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The effect of moisture contamination on the relative permittivity of polymeric composite radar-protecting structures at X-band

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ABSTRACT

The impact of absorbed moisture on the X-band relative permittivity of three composite materials used in aircraft radar-protecting structures (radomes) is investigated, quantified, and analyzed with respect to existing effective medium theories. Two glass-fiber-reinforced epoxy laminates and a quartz-fiber reinforced bismaleimide laminate are fabricated, contaminated with water, and analyzed with a split-post dielectric resonator in order to determine moisture-induced relative permittivity changes at 10 GHz. In the most significant case, a 3.7% increase in water content by weight resulted in a 43% increase in relative permittivity for BMI/quartz laminates. Such an increase may be a root cause of radome-induced radar performance loss for long-service-life aircraft. The relationship between absorbed water volume and relative permittivity is not well described by the existing effective medium theories considered. Support is given to the existence of conditions which lead to restricted molecular dipole rotation of water within a polymer network and a resulting "effective" relative permittivity of water based on polymer chemistry and morphology. A simple power-law expression predicated upon this assumption successfully describes the relative permittivity increase as a result of absorbed water prior to equilibrium moisture condition.

1. Introduction

The increasing use of polymers and their composites in a growing range of applications has led to additional emphasis on material properties beyond structural efficiency and performance. For example, many applications exploit unique properties of fiber-reinforced composites such as thermal or electrical insulating capabilities. With respect to the latter, fiber-reinforced polymers have been effectively used as insulators in high-voltage applications [1], in printed circuit boards [2], and as the radar-protecting structure, or radome, for ground, marine, and aircraft-based radar systems [3]. For radome applications in particular, the ability of the radar signal to pass unimpeded through the radome structure is paramount. Critical to this ability is the electromagnetic wave transmission characteristics of the material used in radome construction, which is closely related to material relative permittivity (dielectric constant) [3,4]. Thus, the relative permittivity of the materials used in radome construction must not change throughout the service life of the radome. Any change in this fundamental material property over time or as a result of environmental effects has the potential to degrade the performance and accuracy of offensive, defensive, and ground-tracking radar systems.

The primary purpose of an aircraft radome, beyond aerodynamics, is to shield the radar system from damage in the form of debris and precipitation. In this role, polymer composite radomes are susceptible to environmental degradation during a service life that can be decades long. Moisture contamination is among the most damaging and widespread source of this degradation due to the ubiquitous nature of water and the propensity of polymer materials to absorb moisture even in hot, dry environments [5]. The detrimental effects of water contamination are well-documented and widely accepted, though most researchers have focused on the associated mechanical property loss. Changes in electrical properties due to environmental damage or water contamination have garnered much less attention, though some researchers have ventured into this area [3,4,6–10].

The deleterious effects of water on radar performance can be the result of surface water or gradually absorbed water over the service life of the aircraft. A quantitative description of the effect of absorbed water on relative permittivity is generally lacking in the literature, although it is generally accepted that even "a small percent of absorbed water can have a significant effect on dielectric constant" [4]. Surface water, likewise, can influence the performance of the radar system. Due to routine exposure to precipitation, radar performance in rain is well-documented and

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understood. However, when compared to absorbed water, the temporary effect of thin layers of liquid water on the surface of a radome is minimal due to water beading and the significant airflow around the structure [11]. In contrast, the gradual absorption of water within the polymer network is generally not understood or considered in terms of radar performance despite the fact that its effects are much more permanent than in-flight precipitation. Water absorption as a result of humid air, condensation, or standing water in the radome interior may have the potential to alter the baseline relative permittivity of the radome material, thus degrading the performance of the radar system over time.

It is well known that the extent of mechanical and/or electrical property changes is directly dependent on the moisture content within the composite. As a result, accurate prediction of moisture content in composite structures is of utmost importance. Researchers have devoted significant effort to the development of predictive models of moisture absorption for a wide range of composites and exposure conditions. The most basic and widely used predictive model is the Fickian diffusion model, which assumes diffusion by random molecular motion [12]. While generally considered adequate, a considerable number of composite material systems have been shown to deviate from this behavior. In order to describe this non-Fickian water uptake, a number of researchers have presented evidence for an additional mechanism based on the interaction between diffusing water molecules and the polymer network [13–15], wherein water molecules are effectively "bound" to sites within the polymer. This mechanism has the effect of hindering diffusion of water molecules, which would otherwise diffuse through the polymer via random molecular motion. While critical in the context of mechanical property loss due to the importance of total moisture content, this mechanism is especially important in the context of dielectric behavior. A bound, dipolar water molecule would necessarily be restricted in its rotation, and would therefore interact differently with an incident electromagnetic wave than an unbound molecule. As noted by Hallikainen [16], this interaction of a bound water molecule with an electromagnetic field is dissimilar to that of a free water molecule and consequently the dielectric dispersion spectrum is very different. The relative permittivity of a water molecule is a function of the energy dissipated by the molecule under the influence of an electric field. In the case of an oscillating radar signal, the dipole water molecule rotates rapidly in order to align with the field. As a result, energy is dissipated through friction (heat) and inertial losses. Therefore, restricting this rotation leads to reduced relative permittivity and reduced energy dissipation.

The published research related to dielectric properties of polymer composites is relatively limited, but the general topic has been addressed by several researchers [17–20]. The literature related specifically to radar-composite interaction skews heavily toward radar absorbing materials [21–24], rather than radar transparency. However, it is accepted that the electromagnetic wave transmission characteristics of a polymer composite radome are influenced by a wide variety of factors, including the relative permittivity of the material [3]. The relative permittivity of water in the liquid state is approximately 80 [25], while the relative permittivity of a typical radome material is approximately 3. As a result, it is postulated that even very low levels of moisture within the composite may heavily influence the radar transmission efficiency of the radome. Due to the complex nature of the interaction of the water molecule with the polymer network, and the subsequent alteration of the energy-dissipative rotation of the molecule, this relationship is not easily defined. Zheng [26] notes the difficulty in accurately predicting the relationship between water content and relative permittivity of a mixture due to the fact that the complex relative permittivity of bound water is not well known.

The objective of this study, then, is three-fold. The primary goal is to investigate and quantify the relationship between absorbed water content and relative permittivity of three composite radome materials at X-band. This is done in an effort to bolster the practical knowledge regarding long-term viability of polymer composite radomes. Relative permittivity is chosen largely due to the fact that it is one of the few radome properties which is not geometry dependent, and thus provides insight which is applicable to all composite radomes. Other parameters, such as insertion loss, are specific to radome construction paramaters such as wall thickness or curvature. The secondary goal is to address the suitability of existing effective medium theories for prediction of relative permittivity changes as a result of absorbed water. The final objective is to use these results to illuminate, to the greatest degree possible given the practical nature of the experimental plan, the theoretical basis for the observed behavior.

2. Materials and methods

Three fiber-reinforced laminates typically used in military and commercial aircraft radomes were fabricated for this study: (1) a 3-ply, 8-harness satin weave quartz fabric (Style 581) in a bismaleimide (BMI) matrix, trade name HexPly® F650, cured in an autoclave at 190 °C and 85 psi for 4 h, followed by an 8-h 232 °C post-cure; (2) a 4-ply 4-harness satin weave glass fabric (Style 4180) in an epoxy matrix, trade name Cycom 919®, cured at 121 °C and 23 inHg vacuum for 2 h; (3) a 4-ply 4-harness satin weave glass fabric (Style 4180) in an epoxy matrix, trade name Cycom 919®, cured at 121 °C and 23 inHg vacuum for 2 h. All materials were used in the as-received pre-impregnated form. Individual plies were cut from the original 500 yard rolls to make a 36 by 36 inch panel for each material type. Five test samples of each material were cut with a wet diamond saw to dimensions of 50 × 80 mm, as required by the dielectric property measurement method. All laminate samples were dried in an oven at 50 °C until a stable fully-dry weight was achieved, followed by storage in a desiccator until test.

Water was introduced into the samples via full immersion in sealed containers of distilled water maintained at 25 °C in a constant temperature water bath. The water content of each sample was calculated based on gravimetric weight gain data, which was collected periodically during the absorption process using a high precision analytical balance according to ASTMD5229. In order to isolate the effect of absorbed water from surface water, all samples were carefully dried with a lint-free cloth and exposed to 25 °C air briefly to allow evaporation of all residual surface water prior to testing. The relative permittivity of each sample at 10 GHz was measured immediately after the weight (and therefore water content) was recorded. The method employed for relative permittivity determination is a resonant technique which uses a split-post dielectric resonator (SPDR) manufactured by QWED© of Warsaw, Poland coupled with an Agilent Programmable Network Analyzer. The fixture is shown schematically in Fig. 1. The device is composed of a metal enclosure and two thin dielectric resonators, enabling the creation of a strong evanescent electromagnetic field in the gap between the resonators. The sample under test is placed in this gap, causing a shift in resonant frequency and Q-factor. The shift in these two values relative to the empty resonator is used to calculate the dielectric properties of the sample. This technique is well-established for measuring the complex permittivity of a variety of materials, including dielectric and ferrite laminar specimens, and low to medium loss solid laminar dielectric specimens [27–30]. Uncertainty of the relative permittivity is better than ±1%, provided that the thickness of a sample is measured with an accuracy of ±0.7% or better [28].