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# ELECTROMAGNETIC ENERGY FOR THE PREVENTION OF ICE DEPOSITION ON AIRCRAFT SURFACES

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## Abstract

Electromagnetic energy can be used for dielectric heating. The main characteristics are fast volumetric and selective heating of materials. A limited number of frequency bands (the ISM bands) in the high frequency and microwave ranges are allowed for this non telecommunication application.

In this paper, microwave properties are exploited for selective heating.

It is shown that the outer skin layer of the leading edge of a composite wing structure can be maintained above 0°C by proper choice of the dielectric properties of the different layers. Ice deposition may then be prevented with low microwave power densities in a wing structure with adjusted properties of the layers.

## Introduction

It is likely that modern and future aircraft structures will use more and more composite materials. Conventional resistive heating for deicing and anti icing has many disadvantages: it is too slow and it produces high temperature gradients. Therefore, other methods like fast heating with microwaves have been proposed since 1975.

In its simples form a microwave system at 2.45 GHz the frequency of the domestic oven would be an antenna inside the composite wing structure for heating up any ice or water layers on the leading wing edge. A simple stratified model consisting of only one single composite layer, a water layer and an ice layer has been used in the past to analyse the microwave deicing systems but was not found economically convenient [1].

Microwave heating is generally non-uniform and this fact can be exploited for selective energy absorption to maintain the outer surface of the leading wing edge above 0°C in practical icing conditions [2].

To understand this selective energy absorption and the model which has been used to analyse the heating of only the surface layer, the principles of microwave heating are presented first.

## Principles of dielectric heating

A dielectric i.e. a material which is an electric insulator becomes polarised when placed in an electric field, for example between the electrodes of a capacitor. If the electric field is alternating like in a domestic oven, successive displacements of the charges of the molecules cause heating which is known as dielectric heating. The heat is produced directly and solely in the mass of the material to be heated. It is this property which provides the essential interest in dielectric heating because electric insulators are often bad conductors of heat.

The characteristics of dielectric heating depend essentially on the properties of the material to be heated and the applicator which is the structure for interaction with the electromagnetic energy. When the frequency of this energy is above 300 MHz then the energy is called microwaves and the frequency is generally 2.45 GHz a designated frequency or ISM frequency for heating applications.

ISM stands for industrial, scientific, medical domestic applications of electromagnetic energy or radiowaves as opposed to telecommunication and information applications.

The basic formulas that govern the microwave interaction with materials are published for example in the book "Industrial Microwave Heating" by A.C. Metaxas and R.J. Meredith [3]. The property which desbribes the behaviour of a dielectric under the influance of a electromagnetic energy is the relative complex permittivity $e_r$*, which is defined by equation (1)

$$\varepsilon_r{}^* = \varepsilon'_r - j\varepsilon''_r \qquad (1)$$

where $e''_r$ is the loss factor and $e'_r$ the dielectric constant. The ratio $e'_r/e''_r$ is also known as the loss tangent. At frequency f(GHz), the energy penetration d(m) in a material with $e'_r$ - $je''_r$ is given by

$$\delta(\mathrm{m}) = \frac{0.0478}{\mathrm{f(GHz)}}\left[\frac{\varepsilon'_r}{2}\sqrt{1+\left(\frac{\varepsilon''_r}{\varepsilon'_r}\right)^2} - 1\right]^{-1/2} \qquad (2)$$

Beyond this distance the energy level is 9 dB down. Eq. (1) is the result of Maxwell's equations for a plane wave inside a homogeneous material infinite in 3 dimensions. The power deposition P in the material with an internal electric field $E_i$(v/m) is equal to

$$\mathrm{P(W/m^3)} = 0.056\mathrm{f(GHz)}\varepsilon''_r[\mathrm{E_i(V/m)}]^2 \qquad (3)$$

This proves that the heat is generated inside the material provided that there is an electric field $E_i$. The engineering problem is to deduce the internal electric field distribution and thus the power density which will give rise to a temperature increase $\Delta T$ in a time $\Delta t$. This increase, neglecting heat conduction, can be assessed with:

$$\frac{\Delta T}{\Delta t}(\mathrm{K/s}) = \frac{P}{C_s \cdot \rho} \qquad (4)$$

$C_S$: specific heat J/kg.K, r: specific mass kg/m$^3$. Some examples of permittivity at 2.45 GHz are: water (25°C) 77 - j12, ice (-12°C) 3.2 - j0.003 and fibreglass (25°C) 4.4 - j0.128.

The high loss factor of water means that water will heat up very fast as a result of (3) and (4). When microwaves are applied to ice on fibreglass then the fiberglas will heat up. The heated fiberglas will melt the ice because of thermal conduction. As soon as water is present its high loss factor will absorb microwave energy.

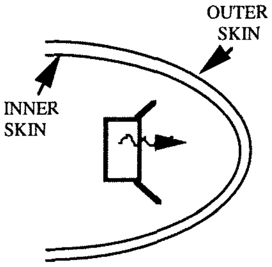
This means that microwave de-icing systems could be effective provided that the ice melting process be started in some way. The fusion of even a very small quantity of ice and the subsequent heating of water starts an unstable process that leads to the complete melting of ice [1].

Continuing the microwave energy application will result in water evaporation. In the present work a simple stratified model simulating an aircraft ice prevention system is analysed taking into account kinetic of the aircraft surfaces.

It is demonstrated that microwaves can slightly heat up only a thin layer of the outer surface in a variety of atmospheric conditions to prevent ice deposition provided the thicknesses and the properties of the different composite layers are properly chosen.

## The model

Fig. 1 shows the proposed anti-icing system in its simplest form. A microwave slotted waveguide applicator focuses the power from the interior of a composite wing onto the leading edge. A typical skin structure for a wing may be composed out of an inner skin 1, a honeycomb layer 2 and an outer skin 3. Each skin is generally a few centimetres thick and is also composed out of different sublayers carbon fibres, glass fibres or quartz web reinforced composites like epoxies for example. Fig. 2 is the plane layered model of such a hypothetical wing structure of 3 cm thick.



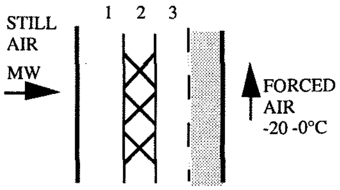


FIG.1 Simple system FIG.2 Plane model

The idea is to switch on the microwaves in areas where icing is likely to occur for the practical speed ranges of 80 to 400 MPH. The outer skin of the leading wing edge should be a high loss composite. The low loss honeycomb structure together with the inner lossy skin merely act as matching layers so that all microwave power is absorbed creating selectively a sufficiently high temperature increase or a hot layer close to the outer surface. The thermal boundary conditions are an outer surface temperature of minimum 0°C for an air temperature range of -20 to 0°C and forced air cooling. The thermal surface loss for this cooling is proportional with the aircraft speed v and has been assessed as

$$h = 0.7\sqrt{\mathrm{v(m/s)}} \qquad \mathrm{W/m^2K} \qquad (5)$$

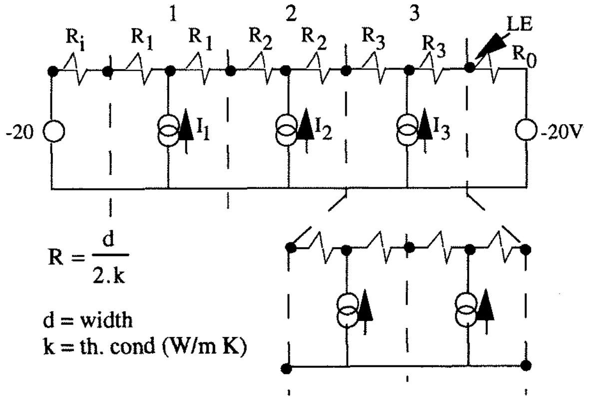


FIG.3 Equivalent network for heat flow

Kinetic heating and the latent heat of melting ice have been neglected. The electric equivalent is shown in fig. 3 (4). The equivalent resistor $R_0$ for the surface losses is in worst case conditions obtained from (5): $R_0 = 0.107$ (W). Carbon fibres loaded epoxy has a thermal conductivity which depends on the fibres content and is very high along the fibres and about 1 W/m K perpendicular to the fibres. The outer layer of 3 cm is then thermally equivalent with the T network of the equivalent resistors $R_3 = 0.015$ (W). The middle layer, 3 cm has thermal insulating properties (0.04 W/m K) and the inner layer is more conductive (0.2 W/m K). For the thermal surface losses in still air (inside the wing) 2 W/m K was taken. The result for the equivalent network is $R_0 = 0.5$, $R_1 = 0.075$, $R_2 = 0.319$. In order to maintain the surface at 0°C, the voltage at LE must be 0V (voltages are equivalent with temperatures). This requires a current $I_3 = 187$ A (currents are equivalent with power) giving a maximum temperature inside the layer of only 2.8°C. The current source $I_3$ must provide the current and any extra current flowing to the left, which is a high resistive path containing other current sources. The current sources are equivalent with the microwave power deposition in the layers. The precision of the calculation can be improved by using sublayers and the correct distribution of the currents. Inspection of the network shows that the only improvement of this system is an absorptive layer as close as possible to LE, for example half the width (1.5 cm). The max. temperature inside the lossy layer would then be 1.4°C. This leads to the conclusion that the lossy layer has to be adjacent to the surface and must be a good thermal conductor. The microwave power is radiated from the left and must be absorbed by that lossy layer. Its width must be at least two skin depths to absorb 99% of the incident power. A typical value for the permittivity of layer 3 is 3-3j for moderate carbon content. At 2.45 GHz the skin depth (10% power) is 1 cm. However with the outer interface with free space a 3 cm layer would transmit 5% of the incident power which is acceptable. The power deposition is determined with the transmission line model of the layered structure which is easily described by a matrix formalism for each constant layer [4]. The power reflection coefficient RC and the transmission coefficient TC are calculated using the product of the characteristic matrixes. A design condition is for example

$$RC = TC = 0 \qquad (6)$$

The power depositions in each layer can be determined starting with the required power in layer 3, as determined with (1). The equations can be solved to obtain the permittivities of the layers 1 and 2, Instead simple iterative calculations have been carried out using MATHCAD 4.0.

The carbon loaded outer skin layer of 3 cm thick has a permittivity of 3-3j. This layer alone would reflect 20% of the incident microwave power. The honeycomb layer (3 cm, 1.2-005) and the inner skin (3 cm, quartz web having 3-04j) match for total absorption. This matching is not sensitive to the permittivities of the layers but absorbs 5% power. This structure, when illuminated with an incident microwave power of 190 W/m$^2$ at the low loss side, will heat up so that in surface temperature is maintained above 0°C. The highest temperature increase (+3°C) appears at the interface between the honeycomb (which is a good thermal insulator and the lossy layer.

The power density rises the surface temperature up to 45°C with 50°C as the highest temperature inside the lossy layer in worst case conditions (80 MPH, 0°C for the air). Composite materials normally support these temperature ranges.

This clearly demonstrates that selective heating is possible in a multilayered structure. The incident microwave power is efficiently (90°C) absorbed to heat the outer layer so that the surface temperature can be maintained above 0°C with less than 200 W/m$^2$ for speed ranges of 80-400 MPH. Many other wing structures are possible for example when using layers with gradually decreasing carbon loads towards the inner layer. More details will be presented at the Conference.

## Conclusions

Microwaves can be used to prevent ice deposition on aircraft surfaces. A typical microwave system would be an applicator in the interior of a composite wing structure against ice deposition on its leading edge. Proper design of the different composite layers allows efficient selective heating of an outer layer for maintaining the surface temperature of the leading edge above 0°C in icing conditions. Ice deposition should then be prevented. The microwave power is less then 200 W/m$^2$ for such a system in the proposed wing structure.

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