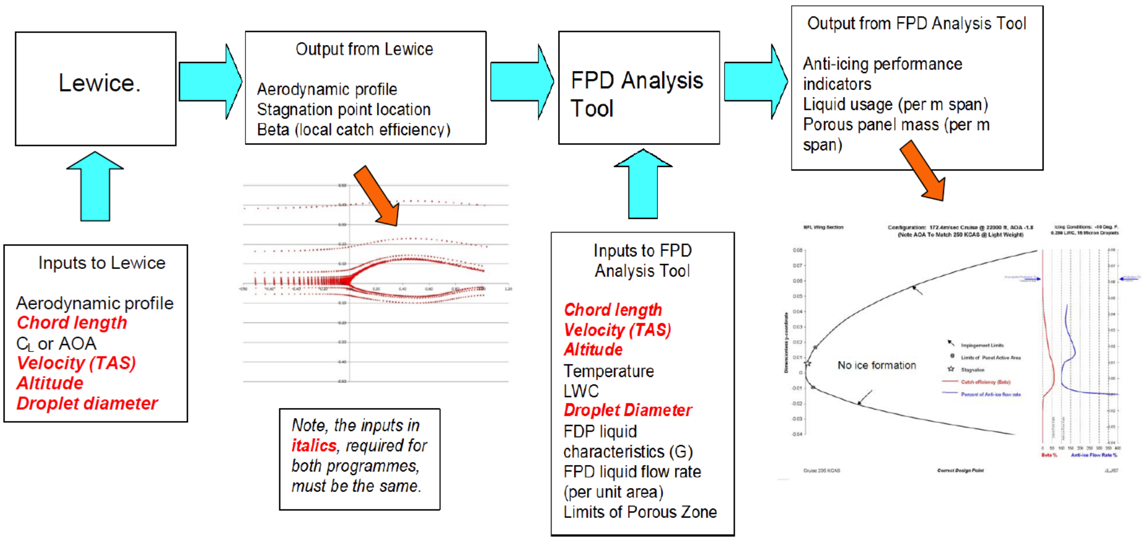

Figure 8: Typical Panel Design Workflow

3. ELECTROTHERMAL SYSTEMS

Electrothermal ice protection systems utilize excess available electrical power within the aircraft to heat the protected surfaces through resistive heating. Unlike FPD systems, electrothermal systems require the addition of energy to raise the temperature of the protected surface above the normal freezing point of water.

3.1 HEATER MATS

Heater mats are typically a composite construction consisting of structural fibers, the resistive heating material, any electrical pathways, and resin. The layers are built in such a way that the resistive heater is electrically insulated from the rest of the composite and is as close to the outer mold line as possible to achieve maximum heat transfer efficiency. This heater mat layup is cured as part of the leading edge of the protected surface and has been demonstrated on both metallic and composite structures.

An example of a heater mat layup on an aluminum surface is shown in Figure 9. CAV has experience working with Carbon Nanotubes (CNT) and graphene as the resistive material, and most recently has developed polycrystalline graphene sheets via printable graphene ink on a carbon veil.

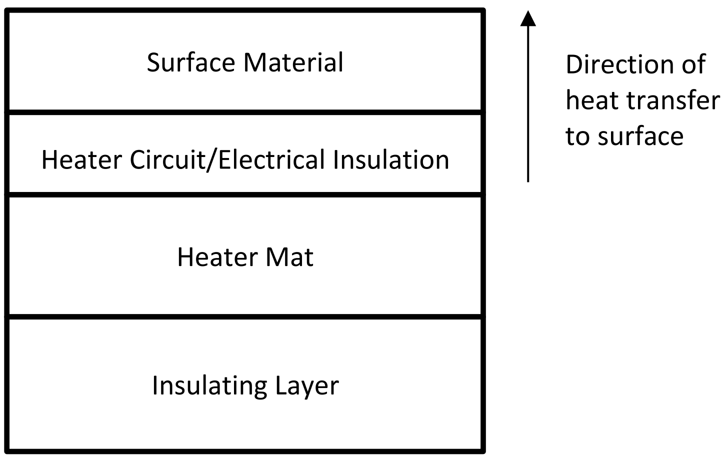

Figure 9: Basic Construction of a Heater Mat on a Structural Substrate

3.2 DESIGN FUNDAMENTALS

The proper design of an electrothermal ice protection system relies on the ability of the system to produce a surface temperature above the natural freezing point of water (0°C). An electrical source (an engine-mounted generator for example) supplies the electrical power that runs through the resistive heater. This electrical resistance produces heat that conductively transfers to the surface. For flight in an icing environment, the design must account for the cooling effects of convection from air passing over the surface, and conduction of supplied heat into the accumulated ice. The chordwise extents of the heater mats are determined based on analyses that provide water catch efficiency and droplet impingement values.

Electrothermal systems can be designed to operate as anti-ice or de-ice systems. Deicing occurs when ice accumulated on the surface is removed by activating the system. When enough power is supplied to the heater, the heat melts a thin ice layer at the surface and allows aerodynamic forces to remove the ice, after which the system can then be cyclically deactivated and activated resulting in a cycle of building and shedding ice. Ideally, the protected surface will heat up and cool down instantaneously and deactivate precisely when the ice sheds to minimize the formation of runback ice. By placing an additional de-ice zone at the area where runback ice is expected to occur, the system can cyclically activate this zone to remove the runback ice; however, it is nearly impossible to prevent all runback ice from forming even further aft on the airframe.

A large portion of the required power to run an electrothermal system in de-ice mode is due to a continuously heated section of the most forward part of the leading edge termed the parting strip. The parting strip provides the means to keep the ice accumulations on the upper and lower surfaces from bridging together at which point the ability of an ET system to properly de-ice becomes drastically more difficult as the aerodynamic forces cannot remove the ice. Because of this, the parting strip must continuously run "wet," where enough thermal energy is being produced to keep the impinging water in the liquid state, requiring a large power draw. An example of a de-ice electrothermal leading edge configuration is shown in .

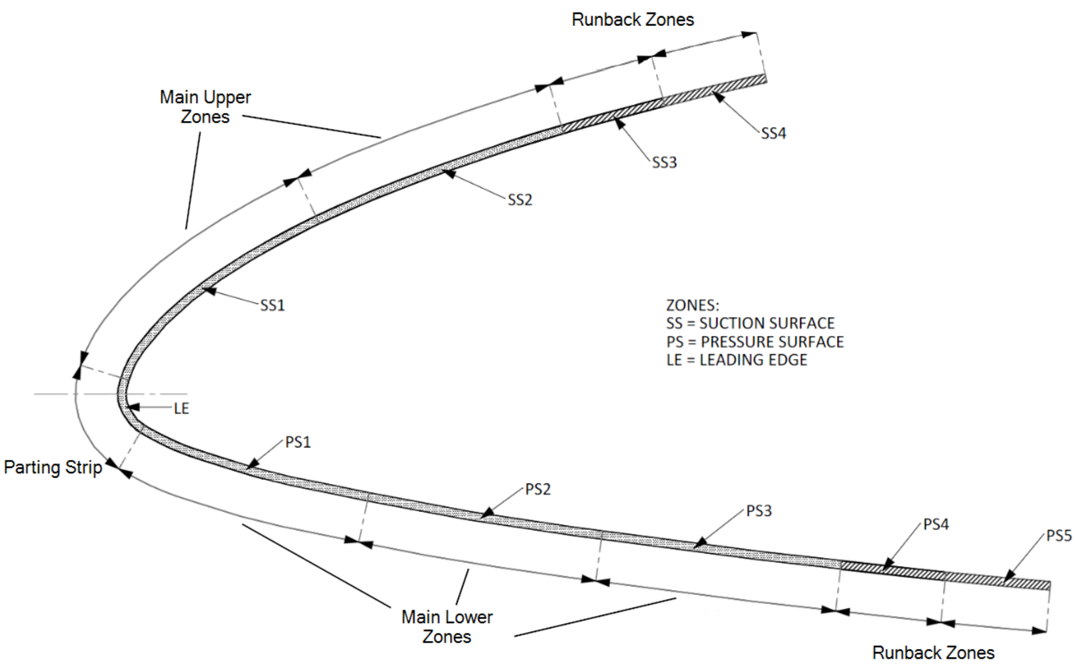

Figure 10: Example of an Electrothermal Leading Edge

For an anti-ice system, enough heating is provided to prevent the formation of ice from both impinging droplets and runback. In an ET system this happens when the system is running in evaporative mode, when the rate of evaporation exceeds the rate of water collection. When this happens, all the impinging water evaporates off the surface before any accumulations occur. Although this is desirable, electrothermal anti-icing requires significantly more power compared to deicing.

4. ELECTROTHERMAL-FPD HYBRID SYSTEM

4.1 HYBRID LEADING EDGE

A freezing point depressant-electrothermal hybrid system supplements an electrically heated leading edge with the low power requirements of FPD zones. This combination can lead to a lower total power requirement when compared to a pure ET system and can also protect the entire surface by using FPD fluid to prevent runback ice.

4.2 DESIGN PHILOSOPHY

A conceptual ET-FPD leading edge consists of 3 general zones: the FPD parting strip at the leading edge, the upper and lower electrothermal shedding zones, and the upper and lower FPD runback zones. A diagram of a possible hybrid leading edge configuration is shown in Figure 11.

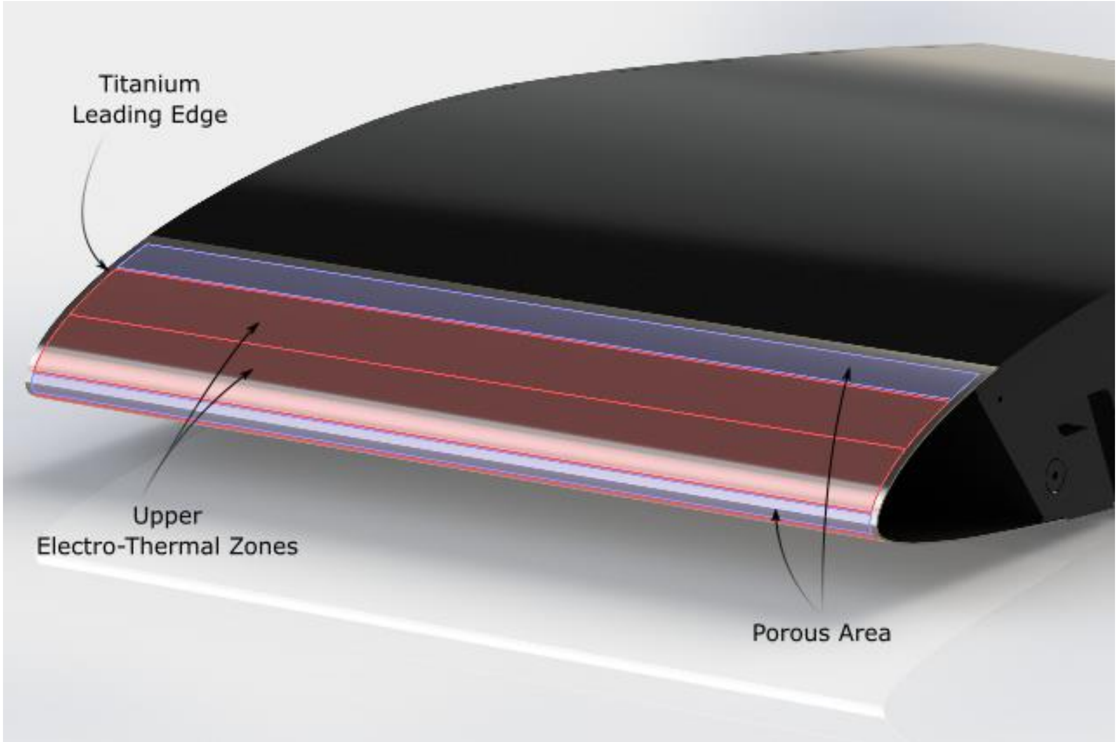

Figure 11: Hybrid Leading Edge Layout (Bottom Zones not Shown)

4.2.1 FPD PARTING STRIP

As discussed in the electrothermal section, the parting strip consumes a large portion of the total power required. In a hybrid leading edge, the high electric power requirement is traded with flowing FPD fluid. Utilizing an FPD parting strip over an ET one allows for a large reduction in power while having the added benefit of having any excess fluid aid with decreasing ice adhesion depending on where the aircraft is in the icing envelope.

Sizing of the FPD parting strip is very similar to the methods utilized in designing a pure FPD system, but to a lesser extent. An analysis or flight data is required to show the maximum travel range of the local stagnation point across the icing envelope. These stagnation point extents plus some additional active area added to both the top and bottom for a margin of safety define the width of the parting strip and are located as close the start of the first electrothermal zone as possible. The flowrate is designed to keep the parting strip and any space prior to the heated zones free from ice.

Because the parting strip is designed based on the extents of the stagnation points, there will be cases where the parting strip is providing excess fluid to a portion of the protected surface. For example, during cruise, the stagnation point is located at the upper extent of the parting strip. This forces most of the FPD fluid exuding from the leading edge to travel to the lower surface where the excess fluid mixes with the incoming water and prevents it from freezing, providing anti-ice performance on the lower surface. This naturally leads to a decrease in power required since the lower surface heater activation is not required.

4.2.2 ELECTROTHERMAL SHEDDING ZONES

Similar to the design previously discussed in the electrothermal section, the ET zones are sized based on an analysis that determines the catch efficiency and water impingement on the airfoil. This defines the aft limit of the heaters, while the forward limit is simply defined by the extent of the FPD parting strip. As demonstrated in Figure 11, the heated zones can be divided up and activated independently.

4.2.3 FPD RUNBACK ZONES

The freezing point depressant runback zones are porous areas, like the parting strip, that exude FPD fluid to prevent the water generated by the heating of the ET zones from refreezing on the aft portion of the protected surface. These zones are located behind the electrothermal areas and are only activated periodically when the buildup of runback ice requires their use.

Because the runback zones are typically beyond the impingement points (other than SLD conditions), the size of the runback zones isn't critical to their performance so long as the system can exude enough fluid at a safe pressure to clear the runback ice. More importantly, it is desired to have the forward starting point of the active area of these zones as close as physically possible to the aft limit of the heater mat. This allows for the heated water running back from the heater mat to successfully reach a point on the surface where the FPD fluid can either mix with it or remove it after it refreezes.

These zones can also function as devices to protect against an SLD encounter. SLD droplets impact further back on the airfoil than a typical icing encounter—something that pure electrothermal system cannot protect against. FPD fluid from the runback zones will travel aft and mix with the SLD droplets preventing or removing ice accretion. These "SLD strips" have previously been proven to be effective against SLD conditions independent of the primary ice protection system.

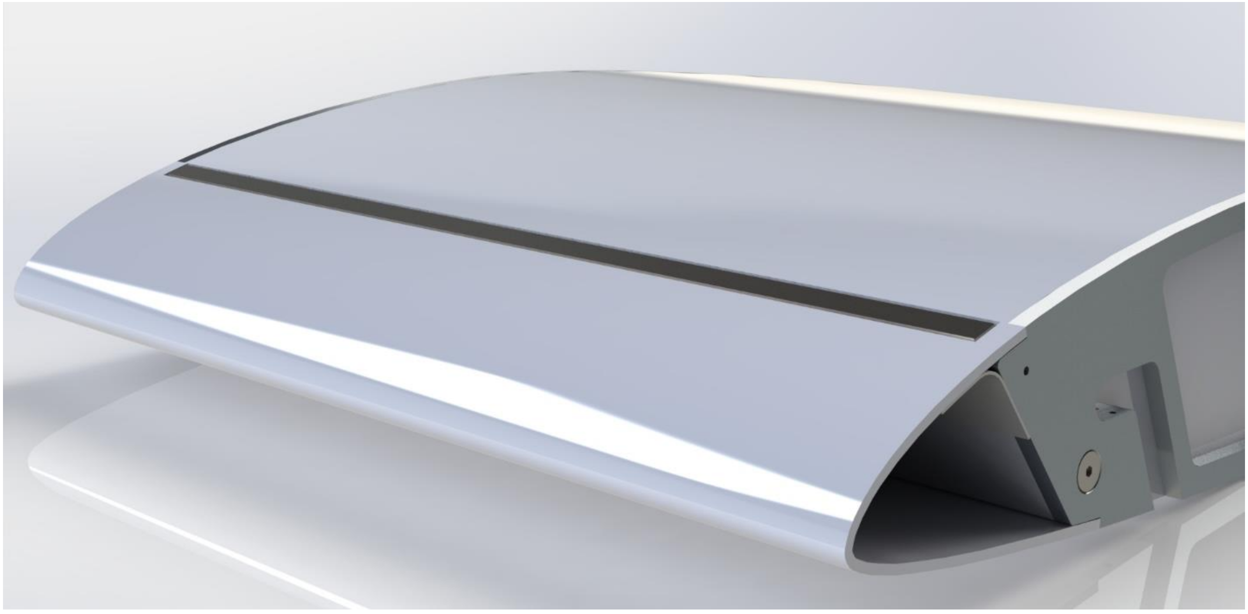

Figure 12: Implementation of an FPD SLD/Runback Zone

4.3 SYSTEM DESIGN

The system design of an ET-FPD hybrid ice protection system does not have a single solution for any given aircraft. It is dependent on the customer's desires and provides a flexible means to lower the required energy demanded by an electrothermal system. Figure 13 shows a typical curve for a single aircraft along which describes the relationship between the power required to effectively run the electrothermal zones and the amount of fluid required to run the parting strip and runback zones. This curve is defined by various configurations for a given aircraft. At the far-left end, the end point of the curve represents a pure electrothermal system whereas the far-right end is representative of a pure FPD system. Points along this line between these two extremes signify configurations that combine them. For example, an intermediate point could be one that utilizes hybrid panels on all protected surfaces.

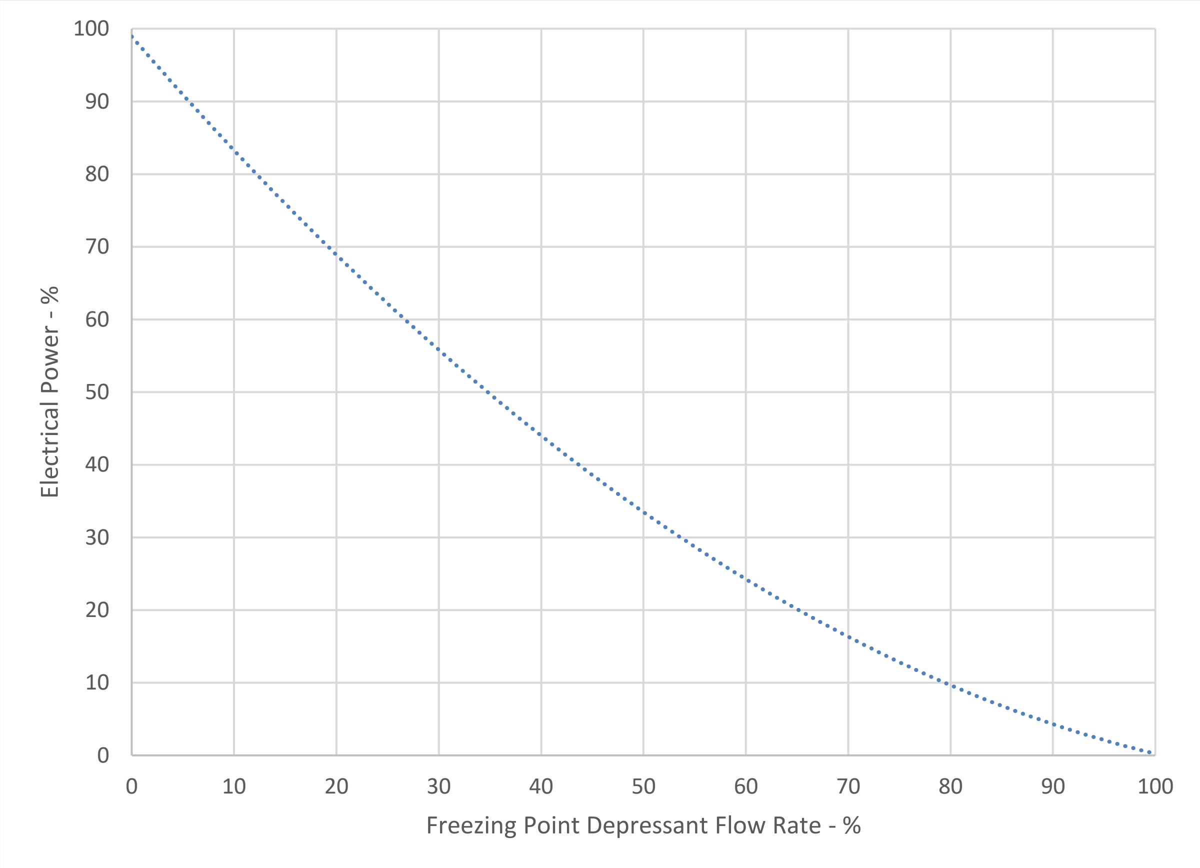

Figure 13: Generalized Hybrid Relation Curve

4.4 TESTING

A physical, full-scale test model built by CAV has been successfully demonstrated in an icing wind tunnel test—the layout of the leading edge is shown in Figure 12 (Note: not shown, the ET zones are further separated into independently-controlled zones--two on the upper surface and three on the lower surface). The aim of the test was to assess both the de-icing and anti-icing capability of the ET-FPD hybrid system, as well as to optimize the relationship between electrical power and fluid flowrate in various icing conditions including those representing the critical conditions in the Appendix C icing envelope.

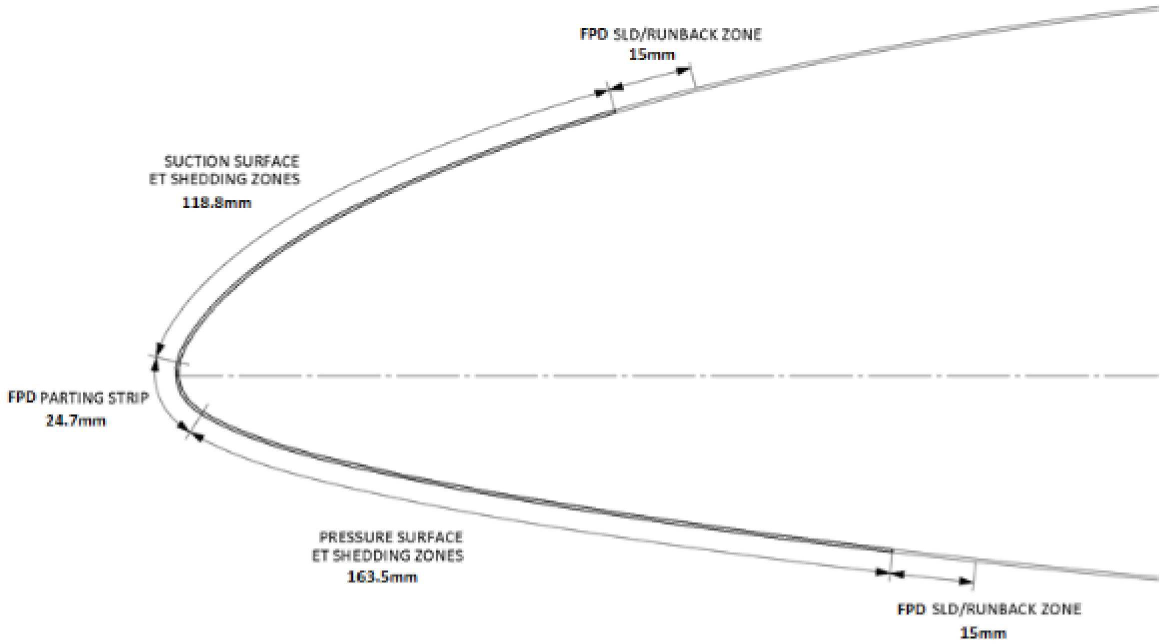

Figure 14: Zones of the Hybrid Test Model

During the tests, the performance of the parting strip and the electrothermal zones were compared to the requirements as predicted by CAV and adjusted up or down to optimize the system for each case (i.e. minimal fluid and power required to de-ice). For this test, the runback zones were operated continuously except for the cases where the parting strip provided enough fluid to fully protect either the upper or lower surface at which point the runback zones were fully disabled. In some cases, it was also possible to deactivate one of the ET zones because of the capability of the parting strip which lead to an overall power requirement reduction. When the ET zones were activated, they were kept on for either 5, 10, or 15 seconds, depending on the temperature of the condition. These times are representative of the amount of time each power would be supplied to each section (8 sections) on an aircraft if a 2-minute aircraft cycle time was used.

The following two pages are pictorial examples of test runs for cruise and climb conditions.

Table 1: Example Cruise Test Point

Altitude (ft)	Temp (°C)	AOA (°)	TAS (m/s)	LWC (g/m^3)	MVD (µm)
13800	-20 (-19.5*)	0.2 (1.8*)	106 (86*)	0.21 (0.37*)	20 (25*)

For this condition, because the parting strip was providing enough fluid, the lower surface runback zone and electrothermal zone were both deactivated.

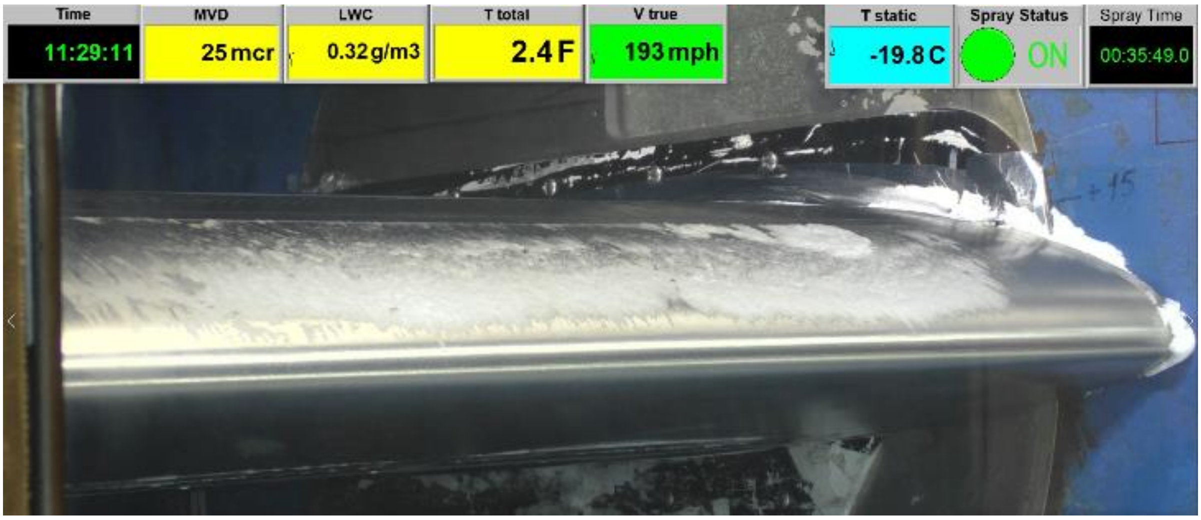

Figure 15: Parting Strip Optimized (16.8 ml/min) and Prior to ET Activation

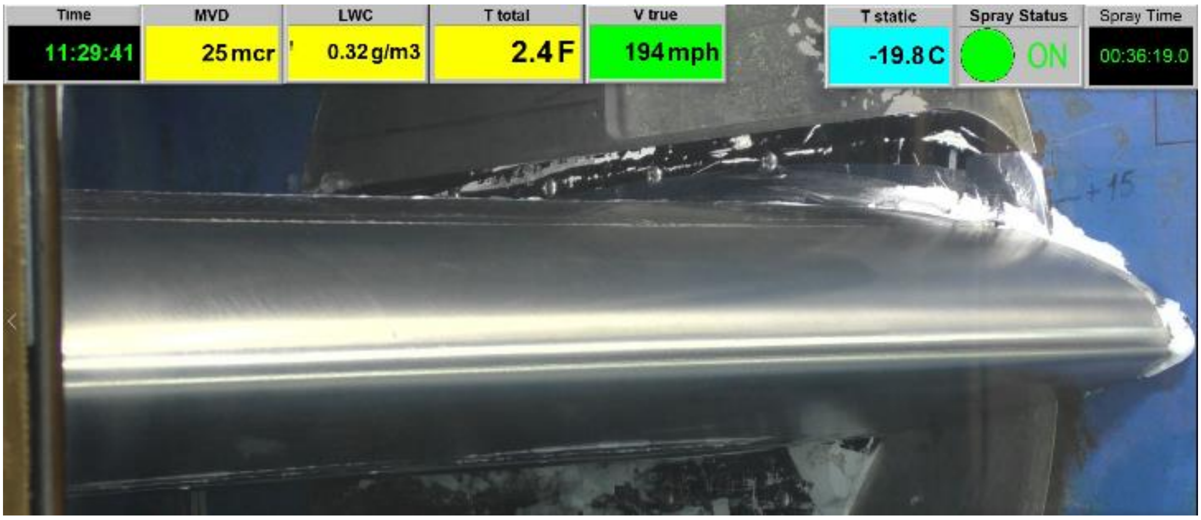

Figure 16: After Activation of the ET Zone (8 kW/m^2)

Table 2: Example Climb Test Point

Altitude (ft)	Temp (°C)	AOA (°)	TAS (m/s)	LWC (g/m^3)	MVD (µm)
22000	-12.5 (-14.4*)	3.2 (3*)	82 (59*)	0.51 (0.74*)	15 (21*)

In contrast to the cruise test point, the fluid from the parting strip was providing enough fluid to now allow the upper surface ET zone and runback zone to be deactivated.

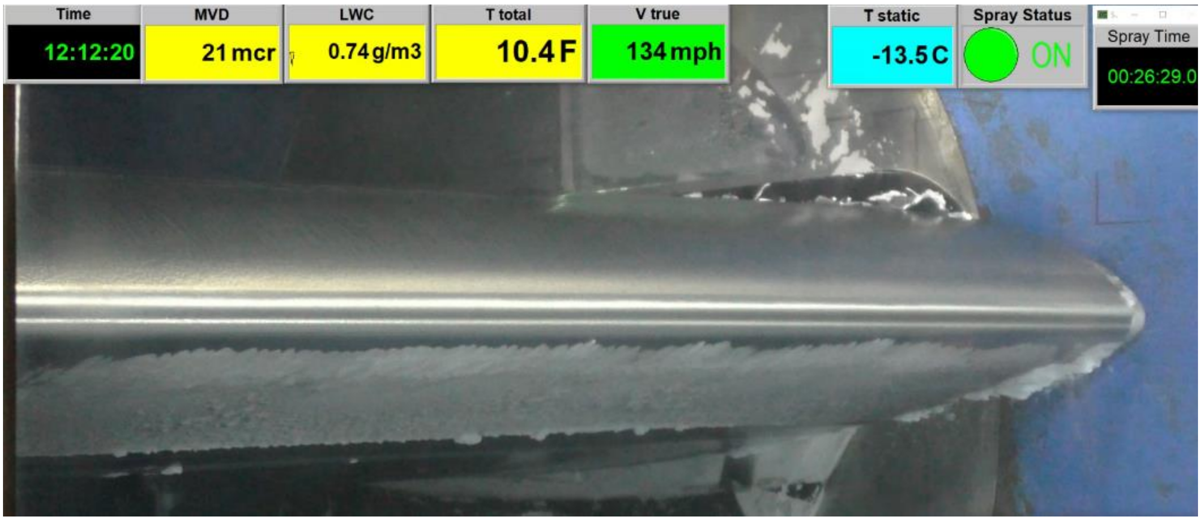

Figure 17: Parting Strip at 17.3 ml/min and Prior to ET Activation

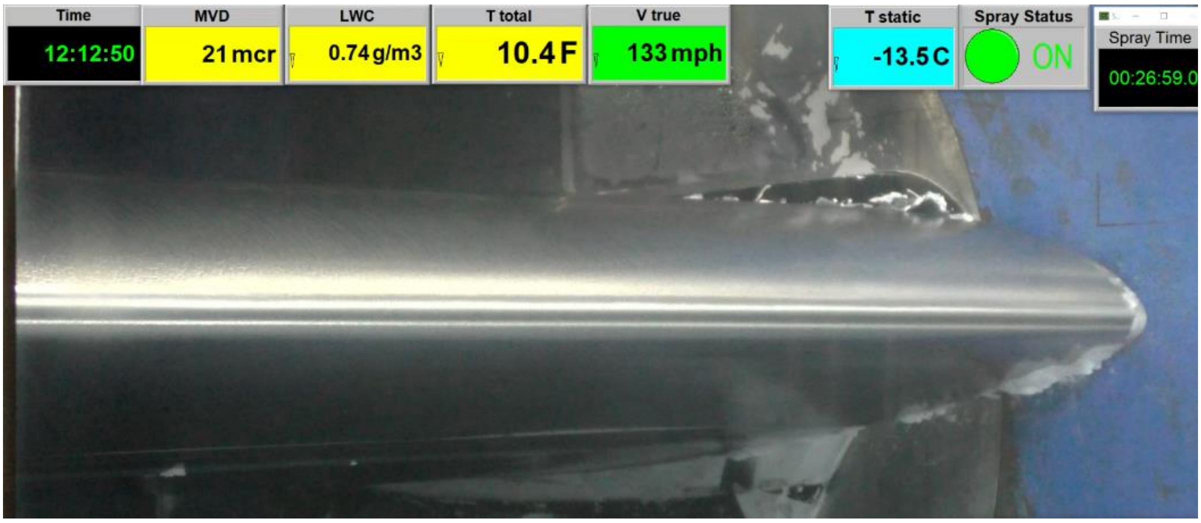

Figure 18: After ET Zone Activation (32.5 kW/m^2)

The result of the testing concludes with the development of data relating the icing conditions to power and fluid requirements per unit area. Projection of this data onto an aircraft as an estimation of the requirements for an ice protection system leads to the development of a design space graph as discussed in Section 4.3. This paper concludes with an example in the following section.

5. CONCLUSION

Based on the results of the wind tunnel testing and the accompanying theoretical analyses, it is possible to show what a hybrid-system design envelope may look like for a given aircraft. Figure 19 below represents the design space for a hybrid system on a transport category turboprop.

As discussed in Section 4.3, the left and right-most points represent an aircraft with solely electrothermal protection or solely FPD protection respectively. The intermediate, labeled points show where different combinations and level of electrothermal protection fall near the line. The values for the points are related to the most critical icing condition. It is assumed that the ET zones are separated such that each zone activates every 2 minutes for up to 15 seconds. The parting strips, whether ET or FPD, run continuously while in icing to prevent ice bridging as discussed previously. The estimated flowrates and power requirements for this graph are shown in Table 3.

This data suggests that a significant reduction in power can be obtained by utilizing an ET-FPD hybrid system. Comparing a fully electrothermal system to the first point representing a hybrid system on all protected surfaces, the power requirement decreases from 85.8 kW to 35.0 kW, a reduction of nearly 60%. The fluid required at this same point is 757.9 ml/min. To comply with regulations, the minimum fluid quantity required for 45 minutes of fluid availability at this flowrate is 9 gallons.

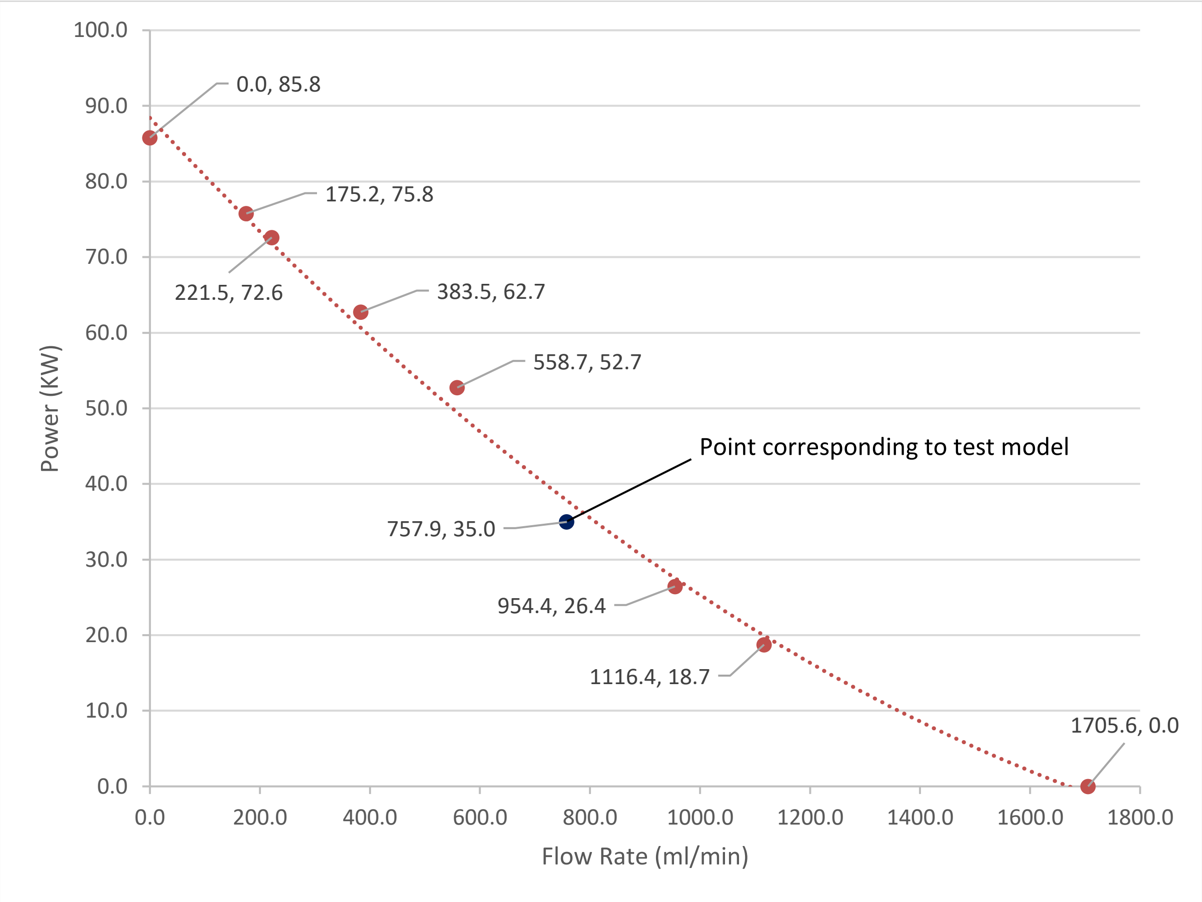

Figure 19: Example Aircraft Hybrid Design Space

Table 3: Example Aircraft Hybrid Configurations

Flowrate (ml/min)	Power (KW)	Description
0.0	85.8	WING & TAIL - Fully Electrothermal
175.2	75.8	WING - Fully Electrothermal TAIL - FPD Parting strip & ET up to 10%Beta 50MVD
221.5	72.6	WING - ET parting strip & ET up to 25MVD impingent limit & FPD beyond TAIL - Fully Electrothermal
383.5	62.7	WING - ET parting strip & ET up to 20MVD impingent limit & FPD beyond TAIL - Fully Electrothermal
558.7	52.7	WING - ET parting strip & ET up to 20MVD impingent limit & FPD beyond TAIL - FPD Parting strip & ET up to 10%Beta 50MVD & FPD beyond
757.9	35.0	WING & TAIL - FPD Parting strip & ET up to 10%Beta 50MVD & FPD beyond
954.4	26.4	WING - FPD Parting strip & ET up to 25MVD impingent limit & FPD beyond TAIL - FPD Parting strip & ET up to 10%Beta 50MVD & FPD beyond
1116.4	18.7	WING - FPD Parting strip & ET up to 20MVD impingent limit & FPD beyond TAIL - FPD Parting strip & ET up to 10%Beta 50MVD & FPD beyond
1705.6	0.0	WING & TAIL - Fully FPD