Indian Journal of Fibre & Textile Research
Vol. 34, June 2009, pp. 191-199

Review Article

Measurement of dielectric properties of textile materials and their applications

Kausik Bal & V K Kothari[a]

Department of Textile Technology, Indian Institute of Technology,
New Delhi 110 016, India

Received 7 July 2008; revised received and accepted 17 September 2008

Dielectric properties of textile materials have been used in process and quality control in relation to the moisture content, unevenness, drying, static generation, etc. Although dielectric properties of fibres and fibrous assemblies have been the subject of study of many researchers for a long time, the understanding of the subject, however, is still incomplete. With the advent of new characterization techniques and development of new textile based products for special applications like composite reinforcement, EMI shielding, etc., the subject requires fresh and further investigation. This paper reviews the state of knowledge regarding the dielectric properties of the fibres and textile materials, the various measurement techniques and some of the major applications of this knowledge in textile industry.

Keywords: Capacitance, Dielectric properties, Fibre, Loss factor, Moisture content measurement, Permittivity, Polymers

1 Introduction

Fibres and textile materials have been the subject of study in relation to electrical and dielectric behaviour for a long time. Research on the electrical and dielectric properties of such materials has been carried out in many directions which range from characterizing the fibre to the application of its dielectric properties in many diverse fields. The present paper attempts to review the various measurement techniques that have been used by various researchers to characterize dielectric properties of fibres and textiles. Many important cases where the dielectric behaviour of these materials have been used or applied successfully have also been reviewed.

Many authors have reported measurement methods of dielectric properties, such as dielectric constant and loss factor of cellulosic[1-4], protein[5,6] and synthetic fibres[7,8]. Dielectric relaxation phenomenon has been studied in relation to the molecular structure of fibre forming polymers[9,10]. The dielectric property also got attention in order to make some efforts to reduce static generation in textile industry[11], to measure the moisture content of textiles[12,13], to measure the linear density of yarns and other linear fibrous assemblies[14], to detect impurities within fibrous mass[3,15], to detect the variation in mass throughout the length of yarns and slivers[16,17], to observe moisture transmission through textiles[18], and many such applications.

It appears that a great potential is there to find new innovative applications of textile materials utilizing their dielectric character. More sophisticated and precise methods of characterization of dielectric behaviour of textile materials are also required. It is hoped that the present review will help in throwing light to these important aspects.

2 Textile Materials as Dielectric

Textile materials such as fabrics and yarns are basically assemblies of fibres. The fibres are generally made of linear long chain polymers and have large length to diameter ratio. The electrical conductivity of most of these polymers is so low that they are generally considered as insulators[19]. When these polymers are extruded in fibre form, the orientation of the long chain molecules may make the material anisotropic[9]. Hence, the behaviour of textile materials as dielectrics depends on the dielectric behaviour of the fibres and also on the fibre forming polymers. However, since the polymers can be produced in the form of isotropic or anisotropic sheets, the measurement of such materials for their dielectric properties becomes relatively easier. This is not always true for fibres and fibrous assemblies. Hearle[11] has explained this difficulty and reported some models which tried to solve this. The dielectric properties and their

[a] To whom all the correspondence should be addressed.
E-mail:ktharivk@gmail.com

measurement methods are discussed in the following sections.

2.1 Dielectric Properties of Polymers

Polymers form an important segment of all dielectrics. For example, polymers are extensively used as insulators in wires and cables. The phenomena of dielectric relaxation processes occurring in case of polymers were studied through comparison of data gathered from dielectric, mechanical and nuclear magnetic resonance experiments on the homologous series of polymers. Based on such studies, the following types of molecular motion and their associated dielectric relaxation were identified[20]:

(i) Primary main chain motion in both crystalline and amorphous regions,
(ii) Secondary main chain motion in both crystalline and amorphous regions,
(iii) Side chain motions, and
(iv) Impurity motions.

The relaxation processes that occur in a particular polymer are denoted as α, β, γ, σ in the order of the increasing frequency at which they occur for a fixed temperature.

The polarization process in polymers under an electric field takes place when units of the polymer chain tend to orient the dipole and strongly polarizable bonds in the direction of the electric field. The polarization is complete at the low frequencies. However, when the frequency is higher, the orientation lags behind the field. This is because the orientation of polar group is a slow process. At frequency of 10^{12} Hz the dipoles cannot track the oscillations of the field. The dipolar part vanishes and only the remaining random orientations contribute to the resultant polarization. Therefore, from the total polarization only vibrational and electronic polarizations remain. At still higher frequencies, the stretching and bending of bonds among atoms become slower so that vibrational polarization no longer occurs. At frequencies higher than 10^{15} Hz (optical frequency range), only electronic polarization takes place.

The polarization is difficult to measure directly but can be measured indirectly by the relative permittivity of the material. This value is low, medium and high for apolar polymers, polymers with polarizable groups and polar polymers respectively[21].

A number of authors[10, 22] have discussed various theories of the static dielectric constant. Theories of Debye, Onsegar, Kirkwood and Frohlich have been explained and it is shown how Frolich's generalization is applied to polymeric systems.

Dielectric properties of polymers have been related with their mechanical and thermal properties[22]. It has been observed that the dielectric loss is a time dependent phenomenon and the extent and nature of the loss also depend on the temperature. However, the heterogeneous structure of a polymer which consists of crystalline and amorphous regions and also presence of other impurities like water and plasticizers make the correct characterization of polymers very difficult[20].

Dielectric breakdown is another important phenomenon in case of polymeric insulators. This occurs at very high electric fields where the local flow of current through the polymer suddenly increases, leading to catastrophic breakdown of the polymer as an electrical insulator[23].

2.2 Measurement Methods of Dielectric Properties of Fibres and Textiles

Many researchers have studied the dielectric properties of textile fibres[1-4, 6-8]. The methods of measurement and the measuring conditions were different in different cases. The shape and size of the sample also varied. Many literatures have incorporated values of permittivity and loss factor in case of fibres[3,11] and also have discussed the effect of various factors on the measured values[2,4,6,11].

Studies on textile fibres incorporate some difficulties and none of the standard methods can be directly applied to measure the dielectric properties of fibres. Measurement with fibres as dielectrics involves measurement of a mixture such as air-fibre mixture. However, in case of textiles, it has been recognized that a textile product is usually a heterogeneous three-phase system and therefore it was suggested to refer it as the capacitance of 'fibre-moisture-air' system[24].

Hearle[2] has reviewed various models of the air-fibre mixture to interpret the observed capacitance in terms of the dielectric constant of the fibres. He compared the theoretical curves and pointed that none of them was able to explain the experimental results correctly in all the cases.

Balls[1] used resonance method with a special type of capacitor system to measure the dielectric constant of cotton fibres in longitudinal and transverse directions at a frequency of 1.755 MHz. The electrode had a live plate sandwiched in between two layers of fibres and two grounded external plates. The whole capacitor was gripped by a vice which could be adjusted to control the packing of the fibres by compressing the plates. This way he could achieve a maximum of 50% packing by volume. The electrode distance was varied from 1 mm to 5 mm and the gap between electrodes was measured using a micrometer. The measurement of dielectric constant of cotton fibres in the longitudinal direction was done by arranging a pack of 10 million fibres on one end, each 4.8 mm long inside a circle of diameter 7 cm with the support of a thin band of varnished muslin. After such measurement was done, the same electrode system was repacked with same weight of cotton inside the same volume in the form of draw frame slivers lying parallel to the plates. Thus, the dielectric constant in transverse direction of cotton fibres was measured. It was found that the dielectric constant in the longitudinal direction was double the dielectric constant in the transverse direction of cotton fibres.

Hearle[2] described a technique in which the sample capacitor was filled with a mixture of liquids whose dielectric constant was changed until the introduction of the fibres makes no effect on the capacitance. Under this condition, the dielectric constant of the fibres was equal to that of the liquid. Although this method could overcome the problem of interpreting the dielectric properties of the fibres from the dielectric properties of air-fibre mixture, the method had some drawbacks, such as it was difficult to find liquids which are perfectly dry and do not penetrate the fibres, and for every frequency and temperature the whole procedure must be repeated. This method was therefore not suitable for fibres containing moisture.

Hearle also reported studies on the electrical resistance[25] and dielectric properties[2] of fibres and yarns under various conditions and using various methods. It has been shown that the electrical resistance and the dielectric constant are related to each other. Hearle tested various types of fibres including cotton, viscose, wool, nylon and polyester. He pointed out the difficulty in measuring the dielectric properties of fibres due to the problem of relating the properties of the air-fibre mixture to the properties of the fibres. He has reviewed different models and associated formulae used for this purpose. He then showed, using his own results under various testing conditions for different fibres in yarn form, that none of the models could be used to give a reliable value for the absolute dielectric constant of the fibre.

Two aluminium cones formed the test condensers in his experiments. A layer of yarn was wound on the inner cone under a certain tension. The outer cone was pressed on it during the testing. A capacitance bridge method was applied to measure the capacitance and power factor. The error due to edge effect was found to be not greater than 0.5%. The density of packing could be adjusted upto a maximum of 0.5 in case of staple fibres. In case of filaments, this approached the theoretical maximum of 0.91. Hearle noted that such arrangement meant that the transverse properties of fibres would dominate, although, particularly with staple fibres, some parts of the fibres might be parallel to the field. Samples were tested at frequencies between 50 Hz and 200 kHz under different densities of packing and different moisture contents. Later in a separate study he used the same condenser system to repeat the experiments at frequencies between 100 kHz and 10 MHz using a Q-meter. From the studies, Hearle could suggest that in order to minimize the effect of moisture on evenness testing, a high frequency should be used, whereas in order to secure the most sensitive moisture testing, a low frequency would be more suitable.

Kirkwood *et al.*[3] have studied the dielectric properties of different varieties of cotton fibre and found that the dielectric constants of different varieties of cotton have practically no difference, although the values of dissipation factor of these varieties were having some difference. From the study of mixture of cotton with different types of trash particles, they suggested that the amount of trash in cotton could be determined through the dielectric behaviour of the mixture. They used a bridge method at 200 Hz to measure the dielectric values and showed that their results were consistent with those obtained by other authors.

Ishida *et al.*[4] have reported a method for obtaining dielectric constant and loss factor of dry cellulose fibres along the fibre axis and dielectric properties of viscose, cuprammonium and cotton sliver. The tests were done over the frequency range 500 Hz–3 MHz and over the temperature range from -60ºC to +20ºC. The measurements were done using a mutual inductance bridge. They observed a clearly defined single dielectric loss peak which is broader than that defined for a single relaxation time τ and described it successfully by a Cole and Cole distribution function. They showed that the loss peak becomes narrower with increasing temperature.

Many authors have reported work on keratin structures[5,6]. King[5] reported study on dielectric properties of keratin using cow horn at a frequency range between 500 Hz and 1 MHz. Algie[6] has studied the dielectric behaviour of wool fibres using some other techniques. In 1955, Mack[26] derived a relationship theoretically to calculate the change in capacitance of a parallel plate capacitor when a cylindrical mass of small diameter is inserted in between the plates. Based on this, Algie[6] designed a condenser setup and tested individual wool fibres at 1.592 kHz. He obtained the real part of the complex permittivity at various relative humidity after conditioning the fibres. He found that the real part of the permittivity is a function of both moisture content and time.

Microwave frequencies have been used to measure the dielectric properties of fibres by some researchers. Shaw and Windle[7] reported a measurement technique at 3 GHz using a modified cavity resonator which is schematically shown in Fig. 1. When a cavity is excited to resonance at a frequency f_0, in the fundamental or TM_{010} mode, the electric field in the cavity is directed parallel to the cylinder axis. The electric field possesses a single maximum at the axis and falls to zero at the cylinder wall. The effectiveness of such a resonator for dielectric constant measurements is due to the fact that when a dielectric specimen is placed in the cavity the resonance frequency is changed and such change in frequency can be related quantitatively to the dielectric properties of the specimen. Using this technique, Shaw and Windle[7] have reported the measurement of dielectric constant of bundles of wool fibre, nylon and cellophane. In a later paper[27], they reported the application of microwave measurement technique at a much higher frequency (26 GHz) to measure the dielectric constant of single wool fibre. The cavity resonator used for this study is shown in Fig. 2. They applied this method to measure the mass variation along the length of a single fibre.

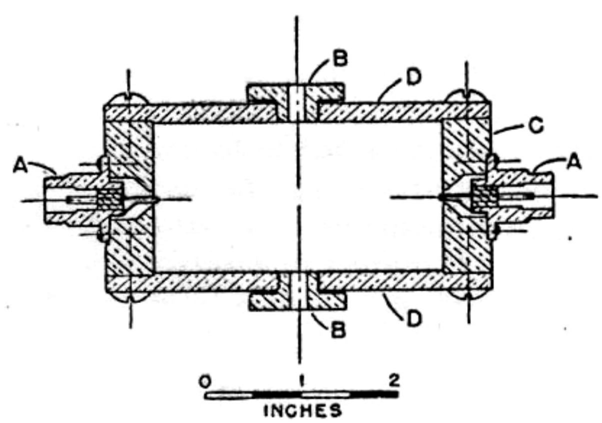

Fig. 1 — Cross-sectional view of cylindrical cavity resonator[7] (A – type N cable connectors, B – plugs to permit specimen to be inserted along axis of resonator, C – cylinder wall, and D – end plates perpendicular to cylinder axis)

Kumar and Smith[8] studied the microwave properties of textiles using a modified cavity perturbation method at 9.8 GHz. They designed a cylindrical cavity which was split into equal parts to operate in the TE_{011} mode. The dielectric yarn was placed across the mid-plane of the cavity and a textile sample was placed in the cavity on a low-loss dielectric sheet of annular form. The complex permittivity was then calculated from the shift in resonant frequency and change in Q-factor. Later, Kumar[28] showed that in case of polyester-water mixture, Weiner's theory of mixtures could be applied successfully. Using microwave measurements at 9.8 GHz, he showed that Weiner's theory predicts the real and imaginary parts of the complex permittivity of wet textile material quite accurately.

Chand[9] measured the dielectric parameters of polyacrylonitrile and polyester fibres and investigated the structure of polymers and fibres through their dielectric relaxation phenomenon. He used bridge method and a LCR meter for the measurement of dielectric properties. The schematic design of the capacitor fixture is shown in Fig. 3. The anisotropic nature of dielectric properties of fibres was studied by measuring the dielectric loss parameter by putting the fibres in parallel and perpendicular to the applied electric field. It was found that the dielectric anisotropy is related with the orientation of the molecules in the fibres.

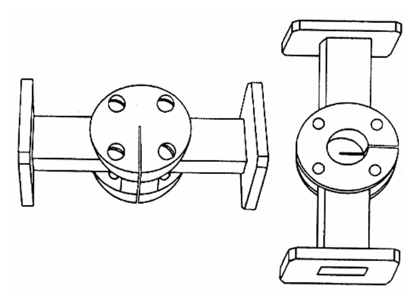

Fig. 2 — Cavity resonator for use with a single fibre at 26 GHz (ref. 27)

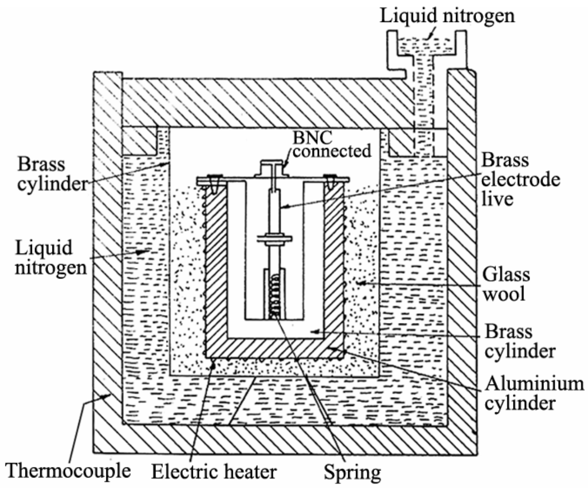

Fig. 3 — Test cell used for studying dielectric anisotropy[9]

Cerovic *et al.*[29] have reported studies on temperature dependence of dissipation factor (tan δ) values of cotton, wool, polyester and cotton-polyester blended fabric samples in the temperature range between -50ºC and +50ºC at a test frequency of 1 MHz using a LCR meter. They have shown that the $\tan\delta$ value increases with the increase in temperature and show a peak in case of wool, cotton and cotton blend, which they attributed to the processes which are specific to the dipolar group, i.e. β-relaxation.

Cerovic *et al.*[30] have also studied the relationship between electrical resistance and dielectric properties for a number of fabric samples in a specially designed test fixture under various humidity values. They reported that the loss tangent decreases as the resistance increases.

Ray Chaudhuri[31] has described a method for the measurement of dielectric properties of fabric samples using LC resonance technique. He found that the differences in effective dielectric constant of raw and degummed silk and that between the raw and the scoured cotton are quite significant. The dielectric constant of finished cotton fabric is in between the raw and the scoured cotton.

2.3 Factors affecting Measurement of Dielectric Properties

Various factors that affect the measured values of dielectric constants and loss factors have been described by a number of researchers[2,4,6,23]. These factors can be divided into two groups, viz. external and internal factors. External factors are the conditions under which the measurement is done, such as test frequency and temperature. Internal factors are those which are decided by the test specimen itself, such as its moisture content and packing density. Some of the major external and internal factors are described below:

2.3.1 External Factors

(i) Frequency**—**The significant effect of frequency on the measured value of permittivity and loss factor of a dielectric substance is a general case and the fibres are no exception to it. Morton and Hearle[11] have demonstrated the dependence of the permittivity (ε_m) and power factor (cos ϕ) on the frequency in case of various types of fibres including cotton, viscose, wool and nylon. At the frequency corresponding to the relaxation time of the dipole present, the energy will be dissipated and the permittivity value will drop while the power factor will show a peak. The influence of frequency on the dielectric properties of fibres is more marked in case of fibres having higher moisture content. The gradual change in permittivity with frequency in case of fibres indicates the presence of a range of relaxation times. Hearle has pointed out from his results that the permittivity of fibres at frequencies less than 5 kHz keeps on increasing with the decrease in frequency in contradiction to the case of ice and ascribed this effect due to the inter-facial polarization phenomenon. Morton and Hearle[11] have shown that the moisture plays a role in the frequency dependence of hygroscopic fibres, such as cotton.

Ishida *et al.*[4] have found similar trend of decrease in dielectric constant with the increase in frequency in case of cotton sliver within the experimental range of frequency between 500 Hz and 3 MHz at different temperatures. They got clear single relaxation peak in the plot of loss factor against log of frequency. The loss peak becomes narrower with the increase in temperature and such plot was explained using Cole and Cole distribution function.

(ii) Temperature**—**The dielectric constant, in general, increases with the increase in temperature in case of solid materials. Algie[6] has reported data on wool-air mixture in a temperature range 0.5º – 95ºC in steps at five different frequencies in the range of 80 Hz – 1.6 MHz.

Ishida *et al.*[4] in their studies found that the real part of the permittivity (ε′) increases with the increase in temperature and the imaginary part of the permittivity (ε″) shows frequency dependence in its behaviour with respect to temperature. A single dispersion could be observed under the given conditions and the dispersion frequency is shifted to a lower value with decreasing temperature.

Chand[9] has measured the variation in tan δ with the increase in temperature in case of polyester fibre from -160ºC to +40ºC at different frequencies ranging from 0.5 kHz to 10 kHz with the applied electric field in parallel as well as in perpendicular to the fibre axis. He obtained relaxation peak which corresponds to the β-relaxation.

In case of solid dielectrics, the dipoles are restrained and an increase in temperature reduces this restriction. As a result, the permittivity is expected to increase with the increase in temperature. The loss factor shows a behaviour reflecting the distribution of relaxation time in case of the dielectric[10]. Thus, the effects of temperature and frequency are often similar.

2.3.2 Internal Factors

(i) Moisture—It has been found that the capacity of a hygroscopic fibrous system is affected by its moisture content[2,5-7,24]. Hearle has measured the effect of moisture content on the dielectric properties of cotton, viscose and many other fibres and found that the permittivity increases with the increase in moisture content.

Hearle has mentioned that the observed increase in the dielectric constant and power factor with the increase in moisture content is due to the polar nature of water molecule, the release of polar groups in the fibre molecule as well as the release of the ions. At higher frequencies, he observed that the water in the cellulose fibres acts as if it is restrained in a manner similar to the restraints in ice. At lower frequencies, in some materials including cotton, the water acts as if it has a dielectric constant greater than 80, which, according to Hearle, indicates the importance of its effect in allowing other units in the structure to polarize.

King[5], Hearle[2], Windle and Shaw[27] and Algie[6] have studied the effect of moisture content on the dielectric properties of keratin. King has studied cow horn, whereas others have studied wool fibres. Hearle studied the dielectric constant and power factor of wool-air mixtures for water contents between 1.3% and 17.8% at 70^0 F within a frequency range from 50 Hz to 1MHz. Algie measured single wool fibres at a frequency of 1.59 kHz at 35^0C with water content between 0% and 25% and found that the results agreed well with those of King. Algie has also studied the effect of moisture content on wool-air mixture over a frequency range 10^{-2} Hz – 2 MHz. Algie[6] has also studied the effect of relative humidity on equilibrium dielectric constant for wool fibres at 1.592 kHz and at 35^0C.

(ii) Packing Density—Strictly speaking, the dielectric constant is a property of homogeneous material and hence it should not vary with mass. But the textile materials such as fibre bundles, yarns and fabrics are not homogeneous, and therefore the measured results will show the gross effects of the heterogeneous mixture of fibre and air. For example, the capacitance will depend on how much solid fibre material is packed inside the gap between the plates. Thus, the capacitance becomes a function of the mass or packing density of material inside the capacitor. This fact has been utilized in many capacitor based instruments for the determination of mass unevenness[14,15,32,33].

Boyd[32] showed the theoretical relationship between the volume fraction of fibres in the form of yarn and capacitance when the yarn is introduced into the parallel plate capacitor. Hearle[2] has measured the effect of yarn packing density using a conical shaped parallel plate capacitor.

3 Applications of Dielectric Properties in Textiles

The dielectric properties have been exploited in a variety of applications involving fibres, yarns and fabrics. Some applications are meant for quality checking, some for quality control, some for processing and some for functional performance. The major application areas where the dielectric properties have been used in various fields of textile technology are briefly described.

3.1 Moisture Content Measurement in Textiles

The significant influence of moisture on the dielectric properties of fibres, as discussed in section **2.3**, has led to the application of capacitance-based sensors for quantitative measurement of the moisture present in textiles. Moisture in textiles is measured in the contexts of measuring the moisture content of fibres, yarns and fabrics, and also for studying the moisture management capabilities of different yarns and fabrics.

The use of capacitance-based testers for measuring the moisture content of textile materials is a quite old concept. For example, Bailey and Phelps[24] have used a Burton-Pitt apparatus to measure the capacitance of cotton fibres, wool yarn, and rayon, cotton, linen and silk fabrics at various levels of moisture regain. They concluded that the use of capacitance method for the determination of moisture requires control of the factors like fibre, humidity, temperature, previous history, arrangement and distribution of samples in the electrode and ratio of air-to-fibre in the textile.

Spencer-Smith[12] has described a capacitance-based method for measuring the moisture contents of fabrics. According to him, if separation of the electrode plates is large in comparison with the fabric thickness, the increase in capacitance will be proportional to the weight of the fabric used. Thus, any fabric weight may be used and the increase in capacity can be obtained to calculate the increase in capacity of desired weight through normalization. The shape of the curve for the increase in capacitance against moisture content is also constant, so to use the curve for one weight of fabric to that for another, it is only necessary to multiply by the appropriate factor. He developed a measurement method by using a large parallel plate capacitor and calibrated the system with respect to the moisture content.

The method requires measurement of capacitance of a specified area of fabric between the parallel plates and the weight of the tested fabric. The measured capacitance is then translated into the expected increase in capacitance for a particular weight of the fabric. The moisture content could then be found from the calibrated graph of capacitance against moisture content. He tested various cellulosic materials including linen, cotton and rayon at various stages of their processing from grey stage to finished stage and found that all points were fitted well into one curve.

Peeters[13] described another interesting method by which the dielectric effect of moisture and dry fibre mass could be independently measured. He designed an instrument which measures the capacitance of the same material at a low (8.6 kHz) as well as high (10 MHz) frequencies. The output signals from the measuring capacitor plate at low (S_l) and high (S_h) frequencies were plotted against regain. The signals S_l and S_h depend on the packing densities of the moisture (P_M) and dry fibres (P_F). The dependence has been approximated by the following linear equations:

$$S_l = AP_M + BP_F \quad \ldots (1)$$

$$S_h = CP_M + DP_F \quad \ldots (2)$$

where A, B, C and D are the constants. The signal S_h is amplified by factors $k_1 = A/C$ and $k_2 = B/D$. The differential signal $S_F = S_l - k_1 S_h = K_F P_F$ (where, K_F is a constant) will be an indication for the quantity of dry fibres. The differential signal $S_M = S_l - k_2 S_h = K_M P_M$ will be an indication for the quantity of water. He also showed that his method gave better results than Zellweger Uster G.G.P. B23 and Fielden Walker WL 1C evenness testers under different regains.

Radio frequency sensors have also been used to measure the water content of textile fabrics. Cote *et al.*[34] have described such a method which they had used for measuring the moisture content of fabric in the infrared drying system. They found that the measured change in dielectric constant, because of wetting, is influenced by many other factors, such as the presence of ionic substances in the water, fabric construction and type of fibres.

3.2 Evenness Measurement in Textiles

The most popular use of capacitance measurement technique in textiles has been the measurement of evenness in terms of mass variation in a linear textile product such as yarn or roving or sliver. Many commercially successful instruments for this purpose have been developed over the course of time, such as Fielden-Walker and Uster. Capacitor type sensors have been used for the measurement of variation in fibre denier, mass regularity of slivers and roving and the mass variation and irregularities of yarns.

Descriptions of capacitance-based electronic instrument for measuring variation in mass of linear fibrous assembles have been reported by various authors including Boyd[32], Walker[16], Onions & Slater[33], Wegener[35]. Various patents are also available which describes capacitance-based methods for measuring mass irregularity of textile materials in linear form[17,36,37].

Boyd[32] described an instrument to measure the change in capacitance due to change in mass of yarn passing through a parallel plate capacitor which was energized with an AC signal of 10 MHz frequency. The DC voltage output of the testing instrument was linearly proportional to the change in capacitance of the measuring capacitor.

One of the most commercially successful instruments for capacitance-based measurement of mass variation in textiles, 'the Fielden-Walker evenness tester', has been described by Walker[16] in 1950. This instrument uses a bridge circuit with two oscillator valves to provide a frequency of 500 kHz modulated with an audio frequency of 500 Hz. The instrument had a set of four parallel plate capacitors each having similar dimensions, varying only in the magnitude of plate separation. Each capacitor had one guarded plate having length of 1 cm. The results were obtained in the form of spot deflection of the beam in a cathode ray oscilloscope which could be photographed in a sequence to give a picture depicting the mass variation in the material under test. Walker has shown that the results obtained by this instrument have good correlation with the results obtained by cut-and-weigh method. It was also shown that the error due to any fluctuation in ambient relative humidity during testing has negligible effect on the results, provided the samples have undergone proper conditioning. It was also pointed out that the overall thickness of cross-section of the material should not exceed 40% of the gap length selected in order to obtain a linear relationship between the net volume of material and the change in capacitance.

Various patents[17,36,37] are available which are filed by Uster, describing method and apparatus for the measurement of irregularity of textile products like yarns, rovings and slivers. Uster evenness tester has become a widely accepted standard testing instrument for the measurement of yarn irregularity and quality throughout the world.

Capacitance type measurement method can also be used for measuring the evenness of fabrics in terms of their thickness. Ray Chaudhuri[31] has described a method employing LC resonance circuit which can be used for this purpose.

3.3 Dielectric Heating of Textiles

Conventional heating methods for drying textiles may lead to baking, uneven drying and slow heating because of the heterogeneity, bulk and poor thermal conductivity of fibrous assemblies. Dielectric heating has the ability to generate heat uniformly throughout the mass of the textile substrate. The heating effect of dielectric energy occurs through the rapid oscillation of molecular dipoles of the dielectric material caused by the application of a high frequency voltage. It can be shown that the energy generated by dielectric heating is given by power density P (W/m^3) as shown below:

$$P = 2\pi f E^2 \varepsilon_0 \varepsilon_r \tan\delta$$

where f is the applied frequency in Hz; E, the voltage gradient across the material (in V/m); ε_0, the permittivity of free space; ε_r, the dielectric constant of the material; and $\tan\delta$, the loss tangent or dissipation factor of the material[38].

Both microwave heating and radio frequency heating are used, although in general microwave heating has found less use in the textile industry than its radio frequency counterpart owing to the matters of design and cost.

3.4 Sensor Type Applications in Textiles

Dielectric property has been used to detect the continuity of a textile strand for certain applications. Slater *et al.*[39] have reported their studies on a capacitive detection method of partial breaks in high speed winding.

Kurt[40] has invented an apparatus for detecting the presence of a running thread. The thread was passed through a capacitor which generates alternating signals due to the unevenness of the yarn. The signal disappears in case of a yarn break and the thread is stopped at that instant.

The liquid moisture transfer in textile materials is an important aspect for determining the comfort of the textile material objectively. The dynamic water transfer mechanism of fabrics and fibre assemblies has been studied using electronic methods. Change in capacitance of a capacitor plate system containing the fabric or fibre as a dielectric, while the water wicks through the fibres, has been used to measure the wicking process by Japanese researchers. Ito and Muraoka[18] have reported such device for measuring water transport through fibre bundles.

Mahlmann *et al.*[41] have described a dielectric measuring method for the determination of evenness and mixing quality of blended nonwovens. They have used parallel plate condensers with the nonwoven passing through the space between the plates. They calibrated the system with a frequency sweep and from the difference of the capacitance profiles between 1 kHz and 1000 kHz to differentiate the different materials.

4 Conclusions

Capacitance type measurement techniques provide accurate and sensitive tools to measure many important properties of textile materials. Dielectric properties determine the level of static generation in textiles. Therefore, understanding the dielectric properties of textile materials is important from the point of view of processing and quality checking and control. The successful use of capacitance-based sensors for moisture and mass variation measurement has made understanding of the dielectric behavior of textiles even more important.

Dielectric properties of textile fibres have been studied for a long time by many researchers. However, because of the complexities involved in manipulating samples of textile materials in their original shape, the inherent lack of homogeneity of the fibres and the porous nature of the textile substrate, exact values of dielectric parameters are still not found conclusively. No model so far has been able to successfully describe the behavior of textile materials as dielectrics.

With the development of new materials based on textile substrates such as composites and with the new applications such as fabrics for EMI shielding and textile antenna, the knowledge of the dielectric properties of these materials has become indispensable. New measurement techniques need to be developed for textile materials, new standards may also have to be established and new models may have to be explored for this purpose. For example, the Time Domain Reflectometry (TDR) method can be explored to measure dielectric properties of textile materials. New fixtures and calibration techniques are required to be developed and standardized also. With better understanding of the subject and with improved state-of-the-art measuring techniques, new applications of textile materials based on their dielectric properties and new technologies to improve characterization, process control and quality control using the dielectric behavior of textile materials can be developed.

References

1 Balls W L, *Nature*, 158 (1946) 9.
2 Hearle J W S, *Text Res J*, 24 (4) (1954) 307.
3 Kirkwood C E, Kendrick N S (Jr) & Brown H M, *Text Res J*, 24 (9) (1954) 841.
4 Ishida Y, Yoshita M, Takayanagi M & Irie F, *J Appl Poyml Sci*, 1 (2) (1959) 227.
5 King G, *Trans Faraday Soc*, 43 (1947) 601.
6 Algie J E, *Text Res J*, 34 (6) (1964a) 477.
7 Shaw T M & Windle J J, *J Appl Phys*, 21 (1950) 956.
8 Kumar A & Smith D G, *IEEE Trans Instrum Meas*, IM-26 (2) (1977) 95.
9 Chand N, *Investigations on the Structure of Polymers and Fibres through Dielectric Relaxations*, Ph D thesis, Indian Institute of Technology, Delhi, 1979.
10 McCrum N G, Read B E & Williams G, *Anelastic and Dielectric Effects in Polymeric Solids* (John Wiley & Sons, London), 1967.
11 Morton W E & Hearle J W S, *Physical Properties of Textile Fibres*, 3rd edn (Textile Institute, Manchester, U.K.), 1993.
12 Spencer-Smith J L, *J Text Inst*, 26 (1935) T336.
13 Peters M, *Text Res J*, 39 (12) (1969) 1081.
14 Lochar H, *CA 725806* (to Zellweger Uster AG), 1966.
15 Ott P & Schmid P, *Eur Pat 1893996* (to Uster Technologies AG), 2008.
16 Walker P H, *J Text Inst*, 41 (1950) P446.
17 Feller P, *US Pat 4051722* (to Zellweger Ltd.), 1977.
18 Ito H & Muraoka Y, *Text Res J*, 63 (7) (1993) 414.
19 David D J & Mishra A, *Relating Material Properties to Structure: Handbook and Software for Polymer Calculations and Materials Properties* (CRC Press), 1999.
20 Bunget I & Popescu M, *Physics of Solid Dielectrics* (Elsevier Science Publishers, The Netherlands), 1984.
21 Pionteck J & Wypych G, *Handbook of Antistatics* (ChemTec Publishing), 2006.
22 Riande E & Diaz-Calleja R, *Electrical Properties of Polymers* (Marcel Dekker Inc., New York, U.S.A.), 2004.
23 Utracki L A, *Polymer Blends Handbook* (Springer Publishing Company, New York, U.S.A.), 2002.
24 Bailey B & Phelps E L, *Text Res J*, 9 (3) (1939) 101.
25 Hearle J W S, *J Text Inst*, 44 (4) (1953) T117.
26 Mack C, *J Text Inst*, 46 (1955) T500.
27 Windle J J & Shaw T M, *Text Res J*, 25 (10) (1955) 865.
28 Kumar A, *J Text Inst*, 69 (4) (1978) 116.
29 Cerovic D D, Dojcilovic J R, Asanovic K A, Mihajlidi T A, Popovic D M & Spasovic S B, *Investigation of Dielectric Properties and Electric Resistance of Some Textile Materials*, Applied Physics Poster Presentation in Fifth General Conference of the Balkan Physical Union, Vrnjacka Banja, Serbia and Montenegro, August 2003.
30 Asanovic K A, Mihajlidi T A, Milosavljevic S V, Cerovic D D & Dojcilovic J R, *J Electrostatics*, 65 (3) (2007) 162.
31 Ray Chaudhuri B, *Man-Made Text India*, Oct (2001) 388.
32 Boyd G N, *J Text Inst*, 40 (1949) T407.
33 Onions W J & Slater K, *J Text Inst*, 58 (1967) 210.
34 Cote B, Forget C, Therien N & Broadbent A D, *Text Res J*, 61 (12) (1991) 724.
35 Wegener E h W & Vogt H J, *Text Praxis*, 2 (1972) 161.
36 Furter R, *GB 2192722* (to Zellweger Uster AG), 1988.
37 Ott P & Schmid P, *US Pat 2008111563* (to Uster Technologies AG), 2008.
38 Burkinshaw S M, *Colourage Annual*, (1986) 83.
39 Slater K, Hoffmeyer F & Hood D A, *J Text Inst*, 3 (1982) 130.
40 Kurt A, *US Pat 4311958* (to Zellweger Uster AG), 1982.
41 Mahlmann I, Zobel S, Hudy S & Gries T, *Technical Text*, 3 (2007) E 191.