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Original Article

2-Sides Interdigital Capacitor Sensor for Determination of Water Added in Raw Milk

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Abstract *- The quality assessment of raw milk before purchasing from local dairy farmers at raw milk collection points is an important factor that affects the pricing of raw milk. The objective of this research is to study the electrical properties and analyse the relationships between electrical capacitance, resistance, frequency, and the water content in raw milk that affect the perception of 2-Sides interdigital capacitor sensors (2s-ICs). The research data was collected by examining the water content in raw milk samples with varying concentrations from 0% to 50%. Each sample of 150 cc. was placed in a 300 cc. glass container, and the water concentration was increased by 5% increments until the total volume reached 300 cc. The research results are as follows: The analysis of electrical properties based on the water content in raw milk using 2s-ICs revealed that at every percentage level of water content, there is a significant impact on the electrical capacitance. 2s-ICs, specifically the a3b6L15 model, measured the electrical capacitance of 22.23 µF with a confidence level (R2) of 0.9788. The rate of increase in electrical capacitance per 1% water content was found to be 41.12 pF.*

Keywords *- 2-Sides Interdigital Capacitor Sensor, Level sensor, Water added in raw milk.*

1. Introduction

The water added to raw milk can indeed pose a challenge in the quality control process of milk production, making it difficult to conduct accurate assessments and evaluations of the final milk product. Ensuring the quality of raw milk is a pivotal concern in the dairy industry, as it directly impacts the pricing and acceptability of the product. One of the prevalent issues in this sector is the water added to raw milk. Traditional techniques for detecting this adulteration, such as lactometers, rely on measuring specific gravity and subsequent calculations to ascertain the adulteration percentage. However, these methods are not instantaneous and require considerable time [1-4].

Advanced methods like cryoscopy, ultrasonic reflection, and infrared wave transmission have been introduced to address these limitations. Cryoscopy assesses milk's freezing point, which changes with water adulteration. Ultrasonic reflection and infrared wave transmission techniques are based on the alterations in wave properties when they pass through adulterated milk. Despite their speed and accuracy, these techniques are not widely used due to their high cost and operational complexity [5-8].

Recent efforts have focused on developing and testing digital interfacial tools to measure the electrical properties of adulterated raw milk. However, these tools have yet to achieve the necessary precision and accuracy for real-world applications [9-15]. A clear research gap exists in developing an affordable, accurate, and user-friendly method for detecting water added to raw milk at collection points. Specifically, the potential of interdigital capacitor sensors for this purpose remains largely unexplored [16]. This study aims to fill the gap by investigating the correlation between the water added to raw milk and its electrical properties using an interdigital capacitor sensor.

This research uses a two-sided digital sensor [17-18] to measure the electrical properties of water added to raw milk at different changes in water quantity. The findings from this study will contribute to developing a practical tool for detecting water added to raw milk, thereby ensuring milk quality and fair pricing in the dairy industry.

2. Theory and Principles

2-side Interdigital Capacitor Sensors (2s-ICs) are multi-fingered printed circuit structures, as shown in Figure 1. They operate on the principle of changing capacitance between fingers when the dielectric adheres to the finger's changes. The dielectric will change accordingly when the level of the dielectric changes.

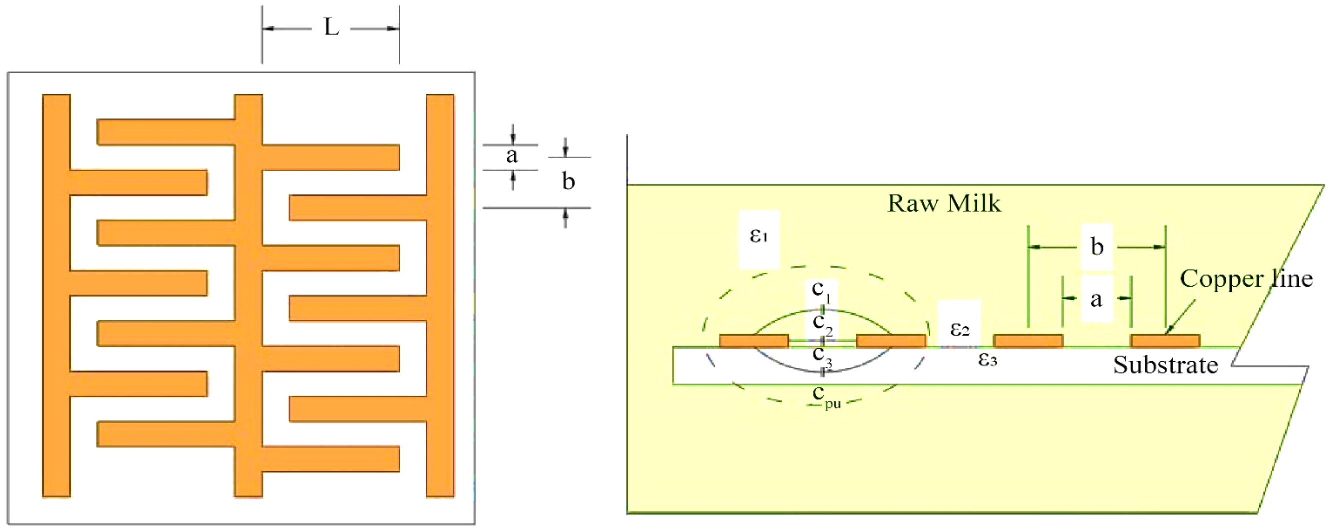

Fig. 1 Structure and parameter of 2s-ICs

The 2s-ICs have a multi-finger structure with regular intervals. Small capacitors are formed in the small gaps between conductors. These values can be increased by increasing the number of fingers or using thin layers of high-dielectric materials, such as ferroelectric, between the conductor and the substrate. The arrangement of conductive sheets in a horizontal plane, rather than in parallel, by alternating between positive and negative pole fingers, is similar to connecting capacitors in parallel. This results in a high capacitance value, which is easy to measure, and due to its single-piece structure, it can be produced using common printed circuit boards (FR4).

$$C_{2s\text{-}ICs} = 2C_{PU}(N-1)L \tag{1}$$

$$C_{PU} = C_1 + C_2 + C_3 \tag{2}$$

$$C_{PU} = \varepsilon_0 \left(\frac{\varepsilon_1+\varepsilon_3}{2}\right) k + \varepsilon_0 \varepsilon_2 \frac{h}{a} \tag{3}$$

$$\text{When} \quad k = \left[\frac{k\left(\sqrt{1-\left(\frac{a}{b}\right)^2}\right)}{k\left(\frac{a}{b}\right)} + \frac{h}{a}\right] \tag{4}$$

Starting from finding the C_{PU} value in Equation 1, which is related to Equations 2 and 3, the components include ε_0, the permittivity of free space, with a value of 8.854×10^{-12} F/m. ε_1 is the relative permittivity of the raw milk. ε_2 is the relative permittivity of the material between the copper electrodes, which is the same value as ε_1, and ε_3 is the relative permittivity of the base material. k is the function of the elliptic integrals of the modulus 1st order in Equations 4, with 'a' being the distance of the fingers and 'b' being the width of the electrodes.

Next is to find the total charge storage of the liquid level sensor. The interdigital charge storage in Equation 1 consists of L, the length of the fingers, and N, which is the number of fingers per side.

3. Experimental Setup

The equipment used in this research includes an electrical impedance, capacitance, and resistance measuring device (LCR Meter) and 2s-ICs. The LCR Meter, model E4980AL by KEYSIGHT, was used to measure electrical capacitance

The design and construction of the 2s-ICs for this research involved 9 configurations (Table 1), with variations in the width of the conductive plate (a) and the distance between the conductive plates (b).

For example, sensor 1, with a1b2L5, means that the interdigital capacitor has a length of the conductive plate (L) equal to 5 mm, a width of the conductive plate (a) equal to 1 mm, and a distance between the conductive plates (b) equal to 2 mm.

A single-sided print plate of FR-4, a conductor thickness (t) = 0.35 µm, a base material dielectric constant $\varepsilon_3 = 4.3$, and milk add water (ε_1, ε_2) dielectric constants of 80 and 68 at room temperature were used.

The 2s-ICs used in this study rely on electrical properties. When placed in a dielectric, the electric field created by the charged conductive plates causes an increase in the capacitance value between the plates, according to the dielectric properties. Different materials have different dielectric values. Using 2s-ICs to measure water added to raw milk involves measuring the capacitance values between two dielectric materials - water and milk. As water has a higher dielectric constant than milk, the presence of water in raw milk leads to an increase in capacitance value.

Table 1. The dimensions and codes used for 2s-ICs size

Model	1	2	3	4	5	6	7	8	9
a (mm)	1	1	1	2	2	2	3	3	3
b (mm)	2	2	2	4	4	4	6	6	6
L (mm)	5	10	15	5	10	15	5	10	15
Code	a1b2L5	a1b2L10	a1b2L15	a2b4L5	a2b4L10	a2b4L15	a3b6L5	a3b6L10	a3b6L15

Table 2. Electrical capacitance of 2s-ICs at 1 kHz frequency

2s-ICs Type	Water mixes in raw milk (10^{-6}F)		Transfer Function (10^{-6}F)	R^2
	0%	50%		
a1b2L5	1.08	5.60	y = 9.3513x + 0.9401	0.9745
a1b2L10	0.57	3.30	y = 5.8764x + 0.2338	0.9442
a1b2L15	0.68	4.11	y = 7.2861x + 0.3303	0.9353
a2b4L5	2.41	5.91	y = 6.9727x + 2.3471	0.9887
a2b4L10	4.11	8.11	y = 9.0218x + 3.5603	0.9774
a2b4L15	4.10	8.60	y = 8.3055x + 4.323	0.9605
a3b6L5	0.66	5.98	y = 11.435x + 0.4784	0.9877
a3b6L10	1.10	13.10	y = 25.002x + 0.2227	0.9897
a3b6L15	1.22	22.23	y = 41.124x + 2.2373	0.9788

Fig. 2 Measuring the electrical capacity of raw milk using a 2s-ICs

This research was conducted using a data collection tool that enabled the study of the water added to raw milk across a range of concentrations from 0 to 50%. A 150 cc raw milk sample was placed in a 300 cc measuring jug for each iteration. The pure water was increased by 5% in each trial and stirred up until the water volume reached 300 cc.

This setup was used to measure the electrical capacity. Each trial was repeated three times to ensure the reliability of the results. The exact procedure can be seen in Figure 2. Each trial's added water volume was in the same condition to achieve the desired water volume.

The experiment was conducted by altering the sensor configuration of the 2s-ICs according to Table 1. Each sensor configuration was tested independently, resulting in a total of 9 models set up. The data collected from these 9 configurations will be further subjected to statistical analysis.

4. Results and Discussion

The experiment aimed to determine the electrical capacitance of the 2s-ICs across three different groups with varying dimensions. The test was conducted at frequency ranges of 1 kHz. Each group consisted of three sensors, with width sizes of 1 mm, 2 mm, and 3 mm and lengths (L) of 5 mm, 10 mm, and 15 mm, respectively. A total of nine tests were performed, starting with a raw milk volume of 150 cc and gradually adding water in 5% increments up to 50% of the total volume. The obtained results for each combination of size and length are summarized in Table 2.

The electrical capacitance values of the 2s-ICs were tested at a frequency of 1kHz, with a width (diameter) of 1mm and varying lengths (L) of 5mm, 10mm, and 15mm, in response to different water content levels in raw milk. The results are as follows :

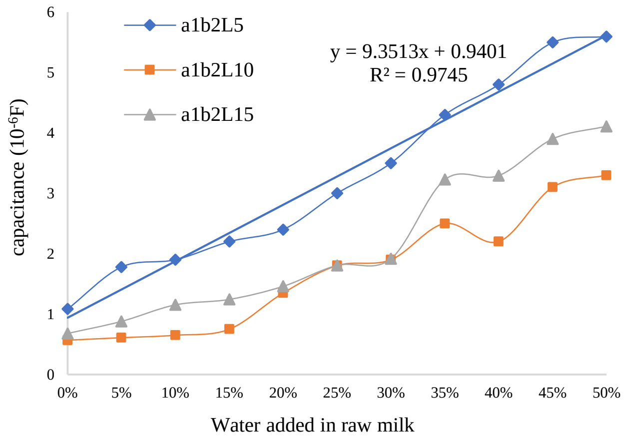

Fig. 3 Electrical capacitance of 2s-ICs model a1b2L5, a1b2L10 and a1b2L15

The results from Fig. 3 test a1b1L5: The sensor showed the lowest electrical capacitance of 1.08 µF in raw milk without added water (0%). As the water content increased to 50%, the capacitance significantly rose to 5.60 µF. The corresponding transfer function was y = 9.3513x + 0.9401, with a high R^2 = 0.9745, indicating a strong linear relationship between water content and capacitance. Test a1b1L10: In raw milk without added water (0%), the sensor exhibited a minimal capacitance value of 0.57 µF. When the water content was increased to 50%, the capacitance rose to 3.30 µF. The transfer function derived from this data was y = 5.8764x + 0.2338, with R^2 = 0.9442, denoting a robust linear relationship between water content and capacitance. Test a1b1L15: The sensor displayed the lowest capacitance at 0.68 µF when immersed in raw milk without any additional water (0%). As the water content was increased to 50%, the capacitance reached 4.11 µF. The transfer function for this case was y = 7.2861x + 0.3303, with R^2 = 0.9353, indicating a strong linear correlation between water content and capacitance.

Similarly, the results from Fig. 4 test a2b2L5: The sensor demonstrated the minimum capacitance of 2.41 µF in raw milk without any added water (0%). With an increase in water content to 50%, the capacitance peaked at 5.90 µF. The transfer function was y = 6.9727x + 2.3471 and R^2 = 0.9887, indicating a strong linear relationship between water content and capacitance. Test a2b2L10: In raw milk without added water (0%), the sensor's minimum capacitance value was 4.11 µF, while it reached a maximum of 8.11 µF at 50% water content. The corresponding transfer function was y = 8.7006x + 3.8752, with R^2 = 0.9461, showcasing a reliable linear relationship between water content and capacitance. Test a2b2L15: The sensor's lowest capacitance in raw milk without additional water (0%) was 4.10 µF. As the water content was increased to 50%, the capacitance peaked at 8.60 µF. The transfer function was y = 8.3055x + 4.3236, with R^2 = 0.9605, signifying a strong linear correlation between water content and capacitance.

Furthermore, the results from Fig. 5 Test a3b3L5: The sensor's minimum capacitance in raw milk without added water (0%) was 0.66 µF, which increased to 5.98 µF at 50% water content. The transfer function was y = 11.435x + 0.4784, with R^2 = 0.9877, indicating a strong linear relationship between water content and capacitance. Test a3b3L10: In raw milk without added water (0%), the sensor's minimum capacitance value was 1.10 µF. With a rise in water content to 50%, the capacitance reached a maximum of 13.10 µF. The corresponding transfer function was y = 25.002x + 0.2227 and R^2 = 0.9897, showcasing a reliable linear relationship between water content and capacitance. Test a3b3L15: The sensor's minimum capacitance in raw milk without additional water (0%) was 1.22 µF. As the water content was increased to 50%, the capacitance peaked at 22.23 µF. The transfer function was y = 41.124x + 2.2373, with R^2 = 0.9788, signifying a strong linear correlation between water content and capacitance.

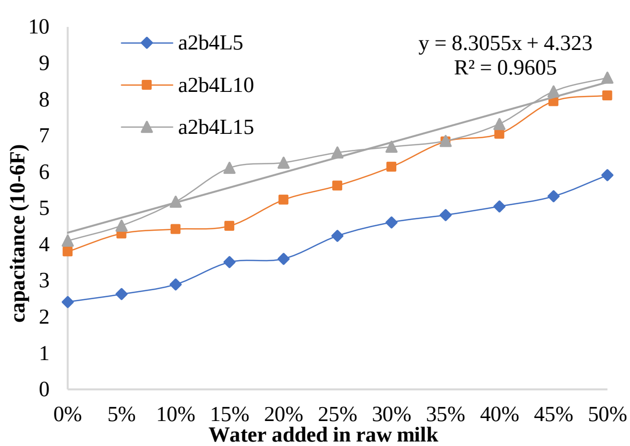

Fig. 4 Electrical capacitance of 2s-ICs model a2b4L5, a2b4L10 and a2b4L15

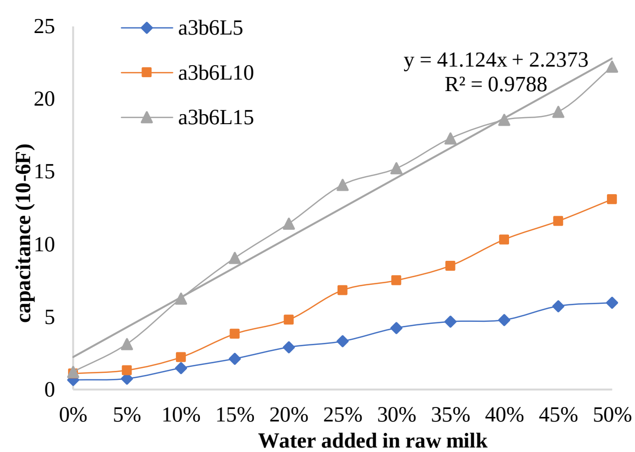

Fig. 5 Electrical capacitance of 2s-ICs model a3b6L5, a3b6L10 and a3b6L15

The results indicate that 2s-ICs exhibit a significant correlation between capacitance and water content in raw milk. This suggests its potential application as an efficient and accurate water content detector in various milk processing and quality control scenarios. Further research and optimization can be carried out to enhance its performance and versatility in practical applications.

5. Conclusion

In conclusion, our study confirms the result that 2s-ICs exhibit a strong linear relationship between water content increase and capacitance [17]. The correlation coefficients (R^2) obtained validate its reliability and sensitivity to changes in water content in raw milk [16]. There is a significant impact on the electrical capacitance. 2s-ICs, specifically the a3b6L15 model, at a measuring frequency of 1 kHz, was able to measure the electrical capacitance of 22.23 µF with a correlation coefficient (R^2) of 0.9788, signifying a strong linear correlation between water content and capacitance. The rate of increase in electrical capacitance per 1% water content was found to be 41.12 pF. This sensor shows promising potential for accurate and cost-effective water content detection in the dairy industry, enabling better quality control and process optimization. Further research can refine its design and explore diverse applications to enhance its performance and impact.

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