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COMPUTATIONAL IMPLEMENTATION OF AN ELECTRICAL ICE PROTECTION SYSTEM IN AIRCRAFT

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Abstract: *Certain weather conditions can influence ice buildups on aircraft surfaces, which can reduce its performance and effectiveness. In order to minimize these effects, ice protection system has been created. Among many systems, electrical systems are being increasingly applied in the aircraft industry. Due to the high energy demand, this system can be used only by aircrafts with high capacity of power generation. Studies to feasibility of this method are increasing, and among them, there is the cyclical electro-thermal de-icing system. In this system, the protected region is divided into anti-icing and deicing system, which surfaces are continuous and cyclic heating, respectively. Thus, in regions susceptible to icing, the system remains turned on constantly, while in other regions the system works with cyclic heating to melt the bond between the ice accretion and the surface. Mathematical models are created to simulate the parameters which influence the ice formation and thus, improve the efficiency of ice protection. This research discusses a model to estimate the power requirement to an electro-thermal cyclical deicing system. This kind of study has extreme importance in the initial design phase, since it is a practical way to estimate the energy required and can demonstrate the feasibility of the cyclical deicing system.*

Keywords*: Cyclic deicing system, Ice Protection, Computational implementation of electrical system*

1. INTRODUCTION

The ice formation causes a reduction in efficiency of an aircraft due to increased weight, reduced lift and increased drag. Moreover, it can lead to wrong indications of the flight instruments and unbalance or freeze control surfaces (Zaparoli and De Andrade, 2012). In order to reduce these effects of ice, different types of ice protection systems have been developed over the years. Several studies to improve the deficiency of the ice protection systems are rising (Al-khalil, 2007).

For better efficiency, cyclic deicing system has been developed which uses two kinds of deicing and anti-icing system by means of a thermal system. The cyclical deicing system aims to reduce the power consumption of a fully resistive system by blinking the thermal load in certain regions.

2. PURPOSE

This paper aims, through the computational implementation, estimate the energy required for a cyclic deicing electrical system with generic configuration on an aircraft with intermittent and continuous heating surfaces.

3. ELECTRICAL ICE PROTECTION SYSTEM

3.1. More Electric Aircraft (MEA)

The proposed concept of More Electric Aircraft is to replace part of the hydraulic system for an electric system. The elimination of the hydraulic system can result in important benefits such as (Gandolfi, 2010):

1. Increased reliability;
2. Simplified maintenance;
3. Possibility to create a fault monitoring system;
4. Weight decreased because the electric power transmission uses wires and hydraulic pipes are not used.

3.2. Electrical deicing system

Electrical deicing system consumes more energy than usual generators provide for this function. However, according to Meier and Scholz (2010), this system only becomes feasible when used for limited periods of time, enough to melt the ice and separate it from the wing surface.

3.2.1. Thermal ice protection systems

Ice protection is mainly done with thermal systems that are differentiated by deicing or anti-icing. Thermal ice protection systems are classified according to three principles (Meier e Scholz, 2010):

1. Evaporative anti-icing systems provide sufficient heat to evaporate all water droplets impinging upon the heated surface.
2. Running-wet anti-icing systems provide heat only enough to prevent freezing in the heated surface. In addition to the heated surface, the water can freeze, resulting in a runback ice. Thus, this system should be carefully designed to not allow the accumulation of runback ice at critical locations. This technique is widely used for surfaces where the effects of runback ice accumulations can be tolerated (e.g., radomes and spinners) (SAE AIR 1168/4, 2014).
3. Cyclical deicing systems periodically shed small ice buildups melting the ice surface interface with a high rate of heat input. When the adhesion at the interface becomes zero, the aerodynamic or centrifugal forces remove the ice.

In this way, between the three thermal systems presented, the evaporative anti-icing system uses more energy than other systems and the cyclical deicing system uses less energy (Meier and Scholz, 2010).

3.2.2. Cyclic deicing system

Through the development of lighter electrical systems, electro thermal deicing system found many applications on new aircraft designs, like energy conservation measure (SAE AIR 1168/4, 2014).

Electrical deicing of large surfaces can be an issue due to high demand of electric power and becomes feasible only due to the combination of surfaces that are heated only during time interval (surfaces with intermittent heating) and partition strips that are continuously heated, as illustrated in Fig. 1. The cyclical electric deicing saves energy because only a small portion is actually ice melted. Most of the ice leaves the surface of the aircraft in solid form (Meier and Scholz, 2010).

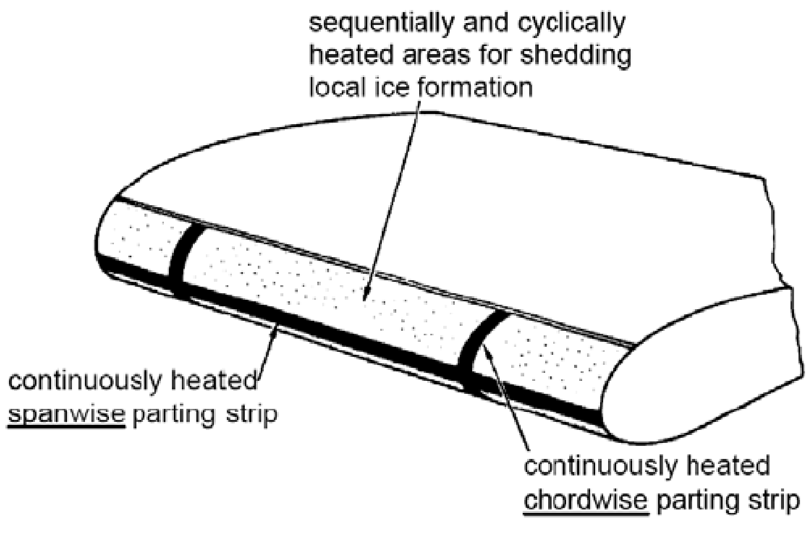

Figure 1. Surface of the wing with cyclic electric deicing system (Meier and Scholz, 2010).

4. TOTAL POWER REQUIREMENT CALCULATION FOR CYCLIC DEICING SYSTEM

The required power calculation method is mainly based on empirical equations. The calculation is an approximation based on thermodynamic and heat transfer equations. In energy required calculation, some assumptions have been adopted (Meier and Scholz, 2010):

1. Effects are considered only in two dimensions;
2. They are considered two factors. One changes the heating time of cyclical surfaces and the other, changes the configuration of the continuously heated surfaces. In this paper, these factors were used as constant values.

The calculation was divided into two parts. One part is to calculate the continuously heated surfaces and other, is to intermittent heating surfaces (Meier and Scholz, 2010).

4.1. Absolute power requirement calculation for cyclic deicing system

Based on a generic heating performance, the absolute power required can be estimated by the Eq. (1).

$$P_{req} = \dot{q}_{total} \cdot S_{ice} \quad (1)$$

Where, P_{req} is the required power in kW, $\dot{q}_{total}$ is the required total heat flow in kW/m² and S_{ice} is the total area to be protected in m², illustrated in Fig. 2.

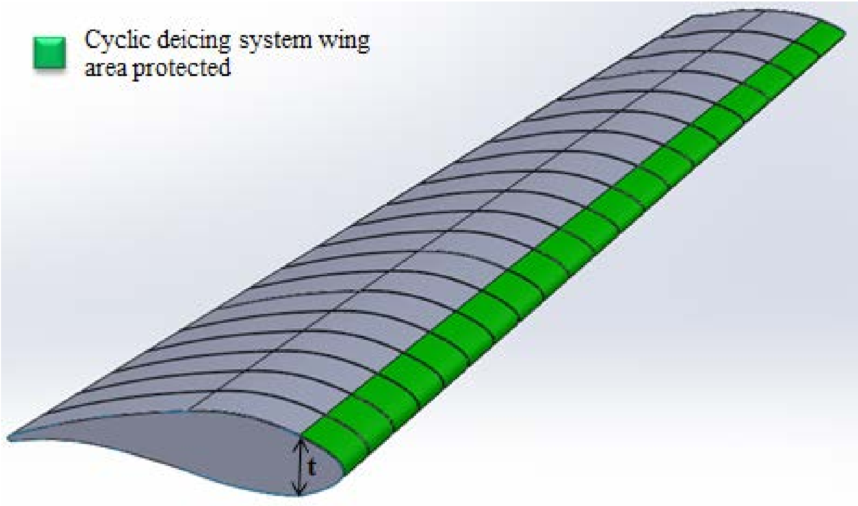

Figure 2. Wing area protected by cyclic deicing system.

4.2. Power requirement calculation of a general configuration heating

The method of cyclic deicing system becomes feasible with two basic principles (Meier and Scholz, 2010):

1) Reduction of continuously heated area (parting strips)

2) Reduction of heat-on time of intermittently heated areas

To calculate the total heat flow is not necessary to know the cyclical deicing system configuration, only specify two important factors k_{PS} and $k_{cíclico}$. k_{PS} is the ratio of continuously heated area (parting strips) by the total area to be defrosted and $k_{cíclico}$ is the ratio of the heat-on time of intermittently heated region by the total cycle time (Meier and Scholz, 2010). According to AIR 1168/4 (SAE AIR 1168/4, 2014), it was assumed the heat-on time is equal to 9 s in a total time of 180 s, resulting in a $k_{cíclico}$ equal to 5% and it was assumed 19% of area covered by parting strips, i.e. k_{PS} equal to 19%.

Equation (2) calculates the total heat flow required to defrost the ice over the aircraft surface (Meier and Scholz, 2010).

$$\dot{q}_{total} = \dot{q}_{PS-total} \cdot k_{PS} + \dot{q}_{cíclico-total} \cdot k_{cíclico} \quad (2)$$

Where, $\dot{q}_{total}$ is the total heat flow required by cyclic deicing system in kW/m², $\dot{q}_{PS-total}$ is the total heat flow required by continuously heated surfaces in kW/m² and $\dot{q}_{cíclico-total}$ is the total heat flow required by intermittently heated surfaces in kW/m².

4.3. Power requirement calculation for continuously heated surfaces

Parting strips are continuously heated surfaces in a defined constant temperature. In this study was assumed to 6°C temperature (279.15K), enough to prevent freezing of the surface. The surface is bombarded by super cooled droplets which become partially ice. The super cooled water need to be heated and requires a heat flow to melt it. The heat flow per unit area ($\dot{q}$), required to maintain the parting strips without ice, can be expressed by an energy balance for each element of airfoil surface (Fig. 3).

The energy required by an anti-icing system is determined by the rate that should be provided to balance the heat loss from heated surfaces. In contrast, the kinetic heating caused by water drops, which are moving in the direction of flow, impinging with the surface generates a positive influence, causing a heating on the surface and reduce the heat flow required. The same principle is applied to the aerodynamic heating. Thus, the heat flow required for the anti-icing system can be considered similar to the heat flow of the parting strips surfaces. It can be calculated by Eq. (3) (Meier and Scholz, 2010).

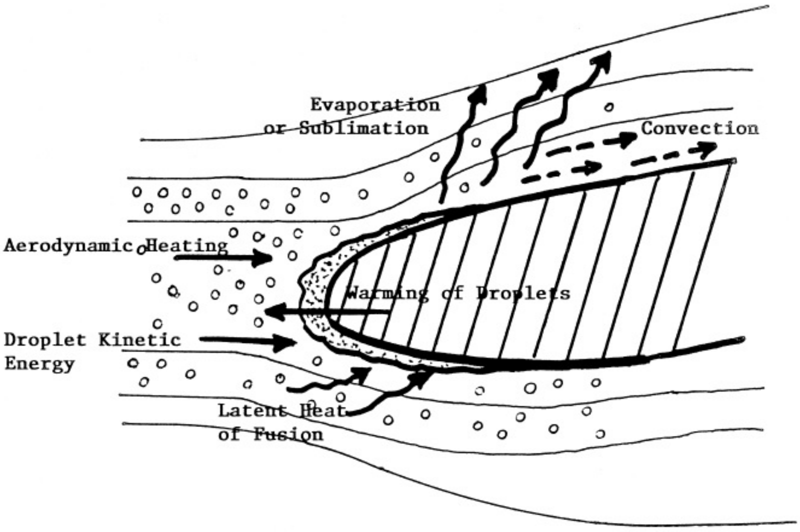

Figure 3. Energy balance on the leading edge of an airfoil (Sherif, Pasumarthi e Bartlett, 1997).

$$\dot{q}_{PS} = \dot{q}_{antiice} = -\dot{q}_{sens} - \dot{q}_{lat} - \dot{q}_{conv} - \dot{q}_{evap} + \dot{q}_{kin} + \dot{q}_{aero} \qquad (3)$$

Where, $\dot{q}_{sens}$ is the heat flow by sensible heat in kW/m², $\dot{q}_{lat}$ is the heat flow by latent heat in kW/m², $\dot{q}_{conv}$ is the convective heat flow in kW/m², $\dot{q}_{evap}$ is the evaporative heat flow in kW/m², $\dot{q}_{kin}$ is the heat flow by heating kinetic in kW/m² and $\dot{q}_{aero}$ is the heat flow by heating aerodynamic in kW/m².

An efficiency of 70% was considered because not all heat supplied is used to melt ice, due to losses to the environment by the aircraft structure.

4.3.1. Heat losses by sensible and latent heat

The super cooled droplets water that impinging at a mass flow per unit area ($\dot{m}_{local}$ in kg/s m²) must be heated to the surface temperature. Through latent heat, firstly, the ice becomes liquid. With the freezing fraction (*n*), it is possible to indicate the amount of liquid water which becomes ice.

$$\dot{q}_{sens} = \dot{m}_{local} \cdot [\Delta T \cdot \left((1-n)\ c_{liq} + n\, c_{ice}\right)] \qquad (4)$$

$$\dot{q}_{lat} = \dot{m}_{local} \cdot n\ L_f \qquad (5)$$

Where, ΔT is the temperature variation in K, c_{liq} is the heat capacity of water in kJ/kg K, c_{ice} is the heat capacity of ice in kJ/kg K and L_f is the latent heat of fusion in kJ/kg.

4.3.2. Convective heat loss

The convective heat transfer occurs at the contact between a fluid in movement and a surface at different temperatures (Incropera, DeWitt, et al., 2007).

The mathematical model developed by Newton is used to calculate the heat loss into a convection system.

$$\dot{q}_{convec} = h_0\ (T_{superf} - T_{amb}) \qquad (6)$$

Where, h_0 is the local heat transfer coefficient in W/m²K, T_{superf} is the aircraft surface temperature in K and T_{amb} is the environment temperature in K.

In this paper we considered the model of the flow in an isothermal flat plate, aiming to build a practical way to get the results to a trade-off study. By Reynolds number calculation is notice that the flow describes a turbulent behavior (greater than $5x10^5$). Thus, the calculations were based on an approach of a turbulent flow over an isothermal flat plate.

4.3.3. Evaporative heat loss

Evaporative heat loss is the mass rate evaporated on the surface multiplied by evaporation latent heat. The evaporated water quantity depends not only on the surface temperature, but also the saturation steam pressure (*e* in hPa) and relative humidity (R_h).

$$\dot{q}_{evap} = 0.7\ h_0\ \cdot L_e\ \left[\frac{(R_h \cdot e_{amb}) - e_{superf}}{p_{amb} \cdot cp_{ar}}\right] \quad (7)$$

Where, L_e is the latent heat vaporization in kJ/kg, p_{amb} is the environment pressure in Pa and cp_{ar} is the specific heat capacity in kJ/kg K.

4.3.4. Kinetic heating

The heat gain by kinetic heating occurs due to the collision accelerated of super cooled water droplets.

$$\dot{q}_{kin} = \dot{m}_{local} \cdot \frac{{v_{amb}}^2}{2} \quad (8)$$

Where, v_{amb} is the air speed in m/s.

4.3.5. Aerodynamic heating

The heat gain by aerodynamic heating occurs due to the compression and friction in the boundary layer over the aircraft surface. At high aircraft speeds it is an extremely important parameter (Nishikawa, 1994).

$$\dot{q}_{aero} = R_c \cdot h_0 \cdot \frac{{v_{amb}}^2}{2 \cdot cp_{ar}} \quad (9)$$

Where, R_c is the boundary recovery factor.

4.4. Power requirement calculation for intermittently heated surfaces

In this study was assumed 6°C (279.15K) as an unheated equilibrium temperature. The amount of ice that must be melted to destroy the bond between the ice and the airfoil surface varies according to the position considered along the airfoil (stagnation point). In this paper we assumed an average value of 0.5 mm ice (Meier e Scholz, 2010).

The calculation of heat flow required by intermittently heated surfaces is approximated to heat losses by sensible and latent heat.

$$\dot{q}_{ciclico} = \frac{\frac{m_{ice}}{A}}{tempo} \cdot \left[\Delta T \cdot c_{ice} + L_f\right] \quad (10)$$

Where, $\frac{m_{ice}}{A}$ is the mass of ice per square meter in kg/m².

An efficiency of 70% was considered because not all heat supplied is used to melt ice, due to losses to the environment by the aircraft structure.

4.5. Block Diagram

The results were obtained from the computational implementation in Matlab® Simulink. The computational implementation of the system, which is shown all inputs and outputs, were made in accordance with the block diagram illustrated in Fig. 4.

4.5. Comparison with literature data

In order to validate the values of heat flows for continuous and intermittent surface, it was made a comparison with the AIR 1168/4 data. The results are shown in Tab. 1.

Table 1. Result of continuous and intermittent heat flow in a typical flight profile.

Heat Flow	Parameter	Simulation $T_{superf} = 6°C$ $T_{amb} = -20.66°C$	Calculated by AIR 1168/4 $T_{superf} = 4.44°C$ $T_{amb} = -17.78°C$
Continuous	$\dot{q}_{PS}$ [kW/m²]	17.544	17.461
Intermittent	$\dot{q}_{ciclico-total}$ [kW/m²]	28.286	34.100

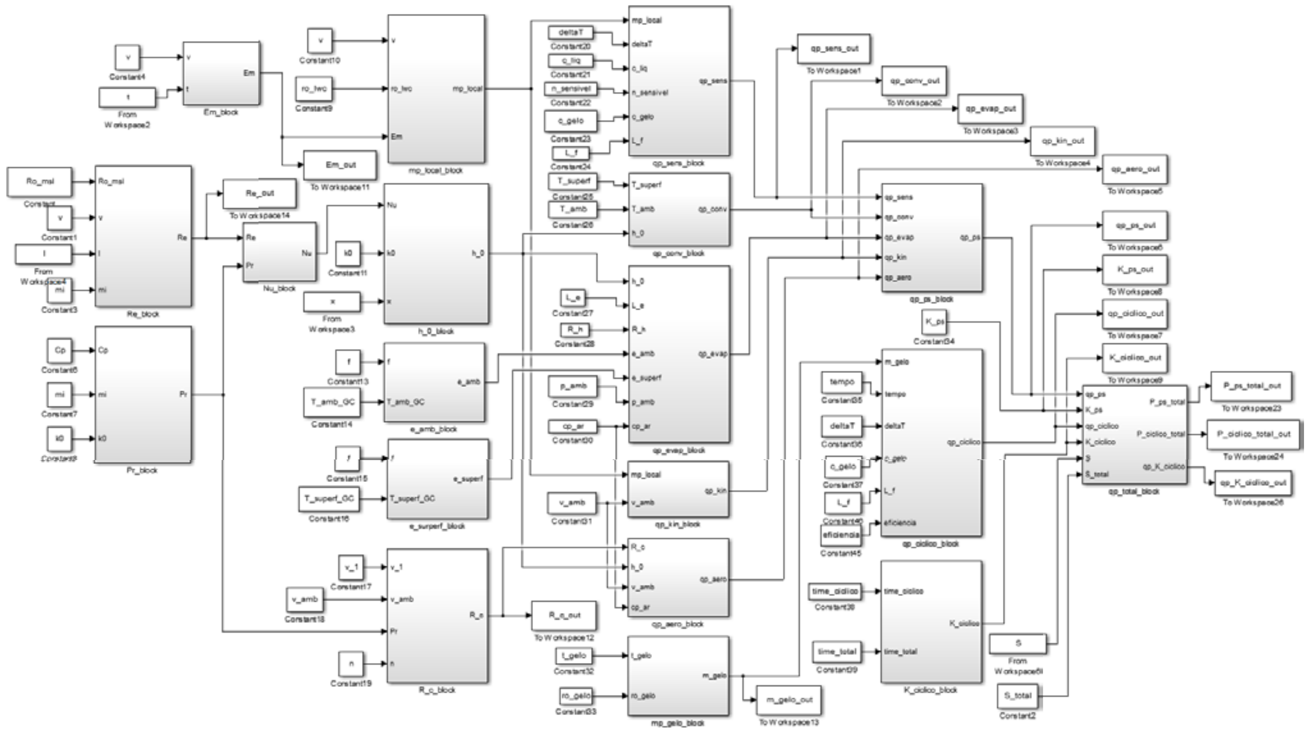

Figure 4. Block diagram of electrical power required calculation for cyclical deicing system.

The small variation of 0.5% in the continuous heat flow portions occurred due to the difference of the mathematical model assumed for calculation of heat transfer, the lack of accuracy in reading the AIR 1168/4 graphics and the considerations of environmental and surface temperatures. In calculating the heat flow by intermittent heating, it was considered only the energy needed to unfreeze a thin layer of ice enough to remove it. A variation of 20% between the simulation and AIR 1168/4 values occur due to empirical values adopted by manual.

5. MODEL APPLICATION TO AN AIRCRAFT

An aircraft of the Specialization Program in Engineering of Embraer (Fig. 5) was used for the model application. It is a commercial aircraft, regional and small, used for small and medium cities transportation to carry 36 passengers.

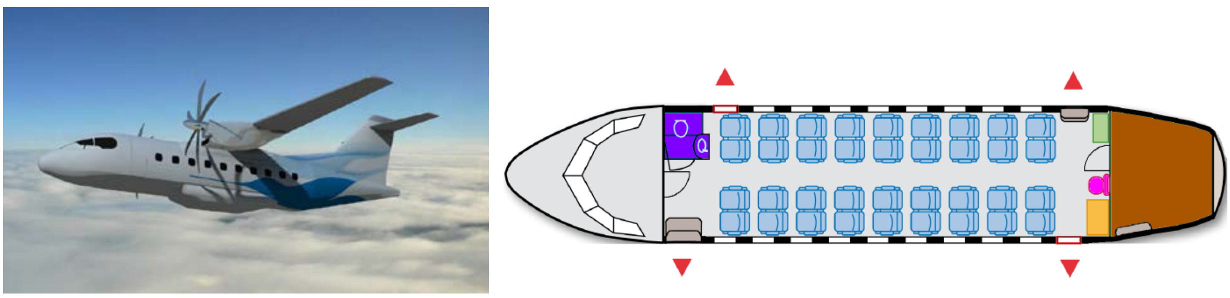

Figure 5. Specialization Program in Engineering Aircraft of Embraer (Union Aerospace - PEE 20, 2013).

The model was applied on a typical aircraft flight profile. The results are shown below. In order to evaluate the sensitivity of the model, four others variables were analyzed: flight altitude, flight Mach, airfoil thickness and heat transfer coefficient.

5.1. Typical flight profile

The energy required results for the electrical cyclic deicing system, in a typical flight profile, are shown in Tab. 2.

Figure 6 illustrates that the heat energy gain from aerodynamic heating, about 1.67 kW eliminates the portion of the equivalent energy lost by the sensible and latent heat, about 0.62 kW. Therefore, the power required by the continuous surface is to supply the energy lost by convective and evaporative modes.

Table 2. Result of continuous and intermittent heat flow in a typical flight profile.

Parameters	Results for aircraft typical values
Mach	0.28
Flight altitude [ft]	18000
Total power required [kW]	29.337
Power required by continuously heated surfaces [kW]	20.463
Power required by intermittently heated surfaces [kW]	8.874

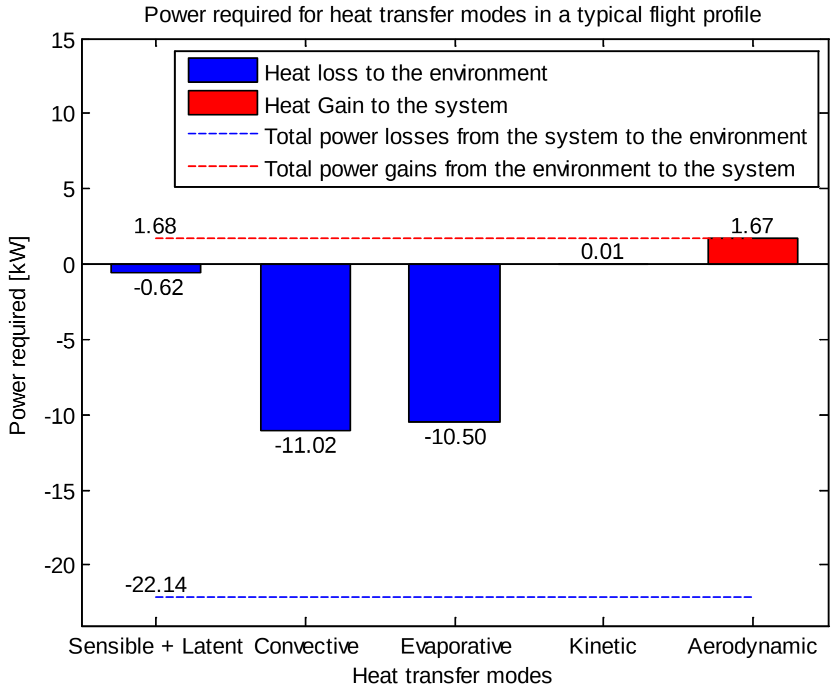

Figure 6. Specialization Program in Engineering Aircraft of Embraer.

5.2. Variation of aircraft flight altitude

The results of powers required for each altitude are shown in Tab. 3.

Table 3. Powers required for the variation of the aircraft flight altitude.

Flight Altitude	Mach	Flight Altitude [ft]	Total Power Required [kW]	Power required by continuous surface [kW]	Power required by intermittent surface [kW]
Minimum	0.28	15000	24.370	15.774	8.596
Typical		18000	29.337	20.463	8.874
Maximum		23000	37.692	28.355	9.337

The results in Tab. 3 indicate that the power required by the heated surface continuously increases in a higher rate than the power required by the intermittent heating surface. As an example, analyzing the power increase in the typical to maximum case, it is observed that the power required for the continuous surface increase 39% where for the power required by the intermittent surface increase 5%. Therefore, the increase of the total power required is given in larger amounts by increasing the energy required by continuously heated surface.

In Fig. 7 is demonstrated that increasing altitude flight, the total power required increases.

5.3. Variation of flight Mach

The results of powers required for each flight Mach are shown in Tab. 4.

Table 4. Powers required for the variation of flight Mach.

Mach	Flight Altitude [ft]	Mach	Total Power Required [kW]	Power required by continuous surface [kW]	Power required by intermittent surface [kW]
Minimum	18000	0.25	27.720	18.846	8.874
Typical		0.28	29.337	20.463	8.874
Maximum		0.33	31.483	22.609	8.874

Table 4 shows that increasing the total power required by the system is only due to the increased power required by the continuous surface, since the power required by the intermittent surface remains constant and independent of flight Mach.

In Fig. 8 is demonstrated that increasing flight Mach, the total power required increases.

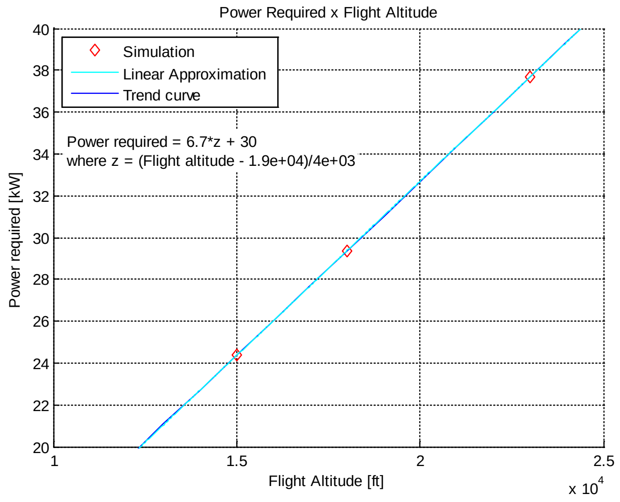

Figure 7. Variation of total energy required by the cyclical deicing system x Aircraft flight altitude.

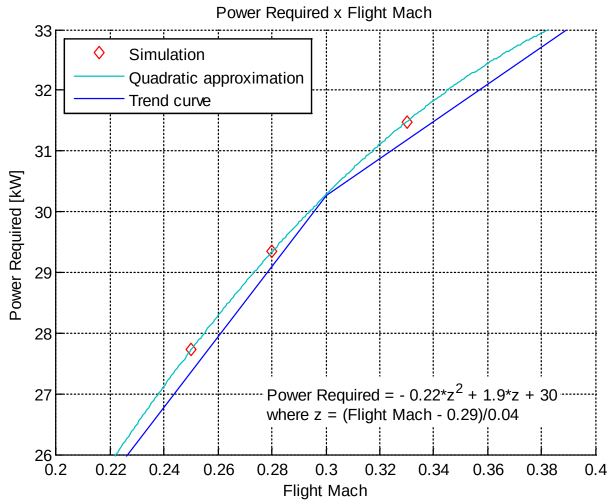

Figure 8. Variation of total energy required by the cyclical deicing system x Flight Mach.

5.4. Variation of airfoil wing thickness

The results of powers required for each airfoil thickness are shown in Tab. 5.

Table 5. Powers required for the variation of airfoil thickness.

Airfoil thickness	Airfoil thickness [m]	Total Power Required [kW]	Power required by continuous surface [kW]	Power required by intermittent surface [kW]
50% of typical case	0.14	14.829	10.392	4.437
75% of typical case	0.21	22.091	15.435	6.656
Typical case	0.28	29.337	20.463	8.874

In the data of Tab. 5, considering the increasing of the total power required by airfoil thickness from "75% of typical case" to "typical case," it is observed that the increase of the total energy required is given in the same amount, 33%, for increased energy required by surfaces with continuous and intermittent heating.

In Fig. 9 is demonstrated that increasing airfoil thickness, the total power required increases.

5.5. Variation of heat transfer coefficient

The results of powers required for each heat transfer coefficient are shown in Tab. 6.

Table 6. Powers required for the variation of heat transfer coefficient.

Heat Transfer Coefficient	Heat Transfer Coefficient [W/m²K]	Total Power Required [kW]	Power required by continuous surface [kW]	Power required by intermittent surface [kW]
50% less typical value	124.0645	19.409	10.535	8.874
typical value	248.1289	29.337	20.463	8.874
50% more typical value	372.1934	39.266	30.392	8.874

Table 6 shows that increasing the total power required by the system is only due to the increased power required by the continuous surface, since the power required by the intermittent surface remains constant and independent of heat transfer coefficient.

In Fig. 10 is demonstrated that increasing heat transfer coefficient, the total power required increases.

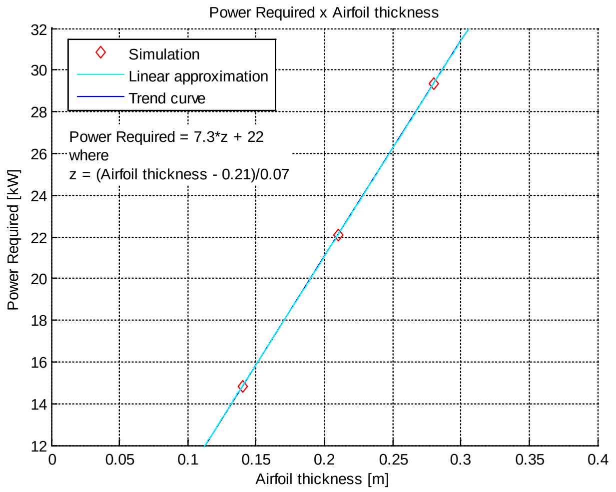

Figure 9. Variation of total energy required by the cyclical deicing system x Airfoil thickness.

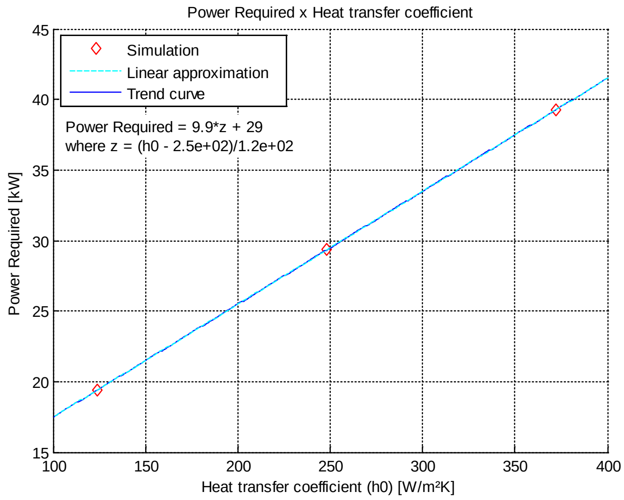

Figure 10. Variation of total energy required by the cyclical deicing system x Heat transfer coefficient.

6. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

This work presents the initial design of the cyclic deicing system in order to estimate the power consumption. The overall calculation becomes efficient and fast because it was based on some assumptions, restrictions and simplifications. The system configuration is given by the estimation of k-factors, which can changes the amount of area with a continuously heated surface and the time that the intermittent surface remains heated. This modeling is useful for a trade-off study, where from the total energy required would be possible to see the feasibility of such a system depending on the availability of electrical power of the aircraft.

In a typical flight profile of the aircraft by computational implementation was obtained the power consumption of 29.337 kW, which 20.463 kW and 8,874 kW equals the portion related to surfaces with continuous and intermittent heating, respectively. In this small aircraft, the power required unfeasible the use of an electrical system like this, making the traditional option hot air system bled from the engine or the pneumatic system (boot) better choices.

In order to understand the impact of variation of flight altitude, flight Mach, airfoil thickness and heat transfer coefficient were made four analyzes.

The first analysis is the flight altitude variation. The increase of the total power required is given in larger amounts by increasing the energy required by continuously heated surface.

The second analysis is the flight Mach variation. It analysis shows that increasing the total power required by the system is only due to the increased power required by the continuous surface.

The third analysis is the airfoil thickness variation. It is observed that the increase of the total energy required is given in the same amount for increased energy required by surfaces with continuous and intermittent heating.

The fourth analysis is the heat transfer coefficient variation. This analysis shows that increasing the total power required by the system is only due to the increased power required by the continuous surface.

Therefore, from the four analyzes it can be concluded that the variation of flight Mach and heat transfer coefficient affect only the energy required by continuously heated surface, the variation of airfoil thickness impacts on the same scale in the energy required by the surfaces continuously and intermittently heated and the variation of flight altitude impacts on a larger scale in the energy required by continuously heated surface.

The high value of the total energy required is due to not optimize some parameters involved in the system so that, as suggestions for future work would be interesting to analyze the variation of cyclic deicing system configuration, i.e. analyze system sensitivity about the variation in time of the intermittent heating surfaces, varying the amount of the region with continuously heated surfaces, varying the size of the water droplet to be captured by the anti-icing system and ice thickness formed on the deicing system.

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