EFFECT OF THE FAT CONTENT ON THE THERMAL EFFUSIVITY IN FOOD PRODUCTS: AN INVERSE PHOTOPYROELECTRIC STUDY

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ABSTRACT

Photopyroelectric (PPE) methods are capable to measure thermal properties of foods in a relatively fast and simple way. In this study a variant of PPE (the so called inverse photopyroelectric configuration, IPPE) was applied to determine the thermal effusivity of cooking cream, mayonnaise and sour cream as a function of their fat content. The effusivity decreases linearly with the increasing fat content. The change of thermal effusivity expressed as a change in effusivity for 1% change in fat content of the cooking cream, sour cream and mayonnaise samples are -13.97 $\mathrm{Ws^{1/2}m^{-2}K^{-1}}$, -11.53 $\mathrm{Ws^{1/2}m^{-2}K^{-1}}$ and -12.11 $\mathrm{Ws^{1/2}m^{-2}K^{-1}}$ respectively.

1. INTRODUCTION

The thermal properties of foods (thermal diffusivity, effusivity, specific heat, conductivity) are very important parameters for economical planning of thermal energy in the industrial processing and technology [1]. These thermal properties are influenced by the food constituents [2]. In most cases, the two main constituents in foods are water (moisture) and fat. The ratio of these constituents determines the thermal properties of foods [3].

The knowledge of thermal properties of milk and milk products is important to the industrial processing (pasteurization, cheese draining, cheese salting). In trade flow some milk products (cooking cream, sour cream) can be purchased with different fat content. Sour cream has two different fat content categories. The first category is the so-called half fatty sour cream with fat content between 10-20%, while the second category is the fatty sour cream at least with 20% fat content or higher [4]. The cooking cream has also different fat categories [5]. Generally, in trade flow one can find cooking cream with 10g, 20g and 30g fat in 100g product.

Beside the milk products, some other foods (e.g. mayonnaise) have different fat content. Mayonnaise is prepared traditionally by carefully mixing egg yolk, vinegar, oil and spices [6] and this is a stable oil-in-water emulsion. The so-called light mayonnaise has 27g fat, while the normal mayonnaise 80g fat in 100g product.

Thermal effusivity, often called heat penetration coefficient or thermal inertia, depends on specific heat c, density ρ and thermal conductivity κ of the sample according to $e=(\kappa\rho c)^{1/2}$. For different materials thermal effusivity differs due to their varying ability to transfer heat. It is also the heat transfer quantity that determines the temperature at the interface of two semi-infinite objects that are brought together.

The relatively new, non destructive photopyroelectric (PPE) method is capable to determine the effusivity value by one single measurement [7]. The PPE method has two different configurations [8]. In both configurations the sample is heated by a modulated laser beam. The difference between the inverse (IPPE) and standard (SPPE) method is the alignment of the modulated laser beam. In the IPPE configuration the modulated laser beam is absorbed directly on the pyroelecric foil [9] while in the SPPE configuration the modulated laser beam reaches the sample first. In the latter case we have to know the thickness of the sample namelly if the sample is thermally thick (the thickness of the sample is larger then the thermal diffusion length) then the generated heat due to the absorption of the sample cannot hot up the pyroelectric foil.

The objective of this study is to apply IPPE technique to determine thermal effusivity of mayonnaise, cooking cream and sour cream with a varying content of fat and to explore the extent of possible correlation between the effusivity and the content of fat in these products.

2. THEORETICAL BACKGROUND

Thin pyroelectric foil (metalized on both sides) acts as a sensor in SPPE and IPPE approaches. Heat generated due to sample's absorption of the modulated light beam produces the thermal wave field T in the photopyroelectric sensor that can be described by:

$$T = T_0 + T_{dc} + T_{ac} \qquad (1)$$

where T_0 is the ambient temperature, T_{dc} is the dc component of the temperature (depends on the modulation frequency and the geometry of the sensor), T_{ac} is the ac (oscillating) component of the temperature field. Due to changing temperature the polarised charge density differs at the two surfaces of the foil [10]. This leads to the polarised current (I_p) across the two sides of the foil given by:

$$I_p = \frac{\Delta Q_p}{\Delta t} \qquad (2)$$

where ΔQ_p is the polarised charges quantity and Δt is the time interval. The polarised charge density is given by:

$$\Delta Q_p = \frac{\Delta\sigma_p \cdot A}{\Delta t} \qquad (3)$$

where $\Delta\sigma$ is the polarised charge density and A is the surface of the pyroelectric sensor.

In the IPPE configuration the modulated laser beam is absorbed at the rear side of the black painted pyroelectric foil. If the sample is heated by the modulated light beam then the charge density will oscillate at the same frequency. The magnitude of this periodic voltage (called IPPE signal V_{sample}) generated accross the foil provides the information about the effusivity of the sample [11]. At the given modulation frequency the phase sensitive lock-in amplifier hitches up the IPPE signal to optimise the signal to noise ratio [12]. The lock-in amplifier is connected to the computer. By a single measurement the computer generates 256 readouts of the lock-in. If the PPE sensor is thermally thin, optically opaque and operates in the current mode the IPPE signal is inversely proportional to the thermal effusivity of the substrate material (sample). For a given experimental arrangement this implies that the ratio of V_{sample} (i.e. signal obtained from the sample being studied) and $V_{reference}$ (signal acquired from a reference sample of which thermo physical parameters are well known) is solely a function of their effusivities, i.e.:

$$V_{sample} \cdot e_{sample} = V_{reference} \cdot e_{reference} \qquad (4)$$

Thermal effusivity e_{sample} of the sample can be obtained in this way by measuring V_{sample} and $V_{reference}$ (under the same experimental conditions) and using the known effusivity of the reference (usually distilled water).

The effusivity value of distilled water is 1580 $Ws^{1/2}m^{-2}K^{-1}$ which can be found in publications.

3. MATERIALS AND METHODS

In this study, sour cream, mayonnaise and cooking cream with different fat content were investigated. Commercially available sour creams have a fat content of 12 % and 20 %. Therefore, a sour cream with higher fat content (31.4 %) was produced by the Hungarian Dairy Research Institute (Mosonmagyaróvár). The remaining three sour cream samples were produced by mechanical mixing sour creams of 31,4% and 12% fat content.

The mayonnaise samples were purchased in a Hungarian supermarket. One of the products had 80% fat content while the other one 27%. The other four samples were produced by mixing these two commercially available samples. Altogether seven samples were prepared with different fat contents.

In total, eight cooking creams were investigated, three of them were commercially available cooking creams with 10g (C1) 20g (C2) and 30g (C3) fat content in 100g product. By mixing C1 and C3 samples five additional samples were produced with 12.28g, 16.2g, 20g, 24.2g, 26.61g fat content in 100g product. Finally, we had eight cooking cream samples with different fat contents and of which two samples have the very same fat content (20%). One of the (20% fat content) cooking cream samples was mixed from C1 and C3, while the other one was purchased in the supermarket.

The effusivity values of the above mentioned samples were measured by the following home made system (*Figure 1.*).

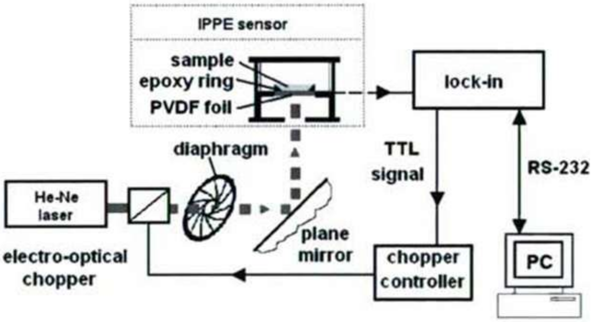

Figure 1. The IPPE measurement system

A Melles Griot 05-LHP-141 He-Ne laser was used as light source at 632 nm. The polarization was 1000:1 and the power of the non-modulated beam was 3.6 mW. The laser beam was modulated by an electro-optical modulator. If the modulator is polarised its refraction coefficient will change. This phenomena diverts the laser beam and the beam cannot pass trough the diaphragm and in this way the laser beam will be modulated. The chopper was controlled by the TTL signal of the lock-in amplifier. The modulated laser beam was absorbed by the black layer at the PVD foil and it has generated the IPPE signal. The sensor was connected to the lock-in amplifier and its output to the computer. The computer read out the amplifier and processed the data. The average of 256 successive readouts of the lock-in amplifier was the representative of a single measurement. Three independent measurements were carried out on each sample.

4. RESULTS

As a first step, the amplitude of the IPPE signal on distilled water was measured. The measurements were carried out in the frequency range of 0.2 and 4 Hz (*Figure 2.*). The obtained signal was linear (R^2=0.9963) between 0.1 and 1.5 Hz on distilled water in the function of the square root of the frequency (symbol o represents the IPPE signal of water). It can be seen that the IPPE signal is not linear anymore at higher frequencies. Not only the IPPE signal of distilled water but the IPPE signal of mayonnaise (27% fat content) are linear (R^2=0.9842) in this frequency range as well. Controlling linearity is important because of the correct analytical frequency (this has to be in the linear range). Therefore, 0.5 Hz was chosen as measuring frequency.

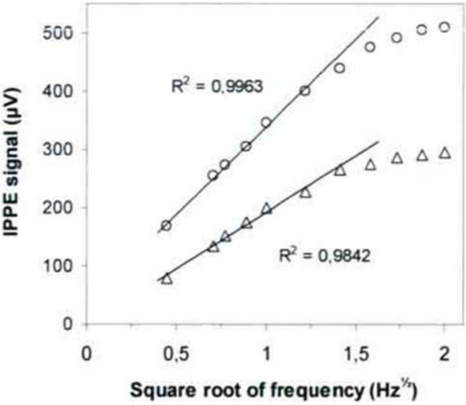

Figure 2. The amplitude of the IPPE signal obtained from distilled water (o) and the mayonnaise (Δ) (fat content 27g/100g product) plotted versus the square root of the modulation frequency.

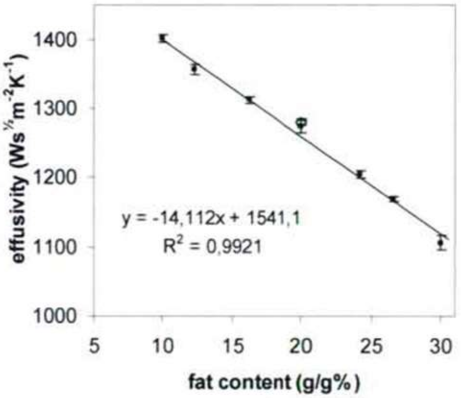

Figure 3. The relationship between thermal effusivity (obtained directly by IPPE experiment) and the content of fat in cooking creams (o symbol represents sample C2)

Next the effusivity values were measured on cooking cream samples (*Figure 3.*). The effusivity value of cooking cream samples were between 1100 $Ws^{1/2}m^{-2}K^{-1}$ and 1410 $Ws^{1/2}m^{-2}K^{-1}$. The effusivity values versus fat content show a linear correlation. If the fat content increases the effusivity decreases (R^2=0.9921).

Figure 4. shows the effusivity values of sour cream samples versus the fat content. The highest effusivity value of sour cream is 1623 $Ws^{1/2}m^{-2}K^{-1}$ and the lowest 1407 $Ws^{1/2}m^{-2}K^{-1}$. The correlation is linear again and a decreasing tendency was obtained versus fat content (R^2=0.9868).

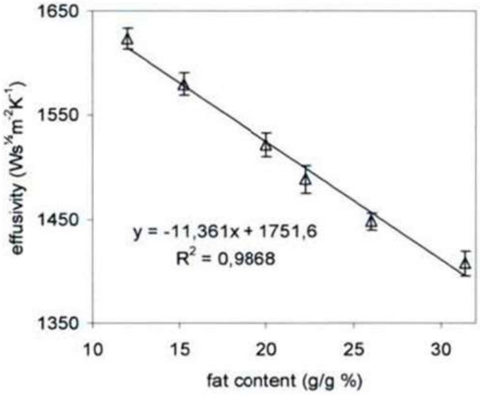

Figure 4. The relationship between thermal effusivity (obtained directly by IPPE experiment) and the fat content in sour cream

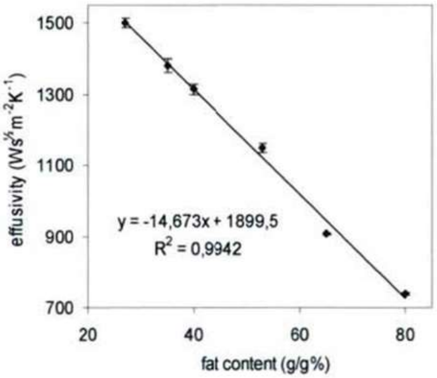

Figure 5. The relationship between thermal effusivity (obtained directly by IPPE experiment) and the fat content in mayonnaise

The obtained effusivity values of mayonnaise are plotted in Fig. 5. The relationship is linear again and 1 % increase in the fat content resulted in 12.11±1 $Ws^{1/2}m^{-2}K^{-1}$ decline of the effusivity value.

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5. CONCLUSIONS

The IPPE method was capable to detect differences in thermal effusivity of sour cream, mayonnaise and cooking cream characterized by varying fat content. The observed relationship between the effusivity and the fat content is linear. Increasing fat content of the product by 1% resulted in 13.97, 11.53 $Ws^{\frac{1}{2}}m^{-2}K^{-1}$ and 12.11 $Ws^{\frac{1}{2}}m^{-2}K^{-1}$ drop in thermal effusivity for cooking creams, sour creams and mayonnaise respectively. The obtained standard deviations of the effusivity values regarding all the samples are smaller than the sensitivity (decline in the effusivity value for 1% increase in the fat content) of IPPE method and therefore, the technique and the thermal effusivity of the samples are very sensitive to the fat content of the investigated samples.

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