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A microwave sensor for the characterization of bovine milk

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ABSTRACT

The use of a moisture sensor, based on microwave absorption at 40 GHz, is explored for the direct determination of the water content in milk. The operating principle of the device is based on the relative decrement of a transmitted signal through the sample. The results of the study are based on the measurements of over 150 samples of milk, taken from individual cows, from bulk tank milk and from skimmed milk sources. A high correlation is revealed between the signal absorption, measured by the sensor, and the nominal main solids content in bovine milk, determined independently. In addition, the fat concentrations in raw milk, considered separately from the other constituents, were also well correlated to the microwave moisture meter readings. As the other solid fractions of milk show less or non-significant correlation to the absorption coefficient, it is concluded that the correlation of fat to signal decrement is due to an excluded volume effect.

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1. Introduction

Bovine milk is one of the main staples of nutrition; consequently it is the subject of intense research, both scientific and industrial. Viewed scientifically bovine milk is a complex multi-component system. Fat droplets, casein micelles, lactose, peptides, ions and other components are immersed or dissolved in an aqueous background to form an intricate substance. The constituents of milk exhibit widely differing characteristic lengths, leading to wide spatial scaling. It is comprised from fat droplets of micron scale to casein micelles of the nanometer size and smaller soluble elements (Walstra, Wouters, & Geurts, 2006).

The interplay between various milk components with water affects the overall structure and dynamics of the milk. Lactose, for instance, strongly interacts with water, forming a water clustered structure with ~123 affected water molecules per lactose molecule (Heugen et al., 2006; Levy, Puzenko, Kaatze, Ben Ishai, & Feldman, 2012; Raicu, 2015). The range of interaction is significantly larger than the size of lactose molecule and its immediate surroundings. In addition, lactose plays a central role in the physical properties of milk and its products (e.g., the concentration of lactose in the milk dominates the glass transition temperature of concentrated milk products) (Fox & McSweeney, 2003). A critical parameter in establishing the quality of raw bovine milk for the food industry is the ratio of solid to liquid components (Buttel, Fuchs, & Holz, 2008) and central to this is the measurement of its moisture content. The composition of raw milk for a required dairy product has a direct influence on yield, taste and on process optimization. Milk quality for the cheese industry is controlled by scaling payment according to solids level (fat and protein) and somatic cells count (Viguier, Arora, Gilmartin, Welbeck, & O'Kennedy, 2009) as well as bacteria count. Consequently, the online determination of moisture content and other milk constituents can help monitor the quality of the milk in the bulk tank.

One of the biggest obstacles in proper determination of milk quality arises from a wide diversity among various milk samples. The origins of this diversity can be traced to a number of factors; 1) As a complex liquid, milk exhibits a multitude of different length scales, linked to fat globules, protein constructs and other factors,

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each affected by the nutrition, age and origin of the cow; 2) The duration of lactation also leads to variation in these parameters as the expected nutritional needs of the calf change; 3) No 2 animals are ever the same, leading to a natural distribution of milk qualities. This is partly related to the biological diversity among different cows and variability between different milk samples from an individual cow (Huybrechts, Mertens, De Baerdemaeker, De Ketelaere, & Saeys, 2014). The concentration of milk constituents changes during milking and it is also affected by milking interval, udder health, etc. (Nielsen, Larsen, Bjerring, & Ingvartsen, 2005). Even bulk tank milk is subjected to noticeable fluctuations in the concentrations of its constituents. For instance, the reported seasonal variation in the fat composition of Danish dairies' tank milk over one year is in the order of ±1% (Larsen, Andersen, Kaufmann, & Wiking, 2014). Nevertheless, the standards for commercial milk are quite exacting.

The main requirements from online milk measurement method are that it should be fast, safe, non-invasive and non-destructive. Thus, chemical approaches as well as ionizing radiation cannot be applied. There are several techniques for real-time evaluation of milk quality and in particular its moisture content (e.g., near-infrared spectroscopy (NIR) (Brandt, Haeussermann, & Hartung, 2010; Tsenkova, Atanassova, Itoh, Ozaki, & Toyoda, 2000), radio frequency (RF) spectroscopy in a wide frequency range of kHz-GHz (Brandt et al., 2010) etc.). Among the other methods the advantages of microwave moisture determination should be emphasized. In contrast to infrared radiation, a significant volume of the material may be sampled at a time (Kupfer, 2005). This fact is particularly important for raw milk measurement, since it may be inhomogeneous to some extent. Furthermore, infrared radiation is much more sensitive to hindrance due to the coating of the sensor window by fat and other particles immersed in the milk. For this reason, the inline infrared probe needs to be rinsed rigorously much more frequently than the microwave sensor. Finally, in comparison with lower RF frequencies, in the microwave region, the measurement is insensitive to the *dc* conductivity of the material (Kupfer, 2005).

Due to its complexity, it is a challenge to investigate milk's dielectric properties. At 25 °C, at frequencies lower than 3 GHz, milk presents a number of dielectric relaxation processes accompanied by a significant *dc* conductivity (Miura, Yagihara, & Mashimo, 2003). Around 20 GHz, similarly to multitudinous biological systems (Pethig & Kell, 1987; Schwan, 1993; Wolf, Gulich, Lunkenheimer, & Loidl, 2011), milk exhibits a dielectric losses peak that is attributed to the presence of bulk water (Miura et al., 2003), whereas *dc* conductivity and other dielectric relaxation processes have merely negligible effect at this frequency (see Fig. 1). It is noteworthy that water in milk is found, besides the bulk form, in the form of bound (or hydration) water (Kaatze, 1990; Raicu, 2015) around various components of the system. However, in aqueous solutions, the dielectric signature of the hydration water shell is insignificant and cannot be detected directly through dielectric experiments, despite numerous attempts in recent decades (Khodadadi, Curtis, & Sokolov, 2011; Khodadadi et al., 2008a; Khodadadi, Pawlus, & Sokolov, 2008b; Oleinikova, Smolin, & Brovchenko, 2007). Therefore, a decrement in the microwave absorption, compared to that of pure water, can be associated with the relative bulk water content of the milk sample. Finally, at 40 GHz, the microwave absorption has a relatively low temperature dependence around ~30 − 40 °C.

The dielectric properties of different materials at microwave frequencies are extensively studied and implemented in industry and this is especially true in the field of food science (Datta & Anantheswaran, 2001; Nelson, 2015; Sosa-Morales, Valerio-Junco, Lopez-Malo, & Garcia, 2010; Venkatesh & Raghavan, 2004). In this work, the feasibility of using a RF sensor operating at 40 GHz, for the measurement of the moisture content and/or total solids content in bovine milk is demonstrated.

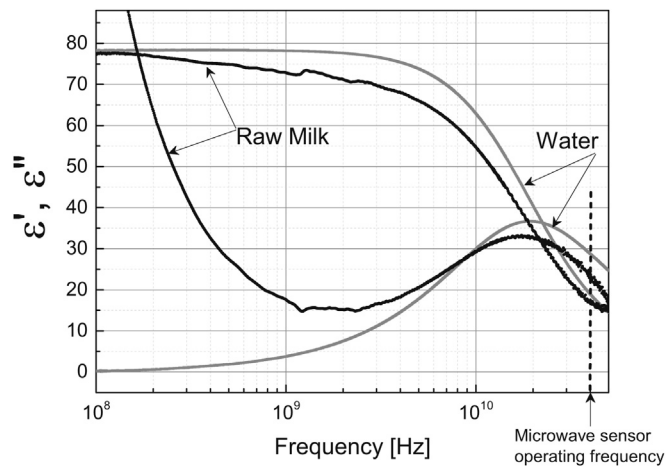

Fig. 1. The dielectric spectra of pure water compared with a typical raw milk sample at 25 °C and 0.1–50 GHz frequency range as was measured by authors using the vector network analyzer: Agilent N5225A. The microwave sensor operating frequency (40 GHz) is marked by dashed line.

2. Materials and methods

2.1. Sample preparation

Two groups of milk samples were probed, 158 in total: 96 raw bovine milk samples collected from individual cows at the farm, provided by Afimilk Ltd. (Kibbutz Afikim, Israel); 62 raw bovine milk samples were taken at different times from different receiving silos, provided by the commercial dairy, Tnuva (Alon Tavor, Israel). Each milk sample supplied by the dairy represented a batch of ~100,000 kg of milk that was collected from four or more farms in northern Israel.

Out of the aforementioned 62 milk samples, 40 samples were further processed to obtain skimmed milk which had less than 0.2% fat.

The cows from the farms supplying the milk used in the study are Israeli-Holstein cows producing >11,000 L milk during ~305 days. The cows are milked three times daily (03:00, 11:00 and 19:00) and are fed a typical Israeli total mixed ration (TMR) containing 65% concentrate and 35% forage (17% protein). Food is offered *ad lib* in mangers located in the sheds.

Each milk sample was tested for milk composition by a Milkoscan 6000 (Foss Electric, Hillerød, Denmark), provided by the Central Milk Components Laboratory, ICBA (Israeli Cattle Breeder's Association) giving weight fractions of fat, protein and lactose with the following measurement uncertainties: fat = ±0.066%, protein = ±0.047%, lactose = ±0.092%. The milk was collected approximately 12 h before the experiment and sustained in a sealed container at 4 °C until measured.

2.2. Microwave measurement

The microwave attenuation for each sample was measured using a microwave moisture sensor, the MMP40 (manufactured by Microradar-Service Ltd.) working at 40.00 ± 0.05 GHz. This device measures the absorption of an electromagnetic pulse passed through the milk and is described in detail below. Measurements took place in a plastic container with the temperature stabilized by a heat reservoir. The various milk samples were maintained at

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