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NOTE

Universality of AC conductance in human hair

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Abstract

The objective of this study was to investigate the possible existence of scaling properties in the AC conductance of human hair by using electrical impedance spectroscopy measurements and scaling the measurement results. The electrical impedance of the tissue was measured using a Solartron 1260/1294 impedance analyzer. The curves showing the conductance as a function of frequency were normalized (each measured value divided by the DC conductance) and the frequency was normalized with regard to both DC conductance and temperature or relative humidity. The results indicate the existence of universality nature of the AC conductance in human hair.

Introduction

Many disordered solids show a remarkable universality in the frequency dependence of the AC conductivity. This has been demonstrated for a range of different materials such as glasses, amorphous conductors, and electron conducting polymers (Jonscher 1996, Sidebottom *et al* 1996, Roling *et al* 1997, Dyre and Schrøder 2000, Murugaraj 2007, Murugavel and Upadhyayr 2011), and applies both to electronic and ionic conductors. Typically, the curves showing the conductance as a function of frequency for different temperatures fall on a common master curve when conductance and frequency are scaled appropriately.

The existence of a master curve is sometimes referred to as the time–temperature superposition principle (TTSP). Biological systems are generally disordered and it is interesting to see if similar scaling properties are found in that case. Earlier studies suggest that human hair may display such properties (Martinsen *et al* 2013) and in this work we will therefore investigate the possible presence of AC universality in human hair.

Impedance spectroscopy on biological materials is not usually performed as a function of temperature. However, the electrical admittance is largely dependent on water content. Therefore we have investigated the dependence of the AC conductivity both on temperature and ambient relative humidity (RH).

The scaling law of AC conductance for temperature dependent measurements can be expressed as (Baranovski 2006):

$$\frac{\sigma(\omega)}{\sigma_{\mathrm{DC}}} = F\left(\frac{\omega}{\omega_{\mathrm{s}}}\right), \qquad (1)$$

where F is a temperature-independent function and ω_{s} is a temperature-dependent scaling parameter.

Many models and postulates have been suggested and studied for the last half century to understand and identify the cause of this AC universality, see Dyre and Schrøder (2000) for a review. The frequency scaling parameter has been approached differently by different researchers (Sidebottom *et al* 1996, Roling *et al* 1997, Sidebottom 1997). We will apply a simple argument based on a resistor–capacitor network (Dyre and Schrøder 2000, Kao 2004) to justify the scaling relation and derive the dependence of ω_{s} on temperature and RH.

As shown by Dyre and Schrøder (2000), one can start from discretizing a macroscopic model and derive an equivalent resistor–capacitor network where the nodes are connected by parallel resistors and capacitors. The resistors have a broad distribution of resistances, while the capacitors are all identical with a capacitance $C \propto \varepsilon_{\mathrm{r}}$ where ε_{r} is the bound charge dielectric constant (relative permittivity). At zero frequency, all current flows through the resistors, and when disorder is large the conductivity will be described by percolation theory. As the frequency is increased, current will also start to flow in the capacitors parallel to the resistors. The conductance will therefore start to be affected by the finite

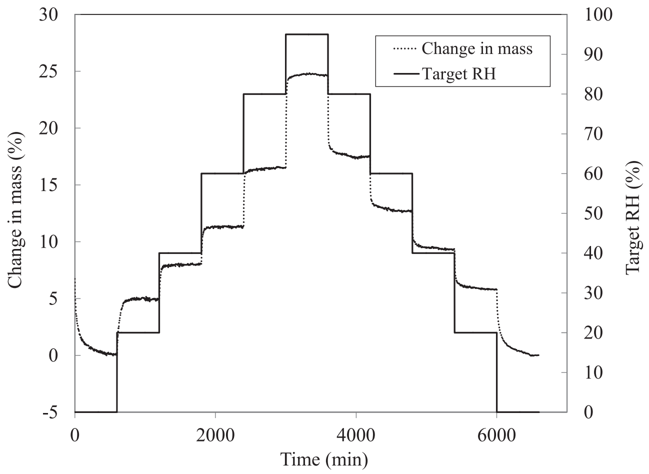

Figure 1. Steps in chamber RH (full line) and resulting change in hair sample mass (dotted line).

frequency when $\omega C = 1/R_C$ where R_C is the critical resistance in the DC percolation network. It is related to the DC conductivity by $R_C = 1/\sigma_{DC}\xi$ where ξ is the correlation length of the percolation network, which is known to be only weakly temperature-dependent (Shklovskij and Efros 1984).

In the following we will also assume that it does not change significantly with RH. We will therefore choose $\omega_s \propto \sigma_{DC}\xi/C$ as a natural frequency scale, and normalize the frequency by this. For this we need to assume some dependence of ε_r on temperature and RH. It is common (Dyre and Schrøder 2000) to assume that $\varepsilon_r \propto 1/T$, although the justification for this is not clear in the present sample. However, as the temperature range over which we have performed experiments is rather limited, the quality of the results does not depend significantly on this, as the main temperature dependence comes from the temperature dependence of the DC conductivity. The dependence on the RH is more important, as the experimental range is larger. Since water has a large dielectric constant, it is natural to assume that ε_r is proportional to the water content of the sample, which it is also reasonable to expect to be proportional to the RH (see figure 1 below). We will therefore assume that $\varepsilon_r \propto$ %RH. Thus we have the following scaling frequencies: for changing temperature at constant RH: $\omega_s = \sigma_{DC} T$ and for changing RH at constant temperature: $\omega_s = \sigma_{DC}/\%\text{RH}$.

Materials and methods

Untreated human hair (washed as normal but otherwise not artificially treated in any way) from a healthy, male volunteer was used as test material in this impedance spectroscopy study. The hairs were prepared by arranging bundles of hairs (more than 5000 hairs) of length 25 mm parallel to each other and they were mechanically and electrically connected together by CircuitWorks® 60 min Conductive Epoxy (the glue contains silver particles giving a resistivity less than 1 mΩ cm). The free length of the hairs between the epoxy lumps was 13 mm. Crocodile clips were used to connect the Solartron 1260/1294 impedance analyzer to the hair bundle in a two-electrode system. The hair bundle was then put inside a CTS® series C type climatic chamber with the impedance analyzer placed outside the chamber.

Gravimetric studies were also performed on samples of hair in order to determine the time needed for the hair to reach an equilibrium moisture level at a given ambient RH. We used a DVS Intrinsic® from Surface Measurement Systems Ltd. The samples were automatically weighed in a closed chamber as a function of ambient RH. Measurements were performed in the range 0%–95% RH at 25 °C to obtain high-resolution isotherms, which were used to study the characteristics of absorption, desorption and diffusion of water molecules in the hairs.

Based on the results of these measurements (see next section), the samples stayed approximately 24 h inside the climate chamber in order to be stabilized at each level of RH before any electrical measurements were performed. The same 24 h procedure was also used when measurements were done with different temperatures at constant RH.

Electrical impedance spectroscopy was performed using a Solatron 1260 impedance analyzer with a 1294 dielectric interface. During the impedance measurements, the sample were scanned at 36 logarithmically distributed frequencies in the range 0.01 Hz–1 MHz while employing a constant voltage signal amplitude of 2 V rms.

Results

Gravimetric measurements

The result from the gravimetric measurements on hair fibers in the DVS Intrinsic are shown in figure 1.

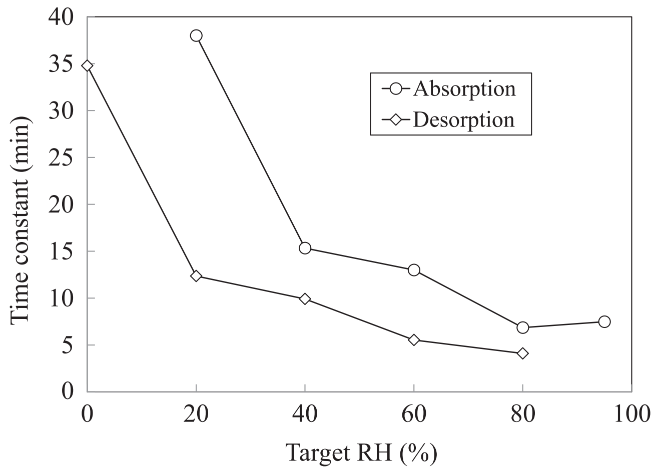

Figure 2. Hair absorption and desorption time constant.

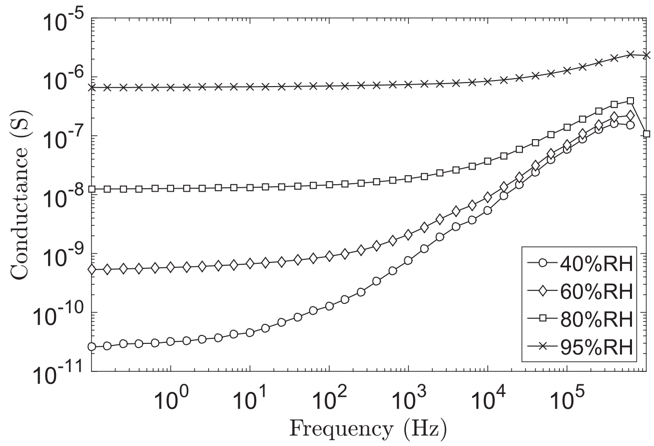

Figure 3. Frequency dependence of hair conductance at constant temperature (298 K) and different RH.

The change in mass after introducing a step in the RH was found to fit well with an exponential time course. Hence, the following relationship was used as a model of the absorption process:

$$y = y_0 - A\,\exp\left(-\frac{t}{\tau}\right), \tag{2}$$

where y is the change in mass, t is time and y_0, A and τ are constants.

The curve fitting parameter τ is the time constant for the sorption process. For each target RH the DVS ran for 10 h (600 min) and the mass was sampled every minute. However, only the first 150 min were used for curve fitting. Approximately up to this point the graph demonstrated exponential growth or decay and after that it became flat. The curve fitting results are shown in figure 2. The time constants are in the ranges 6–38 min and 3–35 min for absorption and desorption, respectively. The result shows that absorption of water in hair is a somewhat more time consuming process than water desorption. In conclusion, it is clear that waiting 24 h at each new RH is more than sufficient to ensure stable conditions for electrical measurements.

AC conductance and scaling

The measured electrical conductance of the bundle of human hairs are shown in figure 3 (constant temperature at 25 °C and varying RH) and figure 4 (constant RH at 80% and varying temperature).

Finally, the AC conductance spectra for different temperatures and different RH are normalized (each measured value divided by the DC conductance) and the frequency is normalized with regard to both DC conductance and temperature or RH. The results are presented in figures 5 and 6, where it can be observed that the curves more or less collapse into one 'master curve', and hence display universal or scaling properties.

Discussion

Figures 3–6 show deviation from the monotonic behavior when approaching 1 MHz. This is due to

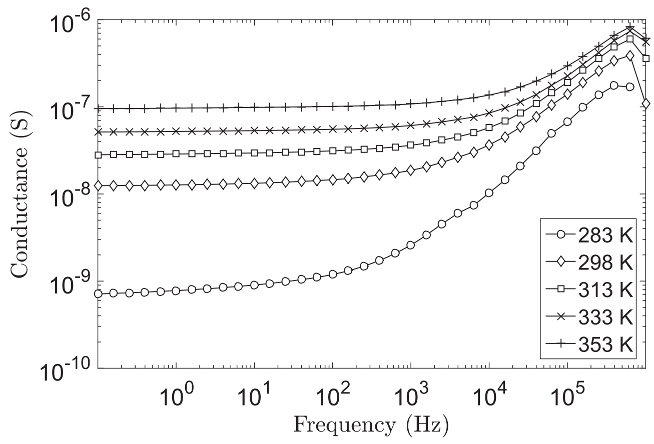

Figure 4. Frequency dependence of hair conductance at constant RH (80%) and different temperatures.

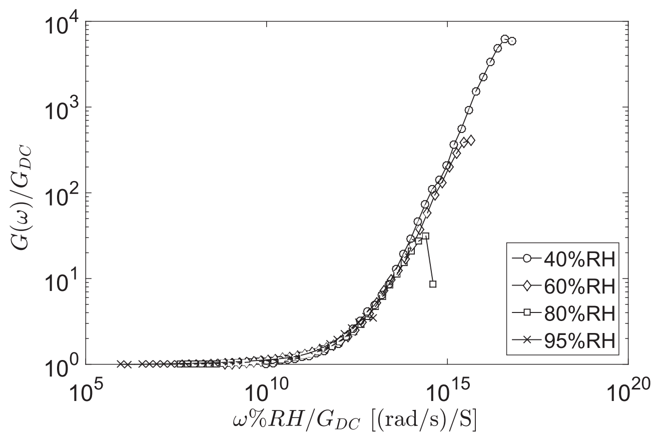

Figure 5. Hair scaled conductance at constant temperature (298 K) and different values of RH.

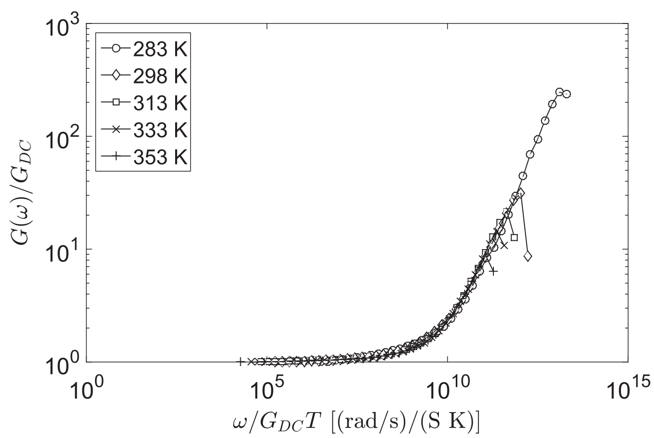

Figure 6. Hair scaled conductance at constant RH (80%) and different temperatures.

the limited bandwidth of the Solartron 1294 preamplifier and does not describe any physical phenomena in the measured samples. Nonetheless, the bandwidth of the phenomena described in this paper is of great interest, e.g., to see if the scaling properties also hold for more than one dispersion range (Schwan 1957). This is an interesting topic for further research.

The impedance of the glue was always less than 1 ppm of the total measured impedance. With hair impedance in the mega- and giga-ohm range, and a large contact area between hairs and glue (more than

5000 hairs), there is no reason to believe that electrode polarization impedance has any influence on the results.

As shown in figures 3 and 4, the conductance varies with both temperature and RH. At a constant temperature, the conductance increases with RH and similarly, at a constant RH the conductance increases with temperature. This shows that both temperature and RH play a vital role in the conductance properties of human hair. The question is how?

It is obvious that electrical conductance of a material is determined by two factors: the concentration of free carriers available to conduct current and their mobility. Increase of water content in keratinized tissue has been found to increase the conductance of the materials (Martinsen *et al* 1997). This increment is because of both molecular mobility and ionic conduction as more water molecules add to the system that creates a good environment for the free oscillations of the molecules. In fact, the water is found in biomaterials in three different states: free, loosely bound and tightly bound (Johnsen *et al* 2011). The variations of hydration state can affect the relaxation time of water and its ability to polarize in an electric field and thus change both the capacitive and conductive properties of the tissue.

In addition to this, keratins are composed of polypeptide chains made from different amino acids. Parts of these polypeptides can form structures (such as α-helical and β-pleated configurations) with different chemical nature of many side chain endings of keratins. These properties of keratins can form bonding to the surrounding water molecules that lead to different arrangement and internal reorganization. This kind of reorganization can cause some kind of conduction energy change and introduce new donor/acceptor levels, thereby considerably modifying the electronic structure and conduction properties of keratins.

As the scaling result shows in figures 5 and 6, the electrical conductance of hair, measured in different environmental condition (temperature and RH) almost fall into a single curve. Hence, it is evident that hair satisfies the so-called TTSP. This means that the frequency dependent conductance, which is measured at varying temperature and RH, demonstrates a similar shape in all cases. In other words, the shape of the frequency dependent conductance of hair does not depend on the temperature and RH.

On the other hand, to a certain degree this temperature dependent conductance nature of the biological materials resembles the temperature dependent conductance nature of semiconductors. It is difficult to draw firm conclusions on this point but there are plenty of proposals and reports which are summarized by Kalia and Avorous (2011) that biological materials such as protein and DNA have a semi-conductive polymeric type nature (polymer is a large molecule, or macromolecule, composed of many repeating units).

Furthermore, the TTSP, which is held by so many amorphous semiconductors and semiconductor polymers, also shows its existence in biological materials.

There are (at least) two possible applications of these findings: one being that with some prior knowledge, universal behavior means that the change in e.g. conductance with altered humidity or temperature can be predicted, which is useful e.g. when working with models of biomaterials. The other and perhaps more important application, is that a new phenomenon like this may provide added insight to the mechanisms behind electrical conduction in biomaterials.

Conclusion

For the measured sample, the conductance in the lower frequency (from 0.1 Hz to 10 kHz) and higher humidity (above 60%) is dominated by DC conductance because the conductance is almost independent of frequency.

Hairs show a clear sign of the existence of universality of AC conductance. The cause of this universality is still unclear. Electrical conductance is sensitive to any change in chemical composition or structure of the studied material. Therefore, in order to know the exact cause of universality in AC conductance of biological materials, such as hair, detailed microscopic studies are needed. That means one has to know and understand what happens to the physical structure and chemical compositions of the materials due to the change of both temperature and humidity, and the mechanism and the path of the charge from one end to the other.

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