CAPACITIVE INTERDIGITATED ELECTRODES SENSOR FOR THE FIELD DEVICE TO MEASURE MOISTURE CONTENT IN THE NITRILE GLOVES MANUFACTURING INDUSTRY

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ABSTRACT

This paper investigates the impedance spectroscopy technique in determining moisture content in Nitrile gloves. Interdigitated electrode was designed and fabricated, then evaluated on LCR Impedance meter subjected to frequency range of 100Hz, 120Hz, 1kHz, 10kHz, 20kHz and 100kHz. Samples of Nitrile gloves were compounded and prepared for different moisture content level and regression analysis was performed to evaluate the relationships between capacitance and moisture content of the glove samples. Experimental results indicated that the capacitance value is a strong function of moisture content in gloves and also that the capacitance of moisture content in Nitrile gloves decreased with increasing drying time over the measured frequency range whilst statistical analysis results have confirmed that the 1kHz, 10kHz and 20kHz signal frequencies have highest reliable prediction of the nitrile gloves' moisture content with high R^2 value of 0.96, 0.97 and 0.97, respectively. The ability to determine average moisture content of Nitrile gloves via a non-destructive and online method, utilizing a low-cost instrument, will be of considerable use in the glove industry. This method could also be extended to other types of gloves and rubber products.

Keywords: Interdigitated electrode sensor (IDE), Capacitive sensor, Field Device, Industry 4.0, Moisture content, Nitrile Glove

1.0 INTRODUCTION

Nitrile rubber also named as Acrylonitrile Butadiene rubber or Nitrile Butadiene Rubber (NBR)(Yew *et al.*, 2019), a copolymer of butadiene and acrylonitrile, has many advantages such as low cost, low allergic risk, good chemical resistivity, low gas permeability, excellent penetration resistance, good dexterity and has static dissipation behaviour (Yew *et al.*, 2019). Therefore, gloves are widely used in many applications, for instance, medical, industrial, laboratory, pharmaceutical, food preparation and processing (Critchley & Pemberton, 2020), (Yew *et al.*, 2019). Vulcanisation is a vital process in producing quality gloves. Vulcanisation explains the curing process of the raw (unvulcanised rubber) material mixed or compounded with curatives, antioxidants, and stabilisers to form the dry (vulcanised) rubber at high temperatures between 140°C and 160°C in the curing ovens (Adam *et al.*, 2020) (Yip *et al.*, 2002).

The common manufacturing of nitrile gloves via dipping process consists of the following steps (Yip *et al.*, 2002) (Yew *et al.*, 2019). First, the latex is compounded with a crosslinker, accelerator, initiator, antioxidants, stabilisers, pigments and additives depending on the product requirement and applications by customers. Second, porcelain mould, commonly known as 'formers', are cleaned and dried before being dipped in coagulant nitrate solutions. After drying the coagulant on the former's surface, they dip the formers into the compounded latex at an ambient temperature. Next, the beading of gloves takes place. This process is to ease gripping of the glove during stripping section. Later, the wet latex films are dipped in a hot water bath called leaching process. This process is to remove chemical particles and materials on latex films. Then, the gloves enter the curing Oven at a high temperature of 70°C to 150°C. The curing or drying of a glove is a critical process for the vulcanisation of latex to take place to prevent defects like blisters or porous forming on the latex film (Chambers, 2017). The cured gloves are further dried in leaching ovens to remove excess moisture and chemical particles from the latex films. Figure 1 below shows the common manufacturing process for nitrile gloves. There are post-treatment methods in certain manufacturing process such as chlorination, polymer coating, and hydrogel coatings which can be referred to here (Yew *et al.*, 2019).

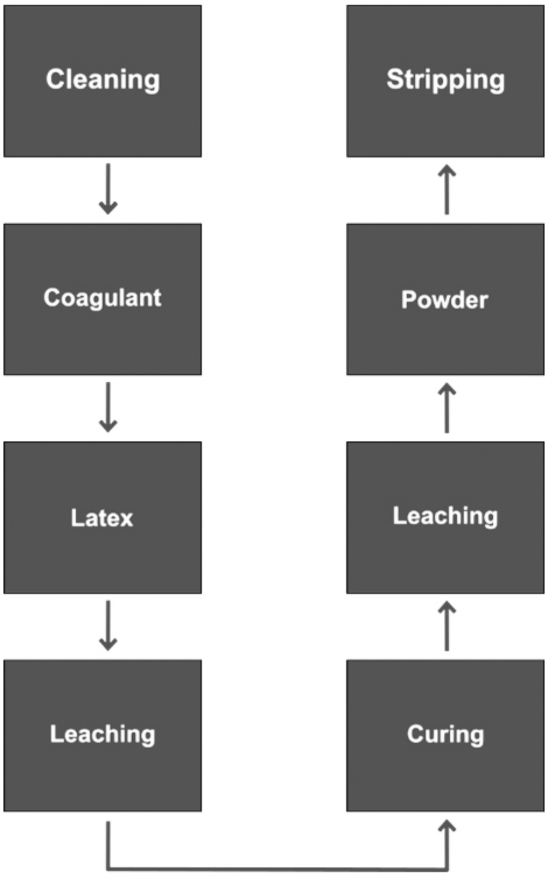

Figure 1: Common Manufacturing process of Nitrile gloves

Moisture content is an essential parameter for quality assessment of latex gloves in the industry; due to its relevance in raw material assessment, mechanical strength and finished product quality as well as in terms of commercial value. Although faster analyser-based techniques are available, the glove industry has traditionally relied on standard inspection method of ASTM D5668 – 19 or familiarly known as the oven drying from monitoring processes up to the release of end product. This is offline, destructive, time-consuming and usually limited to analysing few samples during the process. Furthermore, sampling and preparation can lead to significant analytical errors. Not only in glove making processes but also rubber latex cultivation find moisture content (MC) analysis critical since it greatly affects quality, stability and processing of latex. In the past decades several multiple methods and technologies have been developed to measure MC in rubber latex more rapidly, non-destructively and precisely For instance, infrared, microwave, X-ray, radar, conductive and capacitive.

Near infrared technique uses reflectance and absorbance principles to calculate the moisture content (Puttipipatkajorn & Puttipipatkajorn, 2020; Suchat *et al.*, 2015). The water absorbs certain wavelengths of light in the NIR region. The higher the moisture content, the higher the amount of light absorbed. The filtered beam is directed onto the surface of the sample. A portion of the light is reflected to a detector. Moisture content can be calculated form the amplitude ratio of the reflected wavelengths of the sample beam and the reference beam. Recent studies involving NIR region have shown NIR is a suitable method for quantifying trace amounts of moisture in a rubber sheet due to the strong combination of absorption bands for water at around 1940nm and the first, second and third overtones at 1450nm, 970 and 760nm, respectively. In another method, a calibration models such as Partial Least Square Regression (PLSR), Least Square support and ANN using NIR is constructed to predict the moisture content in a rubber sheet in the wavelength range 900-1700nm. NIR spectroscopy is a fast and non-destructive analytical method. Infrared method can only measure the moisture content of thin films or layers of material, paper, and other thin materials since this non-contact method detects only the material's surface moisture. Therefore, effects of bulk material's particle size, particle shape, particle surface characteristics, and colour may cause high errors in measurement.

Microwave method (Yahaya *et al.*, 2014, 2015) transmits microwaves at a material and then calculates the energy losses emitted from the material and speed variation due to microwave propagation from the material to the moisture content. This technique is based on transmission. An emitter and a receiver are mounted opposite of each other in the process, so they can shine through the material. For this reason, the measuring setup of this method depends on the space between emitter and receiver. Microwave radiation, (frequencies between 1 GHz and 100GHz), has advantages like penetration depth is much larger than that of infrared radiation and permits the sensing of a significant volume of material being transported on a conveyor or in a pipe. Also, water reacts specifically with certain frequencies in the microwave region allowing small amounts of water to be detected. Yahaya and co-workers have conducted studies on the dielectric constant property from the measured reflection coefficient as a function of moisture content at 1 GHz to determine moisture content in rubber latex using Agilent Open Ended Coaxial probe. The lowest mean relative error between actual and predicted moisture contents was 0.02 at 1 GHz when using the Cole-Cole dielectric constant calibration equation. This aforementioned method is an offline, contact method and also, used to measure moisture content of latex in liquid form in the laboratory. Microwave radiation are not convenient to determine the moisture contents of a large number of contact points in gloves. In addition, the equipment of each method is expensive.

X-ray method (Chen *et al.*, 2011) measures the moisture content in material with irradiation of X-ray beams into the material. This method estimates the speed losses of the beam after they pass through the material's water molecules. Synchrotron small-angle X-ray scattering technique was employed to investigate the drying dynamic of latex dispersion. The results obtained were beneficial in understanding the mechanism of latex film formation especially providing clear insights into the effects of temperatures and relative humidity on the evaporation of water after the deformation of latex particles. This method is extremely expensive and not frequently applied in manufacturing process like other methods. Contrary to X-ray method, radar is an advanced technology based on the propagation velocity (PV) of ground penetrating radar (GPR) signals. Radar monitors material's moisture content with the measurement of the travel time through the sample and early time amplitude of the radar signal. The moisture content of testing material with infinite media often cannot be measured by this method. The testing material size effects on accuracy of the measurement. GPR technology is increasingly being used by researchers to determine moisture content including, but not limited to building material, surface soil and log (Hans *et al.*, 2015; Huisman *et al.*, 2003; Klewe *et al.*, 2021). However, to my knowledge, there have been no literature reports investigating moisture content in gloves or rubber latex using radar technology.

To measure electrical properties of products that are resistance or capacitance, correlating to moisture content is an alternative method widely used in the manufacturing industry. A resistance method (Kueseng *et al.*, 2013; Naphon *et al.*, 2020) uses two electrodes inserted directly into the rubber compound to measure its resistivity. As moisture increases, the rubber compound's electrical resistance decreases. The resistance could vary between several hundred kΩ when wet as opposed to several thousand MΩ and more when dry. In a study conducted to determine the effect of wetting intensity on electrical surface resistance in silicone rubber, it can be observed that in dry conditions the surface resistance of the rubber has a large value of 1085 MΩ. In comparison to wet conditions, the resistance decreases to a low value of 253.99 MΩ. Clearly, the higher the wetting intensity, the lower the surface resistance of rubber.

Capacitive sensing provides better advantages such as measurements can be implemented online, simple, low cost and rapid (Bhuiyan *et al.*, 2015; Döring *et al.*, 2019; Khaled *et al.*, 2015). Online and real-time measurement is important, especially where one must not turn off the machine and collect samples to test the MC. Hence, capacitance can be applicable in the production line for continuous monitoring of MC. Recent studies have established several online capacitive methods of measuring moisture which can have either non-contact or contact measurement depending on its application. One of such is measuring MC of a moving stream of spray-dried gelatin powder (Wang *et al.*, 2017). A non-contact capacitance sensing system encompassing test capacitors, signal processing and data acquisition device was applied in MC determination on spray-dried gelatin with different water content (4 – 44% MC). The copper plate electrodes of test capacitors generate an electric field within the measuring cylinder. The strength of capacitance was related to the permittivity of the material between the electrodes. Each electrode was connected to a capacitance-to-voltage transducer so that the output signal could be collected using a data acquisition device. The application of a 4-electrode system and dual-frequency sensing system has improved the accuracy ($R^2 = 0.9$) and reliability of the online MC measuring system. However, the measurement or sampling rate needs to exceed the minimum sampling requirement of data acquisition device.

Besides that, the contact capacitive measurement method utilising interdigital electrode (IDE) sensor has gained increasing attention the last decades due its simplicity and low cost. The technique is suitable to evaluate MC in wood, wood chip and wood pellets (Chetpattananondh *et al.*, 2017) because of the high relative permittivity of water ($\varepsilon_r \approx 80$). The variation of the material permittivity due to the change of MC can be measured as a value of capacitance when the test material is placed between two electrodes. In other words, the fringing capacitance measured between the electrode varies with the dielectric constant, which varies with the MC in material. Therefore, measurement of the capacitive values for the material's moisture properly can be operated. The experimental results indicate IDE sensor has good repeatability and linearity. Also, the sensor offers great benefits in being cost effective, easy to use and portable with rapid measurement and non-destructive. To date, there is no literature reports investigating the application of IDE sensor in determining glove's moisture content.

2.0 DETERMINATION OF MOISTURE CONTENT IN NITRILE RUBBERS

Nitrile rubbers are categorized as polar rubber just like other polymers including acrylic rubbers, hydrogenated nitrile rubber and ethylene-acrylate terpolymers. By the term "polar rubber," it is meant that the rubber contains atoms other than hydrogen or carbon such as nitrogen or oxygen as in nitrile rubber, acrylic rubber, or copolymers of acrylic rubber. The nitrile rubbers are combined polymers of acrylonitrile with a conjugated diene having anywhere from 4 to 8 carbon atoms, with butadiene being highly preferred (Patel *et al.*, 1996). Polymers such as nitrile rubbers are widely used as dielectric materials due to their high flexibility, tractable processing as well as good chemical stability and readily tunable properties. Their dielectric constant is lower than non-polymeric materials.

Dielectric constant relates to the permittivity ε, of the material. The permittivity explains the ability of a material to polarize in response to an applied field. In other words, greater the polarization developed by a material in an applied field of given strength, the greater the dielectric constant will be. The mechanism which contributes to the dielectric properties are the interaction of electric field with electronic, atomic and dipole polarization. The relation between permittivity of the dielectric material with polarizability is $\varepsilon_r = 1 + \frac{N_a \alpha}{\varepsilon_0}$,where ε_r is the relative permittivity, ε_0 is the permittivity in vacuum, α is polarizability and N_a is the Avogadro constant.

Polarizability refers to the proportionality constant for the formation of dipole under the influence of electric field. The polarizability depends on applied field frequency, it has a strong frequency dependence, besides the conductivity and permittivity, because it is a complex function (Ahmad, 2012; Kosumphan *et al.*, 2018). The dielectric properties of most materials depend on many factors, including frequency of the applied alternating electric field, chemical composition and structure of the material, and especially permanent dipole moments associated with water and any other molecules making up the material of interest (Wang *et al.*, 2017). Multiple studies to explain the polarizability and the orientational effects of acrylonitrile–butadiene rubber (NBR) was done by observing changes in these electrical properties (Kueseng *et al.*, 2013; Zhao *et al.*, 2015; Zhu and Zhang, 2017).

For example, studies on changes of electrical properties were introduced and some sort of instruments were recommended to be used in the food industry (Mohamad *et al.*, 2015; Sairin *et al.*, 2019). Parallel plate electrodes are one of the generally used probes to sense the moisture content in peanut oil (Butts, 2008). Another example is by measuring capacitance using a pair of copper electrodes in spray dried products for a non-contact measurement (Wang *et al.*, 2017). Apart from this, Son's findings suggest that the electrical resistivity could be used as an effective alternative for estimating the weathering degree of soil (Son *et al.*, 2010).

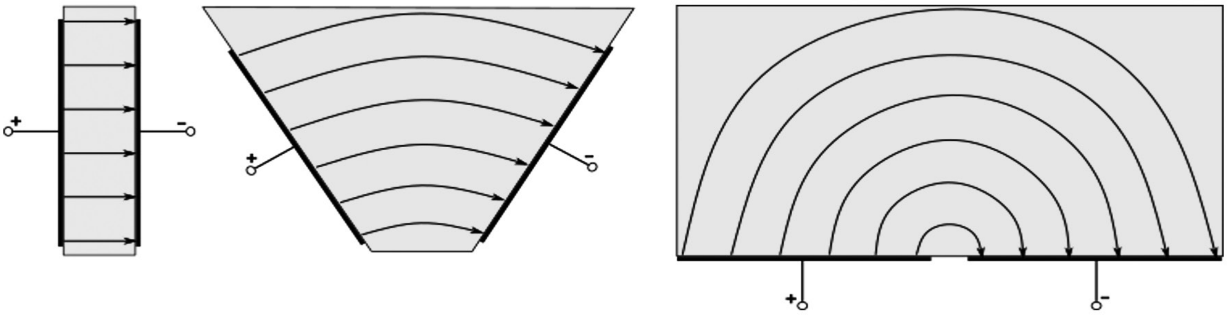

Figure 2: Transition from the parallel-plate capacitor to a planar capacitor

The capacitive interdigitated electrodes (IDE) sensor is a coplanar structure encompassing of multiple interpenetrating comb electrodes. The working principle of the interdigital coplanar capacitive sensor is similar to the two parallel plate capacitors. The parallel plate capacitor is transformed to the interdigital capacitive sensor as shown in Figure 2. When both electrodes are excited by the different voltages to generate fringing electric fields between electrodes, these electric fields then travel from positive electrode to negative electrode while passing through the material in contact with the electrodes. Thus, the material's dielectric properties affect the impedance of electric fields between these electrodes. The sensor behaves as a capacitor in which the capacitive reactance becomes a function of material properties. The fringing capacitance measured between the electrode varies with the dielectric constants, which varies with the moisture contents in material (Afsarimanesh *et al.*, 2019). Therefore, measurement of the capacitive values for the material property measurement can be operated.

As a result of the high sensitivity and simplicity of the sensor, the interdigital capacitive sensor is widely used in different applications such as biosensor for bacterial detection(Varshney & Li, 2009) soil moisture (Markevicius *et al.*, 2012), lard detection (Mohamad *et al.*, 2015), rubberwood (P. Chetpattananondh *et al.*, 2017), concrete moisture (Alam *et al.*, 2010), humidity (Rivadeneyra *et al.*, 2014), and water level measurement (K. Chetpattananondh *et al.*, 2014). Interdigitated electrodes (IDEs) sensor is also effectively being implemented in sensing devices such as, but not limited to, piezoresistive sensors, chemical sensors, environmental monitoring sensors and MEMS biosensors (Ferrari & Prudenziati, 2012). IDE is also used to study oil degradation in determining frying oil quality (Khaled *et al.*, 2015). Bioimpedance measurement utilizing IDE is a well-established method for the detection and characterization of cancerous cells (Alexander *et al.*, 2010). Therefore, IDE sensors could be used in solving complex calibration requirements and improving the accuracy of sensory sensitivity. IDE shape configurations have some advantages such as non-moving parts, ease of fabrication, are flexible in design as well as cost-effectiveness (Bhuiyan *et al.*, 2015; Döring *et al.*, 2019).

Therefore, IDE could be used in solving complex calibration requirements and improving the accuracy of sensory sensitivity. IDE shape configurations have some advantages such as non-moving parts, ease of fabrication, are flexible in design as well as cost effective (Döring *et al.*, 2019; Bhuiyan *et al.*, 2015). The purpose of this research is to develop a new sensor to determine the moisture content of nitrile gloves by measuring the changes occurring in capacitance during the curing process of gloves. To achieve this, a capacitive sensor was designed by integrating IDE platform to assess different moisture content in gloves at varying frequency.

3.0 MATERIALS AND METHODS

3.1 Capacitive Sensor Design

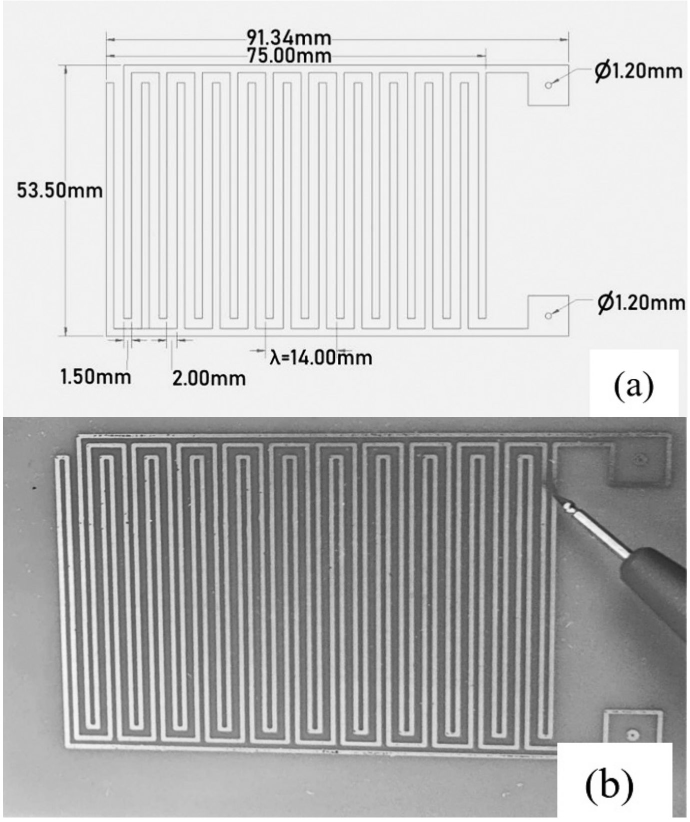

Figure 3: (a) Low-cost IDE sensor drawing in Solidworks
(b) IDE sensor with 22 number of electrodes

The capacitive sensor was designed based on the interdigitated electrodes (IDE) as shown in Figure 3. The sensor was drawn using Solidworks software and then fabricated using conventional photolithography and etching process. The aforementioned fabrication process is adapted from previous research conducted by Zoolfakar and his team (Zoolfakar *et al.*, 2010). This IDE sensor is fabricated with copper electrodes and fiberglass as printed circuit board (PCB) substrate. This sensor gives high sensitivity due to the strong effect on signal area in the numbers of electrode pairs which produces uniform electrical field distribution and measurable output signal (Chetpattananondh *et al.*, 2017). The capacitance of the sensor is varied with dielectric constant of material due to change of the moisture content. Neglecting edge effects, the sensor capacitance C can be computed from the capacitance per unit length C_{uc} of a 2D cell formed by an electrode pair yielding equation (1) (Ferrari and Prudenziati, 2012).

$$C = C_{uc}(N-1)L\,, \tag{1}$$

where N and L are the number and length, measured by mm, of the finger electrodes, respectively. The capacitance per unit cell C_{uc} of electrode pair attached with the material is given by equation (2) (Alam *et al.*, 2010).

$$C_{uc} = \varepsilon_0 \frac{\varepsilon_g + \varepsilon_s}{2} \times \frac{K\sqrt{1-(\frac{a}{b})^2}}{K\left(\frac{a}{b}\right)} + \varepsilon_0 \frac{\varepsilon_g h}{a}\,, \tag{2}$$

where ε_0 is the dielectric constant in free space, $\varepsilon_0 = 8.8542 \times 10^{-12} F/m$, ε_g and ε_s are the dielectric constants of moisture content and the substrate, respectively. Also *a, b* and *h* are the finger spacing width, distance (pitch) and thickness, respectively. K[x] is the complete elliptic integral of the first kind given by equation (3) (Abramowitz *et al.*,1965).

$$K[x] = \int_0^{\pi/2} \frac{1}{\sqrt{1-x^2 sin^2\theta}} d\theta \tag{3}$$

Figure 4 shows a unit cell of an interdigitated sensor without the conducting plane. The variables of the sensor are the number of the electrodes N, width of the electrode w, electrode space s, and the length of the electrode L, with dimension of 22, 1.5mm, 2mm and 75mm, respectively. Every other electrode finger is connected electrically together through a common electrode arm. The variables were suggested by the pioneer work on MC determination (Chetpattananondh *et al.*, 2017). The overall capacitance C between the electrode pair is varied because of variation in the electrode pair attached to the dielectric medium of material. Thus, the moisture content measurement in NBR glove can be determined in term of the varied capacitance of the electrode pair attached on the sample.

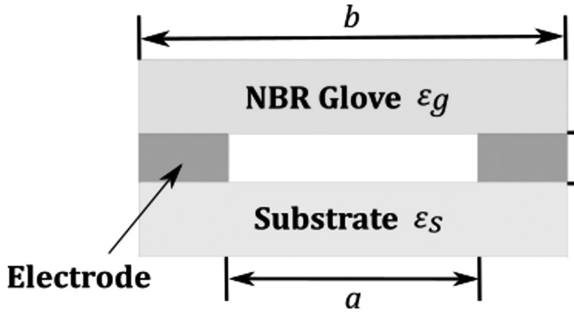

Figure 4: Unit cell of an interdigitated sensor without the conducting plane

3.2 Sample Preparation

Nitrile Butadiene Rubber (NBR) latex is compounded at the chemical lab to prepare a 14% TSC (Total Solid Content) latex. Potassium Hydroxide, pH Adjuster, Accelerator, Metal Oxide Crosslinker, Wetting agent, Surfactant, Opacifier, Antifoam, and water are added during the compounding process. The chemical formulation for preparing 14% TSC Nitrile glove is not disclosed because it is Top Glove's proprietary formula. The compounded sample is stirred at 300rpm for 24 hours for the maturation process to take place.

To prepare sample, a ceramic former mold is used for dipping process throughout this study. The ceramic former is first cleaned at the beginning of the experiment. The ceramic former and coagulant solution are heated to a temperature of 65°C using an immersion heater, this enables the coagulant to coat the former evenly which helps in picking up latex and controlling the thickness of latex film. The ceramic plate is then dipped for 10 seconds in the coagulant solution, which has 8.0 - 9.0% ± 0.5% of Calcium Nitrate. After dipping in the coagulant solution, the former is heated in an oven at 120°C for 5 minutes. Next, the hot former is placed in a desiccator to cool down until temperature drops to 60°C - 65°C. This is then dipped into the latex compound for 8 seconds. Now a wet gel-like film will form over the ceramic former. The ceramic former is withdrawn and is dried in the oven for curing of latex. The curing time of the sample ranges from 1 to 20 minutes, where one sample was removed from the oven every 1 minutes. After curing, all glove samples were kept in petri dish for further analyses.

3.3 Electrical Capacitance and Moisture Content Measurement

The distinction among each glove sample was analyzed by measuring its electrical capacitance and moisture content (MC). The capacitance was measured using the custom built IDE sensor pressed onto the glove sample. The sensor was connected to a LCR meter (4263B, Agilent, Malaysia) with Kelvin clip leads (TH26011AS, Changzhou Tonghui Electronic Co. Ltd, China) as depicted in Figure 5. The LCR meter has a frequency range from 100Hz and 100kHz (Afsarimanesh *et al.,* 2019).

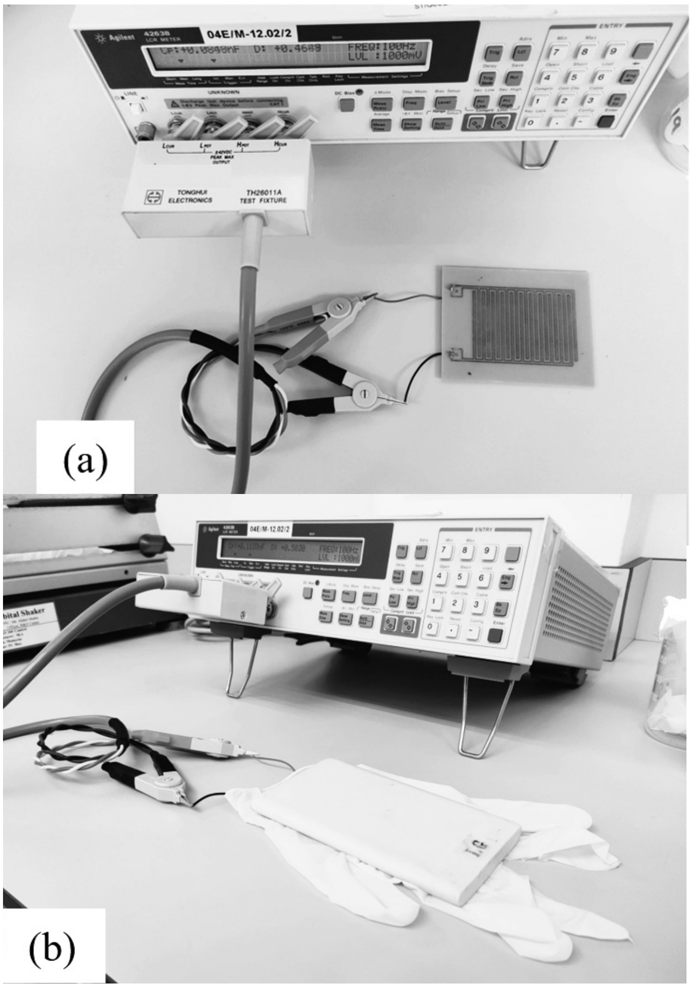

Figure 5: (a) The 4263B Agilent LCR meter connected to interdigitated electrode via TH26011AS Kelvin clip leads (b) Glove is positioned on sensor

Before starting the measurements using the LCR meter, calibration was performed following the standard procedure of the instrument operation manual. Glove samples is pressed on interdigitated electrode with heavy ceramic plate to make sure close contact of sample to sensor. The ceramic plate used is flat and with good surface finish which does not affect the glove's physical properties such as thickness. Then the MC of each dried sample was measured using a Moisture Analyzer (MB120, OHAUS, China). Glove moisture content can be determined by gravimetric method as shown in equation (4).

$$\%MC = \frac{m_w - m_0}{m_0} \times 100 \tag{4}$$

where m_w is mass of wet glove and m_0 is mass of dried glove. Calibration or adjustment of the Moisture Analyzer is not necessary for a correct moisture determination as the measurement is relative. The balance determines the weight of the sample before and after drying and the moisture is calculated on the basis of the ratio between wet and dry weights. After each testing, the IDE sensor and pan in the Moisture Analyzer was cleaned by soft tissues. Each sample is measured thrice for each curing time ranging from 1 to 20 minutes. The experiment is repeated thrice.

3.4 Statistical Analysis

Regression analysis was performed to evaluate the relationship between electrical capacitance with moisture content of the glove samples. The regression equations were evaluated by the coefficient of determination (R^2) and the root mean square error (RMSE) calculated by equation (5) (Chetpattananondh *et al.*, 2017).

$$RMSE = \sqrt{\frac{1}{N_s}\sum_{n-1}^{N}(Y_t - Y_e)^2} \tag{5}$$

where N_s is the number of samples in the dataset, Y_t is the predicted value calculated using the regression equation and Y_e is the measurement obtained through experimental procedures.

4.0 RESULTS AND DISCUSSION

This study is aimed to design a new sensor to measure moisture in Nitrile gloves. The glove's moisture can be quantified with impedance spectroscopy technique using IDE capacitance method. The capacitance measurements were analyzed to evaluate the determination for gloves moisture content. Overall, the capacitance of glove decreased as the heating time increased. For example, as the heating time progressed from 1 to 8 minutes, a rapid drop in capacitance was observed (16.84μF to 62.73pF) at a frequency of 1kHz, along with a decrement of MC values from 50.10% to 2.40% (Figure 6). The capacitance measured by the IDE sensor exhibits good correlation to MC measured using moisture analyzer. Figure 7 shows the regression of capacitance measurements with MC values of gloves at 20kHz during different drying time. This result shows that the electrical capacitance has significant positive correlation with MC. Table 1 shows that the highest correlation between electrical capacitance and MC was computed at 20kHz having R^2 of 0.969 and this was validated using a set validation data and the lowest regression equation RMSE of 2.78 is found at 20kHz. Figure 8 shows the capacitive property of NBR glove with different drying times in a wide range of frequencies. In the high moisture region (between 30 to 60%) lower frequencies exhibited high electrical capacitance and this electrical capacitance sharply decreased as drying time increased. Our findings indicate that Nitrile glove's capacitance is a potential parameter to determine its moisture content. Further large-scale studies are required to calibrate the IDE sensor and accurately predict gloves moisture for online detection method.

Table 1: RMSE of the regression equation and correlation coefficient applied to predict moisture content using electrical capacitance

Frequency	Equation	R^2	RMSE
100 Hz	y = 7.7238x - 14.534	0.944	3.72
120Hz	y = 7.7541x - 14.466	0.945	3.67
1kHz	y = 8.7121x - 14.204	0.960	3.15
10kHz	y = 11.677x - 18.306	0.966	2.91
20kHz	y = 13.449x - 21.105	0.969	2.78
100kHz	y = -0.0022x + 6.9791	0.384	12.30

Consistent with our present findings, Wang *et al.* (2017) also reported that materials with high moisture exhibits greater capacitance due to high dielectric constant of water (ε_r = 80). NBR at 100Hz have a dielectric constant of 10 or more at room temperature (Matsuno *et al.*, 2021). During drying process, water diffuses and dries off from glove surface, causing drastic drop in gloves dielectric constant. Capacitance is related to dielectric constant using the definition $C = \frac{\varepsilon_0 \varepsilon_r A}{d}$ resulting in the rapid drop in capacitance as heating time increases. Hence, this further reinforces the notion that Nitrile glove's capacitance decreases sharply as the moisture content decreased. This finding is also consistent with Butts's where he found capacitance measurement using impedance technique has 87 to 100% predictability having 8 to 21% MC values (Butts, 2008).

It is proven by Zhu *et al.* (2018) and Yang *et al.* (2019), where the permanent dipoles in the NBR attributed to the CN groups orientation polarization was the reason for the large dielectric constant in lower frequencies. Their findings support our study, where at lower frequencies within the same MC level, the electrical capacitance was relatively larger than higher frequencies (Figure 8). The electrical capacitance is proportional to relative dielectric constant as shown in equation 2. The decreased capacitance is attributed to the dipole polarization of CN groups that could not keep up with the increase in frequency. The CN orientation polarization response is slower resulting in more time to reach field of static equilibrium with electronic and atomic polarization. Hence it can be stated that as frequency increases, the electrical capacitance of Nitrile gloves decreases as a result of the lag of CN group orientation polarization in NBR.

Negative electrical capacitance is expected at higher frequencies. The series LC circuit of IDE sensor connection with clip leads of LCR meter behaves such that it measures capacitor at low frequencies and as an inductor at high frequencies. Plonus (2020, p.92) states that at high frequencies the series circuit is inductive as: Inductive Reactance, X_L > Capacitive Reactance, X_C. When the clip leads are connected to a capacitor at a frequency above its series resonance, the capacitor will appear inductive resulting in a negative value in the LCR meter. Reason is that a capacitor at a frequency above its series resonance is an inductor, hence the voltage leads the current. It is important to note in theory, current leads voltage in a (positive) capacitor whereas in a negative capacitor, voltage leads current. Therefore, if the LCR meter is set up to measure the capacitance in a component, where the voltage leads the current, the meter will read a negative number. (Halpin and Card, 2011; Plonus, 2020).

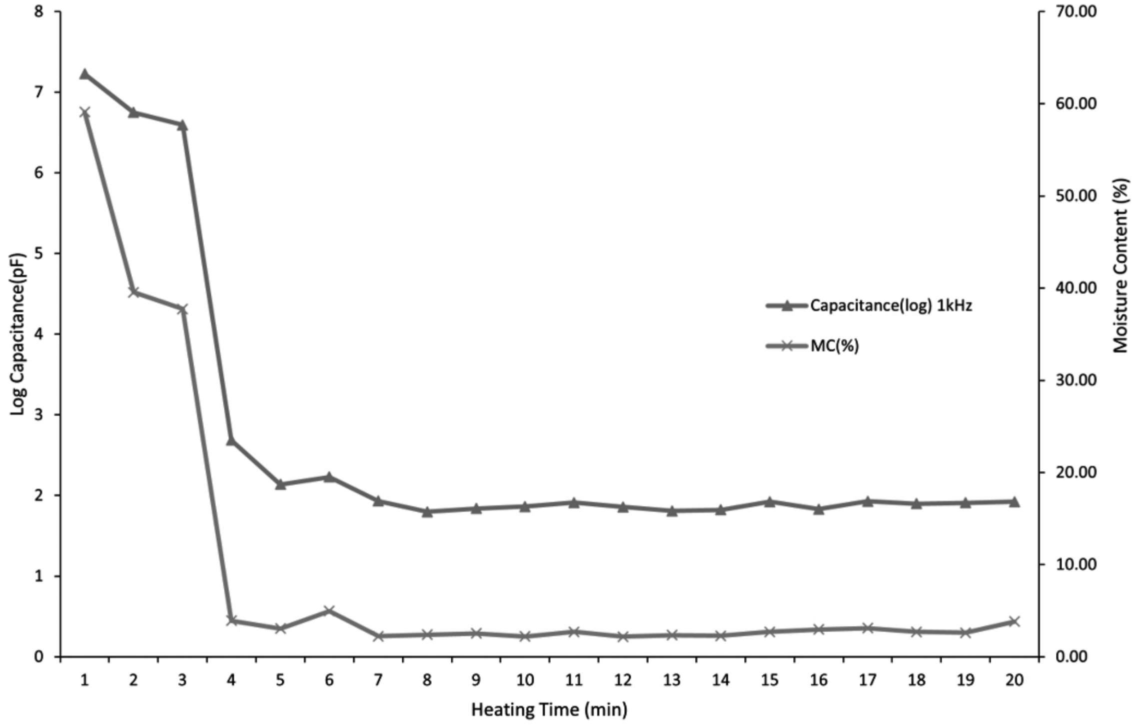

Figure 6: The capacitance and MC measurements at 1 kHz

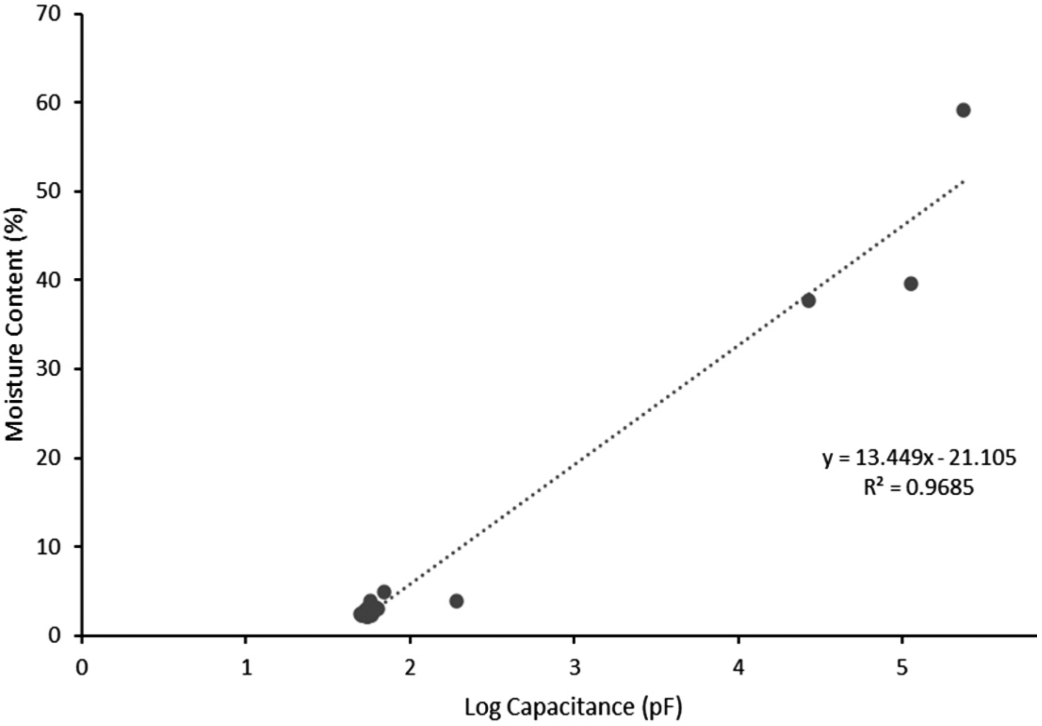

Figure 7: Regression of Capacitance measurements with MC values of gloves at 20 kHz from 1 to 20 minutes during the drying process

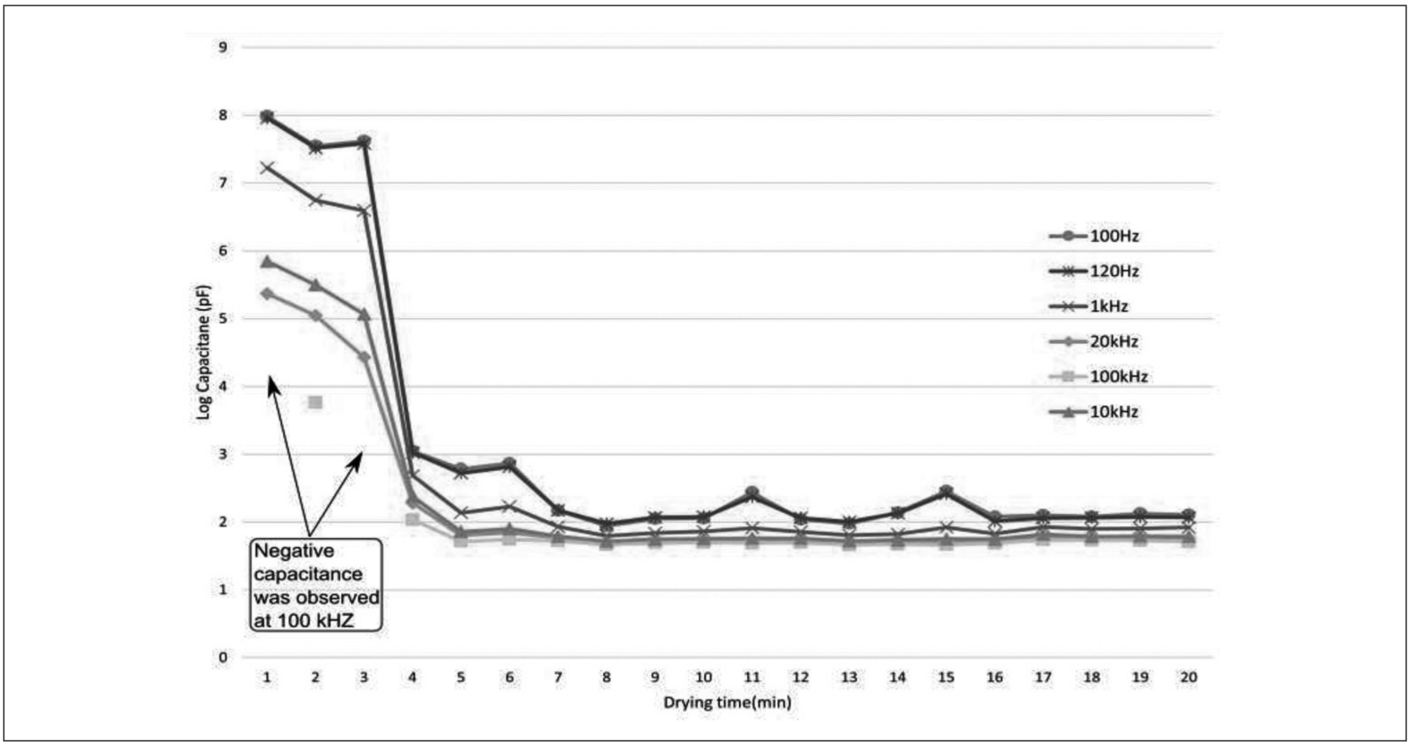

Figure 8: 100Hz, 120Hz, 1kHz, 20kHz, 100kHz, 10kHz frequencies of gloves vs drying times

There are few limitations observed here. Firstly, fluctuations occurring during the experiments in the capacitance might be due to the changes in temperature of the oven. Future study is proposed to stabilize oven temperature to increase accuracy. Next limitation is that the measurement for drying interval of 1 minute is long causing the capacitance dropping drastically. Further study is therefore necessary to determine the accuracy by reducing time interval for assessing the change in capacitance. Another limitation is IDE design which is not the focus in this study. One of the most important factors to be considered in order to analyze the capacitance sensor of the IDE is its electrode geometry. Future studies are required with regards to the output of the capacitance such as selectively designing the dynamic range and penetration depth as well as the ratio of electrode, substrate thickness, shield electrode and placement of coating layer on electrode to study sensor modelling including optimization and performance evaluation. Further experiments should also be conducted to study the effects of glove thickness on the sensor's sensitivity. Results from the experiments have shown that novel interdigital sensing system has the potential to be one of the options to assess the quality of glove products for online monitoring. Findings of this study is significant in automation and IoT device detection. Outcomes from the experiments also provide opportunity for further research in developing a low-cost IDE capacitance sensor with a reliable moisture sensing system for on-line, non-contact measurement of moisture content (MC) of glove products.

5.0 CONCLUSION

This paper proves that the moisture content of Nitrile gloves can be determined with a non- destructive and rapid method using IDE capacitance sensor. Capacitance values of varying moisture in nitrile gloves were characterized with 6 discrete frequencies range from 100Hz, 120Hz, 1kHz, 10kHz, 20kHz, 100kHz and statistical analysis, the coefficient of determination (R^2) and the root mean square error (RMSE) technique, was applied to predict the moisture content in gloves. Experimental results indicate that the capacitance value is a strong function of moisture content measurement. The capacitance of moisture content in nitrile gloves decreased with increasing drying time over the measured frequency range. Statistical analysis results have confirmed that the 1kHz, 10kHz, and 20kHz signal frequencies have highest reliable prediction of the nitrile gloves' moisture content with high R^2 value of 0.96, 0.97 and 0.97, respectively. The findings of this study indicates that with the use of IDE sensor can easily predict the moisture content in Nitrile gloves. Further study is suggested on IDE sensor design with Finite Element Method (FEM) analysis to study sensor modelling, optimization, and performance evaluation to improve accuracy and reliability of MC measuring system. Results from the experiments shows that a low-cost capacitance moisture detection sensing system can be built for an on-line, non-contact measurement of moisture content (MC) of glove products for commercial use by manufacturing industry in their automation process. Future study is proposed to investigate the IDE sensor design configuration such as length, shape and number of electrodes for better sensitivity towards Nitrile Gloves.

6.0 ACKNOWLEDGEMENT

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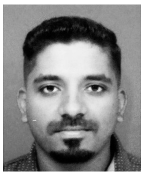
PROFILES



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