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Estimation of Electrical Power Required for Deicing Systems

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19. Abstract In this report, estimations of deicing power requirements of different systems (either electro-thermal, electro-impulse or hybrids) are summarised and presented. A thorough analysis has been conducted for electro-thermal cyclic deicing systems. Power loads of this system are calculated and compared with empirical values found in literature. Furthermore, a quick method for estimating the specific power load of such a system is demonstrated. Results show that parting strip power requirements are decisive for overall power loads. Cyclic power requirements are of second order. The Thermal-Mechanical Expulsion Deicing System (TMEDS) as an alternative to electro-thermal deicing eliminates the need of the continuous heated parting strip. As a consequence, while electro-thermal deicing systems require a specific power of about 4.7 kW/m^2 … 8.7 kW/m^2, TMEDS exhibits the potential to require only 3.1 kW/m^2.		
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19. Kurzfassung In diesem Bericht werden die Leistungsanforderungen von unterschiedlichen Enteisungssystemen aufgezeigt (elektro-thermisch, -impuls oder hybrid). Eine ausführliche Analyse wurde für das Elektro-thermische Enteisungssystem durchgeführt. Dabei wurden die Leistungsanforderungen berechnet und mit empirischen Werten aus der Literatur verglichen. Des Weiteren wird eine Schnellmethodik für diese Berechungen vorgestellt. Die Ergebnisse weisen darauf hin, dass die Trennstreifen des elektro-thermischen Systems ausschlaggebend für die Leistungsaufnahme sind. Das zyklische Enteisen ist zweitrangig. Eine Alternative zum Elektro-Thermischen Enteisungssystem bietet das Thermal-Mechanical Expulsion Deicing Systems (TMEDS) welches die kontinuierlich beheizten Trennstreifen eliminiert. Folglich, während das elektro-thermische System eine spezifische elektr. Leistung von 4.7 kW/m^2 ... 8.7 kW/m^2 benötigt, kommt TMEDS mit nur 3.1 kW/m^2 aus.		
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Definition of Terms

Anti-icing is the prevention of ice build-up on the protected surface, either by evaporating the impinging water or by allowing it to run back and freeze on noncritical areas (**AIR 1168/4,** p. 6).

Continuous maximum icing
The continuous maximum icing condition is characterized by exposure to moderate-to-low liquid water content for an extended period of time. It is applicable to those components such as wing ant tail surfaces that are affected by continuous flight in icing conditions but which can tolerate brief and intermittent encounters with conditions of greater severity (**AIR 1168/4**, p. 29).

Deicing is the periodic shedding, either by mechanical or thermal means, of small ice build-ups by destroying the bond between the ice and protected surface (**AIR 1168/4**, p. 6).

Icing cloud Icing clouds are those containing supercooled water droplets in sufficient concentration to produce ice on an aircraft surface (**AIR 1168/4**, p. 5).

Intermittent maximum icing
The intermittent maximum icing condition is characterized by exposure to high liquid water contents for a short period, usually superimposed upon the continuous maximum. It is applicable to those components such as engine inlets and guide vanes where ice accretions, even though slight and of short duration, cannot be tolerated (**AIR 1168/4**, p. 29).

Liquid Water Content (LWC)
The LWC is the mass of supercooled water per volume (**Scholz 2007**, p. 9-3).

Local water catch is the point-by-point distribution of water (or ice), in kg/s/m² surface area, over the impingement area (**AIR 1168/4**, p. 6).

Supercooled water Liquid water below 0 °C that turns instantly into ice due to any small disturbance encountered (such as the interaction with the aircraft). Below -40 °C all supercooled water will be frozen (**Scholz 2007**, p. 9-2).

Total water catch is the integrated value of the local water catch and is the total amount of water (or ice), in kg/s that impinges on the aircraft surface. For a two-dimensional body (e.g. on a wing) the total catch is more conveniently expressed in terms of a unit span (**AIR 1168/4**, p. 6).

Unheated equilibrium temperature
The surface of an unheated body flying in an icing condition will assume an equilibrium temperature that just balances convection, sensible heating, and sublimation (…) (**AIR 1168/4**, p. 32).

Water catch efficiency (total water catch)
is the dimensionless ratio of the amount of water intercepted by a body to the amount of water contained in the volume of cloud swept by the body when at angle of attack $\alpha = 0°$. This ration can be greater than 1,0 at angle of attack α greater than 0° (**AIR 1168/4**, p. 9).

1 Introduction

Clouds or visible moisture contain supercooled water under meteorological icing conditions. With the aircraft flying trough, supercooled water droplets impinge on aircraft leading edges. The impinging water droplets freeze because they receive the necessary energy input to overcome the latent heat for the phase change. A layer of ice is forming on leading edges and continuing to grow if the respective surface remains unprotected. Ice accumulations on an aircraft are extremely hazardous dependent on the degree of coverage, the shape, size and texture of the ice growth, and the specific location on the surface of the airfoil (**Al-Khalil 2007)**. Flow distribution around the airfoil changes. Those effects will result in a decrease of lift and angle of attack margin to stall while aerodynamic drag increases. Additionally the operation of control surfaces might be influenced negatively.

Ice protection principals can be generally classified into anti-icing or deicing. Where anti-icing systems keep the surface to be protected completely ice free, ice build-ups are allowed to form to get periodical shed with the application of a deicing system. Anti-icing can be achieved by evaporating all of the impinging water (**evaporative anti-icing**) or by allowing to run back and freeze on no critical areas (**running-wet anti-icing**). Deicing requires less power than anti-icing because of a short but periodic energy input in contrast to a continuous one. Thus, during the off-time of the system, ice is forming, which is then shed periodically by destroying the bond between the ice and the protected surface either through mechanical or thermal energy inputs.

Systems for ice protection of non-transparent surfaces (leading edges, radome, inlets, etc.) can be classified as follows, where each technology can be associated with a significant application (Table 1.1):

- pneumatic boot systems
- thermal ice protection systems:
    - hot air systems
    - electrical resistance systems
- fluid systems
- electro impulse deicing (EIDI) systems
- microwave systems

Large transport aircraft traditionally apply evaporative anti-icing by using bleed air from the engines. With the design of fuel-efficient high-bypass engines however, the amount of bleed air is limited. In the course of the development of a *more-electric aircraft*, electro-thermal deicing for ice and rain protection becomes a very attractive alternative to hot bleed air systems. But, even though the thermal efficiency of electrically powered systems is higher than that of bleed air systems the power demand of an electrically powered evaporative anti-icing system is still beyond the reach of available generators. The focus is therefore on the development of ice protection systems that exhibit even greater efficiencies (**Al-Khalil 2007)**.

Table 1.1 Ice protection technologies and the applications (adapted from **Kodet 1988** and **Scholz 2007** (ATA 30))

	large transport	**general aviat./ business jets**	**helicopter**	**engine inlets**	*deicing*	*antiicing*
hot air systems	x	x		turbofan	x	
pneumatic boot systems		x		turboprop	x	x
fluid systems (freezing point depressant)		very rare			x	(x)
electrical resistance systems	a	a	x	turbofan	x	(x)

Legend:

x yes

a only if there isn't enough bleed air

(x) solution usually not applied to protection principle

To lower the power required for ice protection systems, research focuses rather on deicing systems than on anti-icing systems. The energy to evaporate or to melt all of the impinging droplets on an airfoil is simply not necessary. By melting the ice-airfoil interface the adhesion of ice build-ups becomes zero. Aerodynamic forces can then remove the ice. With this idea in mind, many deicing systems have been developed and tested in icing wind tunnels over the past few years. One of those systems is the electro-thermal deicing system which is described in detail within the following chapter. Calculation principles are demonstrated according to the method suggested in AIR1168/4 as well as through general accepted formula to be found in any common thermodynamic book. Additionally, alternative low power ice protection systems are described and power requirements compared with those of the electro-thermal deicing system.

Design Requirements for Ice-Protection Systems

Certification requirements for flight in icing conditions are stated in CS 25.1419 of **CS-25 2008**. The aeroplane must be able to safely operate in **continuous maximum** and **intermittent maximum icing conditions** as defined in CS-25 Book 1 Appendix C. In order to verify this, an analysis must be performed followed either by laboratory dry air simulated icing tests or by flight tests.

2 Electro-Thermal Cyclic Deicing

Areas to be protected (e.g. the wings leading edge) are separated into smaller areas and energized sequentially together with the corresponding areas on the opposite side of the wing to lower the energy demand of the overall system. This separation is accomplished with **continuously heated spanwise and chordwise parting strips** to prevent ice from bridging over from one shedding zone to another. The **cyclic deicing** is then accomplished with the **periodic shedding** of the smaller ice formations between the parting strips. The *ice-airfoil interface* is melted, the adhesion becomes zero and aerodynamic forces remove the separated ice formations. The **heat-on time** depends upon the rate at which the surface cools to 0 °C and upon the icing rate. The **off-time** may be tailored to the maximum allowable ice thickness of the airfoil. It can be as long as 3 to 4 minutes for a fixed-wing aircraft (**Scholz 1997**, p. 9-9). The electro-thermal deicing requires the least amount of heat of all ice protection systems. However, during the "heat-off" period **drag penalties** occur due to ice formation around the leading edge of the airfoil.

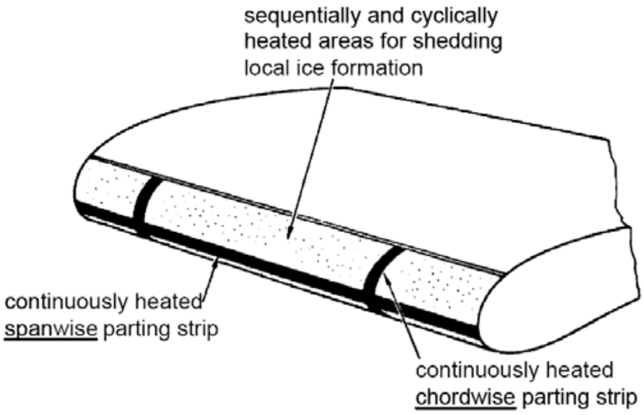

Figure 1.1 Arrangement of an area with electric cyclic deicing (from **Scholz 1997**, p. 9-9)

Difficulties emerge by exactly supplying the **correct amount of heat** to the electro-thermal deicing system. Too little heat might no be sufficient to melt the ice-airfoil interface completely. Too much heat input most likely results into undesirable amounts of runback ice due to an increased amount of ice melted (**Scholz 1997**, p. 9-10). The idea of cyclic deicing can only be applied on surfaces where small ice build-ups are not dangerous. For areas such as on the cockpit windshield, probes and drain masts ice build-ups would be detrimental and the method of (usually electrical) anti-icing becomes necessary. For engine inlets with electro-thermal cyclic deicing, the protected area might be separated even into smaller areas in comparison with those of the leading edge, in order to ensure that only small peaces of ice chunks are getting sucked into the engine.

Heater Construction

For heater construction, the sandwich method is used. The core is build by electrical resistance elements surrounded by dielectric material. Additionally rain and hail resistant is applied to the external surface. Typical values for the deicing efficiency[1] range from 20 - 40% due to following reasons (**AIR1168/4)**:

- some of the heat is absorbed by the surrounding e.g. the leading edge skin
- heating up period of the heater
- non-uniform heating of the external surface (discrete heater elements)

Power requirements

Parting strip power requirements can be calculated in the same manner as for running wet anti-icing. Ice build-ups next to the parting strip are however affecting the power requirements (see par. 7.3 in **AIR1168/4**). As approximate values **AIR1168/4** suggests 18.6 kW/m² for -17.78 °C (= 0° F) ambient temperature and 31 kW/m² for -30 °C (= -22 °F).

Cyclic power requirements are primarily dependent on the *unheated equilibrium temperature* and the heat-on time. A compromise between power intensity and heat-on/off time has to be found. AIR1168/4 suggests 34.1 kW/m² for 9 seconds followed by a heat-off time of about 3 minutes (with aerodynamic drag occurring during this heat-off period).

To verify these suggested values of **AIR1168/4**, detailed calculations are exemplified below.

2.1 Design Point

According to the definition of supercooled water (see definition of terms), aircraft icing is possible if:

- the air contains water (e.g. clouds),
- the air temperature is below 0 °C,
- the air temperature is above -40 °C, or
- the aircraft surface is below 0 °C.

[1] … defined as the heat leaving the surface integrated over the “ON” time divided by the total heat input (**AIR1168/4**, p. 27)

Cyclic Power Requirements

Cyclic power requirements are primarily a function of unheated equilibrium temperature. Consequently, **AIR1168/4** (p. 29) suggests designing the system for minimum unheated equilibrium temperature i.e. (according to Figure 3F-23 of **AIR1168/4**) at low true air speeds (v_{TAS} < 100 kt) together with low ambient temperatures (-30 °C). The second parameter (axis of abscissa) in respective Figures is the ratio of the local water catch rate divided by the local heat transfer coefficient. As a consequence, the lower this ratio the lower the unheated equilibrium temperature.

Parting Strip Power Requirements

The energy from electro-thermal systems, either running wet or cyclic, is constant. For this reason, those systems must be designed for maximum energy requirements. This usually occurs in the vicinity of v_{TAS} = 250 kt … 350 kt (MSL). At higher velocities convective losses are decreasing due to the increase in equilibrium temperature of the kinetic rise (**AIR1168/4** p. 29).

Calculations focus primarily on parting strip power requirements. Due to stated suggestions in the preceding paragraph, the design point for sizing the parting strips for electro-thermal cyclic deicing has been selected with the following constraints:

- continuous maximum icing conditions
- v_{TAS} = 350 kt
- T_{MSL} = 0 °F = -17.78 °C ambient temperature
- pressure altitude 0 ft

The design point (-18 °C at MSL) is in accordance with the flight envelope required by airworthiness authorities as depicted in Figure A.2. Further assumptions are:

- mean effective drop diameter d_{med} = 20 µm
- airfoil section NACA 65_2-015 (in the middle of slat 4; see Figure A.5)
    - c = 2.2 m (airfoil chord perpendicular to the wing leading edge)
    - maximum thickness t = 0.33 m

Parameters of wing geometry of e.g. an Airbus A320 (**Krammer 2008**, Appendix C.1) have been set to following dimensions:

- averaged total slat length y_{SLAT} = 26.2 m (including inner slat 1 that is not considered for wing anti-ice.
- averaged slat chord c_{SLAT} = 0.48 m
- medial wing leading edge sweep φ_{LE} = 27.5°

- wing span $b = 33.9$ m

2.2 Calculation of Running Wet Anti-Icing Power Requirements according to the AIR1168/4 method

Calculations of running wet anti-icing can be used to get a first estimate on parting strip power requirements.

(1) Total Water Catch

Due to the wing sweep the considered airfoil is encountered with a velocity perpendicular to the wing leading edge of about[2]:

$$v_{TAS\perp} = 350\,\text{kts} \cdot \cos(27.5) \approx 310.5\,\text{kts} \tag{2.0}$$

With parameters of airfoil thickness t and flight speed v_{TAS}, the total water catch (mass flow) can be gathered from Figure 3F-3 in **AIR1168/4** (p. 12).

$$\frac{\dot{\text{m}}}{\rho_{LWC}} = 19\,\frac{\text{lb/hr/ft}}{\text{g/m}^3} \tag{2.1}$$

From Figure A.1 of continuous maximum icing atmospheric conditions the Liquid Water Content (LWC) can be gathered with parameters of T_{MSL}, and d_{med}. The EASA continuous maximum requirement in this example is:

$$\rho_{LWC} = 0.24\ \text{g/m}^3 \tag{2.2}$$

$$\dot{\text{m}} = 19\,\frac{\text{lb/h/ft}}{\text{g/m}^3}\,0.24\,\text{g/m}^3 = 4.56\,\frac{\text{lb}}{\text{h}\cdot\text{ft}} = 4.56\,\frac{0.4536\,\text{kg}}{3600\,\text{s}\cdot 0.3048\,\text{m}} = 1.89\cdot 10^{-3}\,\frac{\text{kg}}{\text{m}\,\text{s}} \tag{2.3}$$

Optionally, the equation derived in **Scholz 2007** (p. 9-4) can be used to compute the total water catch of the airfoil by means of:

$$\dot{\text{m}} = v\,t\,\rho_{LWC}\,E_m \tag{2.4}$$

where the water catch efficiency E_m (Figure 2.1) is a function of aircraft speed, droplet size, airfoil shape, airfoil thickness, viscosity and density of the air. Based on typical airfoils with

[2] The airfoil is considered to be within a plane that is perpendicular to the wing leading edge (i.e. not parallel to the longitudinal axis of the A/C)

a relative thickness of 6 … 16% at an angle of attack of α = 4°, a simplified formula for calculating E_m is presented:

$$E_m = 0.00324\left(\frac{v}{t}\right)^{0.613} = 0.00324\left(\frac{310.5 \cdot 1.852/3.6\,\mathrm{m/s}}{0.33\,\mathrm{m}}\right)^{0.613} = 0.1433 \qquad (2.5)$$

The formula as well as Figure 3F-3 in **AIR1168/4** (p. 12) are strictly true for d_{med} = 20 µm and an altitude of h = 10000 ft. Other altitudes from sea level to h = 20000 ft will result in error lass than 10%. With equation 2.4 total water catch yields:

$$\dot{m} = 159.7\frac{\mathrm{m}}{\mathrm{s}}0.33\,\mathrm{m}\cdot 0.24\frac{\mathrm{g}}{\mathrm{m}^3}\,0.1433 = 1.81\frac{\mathrm{g}}{\mathrm{m\,s}} = 1.81\cdot 10^{-3}\frac{\mathrm{kg}}{\mathrm{m\,s}} \qquad (2.6)$$

Comparison of equations 2.3 and 2.6 shows an acceptable discrepancy within the results of about 0.08 kg/m/s in total water catch. The greater value (equation 2.3) is taken for further calculations.

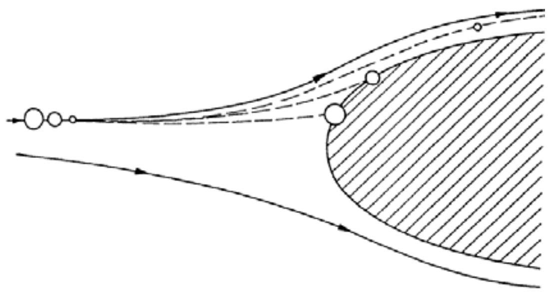

Figure 2.1 Flow around wing leading edge with streamlines of dry airflow and trajectories of differently sized droplets. The air and with it very small droplets pass around the wing; only larger droplets hit the surface. This phenomenon is expressed by the water catch efficiency E_m, from (**Scholz 2007** (p. 9-4)

(2) Freestream Reynolds Number

In order to predict the power required for electro-thermal running wet anti-icing, local **heat transfer coefficients** have to be taken into account. The coefficients are dependent on velocity and static pressure p over the airfoil. A distinction is made between *laminar and turbulent heat transfer coefficients*. For this reason, the Reynolds Number has to be calculated in advance. For the characteristic length in equation 2.7, averaged slat chord c_{SLAT} = 0.48 m is used. Since for slat 1 (see Figure A.5) no anti-icing or deicing is required, the averaged slat chord should be approximated even smaller. Thus: c_{SLAT} = 0.35 m. The point of calculation is considered at half slat chord distance from the leading edge. The Reynolds number is thus calculated at $l = c_{SLAT} / 2$ = 0.175 m. The dynamic viscosity μ at -30° C ambient temperature has been found at μ = 1.5636 10^{-5} kg/m/s from **LTH 2008** (AT 01500 01 / chapter 3.6) and the density of the air set to that at MSL. Equation 2.7 is in accordance with equation 3F-11 of **AIR1168/4** (p. 19) that is derived from bodies of revolution.

$$\text{Re},o = \frac{\rho_{MSL}\, v\, l}{\mu} = \frac{1.225\,\text{kg/m}^3 \cdot 159.7\,\text{m/s} \cdot 0.175\,\text{m}}{1.5636 \cdot 10^{-5}\,\text{kg/m/s}} = 2.19 \cdot 10^6 \qquad (2.7)$$

With electro-thermal cyclic deicing, ice build-ups are likely to occur at the leading edge of the wing. Not only will this result in aerodynamic drag increase, but also in an earlier transition of the air-stream from laminar into turbulent.

(3) Local Heat Transfer Coefficient

To calculate the heat transfer at a boundary within a fluid the Nusselt number can be used. The Nusselt number (named after *Wilhelm Nusselt*) is defined as the ratio of convection heat transfer to fluid conduction heat transfer under the same conditions (**White 2009**). The local heat transfer coefficients can be derived from Figures 3F-12 and 3F-13 (airfoil nose approximated by a cone). The latter one is for turbulent heat transfer coefficients. Considering a location in the middle of the slat the ratio of surface distance from apex divided by slant length of cone becomes 0.5. Therefore, the dimensionless turbulent heat transfer coefficient in this example yields:

$$\frac{\text{Nu}}{\text{Re},o^{0.821}} = 0.022 \qquad (2.8)$$

The thermal conductivity of air k_0 at free stream static temperature is:

$$k_0 = 0.0132\,\text{Btu/hr/ft/°F} = 0.0132 \frac{1055.056\,\text{J}}{3600\,\text{s}\ 0.3048\,\text{m}\ 5/9\,\text{°K}} = 0.0228 \frac{\text{W}}{\text{m}\,\text{K}} \qquad (2.9)$$

And with (equation 3F-11),

$$\text{Nu} = \frac{h_0\, l}{k_0} \qquad (2.10)$$

the external heat transfer coefficient h_0 becomes (with equation 2.8):

$$h_0 = \frac{0.022\left(2.19 \cdot 10^6\right)^{0.821} 0.0228\,\text{W/m/K}}{0.175\,\text{m}} = 460.1 \frac{\text{W}}{\text{m}^2\,\text{K}} \qquad (2.11)$$

(4) Power Requirements

According to the calculation scheme of **AIR1168/4**, the last step in estimating the power requirements for running wet anti-icing is computing the ratio of $m(t)$ / h_0 that is used to get the ratio of heat required divided by local heat transfer coefficient in Figure 3F-18. Unfortunately, this graph is drawn in units of the imperial system. Thus, total water catch $m(t)$

(mass flow) as well as external heat transfer coefficient have to be transferred back into imperial units[3]:

$$h_0 = 460.1\frac{\mathrm{W}}{\mathrm{m^2K}} = 460.1\frac{3600\,\mathrm{J}\cdot 5/9\,°\mathrm{F}}{1055.056\,\mathrm{s}\ 3.281^2\,\mathrm{m}} = 81.2\frac{\mathrm{Btu}}{\mathrm{h\,ft^2\,°F}} \tag{2.12}$$

Using equation 2.3, the total water catch per area i.e. the local water catch becomes:

$$M_\beta = \frac{\dot{\mathrm{m}}}{t} = 19\frac{\mathrm{lb/h/ft}}{\mathrm{g/m^3}}0.24\,\mathrm{g/m^3}\frac{1}{0.33\cdot 3.281\,\mathrm{ft}} = 4.21\frac{\mathrm{lb}}{\mathrm{h\cdot ft^2}} \tag{2.13}$$

The ratio necessary for Figure 3F-18 in **AIR1168/4** (p. 26) yields:

$$\frac{\mathrm{M}_\beta}{h_0} = 0.05\frac{\mathrm{lb\,°F}}{\mathrm{Btu}} \tag{2.14}$$

Figure 3F-18 is strictly true for a surface temperature of 4.44 °C, 10000 ft altitude and an ambient temperature of -17.78 °C. **AIR1168/4** suggests subtracting 11.0 from the result for conditions at sea level. Therefore, the heat required divided by the local heat transfer coefficient out of Figure 3F-18 becomes:

$$\frac{q}{h_0 S_0} = 50°\mathrm{F} - 11°\mathrm{F} = 39°\mathrm{F} \tag{2.15}$$

And with h_0 from equation 2.12 the required local power intensity can finally be calculated:

$$\frac{\mathrm{q}}{\mathrm{S}_0} = 39°\mathrm{F}\cdot 81.2\frac{\mathrm{Btu}}{\mathrm{h\,ft^2\,°F}} = 3167\frac{\mathrm{Btu}}{\mathrm{h\,ft^2}} = 3167\frac{1055\mathrm{J}}{3600\mathrm{s}\ 0.3048^2\,\mathrm{m^2}} = 9.99\frac{\mathrm{kW}}{\mathrm{m^2}} \tag{2.16}$$

Likewise the temperature difference in equation 2.15 can be transferred from °F into °C (or K respectively) and multiplied by the local heat transfer coefficient (equation 2.11). Since the temperature in equation 2.15 represents a margin and not an absolute value the conversion must be:

$$\Delta°\mathrm{F} = \Delta 5/9\,°\mathrm{C} = \Delta 5/9\,\mathrm{K} \tag{2.17}$$

$$\frac{\mathrm{q}}{\mathrm{S}_0} = 39\frac{5}{9}\mathrm{K}\cdot 460.1\frac{\mathrm{W}}{\mathrm{m^2K}} = 9.97\frac{\mathrm{kW}}{\mathrm{m^2}} \tag{2.18}$$

Figure 3F-18 assumes 100 % heating efficiency. On page 24 of **AIR1168/4** a heating efficiency of 70 % for electrical resistance elements is suggested. Thus:

[3] Btu = British thermal unit; Definition: the amount of heat required to raise the temperature of one pound of water through *1°F (58.5°F - 59.5°F)* at sea level *(30 inches of mercury)*

$$\frac{\mathrm{q}}{\mathrm{S}_0} = \frac{9.99}{0.7}\frac{\mathrm{kW}}{\mathrm{m^2K}} = 14.27\frac{\mathrm{kW}}{\mathrm{m}^2} \tag{2.19}$$

In Figure 3F-18 it can be noticed that energy requirements are a strong function of the true air speed: the lower the airspeed the higher the energy requirement. As stated above, maximum energy requirements for electro-thermal running wet anti-icing can be found in the vicinity of v_{TAS} = 250 kt … 350 kt (MSL). Power requirements as in formula 2.19 are calculated with v_{TAS} = 350 kt. To estimate the power required for v_{TAS} = 250 kt , the stated formula above is used with relevant parameters adapted:

(1) Total Water Catch

$$v_{TAS\perp} = 250\,\mathrm{kts}\cdot\cos(27.5) \approx 222\,\mathrm{kts} \tag{2.20}$$

$$\frac{\dot{\mathrm{m}}}{\rho_{LWC}} = 12\frac{\mathrm{lb/hr/ft}}{\mathrm{g/m^3}} \tag{2.21}$$

EASA continuous maximum requirement:

$$\rho_{LWC} = 0.24\ \mathrm{g/m^3} \tag{2.22}$$

(2) Freestream Reynolds Number

$$\mathrm{Re},o = \frac{\rho_{MSL}\,v\,l}{\mu} = \frac{1.225\,\mathrm{kg/m^3}\cdot 114\,\mathrm{m/s}\cdot 0.175\,\mathrm{m}}{1.5636\cdot 10^{-5}\,\mathrm{kg/m/s}} = 1.56\cdot 10^6 \tag{2.23}$$

(3) Local Heat Transfer Coefficient

Dimensionless turbulent heat transfer coefficient:

$$\frac{\mathrm{Nu}}{\mathrm{Re},o^{0.821}} = 0.022 \tag{2.24}$$

Thermal conductivity of air k_0 at free stream static temperature:

$$k_0 = 0.0132\,\mathrm{Btu/hr/ft/°F} = 0.0132\frac{1055.056\,\mathrm{J}}{3600\,\mathrm{s}\ 0.3048\,\mathrm{m}\ 5/9\,\mathrm{°K}} = 0.0228\frac{\mathrm{W}}{\mathrm{m\,K}} \tag{2.25}$$

External heat transfer coefficient:

$$h_0 = \frac{0.022\left(1.56\cdot 10^6\right)^{0.821} 0.0228\,\mathrm{W/m/K}}{0.175\,\mathrm{m}} = 348\frac{\mathrm{W}}{\mathrm{m^2\,K}} \tag{2.26}$$

(4) Power Requirements

$$\frac{q}{h_0 S_0} = 63°\text{F} - 11°\text{F} = 52°\text{F} \tag{2.27}$$

Local power intensity:

$$\frac{\text{q}}{\text{S}_0} = 52°\text{F} \cdot 61.3 \frac{\text{Btu}}{\text{h ft}^2 °\text{F}} = 3188 \frac{\text{Btu}}{\text{h ft}^2} = 3188 \frac{1055\text{J}}{3600\text{s } 0.3048^2 \text{ m}^2} = 10.1 \frac{\text{kW}}{\text{m}^2} \tag{2.28}$$

Power required:

$$\Delta°\text{F} = \Delta 5/9\,°\text{C} = \Delta 5/9\,\text{K} \tag{2.29}$$

$$\frac{\text{q}}{\text{S}_0} = 52 \frac{5}{9} \text{K} \cdot 348 \frac{\text{W}}{\text{m}^2\text{K}} = 10.1 \frac{\text{kW}}{\text{m}^2} \tag{2.30}$$

Power required with 70 % of heating efficiency:

$$\frac{\text{q}}{\text{S}_0} = \frac{10.1}{0.7} \frac{\text{kW}}{\text{m}^2\text{K}} = 14.43 \frac{\text{kW}}{\text{m}^2} \tag{2.31}$$

2.3 Results of Parting Strip Power Requirements (AIR1168/4)

The power required for running-wet anti-icing has been calculated according to AIR1168/4 at two different true air speeds. By introducing a heating efficiency, the values of running-wet anti-icing power requirements can be transferred into values of parting strip power requirements of an electro-thermal cyclic deicing system. With a lower true air speed the total water catch decreases whereas the Liquid Water Content (LWC) remains the same. A change in true air speed leads furthermore to a different Reynolds number. The lower the Reynolds number the lower the external heat transfer coefficient h_0. With a lower true air speed, the temperature margin (heat required divided by local heat transfer coefficient in Figure 3F-18) increases. However, the increase in temperature margin and the decrease in external heat transfer coefficient are compensating. Multiplication of both leads to almost the same power requirement with a higher true air speed:

$$\left[\frac{\text{q}}{\text{S}_0}\right]_{350\,\text{KTAS}} = 14.27 \frac{\text{kW}}{\text{m}^2} \tag{2.32}$$

$$\left[\frac{\text{q}}{\text{S}_0}\right]_{250\,\text{KTAS}} = 14.43 \frac{\text{kW}}{\text{m}^2} \tag{2.33}$$

It has to be kept in mind that the point of calculation along the airfoil shape has been considered at half slat chord distance from the leading edge. Additional assumptions such as turbulent flow have an influence on the Reynolds number and thus on the local heat transfer coefficient. As a result, power requirements in the stagnation point of the airfoil will be different from the ones obtained.

2.4 Results of Cyclic Power Requirements (AIR 1168/4)

In general, cyclic requirements are a strong function of unheated equilibrium temperature and heat-on time. The latter one has to be verified in wind-icing channels (**AIR1168/4**). No principal calculation scheme of cyclic power requirements is presented in AIR 1168/4. Calculations in the chapters above focus therefore on parting strip power requirements and thus on running wet anti-icing only. However, AIR 1168/4 suggests empirical values that have been summarised in Table 2.3. Thus, a cyclic power requirement of 34 kW/m^2 would be necessary for the stated total cycle time of three minutes that is followed by a heat on time of nine seconds.

2.5 Calculation of Running Wet Anti-Icing Power Requirements with General Accepted Formula

Generally speaking, the heat quantity Q depends on the considered mass, the specific heat capacity and on the temperature rise:

$$Q = c\, m\, \Delta T \quad [\mathrm{J}] \tag{3.1}$$

When referring to thermodynamic cyclic processes the use of the specific heat becomes more convenient:

$$q = \frac{Q}{m} = c\, \Delta T \quad \left[\frac{\mathrm{J}}{\mathrm{kg}}\right] \tag{3.2}$$

When it comes to calculations of required heat for anti-icing or deicing the heat flux is used, though it is possible to express the power required per unit of area per unit of time. It is a vector defined by magnitude and direction.

$$\dot{q} = \frac{Q}{t\, A} = \frac{\dot{Q}}{A} = \frac{c\, m \Delta T}{t\, A} \quad \left[\frac{\mathrm{J}}{\mathrm{s\, m^2}} = \frac{\mathrm{W}}{\mathrm{m^2}}\right] \tag{3.3}$$

This makes it possible to calculate power requirements independent of wing span or airfoil thickness. However, both geometric parameters have a significant influence on the fluid flow around the airfoil, thus also on the local water catch. Among others, those effects are taken into consideration with the parameter of the water catch efficiency E_m (Figure 2.1). As a result, the local water is the point-by-point distribution of water over the impingement area. And furthermore, the total catch is defined as the integrated value of the local catch.

For certification purposes atmospheric icing conditions are standardised and stated in the Certification Standards (CS, see appendix). The parameter of the liquid water content for the considered atmospheric condition is left constant for the rest of the calculation. The aircraft, however, must be certified for all possible atmospheric conditions to be encountered during the flight mission, thus more than one calculation has to be done with different atmospheric conditions and different liquid water contents. With the selected design point for this demonstrative calculation the local water catch m_{local} (different to LWC = liquid water content) can be gathered from Figure A.1 with parameters of T_{MSL}, and d_{med} as in equation 2.2. Instead of calculating and dealing with the total water catch, the local water catch is used since it is more appropriate to gather directly results on the heat flux. As a result, equation 2.4 now yields:

$$\dot{\mathrm{m}}_{local} = v\,\rho_{LWC}\,E_m \quad \left[\frac{\mathrm{kg}}{\mathrm{s}\cdot\mathrm{m}^2}\right] \tag{3.4}$$

and with parameters from chapter 2 (v_{TAS} = 350 kt):

$$\dot{\mathrm{m}}_{local} = 159.7\,\frac{\mathrm{m}}{\mathrm{s}}\cdot 0.62\,\frac{\mathrm{g}}{\mathrm{m}^3}\;0.1433 = 4.682\,\frac{\mathrm{g}}{\mathrm{m\,s}} = 14.19\cdot 10^{-3}\,\frac{\mathrm{kg}}{\mathrm{s\,m}^2} \tag{3.5}$$

The heat flux required to anti-ice the aircraft surface can be expressed in the simplest form by an energy-and-mass-balance for each surface element along an airfoil. The energy requirements for an anti-icing system are determined by the rate of which heat must be supplied to balance the heat losses from the protected surface that are convective cooling, evaporation, and sensible heating. In contrast, the kinetic heating due to droplets that are coming to rest when striking the surface do have a positive influence, thus heating up the surface and lowering the required heat flux.

$$\dot{q}_{A/I} = \dot{q}_{evap} + \dot{q}_{convec} + \dot{q}_{sensible} - \dot{q}_{KE} + \dot{q}_{aero} \tag{3.6}$$

The impinging super cooled water will partially freeze. The super cooled water that is short before striking the airfoil, holds a specific amount of heat quantity. This energy is (in our example to a 100 %) used to convert supercooled water from liquid to solid i.e. the latent heat of fusion. Thus, the amount of super cooled water that turns into ice can be calculated as follows:

$$\dot{q}_{A/I} = \text{const} = \dot{m}_{local} c \Delta T = \dot{m}_{ice} L_m \tag{3.7}$$

$$n = \frac{\dot{m}_{ice}}{\dot{m}_{local}} = \frac{c\Delta T}{L_m} \tag{3.8}$$

And furthermore, with the latent heat of fusion L_f for water, the freezing fraction n yields:

$$n = \frac{\dot{m}_{ice}}{\dot{m}_{local}} = \frac{c(T_0 - T_\infty)}{L_f} = \frac{4.19 \frac{\text{kJ}}{\text{kg K}} 17.78\text{K}}{332.5 \frac{\text{kJ}}{\text{kg}}} = 22\% \tag{3.9}$$

Thus, 30 % of all impinging water turns in to ice, which is strictly true only for the selected design point (freestream air temperature, etc.). Interesting to see is that the energy, supercooled water holds, is just too less to convert all of the water into ice. The amount of water that turns into ice is only dependent on the temperature margin. Though, as an illustrative example, the temperature difference required to convert all of the supercooled water into ice would be:

$$(\Delta T)_{\dot{m}_{ice} = \dot{m}_{local}} = \frac{332.5 \frac{\text{kJ}}{\text{kg}}}{4.19 \frac{\text{kJ}}{\text{kg K}}} = 79.4\,\text{K} \tag{3.10}$$

With our suggest value of 6 °C surface temperature, the ambient temperature required to convert all super cooled water into ice is -73.4 °C and therefore not likely to be encountered during any flight operation.

(1) Convection

The convective heat loss can be found by:

$$\dot{q}_{convec} = h_0 (T_{sk} - T_\infty) \tag{3.11}$$

where h_0 is again the local heat transfer coefficient that is in this chapter calculated from formula in **Incropera 2007**:

$$h_0 = \text{Nu} \cdot \frac{k_0}{x} \tag{3.12}$$

$$\text{Nu} = 0.0296\,\text{Re}_x^{\;4/5}\,\text{Pr}^{1/3} \tag{3.13}$$

Convection can be classified into: forced or free, internal or external, overall or local and laminar or turbulent convection. All conditions are affecting the Reynolds number in a different way. In our case we are seeking for a convection that is forced, external, overall and turbulent. In addition to the Reynolds number (taken from above) the Prandtl number has to be calculated (with k_0 thermal conductivity of air (see above) and $c_{p,air}$ the specific heat capacity of air).

$$\mathrm{Pr} = \frac{c_p\,\mu}{k_0} = \frac{1003.5\,\frac{\mathrm{J}}{\mathrm{kg\,K}} \cdot 1.5636 \cdot 10^{-5}\,\frac{\mathrm{kg}}{\mathrm{m\,s}}}{0.0228\,\frac{\mathrm{W}}{\mathrm{m\,K}}} = 0.688 \tag{3.14}$$

$$\mathrm{Nu} = 0.0296\left(2.19 \cdot 10^{6}\right)^{4/5} 0.688^{1/3} = 3087 \tag{3.15}$$

$$h_0 = 3087 \cdot \frac{0.0228\,\frac{\mathrm{W}}{\mathrm{m\,K}}}{0.175\,\mathrm{m}} = 402.2\,\frac{\mathrm{W}}{\mathrm{m^2\,K}} \tag{3.16}$$

The derived local heat transfer coefficient is similar to the calculated one according to **AIR1168/4**. Finally the convective cooling heat loss per temperature margin is to be multiplied by the difference in skin and ambient temperature. The desired skin temperature for running wet anti-icing is according to **AIR1168/4** between 2-10 °C. The average of this margin (6 °C) is selected for our calculation. Thus,

$$\dot{q}_{convec} = h_0\left(T_{sk} - T_{aw}\right) = 272.2\,\frac{\mathrm{W}}{\mathrm{m^2 K}}(279.15\,\mathrm{K} - 255.37\,\mathrm{K}) = 6.47\,\frac{\mathrm{kW}}{\mathrm{m^2}} \tag{3.17}$$

(2) Sensible Heating

The impinging droplets (either ice or water) have to be heated up to skin or surface temperature. The ice must additionally first become liquid. Thus:

$$\begin{aligned}
\dot{q}_{sensible} &= \dot{m}_{local}\left\lfloor \Delta T\left(0.78\,c_{liq} + 0.22\,c_{ice}\right) + nL_f \right\rfloor = \\
&= 14.19 \cdot 10^{-3}\,\frac{\mathrm{kg}}{\mathrm{m^2\,s}} \begin{bmatrix} 23.78\,\mathrm{K}\left(0.78 \cdot 4.19\,\frac{\mathrm{kJ}}{\mathrm{kg\,K}} + 0.22 \cdot 2.06\,\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right) \\ + 0.22 \cdot 332.5\,\frac{\mathrm{kJ}}{\mathrm{kg}} \end{bmatrix} = \\
&= 2.29\,\frac{\mathrm{kW}}{\mathrm{m^2}}
\end{aligned} \tag{3.18}$$

(3) Evaporation

The evaporative heat loss equals the rate of mass evaporated from the surface multiplied by the latent heat of evaporation L_e. For fully evaporative anti-icing the surface is heated sufficiently to evaporate all of the impinging liquid water and ice crystals. For a running-wet system, however, the surface water is only partially evaporated. How much of the water evaporates depends not only on the surface temperature but also on the saturation pressure *e* as well as on relative humidity R_h. An equation for calculating the evaporative heat loss can be found in **LTH 2008**:

$$\dot{q}_{evap} = 0.7 h_0 L_e \frac{R_h e_\infty - e_{surf}}{p_\infty c_{p,air}} \tag{3.19}$$

Where, according to **LTH 2008**, 0.7 is an empirical factor. The saturation pressure is dependent only on the substance temperature. In literature many equations can be found to calculate the saturation pressure. For calculation in this report the online calculation tool of the **Kean University** (**2009**) has been used to derive required values for the selected atmospheric temperature (0 °C) and the suggested surface temperature for running wet anti-icing (6 °C).

Table 2.1 water saturation vapour pressure over water and over ice (from **Kean University 2009,** Goff-Gratch equation)

temperature °C	**saturation vapour pressure over water hPa**	**saturation vapour pressure over ice hPa**
0	6.11	6.10
6	9.34	above freezing
-17.78	1.51	1.27

According to values in Table 2.1, a slight difference in saturation pressure over water and over ice exists. For our calculation, however, the difference in saturation vapour pressure over ice is neglected. The whole local water catch (ice and liquid) will be multiplied by values of the saturation vapour pressure over water. In principal, the higher the vapour pressure the lower the normal boiling point. The latent heat for water evaporation is L_e = 2257 kJ/kg, thus equation 3.15, yields:

$$\dot{q}_{evap} = 0.7 \cdot 272.2 \frac{\mathrm{W}}{\mathrm{m^2K}} 2257 \cdot 10^3 \frac{\mathrm{J}}{kg} \frac{(9.34\ \mathrm{hPa} - 1 \cdot 1.51\,\mathrm{hPa})}{1013.25\,\mathrm{hPa} \cdot 1003.5 \frac{\mathrm{J}}{\mathrm{kg\,K}}} = 3.31 \frac{\mathrm{kW}}{\mathrm{m^2}} \tag{3.20}$$

(4) Kinetic Heating

$$\dot{q}_{KE} = \dot{m}_{local} \frac{v_\infty^{\ 2}}{2} = 14.19 \cdot 10^{-3} \frac{\mathrm{kg}}{\mathrm{m^2\ s}} 159.7^2 \frac{\mathrm{m^2}}{\mathrm{s^2}} 0.5 = 0.18 \frac{\mathrm{kW}}{\mathrm{m^2}} \tag{3.21}$$

(5) Aerodynamic Heating

$$\dot{q}_{aero} = h_0 \frac{v_\infty^{\ 2}}{2c_{p,air}} = 272.2 \frac{\mathrm{W}}{\mathrm{m^2K}} \frac{159.7^2 \frac{\mathrm{m^2}}{\mathrm{s^2}}}{2 \cdot 1003.5 \frac{\mathrm{J}}{\mathrm{kgK}}} = 3.46 \frac{\mathrm{kW}}{\mathrm{m^2}} \tag{3.22}$$

(6) Heat flux required to anti-ice the aircraft surface

$$\dot{q}_{A/I} = \dot{q}_{evap} + \dot{q}_{convec} + \dot{q}_{sensible} - \dot{q}_{KE} + \dot{q}_{aero}$$

$$\dot{q}_{A/I} = 3.31 \frac{\mathrm{kW}}{\mathrm{m^2}} + 6.47 \frac{\mathrm{kW}}{\mathrm{m^2}} + 2.29 \frac{\mathrm{kW}}{\mathrm{m^2}} - 0.18 \frac{\mathrm{kW}}{\mathrm{m^2}} + 3.46 \frac{\mathrm{kW}}{\mathrm{m^2}} = 15.35 \frac{\mathrm{kW}}{\mathrm{m^2}} \tag{3.23}$$

Power required with 70 % of heating efficiency:

$$\dot{q}_{A/I} = \frac{\mathrm{q}}{\mathrm{S_0}} = \frac{15.35}{0.7} \frac{\mathrm{kW}}{\mathrm{m^2}} = 21.9 \frac{\mathrm{kW}}{\mathrm{m^2}} \tag{2.24}$$

The result in power required is higher than the calculated one above, of about 14 $\mathrm{kW/m^2}$ and higher than the suggested value in **AIR 1168/4** of about 18.6 $\mathrm{kW/m^2}$. A comparison of all results obtained can be found in the next chapter.

2.6 Calculation of Cyclic Power Requirements with General Accepted Formula

To calculate cyclic power requirements, the unheated equilibrium temperature has to be known. Furthermore, the amount of ice to be melted to destroy the bond between the ice and the airfoil varies with the considered position along the airfoil (stagnation point, etc.). To develop a principal understanding of heat flux required for cyclic deicing the following assumptions have been made to easy calculation:

- ice thickness to be melted to overcome the ice-airfoil interface is 0.3 mm
- unheated equilibrium temperature is equal to ambient temperature
- heat on time is about 9 seconds, every 3 minutes

Thus, per square meter, a volume of 0.27 kg of ice with an ice density of about 900 $\mathrm{kg/m^3}$ has to be melted

$$m_{ice} = 1\,\mathrm{m^2} \cdot 0.0003\,\mathrm{m} \cdot \frac{900\,\mathrm{kg}}{\mathrm{m^3}} = 0.27\,\mathrm{kg} \tag{2.25}$$

The power required to melt 0.27 kg of ice can be calculated as follows:

$$q_{sensible} = \frac{m_{ice}}{t}\left[\Delta T\, c_{ice} + L_f\right] = \frac{0.27\,\mathrm{kg}}{9\,\mathrm{s}}\left[23.78\,\mathrm{K}\cdot 2.06\frac{\mathrm{kJ}}{\mathrm{kgK}} + 332.5\frac{\mathrm{kJ}}{\mathrm{kg}}\right] = 11.44\,\mathrm{kW} \quad (2.26)$$

Since, the amount of ice has been referred to one square meter, the result in equation 2.26 can be referred to as heat flux per square meter:

$$\dot{q}_{sensible} = 11.44\frac{\mathrm{kW}}{\mathrm{m}^2} \quad (2.27)$$

Finally, the above used heating efficacy has to be considered:

$$\dot{q}_{sensible} = \frac{11.44}{0.7}\frac{\mathrm{kW}}{\mathrm{m}^2} = 16.35\frac{\mathrm{kW}}{\mathrm{m}^2} \quad (2.28)$$

2.7 Summary of Electro-Thermal Cyclic Deicing Specific Power Requirements

Throughout the calculation process, it can be seen, that results are processed with a number of assumptions and simplifications. So, many variations are in fact possible which would lead to various different results than that one derived in this report. As an example, parameters that are most likely to have a keen influence on running wet anti-icing and thus on the parting strip power requirements are:

- atmospheric icing conditions (continuous maximum or intermittent maximum)
- true air speed
- ambient temperature
- pressure altitude
- mean effective drop diameter d_{med} = 20 µm
- airfoil geometry
- Reynolds number
- heater layout / geometry (compare Figure 1.1)

The calculation scheme exemplified in this report can be used for further computations. Usually, power requirement calculations of ice protection systems are extremely tedious. To reduce the number of calculations **AIR1168/4** provides graphical presentations of water catch and heat transfer equations that have produced a good correlation in both icing tunnel tests and natural icing flights. However, the chapter of electro-thermal cyclic deicing is not described in full detail. In fact, calculations are referred to similar protection principles such as running wet anti-icing. For this reason, it is obvious that obtained results are vague.

Table 2.2 Results of specific parting strip power requirements

source	parting strip power requirements	ambient conditions	
	kW/m²	°C	°F
calculated (according to AIR 1168/4 calculation scheme) chapter 2.3	14.43	-17.78	0.00
caculated with general accepted formula – chapter 2.5	21.90	-17.78	0.00
suggested value of AIR1168/4 (p. 28)	18.60	-17.78	0.00
suggested value of AIR1168/4 (p. 28)	31.00	-30.00	-22.00

Discrepancies in the results of parting strip power requirements as presented in Table 2.2, are primarily due to the fact that the method of AIR1168/4 (with is graphical presentations) has been adapted to meet all possible design points. Thus, graphs and Figures in AIR1168/4 must have been adapted to meet the *average* in order to provide a more generic method.

For calculations deduced from thermodynamics general formula, it must be kept in mind, that only one point along the airfoil's leading edge has been evaluated. Reynolds number, static pressure, temperature, water catch etc. are different in magnitude and direction at each point along the airfoil. The overall cyclic power requirement is in fact the **integrated value over all local cyclic power requirements**. In addition to that, various design points with different e.g. ambient temperatures and flight speeds have to be considered to get required cyclic power requirements. The calculation principle explained above can be used to evaluate the power load for electro-thermal deicing for a specific type of airfoil and flight condition by computing (**LTH 2008**):

- the flow field around the considered airfoil,
- the trajectories of water catch,
- the local heat transfer coefficients,
- for cyclic deicing areas: the ice accumulation, and finally
- the required heat flux for parting strips and cyclic deicing.

The suggested values of **AIR1168/4** for electro-thermal cyclic deicing deliver the most promising results, since those are **empirical values**.

Table 2.3 Results of specific cyclic power requirements

source	cyclic power requirements	heat-on time	total cycle time
	kW/m²	s	min
calculated	16.35	9	3
AIR1168/4 (p. 28)	62.00	2.5	not stated
AIR1168/4 (p. 28)	34.10	9	3

In Table 2.3 results of cyclic power requirements are summarised. It can be seen that the reproduced value is much lower (approximately about the half) than suggest values of AIR1168/4. The difference can be explained by the various assumptions taken to get a very quick and first result. Thus, the unheated equilibrium temperature might even be lower than the ambient temperature. Or, 0.3 mm of ice to be melted might not be enough for a thorough cyclic deicing (especially in the vicinity of the stagnation line). The calculation presented in chapter 2.6 could be easily adapted to meet the value of AIR1168/4 (e.g. 0.6 mm of ice thickness). In summary, suggest empirical values of AIR1168/4 deliver the most promising results for parting strip and cyclic power requirements. The parting strip power requirement of about 31 kW/m^2 as well as the cyclic power requirement of about 34 kW/m^2 with a heat-on time of about 9 s and a total cycle time of about 3 min is considered for further calculations.

Technology factors should additionally be considered since the parameters and values are based on year 1989 standards.

3 Alternative Low Power Ice Protection Systems

Research and development on so-called Low-Power Deicing (LPDI) systems reaches back to the 1980's. Thus, electro-impulse deicing as an alternative to conventional ice protection systems such as hot bleed air systems was already investigated (**Kodet 1988).**

3.1 Electro-Magnetic Expulsion Deicing System

Electro-Magnetic Expulsion Deicing System (EMEDS) consists of Deicing Control Unit (DCU) and an Energy Storage Bank (ESB) consisting of capacitors and electro-mechanical actuators (copper strips coiled into a tubular from with an elliptical cross section). The actuators are located right under the metal skin of the leading edge and are approximately 38 cm in length. With an electrical charge from the ESB, a magnetic field is induced changing the elliptical cross section into a circular one. However, due to the limited space between the actuator and the airfoil skin, a force is imparted that results in a high acceleration of the airfoil with a low deflection. Thus, ice build-ups can be shattered and removed by firing alternately the actuators of the upper and lower surfaces three times in deicing cycle. The energy required to fire an actuator is about 45 J (550 V and 300 μF capacitance). This energy is released in less than 0.005 sec. (**Al-Khalil 2007).**

As often for mechanical deicing systems, residual ice is left on the surface. Also, this method does not remove very low levels of ice accretions (**Al-Khalil 2007)**. The system is therefore not quite appropriate for high performance aircraft wings where ice accumulations must be less than 1.3 mm.

3.2 Hybrid Running-Wet Anti-icing System

A hybrid running-wet anti-icing system consists of thermal subsystem (operating a running-wet mode) and an EMEDS (Figure 3.1). With the thermal subsystem, the surface temperature is held just above freezing. The frozen runback ice can than be removed by means of an EMEDS. To properly deice the surface, a minimum ice thickness is needed of about 1.5 mm is needed (**Al-Khalil 2007**).

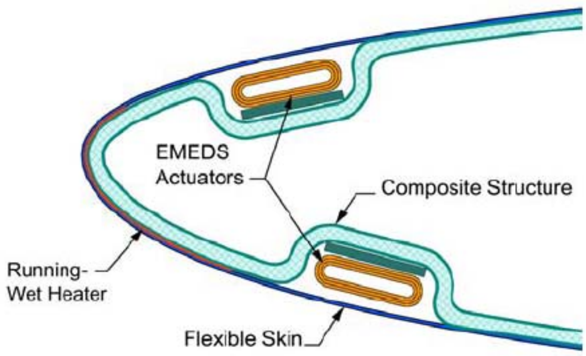

Figure 3.1 Schematic of hybrid running-wet anti-icing system (from **Al-Khalil 2007**, p. 7).

3.3 Thermal-Mechanical Expulsion Deicing System

Thermal-Mechanical Expulsion Deicing System (TMEDS) is the combination of electro-thermal and EMEDS deicing (Figure 3.2). In this case, the electro-thermal deicing heater does not operate continuously like in the case of a running-wet anti-icer. It is powered only for a short period of time in order to melt just a thin layer of ice to weaken the ice-airfoil interface. The EMEDS actuators are then fired to remove the ice. The idea of TMEDS is somehow connected to electro-thermal cyclic deicing. The system eliminates, however, the need of a continuously operated parting strip along the entire span of a protected wing or tail. According to **Al-Khalil (2007)** runback ice can be removed promptly so that continuous ice growth can be prevented. Considering the same actuators in Figures 3.1 and 3.2, TMEDS, requires less power than a hybrid running-wet anti-icing system because the heater does not operate continuously.

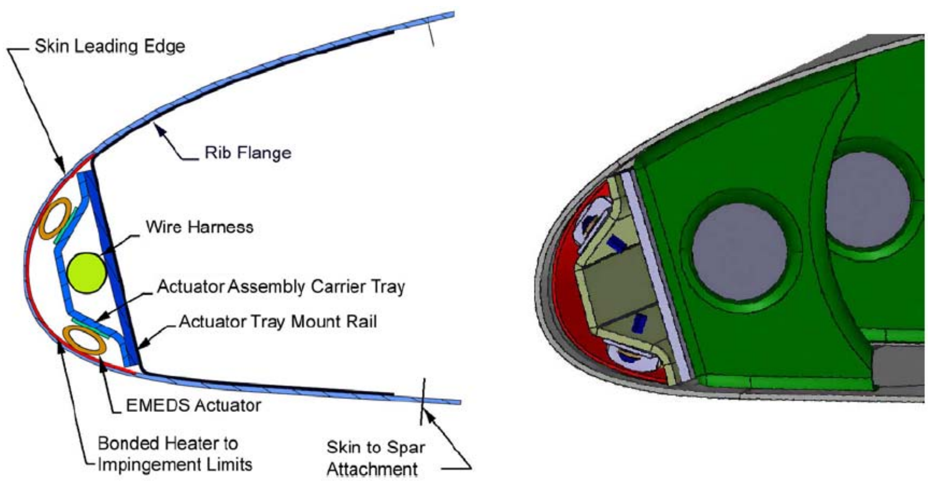

Figure 3.2 TMEDS (from Al-Khalil 2007, p. 7).

4 Comparison of Deicing Systems

To compare derived results on electro-thermal cyclic deicing systems with power requirements for alternative low power ice protection systems as stated in **Al-Khalil** (**2007**), parting strip power requirements and cyclic power requirements have to be combined. To do so, a heater layout has to be found in combination with a firing sequence for cyclic deicing.

4.1 Possible Heater Layout

A possible heater layout for a conventional aircraft with four slats on each wing is presented in Figure 4.1. Each slat consists of nine segmented deicing zones. The area of one zone may be 0.08 m^2 where the zone width (spanwise) is equal to an actuator length (EMEDS) i.e. 38 cm. Thus, for each slat, equipped with e.g. an EMEDS system, nine actuators would be necessary for the upper surface and nice for the lower surface. One ESB is in charge of two slats and used to power actuators individually. With this arrangement, the length of the power cables can be limited (**Al-Khalil 2007**).

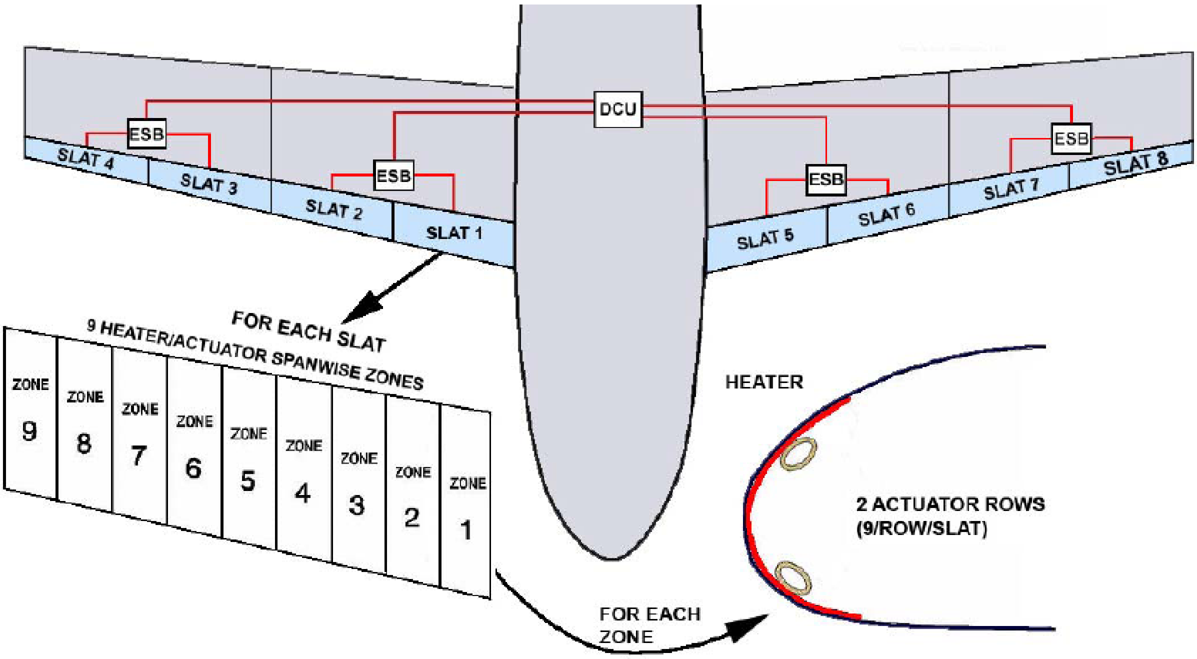

Figure 4.1 Possible layout of spanwise deicing segments (from **Al-Khalil 2007**).

Deicing Sequence

The sequence starts with deicing of zone 1 on slats 1, 3, 5, and 7 simultaneously and continuous with deicing of zone 2 through 9 for respective slats. After that, slats 2, 4, 6, and 8 are deiced by simultaneously heating 4 zones starting from zone number 1 through 9 on each respective slat. The whole process itself is repeated over and over again (**Al-Khalil 2007**).

4.2 Power Required of Different Deicing Systems

EMEDS applied on this deicing sequence will result in firing 4 actuators located on the upper wing surface followed by 4 actuators on the lower wing surface. Total power load is therefore the sum of energy necessary to fire 4 actuators at the same time, thus the total power required would be less than 1 kW (**Al-Khalil 2007**).

TMEDS applied on this deicing sequence will require a pre-energy load that is used to heat the wing surface to the specified temperature. With a suggested heater power density of about 54 kW/m^2 (**Al-Khalil 2007**), the power load for TMEDS should be as high as:

$$\dot{Q}_{TMEDS} = \frac{q}{S_0} \cdot S_{zone} \cdot n_{zone} + \dot{Q}_{EMEDS} = 54\,\frac{\mathrm{kW}}{\mathrm{m}^2}\,0.08\,\mathrm{m}^2 \cdot 4 + 1\,\mathrm{kW} = 18.4\,\mathrm{kW} \tag{4.1}$$

The required power load for the above explained **hybrid running-wet anti-icing system** is according to **Al-Khalil (2007)** 55 kW. Out of the report it is however not quite clear how calculations have been done to gather this value.

In the case of an **electro-thermal cyclic deicing system**, the total power load is the sum out of continuous heated (spanwise and chordwise) parting strips and cyclic power requirements. The spanwise parting strip extends over the entire wing and 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 (**Al-Khalil 2007**). **AIR1168/4** suggests 25.4 mm in width for the spanwise parting strip and 19.1 mm in width for the chordwise parting strip. With Figure 4.1 in mind, total wing span equals the sum of the spanwise extension of all zones (chordwise partint strips must be accounted for the upper and the lower surface). The maximum value of specific parting strip power requirements is taken from Table 2.2. Thus, parting strip power load, according to the layout depicted in Figure 4.1, yields:

$$\begin{aligned} \dot{Q}_{PS} &= \frac{q}{S} \cdot \left(S_{PS\,span} + S_{PS\,chord} \right) = \\ &= 31\,\frac{\mathrm{kW}}{\mathrm{m}^2} \cdot 9 \cdot 8 \cdot \left(0.0254\,\mathrm{m} \cdot 0.38\,\mathrm{m} + 0.0191\,\mathrm{m} \cdot 0.21\,\mathrm{m} \cdot 2 \right) = 39.5\,\mathrm{kW} \end{aligned} \tag{4.2}$$

In order to calculate cyclic power requirements, total cycle time of about three minutes and heat-on time of about 9 sec. are crucial. Three minutes divided by 9 sec. yields 20. Thus, 20 zones could be individually heated before zone one must be heated again in order to heat it every three minutes. In our example (Figure 4.1), the deicing sequences could be similar to the one addressed above: zones one through 9 are individually heated on slats 1, 3, 5, and 7 simultaneously which is continued with zones one through 9 on slats 2, 4, 6, and 8. If each zones is heated 9 sec. long, the heat off period would be 2.7 minutes, thus under the required

3 minutes. As a result, 4 zones must be heated at one time for deicing (specific power requirements from Table 2.3):

$$\dot{Q}_{cyclic} = \frac{q}{S} \cdot S_{zone} \cdot n_{zone} = 34.1 \frac{\mathrm{kW}}{\mathrm{m}^2} 0.08\,\mathrm{m}^2 \cdot 4 = 10.9\,\mathrm{kW} \tag{4.3}$$

Total power load of electro-thermal cyclic deicing in our example yields:

$$\dot{Q}_{electro-thermal\,cyclic\,deicing} = \dot{Q}_{PS} + \dot{Q}_{cyclic} = 39.5\,\mathrm{kW} + 10.9\,\mathrm{kW} = 50.4\,\mathrm{kW} \tag{4.4}$$

It can be seen that total power load of electro-thermal cyclic deicing is primarily dependent on parting strip power requirements and therefore on the area of the parting strip. By increasing the surface area of respective zone, fewer chordwise parting strips would be required, though decreasing total power parting strip power load. However, this effect is downsized because of the fact that the width of the chordwise parting strips is less than that of the spanwise parting strip. Designing the zone area twice as big and heating only 2 zones instead of 4 at one time for cyclic deicing, would result in 41.4 kW of total power load but also in a reduction of deicing efficiency. This emphasis that reducing the need of chordwise parting strips, does not heavily influence total power load. In fact must additionally the area of the spanwise parting strip be decreased, which would automatically mean that the deicing system might not properly work with e.g. the aircraft at high angle of attacks and the stagnation point out of the parting strip region. Thus, lowering total power load of an electro-thermal cyclic deicing system is simply limited and not possible to a certain extend.

Table 4.1 summarises total power loads of the general electro-thermal cyclic deicing system as well as all mentioned alternative low power ice protection systems. Specific power loads have been calculated by dividing the value of total power load by the total area considered. This area is in our example the area of a single zone times the number of zones (S_0 = 5.76 m^2).

Table 4.1 Comparison of total power load of different deicing systems with a heater layout according to Figure 4.1 (values stated in **Al-Khalil 2007** are not comprehensible and should be considered as another rough examples)

ice protection system	**total power load** kW	**specific power load** kW/m^2
electro-thermal cyclic deicing system (one zone 0.08 m^2)	50	8.7
electro-thermal cyclic deicing system (one zone 0.16 m^2)	41	7.1
electro-thermal cyclic deicing system according to **Al-Khalil** (**2007**) with same simultaneous zones as TMEDS	27	4.7
hybrid running-wet anti-icing system according to **Al-Khalil** (**2007**)	55	9.6
TMEDS - Thermal-Mechanical Expulsion Deicing System	18	3.1
EMEDS - Electro-Magnetic Expulsion Deicing System according to **Al-Khalil** (**2007**)	< 1	<1

By comparing specific power loads for electro-thermal cyclic deicing in Table 4.1 with parting strip power requirements in Table 2.2 it can be noticed that, due to the areas of cyclic deicing, the maximum parting strip power requirement of about 31 kW/m^2 (for the whole area to be protected and with no cyclic deicing) is lowered to approximately 8 kW/m^2 (parting strip plus cyclic deicing). This comparison shows that e.g. 75 % of energy can be saved by applying a cyclic deicing system instead of a conventional running wet system, as it is today on commercial aircraft.

4.3 Quick Method for Estimating the Power Required of Electro Thermal Cyclic Deicing Systems

It can be noticed that the method of cyclic deicing uses two basic principles:

- decrease of the continuous heated area (parting strips), and
- decrease of the heat-on time (cyclic deicing)

that will be demonstrated in the following calculations. With equations above (equation 4.2, etc.) the relative portion of the parting strip area with respect to the overall area to be protected can be evaluated:

$$S_{PS} = \left(S_{PS\,span} + S_{PS\,chord}\right) = 9 \cdot 8 \cdot \left(0.0254\,\mathrm{m} \cdot 0.38\,\mathrm{m} + 0.0191\mathrm{m} \cdot 0.21\mathrm{m} \cdot 2\right) = 1.27\,\mathrm{m}^2 \quad (4.5)$$

$$k_{PS} = \frac{S_{PS}}{S_0} = \frac{1.27\,\mathrm{m}^2}{5.76\,\mathrm{m}^2} = 0.221 = 22.1\ \% \quad (4.6)$$

As a result, 22 % of the total area accounts for the parting strips (spanwise and chordwise as well as upper and lower surface of the leading edge). This automatically implies that the area to be heated permanently is reduced to 22 % of the total area considered.

The second principle reduces the heat on time of the areas between the parting strips. Thus, the relative portion of the actual heat-on time with respect to the total cycle time can be expressed by an additional factor:

$$k_{cycl} = \frac{t_{heat-om}}{t_{cycl}} = \frac{9\ \mathrm{s}}{180\,\mathrm{s}} = 0.05 = 5\ \% \quad (4.7)$$

Equation 4.7 implies that the heat-on time of the respective surface is reduced to 5 % of total cycle time. To finally calculate specific power loads of the overall electro-thermal cyclic deicing system, the *k* factors have to be multiplied with specific power requirements as stated in Table 2.2 and Table 2.3:

$$\dot{q}_{total} = \dot{q}_{PS} \cdot k_{PS} + \dot{q}_{cycl} \cdot k_{cycl} = 31\frac{\mathrm{kW}}{\mathrm{m}^2} \cdot 22.1\% + 34.1\frac{\mathrm{kW}}{\mathrm{m}^2} \cdot 5\% = 8.6\frac{\mathrm{kW}}{\mathrm{m}^2} \tag{4.8}$$

With equation 4.8 it becomes possible to estimate the power requirement of an electro-thermal cyclic deicing system without defining a heater layout and a deicing sequence in advance. By estimating the *k* factors in combination with empirical values of specific power requirements (either from literature or from this technical note), the overall calculation becomes very short and convenient. Thus, a first statement of the system's required power load (either specific or overall) can be accomplished very easily.

Parameters stated in equation 4.8 are strictly true for the above stated example. However, the *k* factors might be considered as first estimates for further calculations. A slight difference between the specific power load in equation 4.8 and in the specific power load listed in Table 4.1 can be noticed. This is because calculations in the preceding chapters' uses a heat-off time of about 2.7 min (162 s) instead of 3 min as suggested in AIR1168/4. The adaptation to 2.7 min was necessary due to the specific heater layout and deicing sequence explained above.

4.4 Discussion

EMEDS leaves residual ice on the surface and is furthermore not capable of removing very low levels of ice. EMEDS is therefore not suitable for high-performance wings and not considered in further discussion. TMEDS features the lowest total power load because of the elimination of the continuously heated parting strip. The parting strip for electro-thermal cyclic deicing is crucial and great care must be taken during sizing especially with respect to the chordwise width. The range of movements of the stagnations must be encompassed by the parting strip area. Otherwise, ice will build up at the aerodynamic attachment which cannot be removed because of the aerodynamic forces that hold the ice layers against the aircraft surface. Thus, in order to ensure a proper deicing, the parting strip would be designed somehow above 25.5 mm. According to Figure 4.2 the parting strip width seems to amount to approximately 25 % of maximum airfoil thickness (t = 0.33 m) which is in our case 82.5 mm. However, heating of the parting strip additionally influences the adjacent area. Thus the ice-free area might appear greater compared to the size of parting strips underneath the metal cladding. Considering that 25.5 mm is the absolute minimum value of spanwise parting strip width, leads to the conclusion that TMEDS features the best perspective of an alternative and low power deicing system.

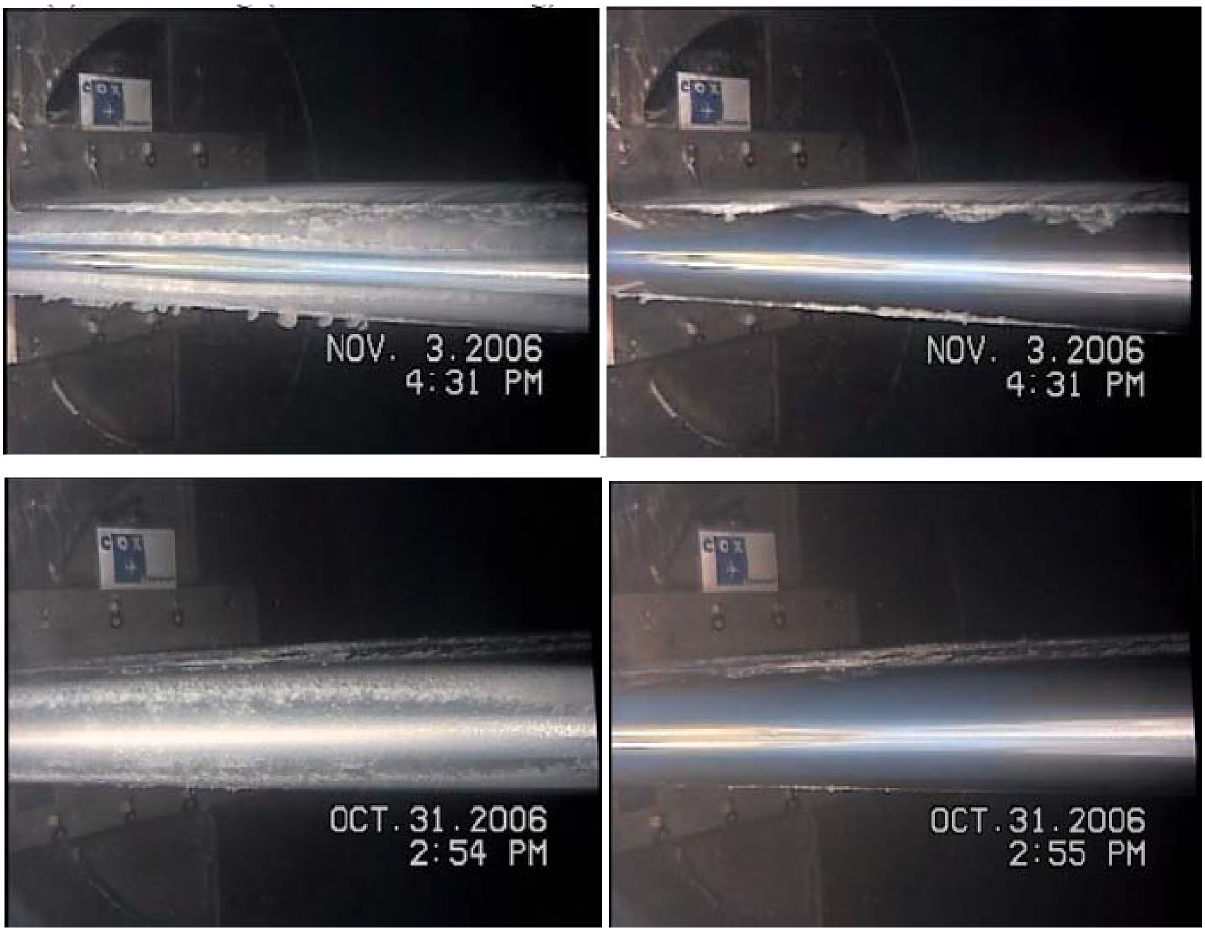

Figure 4.2 Comparison of an **electro-thermal deicing system (above)** with a **TMEDS (below)** at approximately the same conditions (total icing time = 44 min, v_{TAS} = 175 kt, $LWC_{(above)}$ = 0.7 g/m³, LWC $_{(below)}$ = 0.5 g/m^3, $TAT_{(above)}$ = -6 °C, $TAT_{(below)}$ = -3 °C). **Left: pre-deicing**. **Right: post deicing**. Figures from **Al-Khalil (2007**).

Deicing means that a heat-off period is desired. Ice build ups will be visible especially for passengers sitting right next to the aircraft wing attachment. Figure 4.2 shows the impact of ice growth after a very long heat-off period of about 44 minutes total icing time. In must be kept in mind, that general heat-off time is a maximum of about three minutes. Thus, ice accumulations as shown in Figure 4.2 are not to be encountered during normal flight operation. The surface will get covered with ice to a much lesser extend. However, under these circumstances of ice growth it must be shown that the aircraft is capable of receiving a reduction of lift and angle off attack margin-to-stall as well as an increase in drag during various flight conditions. In Figure 4.2 it can be noticed that runback ice in the case of TMEDS is significant less which would be another point in favour of TMEDS.

5 Summary

Ice protection can either be accomplished by anti-icing, deicing or by a combination of both (referred to as hybrid). Where anti-icing systems keep the surface to be protected completely ice free, ice build-ups are allowed to form to get periodical shed with the application of a deicing system. Deicing requires less power than anti-icing because of a short but periodic energy input that is used to melt the ice-airfoil interface so that the adhesion of ice build-ups becomes zero. Aerodynamic forces can then remove the ice. However, during the heat-off period the aircraft must be capable of receiving ice accumulations on its wings, engine nacelles etc. The heat off time is tailored to the maximum allowable ice thickness that is lower in the case of high performance aircraft wings.

One of most discussed deicing system is the electro-thermal deicing system. In order to prevent ice bridging, the stagnation line has to be heated continuously through parting strips. Additionally, chordwise parting strips are necessary to split the surface to be protected into smaller areas. Parting strip power requirements are calculated by means of running-wet anti-icing calculation principles because of the continuous heating of the parting strip. Calculation principles are demonstrated according to the method suggested in AIR1168/4 as well as through general accepted formula to be found in any common thermodynamic book. The design point for calculations has been set to -18 °C at MSL in continuous maximum icing conditions. Calculations according to AIR1168/4 demonstrate that final results of about 14 kW/m^2 are almost independent of the aircraft's true air speed (calculations at v_{TAS} = 250 kt and v_{TAS} = 350 kt). This is because changes in Reynolds number and external heat transfer coefficient are compensating each other. Further calculations with general available formula show a similar power requirement of about 22 kW/m^2. Those values are compared with a suggested value of AIR1168/4 of about 19 kW/m^2. The discrepancies in the values are primarily due to the fact that the method of AIR1168/4 (with is graphical presentations) has been adapted to an average design point. Calculations exemplified in respective chapters are strictly true for the stated design point and at the considered position on the leading edge. All stated calculations and formula provide a generic understanding of the effects that determine electro-thermal cyclic power requirements. The simplest form to calculate the required heat flux is an energy-and-mass-balance for each surface element along an airfoil.

In the last chapter, alternatives to electro-thermal deicing are explained and discussed. In order to compare all deicing systems with each other on a generic level, a heater layout in context with a heating sequence has been defined in advance. Results show that the parting strip area and therefore the width of the parting strip is decisive for electro thermal deicing systems. Cyclic power requirements are of second order. Thermal-Mechanical Expulsion Deicing System (TMEDS) as an alternative to electro-thermal deicing focuses exactly on this problem: it eliminates the continuous heated parting strip and thus lowers the energy demand. In contrast to the specific power load of about 4.7 to 8.7 kW/m^2 for an electro-thermal cyclic deicing system, TMEDS exhibits a potential to get along with only 3.1 kW/m^2 of specific power while lowering the extend of runback ice at the same time.

In every low power deicing system, either one or both of the following principals are to be found: (1) decrease of the continuous heated area (parting strips) and/or (2) decrease of the heat-on time (cyclic deicing). In this report, this methodology has been demonstrated on an electro thermal cyclic deicing system, which provides a very good and quick method to estimate total power loads.

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Appendix A

A.1 CS-25 Book 1 Appendix C / Part I – Atmospheric Icing Conditions Overview

The maximum continuous and intermittent maximum intensity of atmospheric icing conditions is defined by the variables of the **cloud liquid water content**, the **mean effective diameter of the cloud droplets**, the **ambient air temperature**, and the interrelationship of these three variables as shown in Figure A.1. The **limiting icing envelope** in terms of altitude and temperature is given in Figure A.2. The interrelationship of cloud liquid water content with drop diameter and altitude is determined from Figures A.1 and A.2. The **cloud liquid water content** for

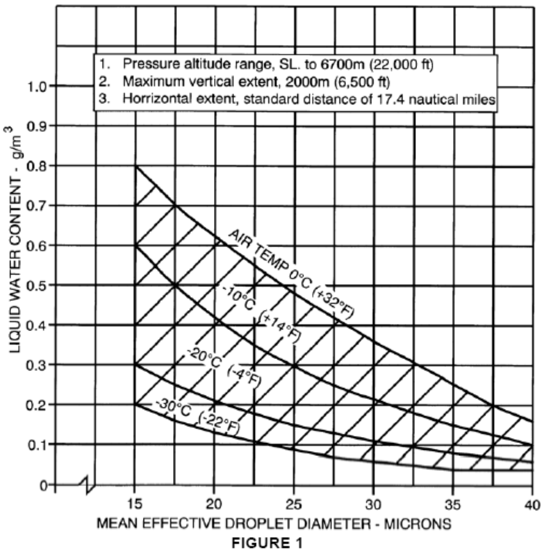
- continous maximum icing conditions of a horizontal extent, other than 32,3 km,
- intermittent maximum icing conditions of a horizontal extent, other than 4.8 km,

is determined by the value of liquid water content of Figure A.1 multiplied by the appropriate factor from Figure A.3 in Table A.1.

Figures as presented in Table A.1 allow for a comparison between continuous maximum and intermittent maximum atmospheric icing conditions.

Table A.1 Atmospheric icing conditions (**CS-25 2008,** Appendix C)

Continuous maximum icing	Intermittent maximum icing



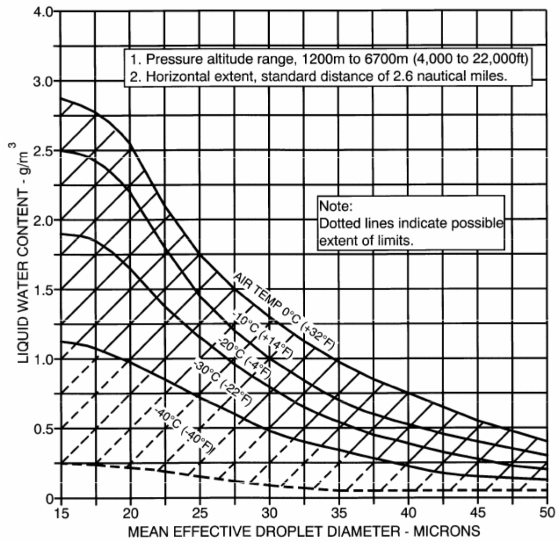
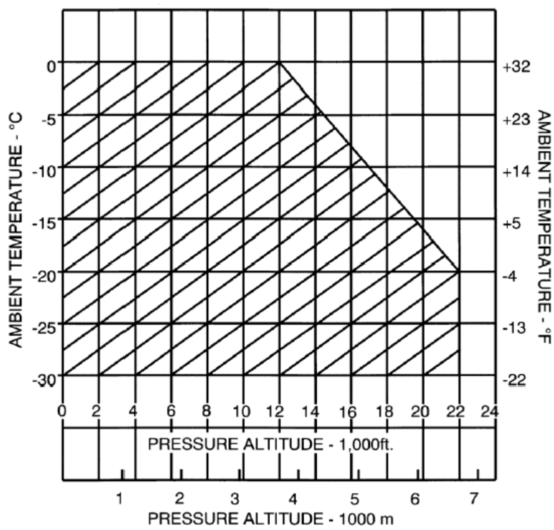


Figure A.1 Liquid water content vs mean effective drop diameter



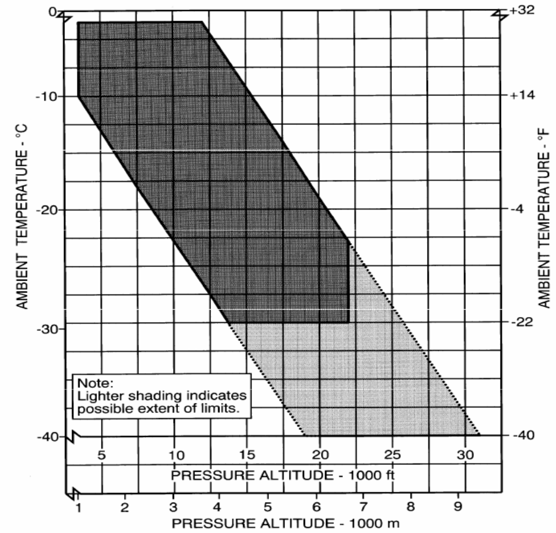
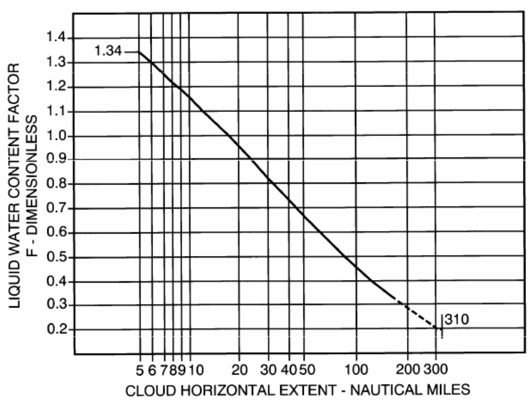


Figure A.2 Ambient temperature vs pressure altitude



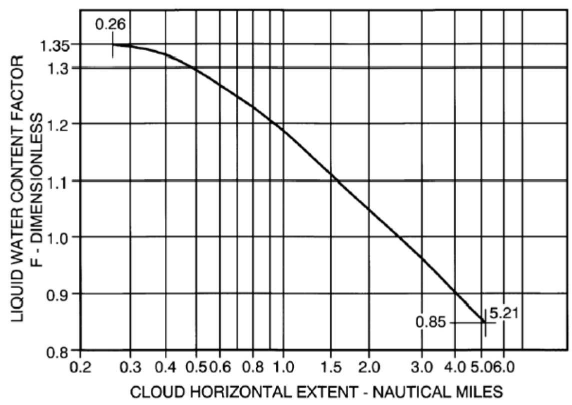


Figure A.3 Liquid water content factor vs cloud horizontal distance

A.2 Principal wing and heater (bleed air system) layout of an Airbus A320/A321 wing

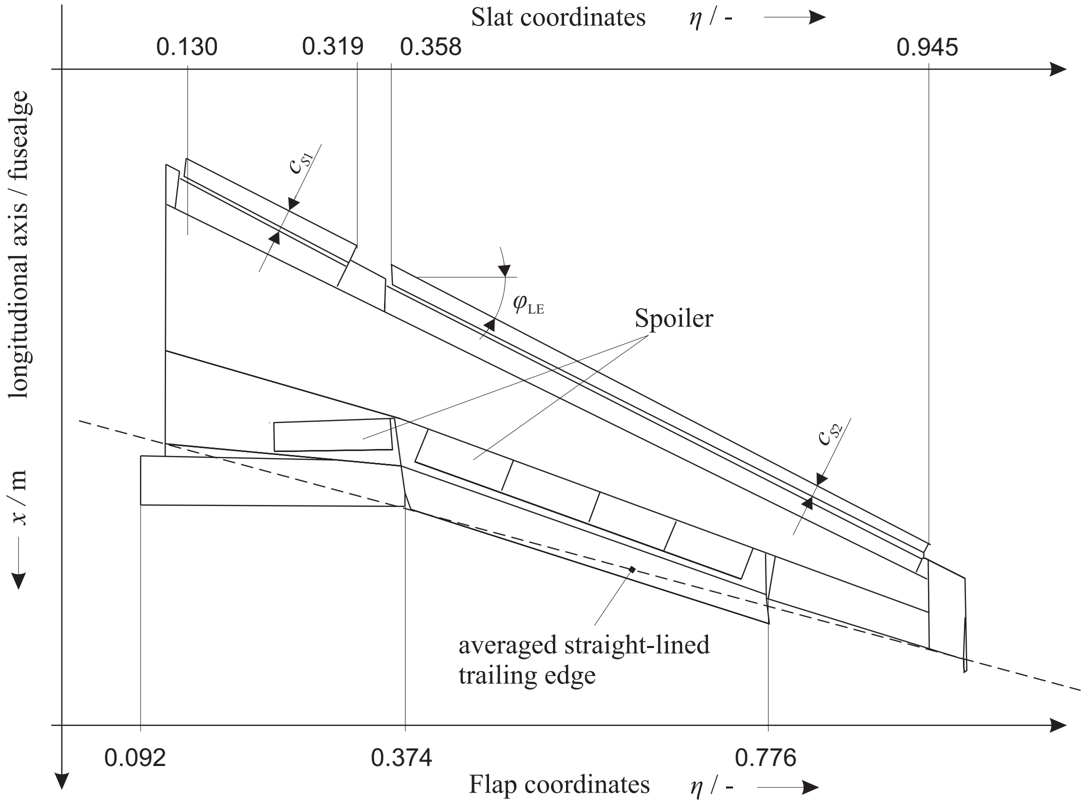


Fig. A.4 Airbus A320 wing geometry in relative spanwise coordinates. η-coordinate is defined perpendicularly to the aircraft's longitudinal axis for describing a percentage spanwise extension (from **Krammer 2008**)

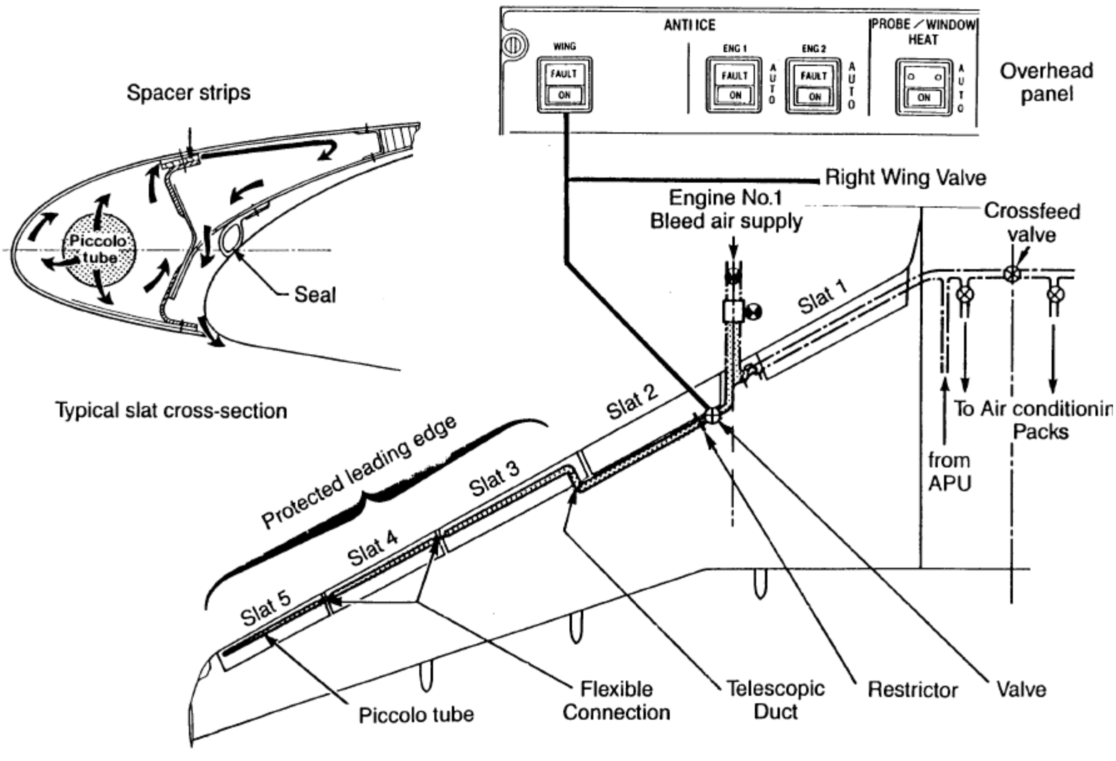


Fig A.5 Wing anti-ice of an Airbus A321 (from **Scholz 1997**, p. 9-15)