Impact of water on the dielectric properties of papers in the radiofrequency domain

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***Abstract*—Considering its different interaction forms with cellulose, water is very problematic as we consider high frequencies electromagnetic applications of papers. Thereby, cellulosic materials exhibit big losses in the radiofrequency (RF) domain. In this paper, we describe the RF dielectric behavior of different papers versus their moisture content and display the huge impact of water upon losses. We also present a three components effective medium theory that is able to describe and predict the impact of this water upon cellulose losses and permittivity.**

Keywords—Cellulosic materials; Moisture content; Free Water; Bound Water; Radiofrequency; Effective medium theory.

I. INTRODUCTION

Cellulosic materials, although not new, show a not-surprising increase in interest for different new technologies as papers are cheap, flexible, and respectful of the environment. They are used in the fabrication of many different high frequency devices such as: antennas [1], capacitors [2] and inductors [3]. However, in the radiofrequency domain, cellulosic materials show very high losses (tan δ close to 2.10^{-1} at 900 MHz). This paper presents the impact of moisture content upon cellulosic material and proposes a theoretical approach to predict it. For this purpose, an effective medium theory applied to a three component system is used and permit to predict the behavior of both the permittivity and the loss tangent with the water content change.

II. IMPACT OF THE MOISTURE CONTENT ON PAPER

Four types of paper are analyzed: a blotter (70 g/m² density, 115 µm thickness), a standard printing paper (80 g/m², 110 µm), a thick printing paper (160 g/m², 220 µm) and a tracing paper (115 µm). These samples were chosen to represent the widest range of physical and chemical paper's composition. Indeed, blotter is composed of 100% cellulose and printing papers, of two different thicknesses, are both constituted of 15% of mineral filler (50% of $CaCO_3$ and 50% of kaolin) and 85% cellulose. Finally, tracing paper is a 100% cellulose material that has been calendered.

A preliminary study has allowed to determine the relation between the moisture content of the four papers and the humidity rate of the atmosphere (Fig. 1). Thereby, the masses of the four samples were studied in a controlled environment in which the humidity rates were varied from 0% to 90%. Then, for each values of the moisture content (converted in volume ratios), the dielectric properties (permittivity and loss tangent) were measured using two resonant cavities at 900 MHz and 2.45 GHz [4], associated with a Vector Network Analyzer (VNA).

Fig. 1 presents the losses measured with the moisture content in the four papers at 900 MHz. The inset shows the moisture content inside the paper compared to the humidity of the atmosphere. On the main graphs, we can notice that for the four different papers their behavior in regard of the moisture content remains very similar. It means that the losses, as the amount of absorbed water increase, do not noticeably depend on the paper properties like the thickness of the sheet, the presence of mineral materials or the mechanical treatment. Lets' notice that the increase of these losses is very significant as it can reach several hundred percent for high water rate. For example, the loss tangent in a dry blotter is about tan (δ) = 0.042 whereas it is multiplied by four (tan (δ) = 0.18) when the humidity rate of the air reaches 80% (12% of water content). In order to discuss this result, we plotted, in Fig. 2, the contribution of the four dry papers and water contribution to the losses compared to the moisture content in volume at 900 MHz.

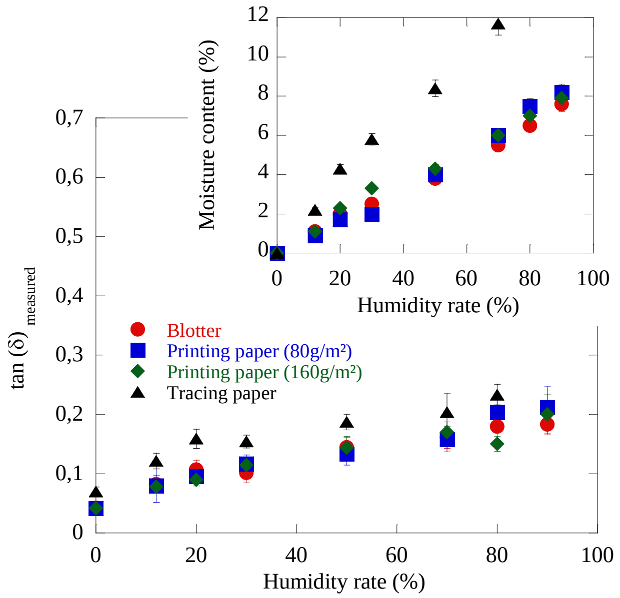

Fig. 1. Losses of the four papers at 900 MHz with the humidity rate of atmosphere. Inset : Moisture content of papers with the humidity rate.

We want to thank, here the ANR MACEO for their support.

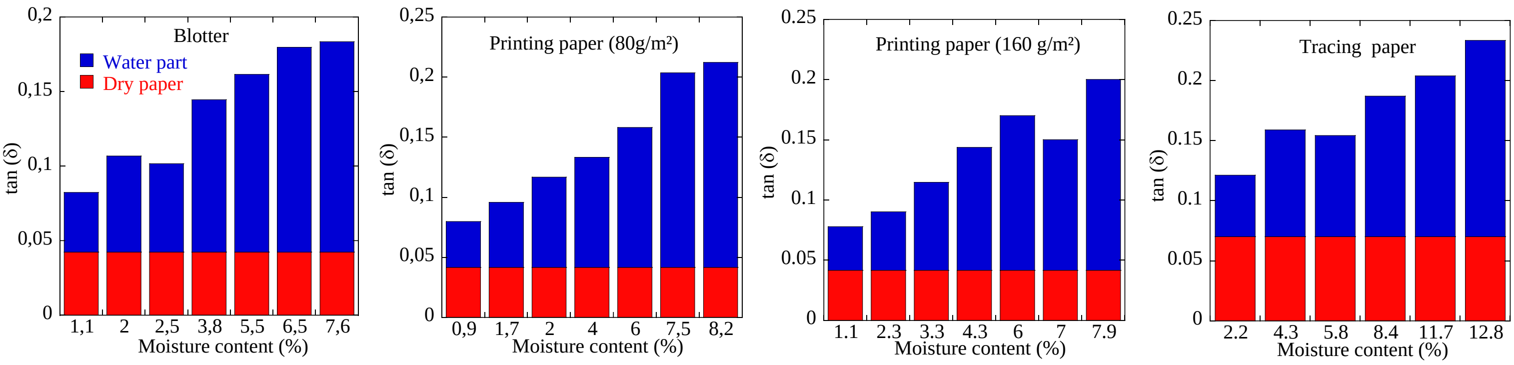

Fig. 2. Contribution of the water (blue) and the dry paper (red) to the losses at 900 MHz.

The bars in red characterize the contribution of the dry material (dried at 105°C for two hours) and represent the losses of reference to evaluate the water contribution. Thus, the bars in blue show the contribution of the losses induced by water, simply deduced by subtracting losses measured on the dry material from the total losses measured on the wet one. At 900 MHz, the losses of the dry paper are tan (δ) = 0.04 for both the blotting paper and the two printing papers whereas it is worse for the tracing paper (tan (δ) = 0.07). As expected, we can observe an increase in losses with the water content of paper. Note that we obtained very comparable results at 2.45 GHz.

Moreover, as previously described, the sum of the blue and red parts corresponds to the total losses for each of the different moisture rate of interest. It can therefore be highlighted that the losses attributable to the water inside the material can represent between 60 and 90% of the total losses; this limit value being obtained for a water content of 8% for the first three papers and of 13% for the tracing paper. The higher the humidity rate, the greater the losses and the greater the water contribution.

In summary, water has an extremely important impact on paper losses and can contribute to almost all of them. Such impact must be taken into account in any attempt to design RF component. In the following paragraph, we validate a method to quantitatively predict the behavior of cellulose based materials, according to the moisture content. The results are only shown for the blotter paper. Indeed, as previously described, the evolution of the losses but also of the permittivity (results not presented in Fig. 1 and 2) as a function of the humidity is comparable for all the cellulosic materials that we analyzed.

III. Modeling of the Cellulose/Water Behavior

For this purpose, we selected four effective medium approaches (EMA): Maxwell Garnett (MG), Landau, Lifshitz and Looyenga (LLL), Lichtenecker and Rother (LR) and Wiener (W). These approaches, even though, often used, were selected because of their ability to describe a three components system (air, cellulose and water).

A good representation of a paper is a cellulose matrix with many pores. In those pores, water and air are in an equilibrium, which depends on the atmosphere humidity. When the atmosphere changes radically, the return to equilibrium between air and water can take up to two hours. The EMAs were carried out considering the following assumptions: the cellulose in the four samples is of the same type, the cellulose ratio and the volume of the samples remains constant whatever the moisture content is. It means that any increasing of the quantity of water, only decreases the air volume.

Our modelisation reduces the paper of a mixture of three components: air, cellulose and water. The properties of air were the standard's ones: ε_r = 1, tan (δ) = 0. Cellulose properties couldn't be directly determined by measurement. Indeed, paper is always, at least, composed of air and cellulose. The samples were measured for all moisture content, including 0% i.e. for a dry material. For this last ratio, the sample can be considered as only composed of air and cellulose. Using the previous listed EMAs for two medium mixtures (air and cellulose), the cellulose properties were extracted by making a retrofit. For example, for pure cellulose, Maxwell Garnett model, led to, ε_r = 3.2 and tan (δ) = 0.24 at 900 MHz. The determination of the properties of water is more complicated. In papers, water interacts with cellulose and can be described by two different states: bound and free water [5]. Bound water creates hydrogen bounds with the alcoholic sites of the cellulose and free water can freely move inside the material. The dielectric properties of the two states of the water are drastically different. Table I, extracted from [6] and [7], gives the dielectric properties of both the bound and free water at 900 MHz and 2.45 GHz.

TABLE I. Dielectric properties of free and bound water extracted from [6] and [7].

	Free water		Bound water	
Freq	*900 MHz*	*2.45 GHz*	*900 MHz*	*2.45 GHz*
ε'	79.7	78.5	18.4	12.9
ε"	3.7	10	9.5	7.2

Fig. 3 shows, both the real part of the permittivity and the loss tangent measured of the blotter paper, in comparison with the different EMAs predictions, considering free water parameters. Lets' noticed that only the LLL approach well fits the experimental results for the real part of the permittivity. Nevertheless, it is not the case for the loss tangent, no more than the other models. We conclude that one of the reasons of such a discrepancy is that free water is not adapted to describe the dielectric behavior of water contained in paper.

In Fig. 4. we plotted the same curves than on Fig. 3, but using the properties of bound water. A better agreement is obtained with the LR approach for k=1 for the permittivity and

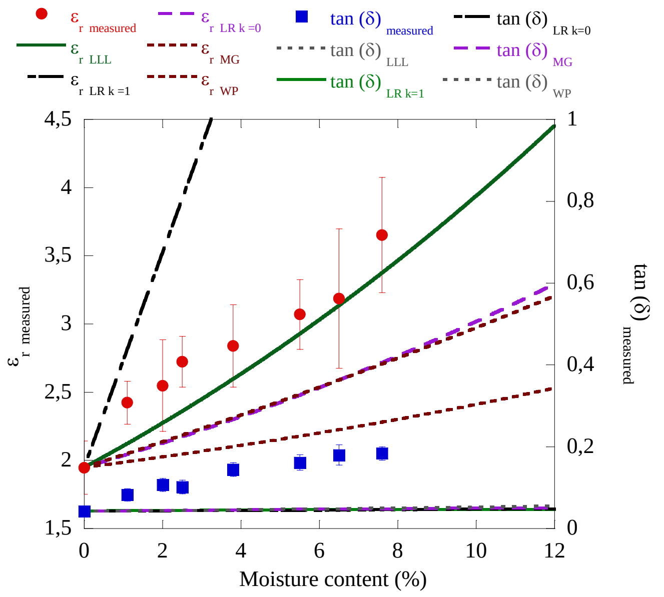

Fig. 3. Dielectric real permittivity and losses of Blotter at 900 MHz with free water properties compared to the simulation of LLL, LR for k=1, LR for k=0, MG and Wiener for perpendicular orientation of molecules.

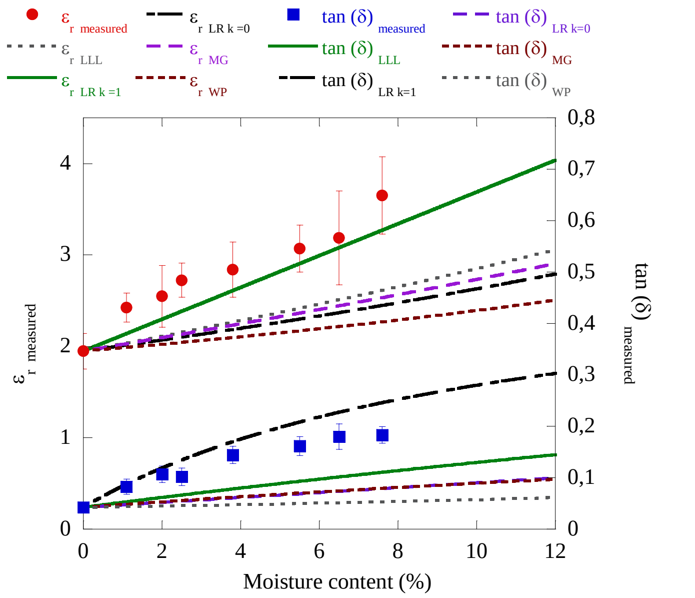

Fig.4. Dielectric real permittivity and losses of Blotter at 900 MHz with bound water properties compared to the simulation of LLL, LR for k=1, LR for k=0, MG and Wiener for perpendicular orientation of molecules.

the losses whereas it is not the case for the others EMA. This model allows to well predict the behavior of the paper when the moisture content changes. This result is in well agreement with B. L. Shrestha and. al. [8] who show that for moisture content below 20%, the water inside papers is mainly bounded. Water molecules, that are bounded to the alcoholic site of cellulose, tend to align their dipole moment to the field applied, justifying the value of k=1. LR approaches is perfectly adapted to qualitatively and quantitatively predict the dielectrics properties of paper when the moisture content varies.

Indeed, MG model is based on spherical particles shapes without any interaction and only considers small amount of particles embedded in a host matrix (cellulose) i.e. for large dilution. The LR model, which fits with our results, is defined by the electric dipole moment direction of the geometrical arrangement responding to an electric field. For k=1 (corresponding to Wiener parallel frontier limit) the dipole moment of the different phases is parallel to the applied electric field. When k is equal to -1, the system is perpendicular to the field (Wiener perpendicular frontier limit) whereas for k=1/3, the system corresponds to a LLL model. Taking into account these considerations, we can conclude that it is not surprising that MG, Weiner and LLL model cannot be able to well fit the experimental data.

IV. Conclusion

In this paper, we presented the impact of water upon the dielectric properties of papers. To well evaluate its effect, we presented the radiofrequency response of four types of paper to cover the widest range of class of cellulosic materials. For the four samples measured at 900 MHz and 2.45 GHz, we show, that water can be at the origin of at most 90% of the total losses and that response of papers is similar, whatever is their composition.

We also show that an effective medium approach, such as Lichtenecker and Rother, can well estimate the behavior of cellulosic materials in regards of humidity variation. For this purpose, a three components effective medium approach has been applied to air, cellulose and bound water. The correlation between measurement and theory led to very interesting opportunities to predict such behavior of paper in the design of RF devices.

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