A HANDBOOK METHOD FOR THE ESTIMATION OF POWER REQUIREMENTS FOR ELECTRICAL DE-ICING SYSTEMS

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Abstract

Electrical de-icing consumes more power than is generally available from the generators. Therefore, electrical de-icing only becomes feasible, if the power is merely used during limited time intervals to melt the ice and separate it from the wing. The airflow then simply carries the ice away which avoids the need for further power to melt or even evaporate the ice totally. The ice slabs forming on the wing can be carried away by the airflow, if the slabs are separated from one another. Separation is achieved by constantly heated parting strips. This paper provides an easy to use method to estimate power requirements for such electrical de-icing systems taking account of described power saving technologies. In contrast to an established method by SAE, equations are derived here from first principles and SI units are applied. Based on the example of the Boeing 787 aggregated general technology parameters (k-factors) are derived. Applying these Boeing 787-based k-factors power estimations for other similar aircraft are greatly simplified. Without own experimental results for verification, the method is eventually calibrated based on findings published in the literature and own assumptions. Example calculations yield power requirements in the right order of magnitude. Based on the calculations of this paper the Boeing 787 would require 3.61 kW/m² for de-icing. The total required installed power for a Boeing 787 with an electrical de-icing system (and technologies as described) would be 75.8 kW which is in good agreement with the published power range of 45 to 75 kW.

NOMENCLATURES

e_{surf} iced wing span $[\mathrm{m}]$

c_{ice} heat capacity of ice $\left[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right]$

c_{liqu} heat capacity of water $\left[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right]$

cp_{air} specific heat capacity $\left[\frac{\mathrm{kJ}}{\mathrm{kg\,K}}\right]$

E_m water catch efficiency $[1]$

e_∞ ambient saturation pressure $[\mathrm{Pa}]$

e_{surf} surface saturation pressure $[\mathrm{Pa}]$

h_0 local heat transfer coefficient $\left[\frac{\mathrm{W}}{\mathrm{m^3\,K}}\right]$

k_0 thermal conductivity of air $\left[\frac{\mathrm{W}}{\mathrm{m\,K}}\right]$

k_{cycl} total cycle time factor $[1]$

k_{ps} parting strip factor $[1]$

L_c latent heat of vaporization $\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right]$

L_f latent heat of fusion $\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right]$

$\dot{m}_{local}$ local water catch $\left[\frac{\mathrm{kg}}{\mathrm{sm^2}}\right]$

Nu Nusselt number $[1]$

n freezing fraction $[1]$

p_∞ ambient air pressure $[\mathrm{Pa}]$

Pr Prandtl number $[1]$

P_{req} required electrical power $[\mathrm{W}]$

P_{elec} available. electrical power $[\mathrm{W}]$

$q_{A/I}$ overall heat $\left[\frac{\mathrm{kW}}{\mathrm{m^2}}\right]$

q_{KE} kinetic heating $\left[\frac{\mathrm{kW}}{\mathrm{m^2}}\right]$

q_{aero} aerodynamic heating $\left[\frac{\mathrm{kW}}{\mathrm{m^2}}\right]$

q_{convec} convective heating $\left[\frac{\mathrm{kW}}{\mathrm{m^2}}\right]$

q_{evap} evaporative heating $\left[\frac{\mathrm{kW}}{\mathrm{m^2}}\right]$

$q_{sensible}$ sensible heating $\left[\frac{\mathrm{kW}}{\mathrm{m^2}}\right]$

R_h relative humidity $[1]$

R_c boundary recovery factor $[1]$

$R_{c,p}$ Reynolds Number $[1]$

T_∞ ambient Temperature $[\mathrm{K}]$

T_{MSL} air temperature at mean sea level $[\mathrm{K}]$

T_{sk} skin Temperature $[\mathrm{K}]$

t maximum airfoil thickness $[\mathrm{m}]$

v_{TAS} true air speed $\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$

ρ_{LWC} mass of supercooled water p. vol. $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$

ABBREVIATIONS

AIR Aerospace Information Reports
CS Certification Specifications
FAA Federal Aviation Administration
SAE Society of Automotive Engineers

1. INTRODUCTION

"Power by Wire", the "All Electric Aircraft" or the "More Electric Aircraft" have been discussed for years. The application of these concepts in civil aviation however was much delayed by the fact that in an "All Electric Aircraft" not only power generation but also all consumers have to be electrical. For example the introduction of electrical primary flight controls, braking systems or de-icing systems has seen many challenges and their overall economical benefits were often unclear.

In order to prove the benefits of electrical systems, trade-off studies are always necessary. These trade-off studies are required already in the very early phases of an aircraft project. These early phases of a project are characterized by a lack of data and very limited investigation time. Often many system variants have to be checked with a limited amount of engineering man power. Quick and easy to use handbook methods are generally a good way to work within such a situation.

2. AIM, APPROACH AND APPLICATION

The aim of this paper is to estimate **power requirements** for electrical de-icing systems. Literature was checked for available existing handbook methods. An understanding from first **thermodynamic principles** was sought and the use of SI units self-evident. The handbook method from this paper should be so simple that it can be part of the preparation of trade-off studies. **Trade-off studies** compare various design principle with one another during early aircraft development. Hence many quick calculations for one aircraft project with very little time need to be supported.

3. CLASSIFICATION OF THERMAL ICE PROTECTION SYSTEMS

Ice protection is achieved mostly with **thermal** systems. Other means of ice protection are possible. The ice protection on large turbo prop aircraft is done with **mechanical** systems: Ice is shed by rubber boots that inflate due to applied internal air pressure. This paper only considers thermal ice protection.

It is differentiated between de-icing and anti-icing. The terms are defined in AIR 1168/4 [1]:

- **De-icing** is the periodic shedding, either by mechanical or thermal means, of small ice buildups by destroying the bond between the ice and the protected surface.
- **Anti-icing** is the prevention of ice buildup on the protected surface, either by evaporating the impinging water or by allowing it to run back and freeze on noncritical areas.

Thermal ice protection systems are classified according to three principals:

1. **Evaporative anti-icing systems** supply sufficient heat to evaporate all water droplets impinging upon the heated surface.
2. **Running-wet anti-icing systems** provide only enough heat to prevent freezing on the heated surface. Beyond the heated surface of a running-wet system, the water can freeze, resulting in runback ice. Running-wet systems must be designed carefully so as not to permit buildup for runback ice in critical locations.
3. **Cyclic de-icing systems** periodically shed small ice buildups by melting the surface-ice interface with a high rate of heat input. When the adhesion at the interface becomes zero, aerodynamic or centrifugal forces remove the ice.

An evaporative antiicing system uses the most energy of the three ice protection principles presented, cyclic de-icing uses the least energy.

4. CONVENTIONAL THERMAL ICE PROTECTION OF TODAY'S JET AIRCRAFT

Jet aircraft are classically provided with thermal ice protection systems. Ice protection of larger surfaces of these aircraft is done with pneumatic power. **Pneumatic power** is taken as bleed air from the aircraft engines and holds sufficient power for de-icing (Figure 1). The engine bleed air system extracts pressurized air from one or more bleed ports at different stages of the engine compressor of each engine on the aircraft. The bleed air system controls the pressure and temperature of the air and delivers it to a distribution manifold. The pressure is controlled by a pressure-regulating valve, and the temperature is lowered in a precooler with fan air or ram air.

The engine bleed air system supplies the hot air to the anti-ice system. The Airbus A321 wing **ice protection** system (Figure 4) is a thermal (hot air) evaporative anti-ice system. Only slats 3, 4, and 5 on the outboard wing need to be ice protected on this aircraft. An anti-ice valve isolates the anti-ice system from the bleed air supply. Ducts connect the anti-ice valve to a telescopic duct at slat 3. A piccolo tube runs along slat 3, 4, and 5 and supplies the hot air to the leading edge. A piccolo tube is a tube with calibrated holes that ensures that hot air is evenly distributed along the leading edge, although bleed pressure decreases towards the wing tip. The bleed air in the slats is released overboard through the holes in the bottom surface of the slat.

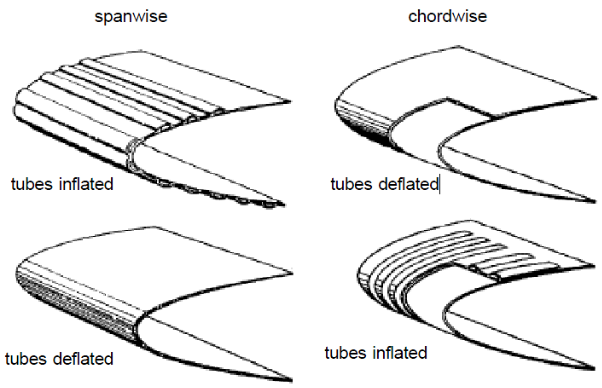

FIG 1: FAA: boot surfaces

5. PRESENT AND FUTURE CYCLIC ELECTRICAL WING DE-ICING SYSTEMS

Electrical power is taken from generators on board the aircraft. Generators are often engine driven, but can provide considerably less power than the available pneumatic power, taken as bleed air from the engine (compare with Section 4) [2]. Electrical de-icing of larger components or surfaces can hence cause a problem due to (maybe too) high power demands [3].

Cyclic electrical de-icing is only possible with a combination of (see Figure 2) [4]:

a) surfaces that are only heated during some time intervals (**cyclic heated surfaces**) just melting the bonding contact area of the ice and with

b) permanently heated **parting strips** ensuring separation of the ice layers, which are finally carried away by the air stream.

Cyclic electrical de-icing [4] saves energy because only a small portion of the ice is actually melted. Most of the ice leaves the aircraft in solid form.

The intention of this paper is to calculate the power requirements of cyclic electrical de-icing systems as presented in Figure 2 by means of a simple handbook method (see Section 10).

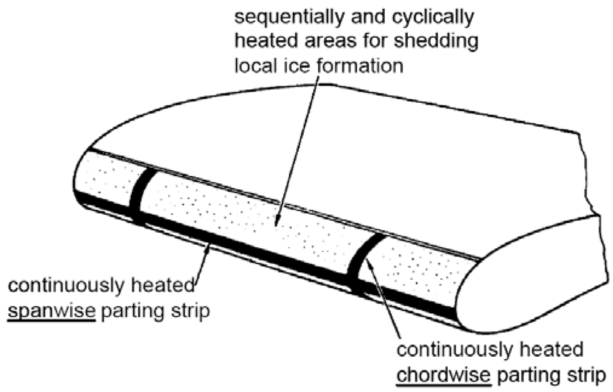

FIG 2: Arrangement of a wing area with electric cyclic de-icing (from [5], p. 9-9).

6. ICING FUNDAMENTALS

(Liquid) water below 0 °C is called supercooled water. Supercooled water can exist because the water has been totally undisturbed during cooling – nothing has caused it to turn to ice. When an aircraft hits the droplet, however, the droplet receives the necessary input for the phase change and turns to ice. The phase change from water to ice requires some latent heat extraction, but when the droplets are supercooled water, the heat extraction has already taken place. The ice water mixture will be slightly warmer than the supercooled water was just a second earlier. Hence: Supercooled water turns instantly to ice due to the interaction with the aircraft.

7. STATE-OF-THE-ART IN HANDBOOK METHODS

Only one handbook method seems to exist that is readily available. It is published by SAE [1]:

SAE: *Ice, Rain, Fog, and Frost Protection*. Warrendale, PA : Society of Automotive Engineers, 1990 (AIR 1168/4)

This method is mainly based on empirical equations. An approach based on internationally known equations from thermodynamics and heat transfer based on first principles together with the use of SI units would be beneficial.

8. ASSUMPTIONS FOR A HANDBOOK METHOD

Detailed simulations of ice accretion on airfoils are already used in industry. There are many different numerical approaches to calculate ice shapes for various atmospheric and flight conditions. Several two-dimensional and three-dimensional ice accretion codes have been developed. A literature review is given in [6] and [7].

In contrast to these numerical codes, a quick and easy to use handbook method inevitably has to make simplifying assumptions:

- Only two dimensional effects are considered.
- Only one point along the airfoil's leading edge is evaluated. Reynolds number, static pressure, temperature, water catch etc. are different in magnitude and direction at each point of the wing. Average values are used.
- The overall cyclic power requirement is the integrated value over all local cyclic power requirements taking into account the time fraction of cyclic surface heating and the relative surface area of the parting strips.
- Power requirements for de-icing depend on atmospheric conditions [8]. Certification rules from CS-25 [9] require the calculation of various design points with different e.g. ambient temperatures, liquid water contents, droplet diameters on the one hand and flight speeds *v* and airfoil thickness *t* on the other hand (Figure 3). The handbook method only considers one design point that is considered critical.

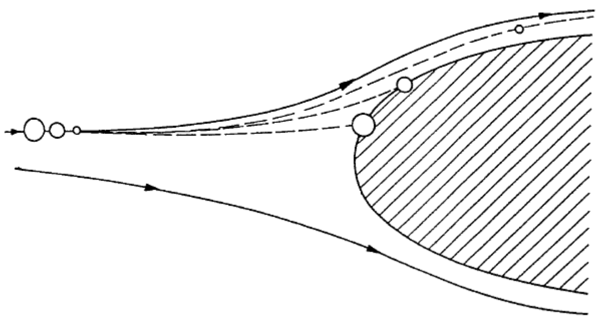

FIG 3: Not all droplets impinge on the wing surface. This fact is expressed by the water catch efficiency, [5]

9. SIMPLIFIED WATER CATCH CALCULATION

In order to calculate the total water catch of the wing, let us cut off a piece of a wing with a spanwise extension Δy and maximum thickness t. This piece of wing may fly at a speed v through a volume of air with a certain mass of supercooled water. The mass of supercooled water per volume is called *liquid water content* (LWC) and is something like a density named ρ_{LWC}. We consider $t \Delta y$ as the area of an imaginary sieve at an angle perpendicular to its flight path. The mass flow rate of supercooled water through the sieve would be as much as $\dot{m} = v\, t\, \Delta y\, \rho_{LWC}$. The impingement of water on the leading edge of the wing will, however, be different from the flow through the sieve as shown in Figure 3 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. The imaginary sieve shows an efficiency $E_m = 1$. The water catch at a certain spanwise location y and a spanwise extension Δy on the wing is calculated by

(1) $\dot{m} = v\, t\, \rho_{LWC}\, E_m$

E_m is a function of aircraft speed and droplet size, airfoil thickness and shape, viscosity and density of the air:

- High aircraft velocities and a large droplet size cause an increase in water catch efficiency.
- Thin wings divert the flow less and increase the water catch efficiency.

AIR 1168/4 [1] presents detailed methods to calculate E_m.

A simplified method to calculate the water catch efficiency E_m is presented here based on Figure 3F-3 of AIR 1168/4 [1] as a function of aircraft speed *v* and wing thickness *t* (Figure 5). Based on typical airfoils with a relative thickness of 6 … 16 % at an angle of attack of α = 4 °, a simplified formula for calculating E_m is presented:

(2) $E_m = 0.00324 \left(\frac{v}{t} \right)^{0.613}$

for v in m/s and t in m .

This formular is 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 %. For a simple method, we do not distinguish between difference due to spanwise location. For the total wing it is $\Delta y = b$ where b is the wing span. The total water catch of the wing is thus calculated by

(3) $\dot{m} = v\, t\, b\, \rho_{LWC}\, E_m$

10. CALCULATION OF POWER REQUIREMENTS

10.1 Calculation of Power Requirements for Continuously Heated Surfaces

The **parting strips** (presented in Section 5) are continuously heated surfaces. They are heated to a defined constant temperature. It is assumed here that this temperature is 6 °C. This temperature is sufficient to prevent the surface from freezing.

The surface is bombarded with supercooled droplets that turn partially into ice. It is interesting to note that at e.g. -18 °C only 22 % of the water will be ice after impact. No matter if ice or water, the supercooled H_2O needs to be warmed up and that requires a heat flow.

The heat flow per unit area $\dot{q}$ required to keep the parting strips free of ice can be expressed by an energy balance [10], [11] for each surface element on the wing. In the simplest form, the energy required by an anti-icing system is determined from the rate that must be supplied to balance the heat losses from the heated surface. In detail there is sensible heating, convective cooling, and evaporative cooling. 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 flow. The same is true for aerodynamic heating. The required heat flow for anti-icing (A/I) is similar to the parting strips heat flow [12], [11] thus calculated from

(4) $$\dot{q}_{A/I} = \dot{q}_{PS} = \dot{q}_{sens} + \dot{q}_{conv} + \dot{q}_{evap} + \dot{q}_{kin} + \dot{q}_{aero}$$

a) **Sensible Heating**

The supercooled droplets impinging at a mass flow per unit area of the imaginary sieve $\dot{m}_{local}$ have to be heated up to the surface temperature. The ice must additionally first become liquid; latent heat needs to be added. With freezing fraction *n* which indicates the amount of liquid water that turns into ice:

(5) $$\dot{q}_{sensible} = \dot{m}_{local}[\Delta T((1-n)c_{liq} + nc_{ice}) + nL_f]$$

(6) $$E_m = 0.00324\left(\frac{v}{t}\right)^{0.613}$$

(7) $$\dot{m}_{local} = v\,\rho_{LWC}\,E_m$$

a) **Convection**

The convective heat loss can be calculated from

(8) $$\dot{q}_{convec} = h_0(T_{skin} - T_\infty)$$

Where h_0 is the local heat transfer coefficient.

(9) $$h_0 = Nu\frac{k_0}{x}$$

with $k_0 = 0.0227\frac{W}{mK}$ for air at 255.3 K.

The dimensionless quantities are calculated as follows:

Nusselt number:

(10) $$Nu = 0.0296 \cdot Re_X^{\frac{4}{5}} \cdot Pr\frac{1}{3}$$

Prandtl number:

(11) $$Pr = \frac{c_p\ \mu}{k_0}$$

Reynolds number:

(12) $$Re = \frac{\rho_{MSL}\ v\ l}{\mu}$$

c) **Evaporation**

The evaporative heat loss equals the rate of mass evaporated from the surface multiplied by the latent heat of evaporation. For fully evaporative anti-icing the surface is heated sufficiently to evaporate all of the impinging supercooled liquid water. 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* [13] as well as on relative humidity R_h. The latent heat for water evaporation is $L_e = 2257\frac{kJ}{kg}$.

In literature many equations can be found to calculate the saturation pressure

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

(11) $$e = \frac{f}{100}6.107\,10^{7.5\frac{T}{237+T}}$$

TAB 1. Results of specific parting strip power requirements

source	$\dot{q}_{PS}$ [kW/m²]	t [C°]
Example Calculation for parting strip power requirements	11.82	-17.78
AIR 1168/4 calculation scheme	14.13	-17.78
AIR 1168/4 suggested value (p. 28)	18.6	-17.78

d) **Kinetic Heating**
Heat gain due to the impinging accelerated super cooled droplets.

(12) $$\dot{q}_{KE} = \dot{m}_{local} \frac{v_\infty^2}{2}$$

e) **Aerodynamic Heating**
Heat gain due to friction in the boundary layer over the surface. Like with all other heat gains, power requirements for the de-icing system are lowered due to heat gains. Hence, at high aircraft speeds no more ice protection is needed.

(13) $$\dot{q}_{aero} = R_c h_0 \frac{v_\infty^2}{2\, c_{p,air}}$$

R_c represent the boundary recovery factor with $n = 0.5$ due to laminar boundary layer [12].

(14) $$R_c = 1 - \left(\frac{0.99 \;\; v_1^2}{v_\infty^2} \right) (1 - Pr^n)$$

In all of the calculations (a) to (e) various aircraft depending and environment depending parameters are required as input. A calculation is only possible with a certain aircraft and and icing condition in mind. As an example, parameters listed below have most likely a keen influence on running wet anti-icing (and thus on the parting strip) power requirements:

- atmospheric icing conditions (continuous maximum or intermittent maximum)
- true air speed
- ambient temperature
- pressure altitude
- mean effective drop diameter (20 µm)
- airfoil geometry
- Reynolds number
- heater layout / geometry

Using Boeing 787 parameters and dimensioning icing conditions from CS-25, specific power requirements can be calculated and are given an compared with values from literature in Table 1.

10.2 Calculation of power requirements for cyclic heated surfaces.

- To calculate cyclic power requirements, the unheated equilibrium temperature has to be assumed (6 °C).
- 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.). An average value of 0,5 mm has been assumed due to general considerations and coincides the over all de-icing performance of Boeings 787 [3].
- Some of the supplied heat is not reaching the ice but is lost to the environment via the aircraft structure. The efficiency is assumed to be 70 %.

With the following equation it becomes more convenient:

(15) $$\dot{q}_{sensible} = \dot{q}_{Cycl} = \frac{\dot{m}_{ice}}{t} [\Delta T \, c_{Ice} + L_f]$$

With:

(16) $$m_{ice} = t \rho$$

Thus, per square meter, a mass of 0.45 kg of ice has to be melted. With the assumptions from above this yields a specific power requirement as given and compared in Table 2. The calculated value is not dependent on any aircraft parameters.
Compared to the AIR 1168/4 value the computed one it is very low due to the adopted water film who is responsible for the ice slip of.

TAB 2. Results of specific parting strip power requirements

source	$\dot{q}_{Cycl}$ [kW/m²]	t [C°]
Calculated	27.25	-17.78
AIR 1168/4 (p. 28)	34.10	-17.78

10.3 Calculation of Power Requirements for a Generic Heater Layout

It can be noticed that the method of cyclic deicing with parting strips an shown in Fig. 2 uses two basic principles:

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

In order to calculate the overall (average) specific heat flow, it is NOT necessary to know the detailed layout of the de-icing system. Only two factors are required:

- k_{PS} gives the ratio of the area of continuously heated parting strips against total area to be de-iced. A given layout shows 19 % area covered with parting strips.
- k_{cycl} gives the ratio of cyclic heat on time against total cycle time. From AIR 1168/4 we take 9 s heat-on-time in a 3 min. = 180 s cycle time. This is 5 % heat-on-time.

(17) $\dot{q}_{total} = \dot{q}_{PS} \cdot k_{PS} + \dot{q}_{cycl} \cdot k_{cycl}$

For the k-factors as given above the average heat load is **3.61 kW/m²**. Other heater layouts and heating cycles will have other heat loads. The value of **3.61 kW/m²** is the result from this paper based on assumptions, general thermodynamic equations and considered parameters ([9], [1]).

11. ABSOLUTE POWER REQUIREMENTS FOR DE-ICING

Based upon the generic heating performance the absolute power requirements can be estimated. With parameters of the Boeing 787 and its heated leading edge area a calculation is possible for the area of the imaginary sieve.

(18) $S_{ice} = t \ \ b_{ice}$

With parameters for the B787: $S_{ice} = 20.95 \mathrm{m}^2$

Based on the definition in 10.1 a) the required power is calculated from

(19) $P_{req} = \dot{q}_{total} \ \ S_{ice}$

The computation of required power respects that 8 slats could be energized cyclically (sequentially). Based on AIR 1168/4 k_{cycl} is taken as 5 %. With the dimensions of Boeing's new 787 with 8 heated slats:

(20) $P_{req,cycl} = 75.8 \,\mathrm{kW}$

Surfaces on the B787 can also be heated simultaneously. In this case k_{cycl} = 1 and

(21) $P_{req,simul.} = 247.4 \,\mathrm{kW}$

These values may be compared with the available electrical power on board the B787. All B787 generators produce together

(22) $P_{elec} = 1000 \,\mathrm{kVA}$

12. SUMMARY AND RECOMMENDATIONS

This paper deals with the pre-dimensioning of electrical de-icing system in order to predict the power consumption of the system. Based on some constraints and assumptions a final and simple equation (17) was derived. With this equation 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 paper) the overall calculation becomes very efficient. Thus, a first statement of the system's required power load (either specific or overall) can be accomplished very fast and easy. Parameters for the sum of all heat flows - Equation (4) - are strictly true for the conditions as selected in this paper. Compared with results from **AIR 1168/4** the computed results as given in TAB 1 and TAB 2 differ only about 16 % for continuously heated surfaces $(\dot{q}_{AI\,I} = \dot{q}_{PS})$ and 20 % for cyclic heated surfaces $(\dot{q}_{Cycl})$. The calculated power requirements for the B787 indicate one more time that electrical wing de-icing requires a lot of energy or an intelligent layout of the system. At the chosen design point and with selected assumptions the computed results (75.8 kW) are in good agreement with published data [3] (45-75 kW). It also turned out that design parameters like slat chord c_{slat} or airfoil thickness t affect the results only marginally so that for preliminary computing a preliminary geometry can be used.

The k-factors may be considered as first estimates for trade studies and other preliminary calculations. Of course once the detailed layout for a specific electric wing heating system is known the k-factors have to be recalculated. Also the parameters $\dot{q}_{PS}$ and $\dot{q}_{cycl}$ can be adapted and corrected to gain better results. Here crucial input parameters are the heating efficiency (taken as 70 %) and the melted ice layer thickness (taken as 0.5 mm). These values were identified from the known power consumption of the B787 together with data from AIR 1168/4 and logical coherence's. The 3D effect of the wing has not been considered. In this paper it was just assumed that the flow passes through an area projected into the flow direction. Further investigations could look closer into the effects of a swept wing on icing.

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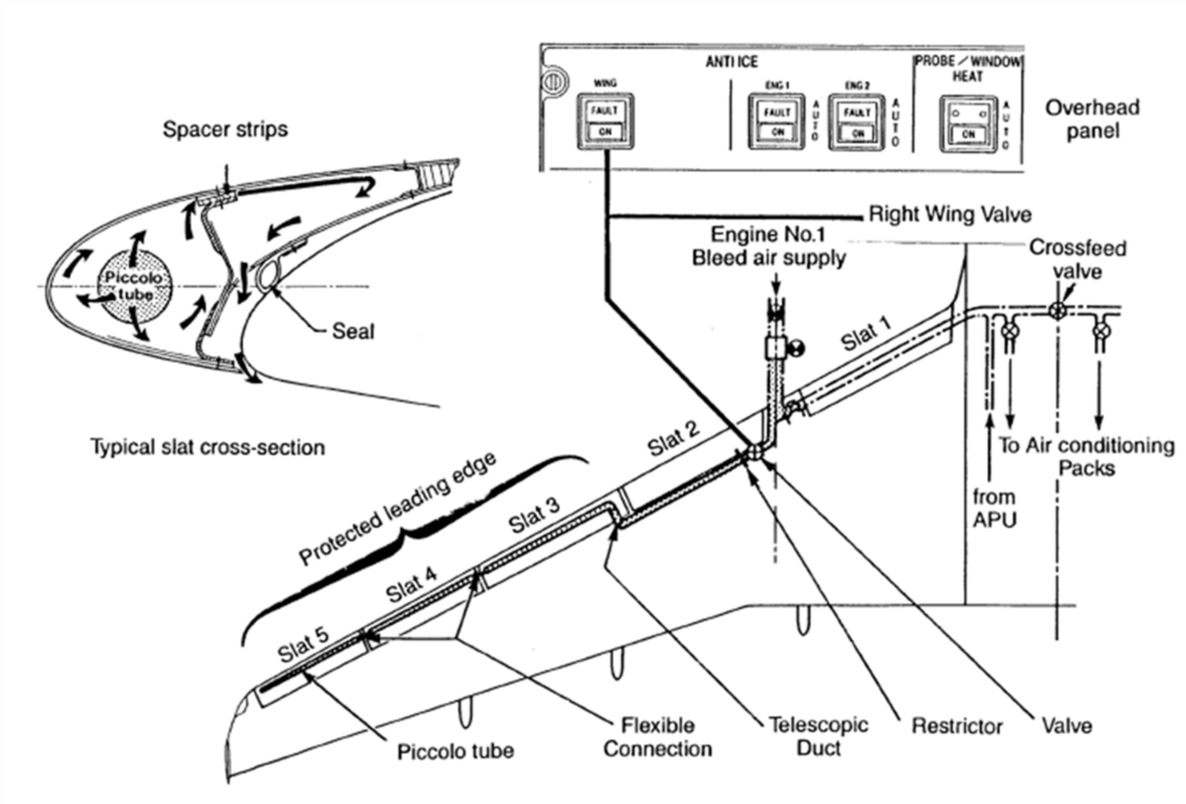

FIG 4: Wing anti-ice of an Airbus A321 (from [5], p. 9-15)

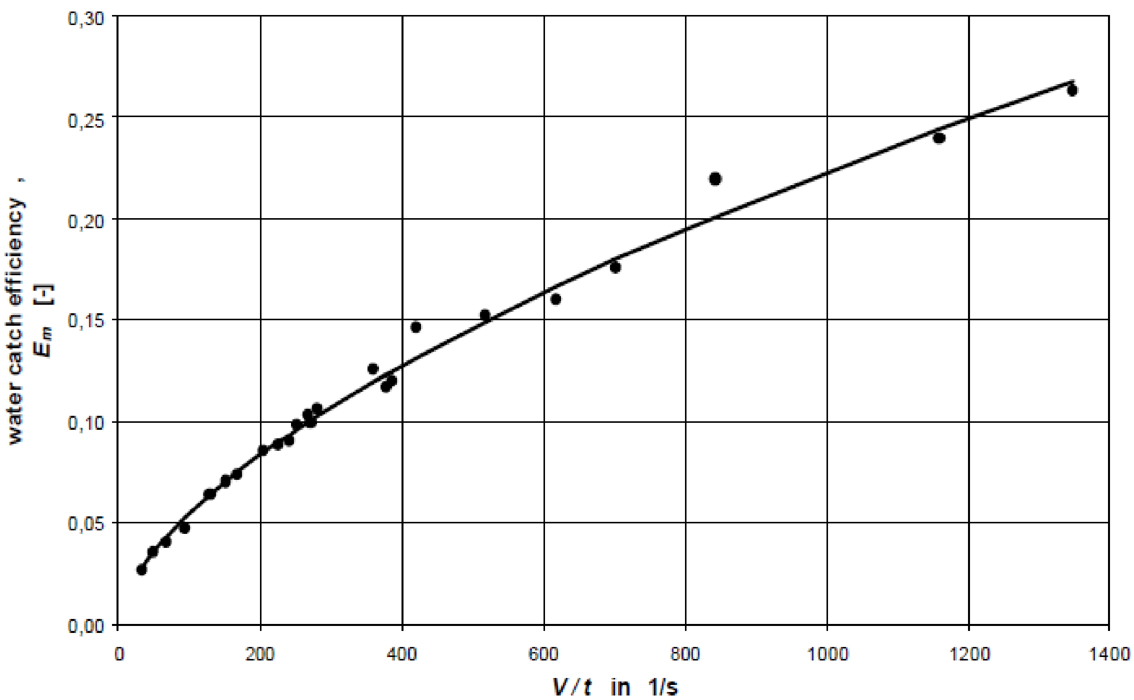

FIG 5: Catch efficiency rises with higher velocity and thinner airfoils.