Direct measurement of thermal effusivity of foods by front configuration of the photopyroelectric method

G. Szafner[1], D. Bicanic[2], R. Kulcsár[3], O. Dóka[4*]

[1]Hungarian Dairy Research Institute
[2]Laboratory of Biophysics, Wageningen University,
[3]PEZ Produktione Europe Kft.,
[4]Institute of Mathematics, Physics and Informatics, University of West Hungary Faculty of Agricultural and Food Sciences
dokao@mtk.nyme.hu

Abstract. Thermophysical properties of foods are of considerable relevance to food industry. The One among less explored thermophysical quantities is the thermal effusivity. In this paper the front variant of the photopyroelectric method was applied to determine thermal effusivity of both, fresh hen egg's yolk and white as well as of their blends. The amount of egg yolk added to the blend affected the thermal effusivity of egg's white. Thermal effusivity of mixtures containing pork meat and lard was also investigated. Addition of lard reduces significantly thermal effusivity of pork meat (the 1% increase of lard content leads to 6.93 $Ws^{½}m^{-2}K^{-1}$ drop of thermal effusivity).

Keywords:

thermal effusivity,
photopyroelectric method,
hen's egg, pork meat,
fat content

INTRODUCTION

Thermal properties (specific heat, thermal diffusivity, conductivity and effusivity) of foods are very important to food industry, in particular when optimizing the application of heat in processing (Mohamed, 2009). In general, thermal properties are influenced by the composition of foods (Sablani and Rahman, 2003). In most cases the two main constituents are water and fat. The ratio of these constituents determines the thermal properties of foods (Gustavsson and Gustafsson, 2006). Different techniques used to measure fat content in foods include differential scanning calorimetry (DSC) (Hu et al., 2009), van Gulik method (Koca and Metin, 2004), gravimetry (Evers et al., 1999), variety of spectrophotometric methods (Almendingen et al., 2000) and Gerber's approach (Ceirwyn, 1994). Photopyroelectric (PPE), method, a relatively new sort of photothermal techniques, is capable of measuring dynamic thermophysical properties (such as diffusivity and effusivity) of foods in a relatively quick,

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simple and in non-destructive manner (Chirtoc et al., 1992). Two variants of the PPE method are currently being distinguished: the so-called back (BPPE) and the front configuration (FPPE). The major difference between the two configurations is the way in which the pyroelectric sensor is being heated (Dadarlat et al., 1990). In the BPPE configuration, the incident light beam heats the sample directly while in the FPPE configuration the incident light beam is absorbed at the rear side of the pyroelectric foil, which maintains has very good thermal contact with the sample (substrate). The use of BPPE configuration requires the knowledge of thermal diffusion length and the thickness of the sample. The thickness of the sample must be greater than sample's diffusion length (the sample is thermally thick) so that the generated heat cannot reach pyroelectric foil. However, in the FPPE configuration the radiation initially impinges on the absorbing pyroelectric foil and therefore the thickness of the sample plays not a role of significance in the generation of the PPE signal (Dadarlat et al., 1995).

Eggs and eggs products are frequently used as raw materials (baking, dried pasta industries). In addition, fresh eggs and products with high egg content (such as mayonnaise, salad dressing) are in the current trade flow. Increased consumption of eggs is associated with their high biological value, protein content and the presence of vitamins (A, E, D, K, B_6, B_{12}) (Watkins, 1995). In eggs and egg products the fat content is one of the most important constituent because of its large energy, content of omega 3 and omega 6 fatty acids; in additional conduces to intake of some vitamins. The fat contents of egg yolk and egg white differ. The hen egg's yolk contains 31.2g/100g while egg white contains only 0.7g/100g fat. The specific heat and thermal conductivity of egg yolk, white, and of their blends are well known (Coimbra et al., 2006). Thermal effusivity of egg yolk and white has been determined previously (Szafner et al., 2012).

The arguments for eggs and egg products stated above apply to many other foods as well, good examples are meat and meat products that is usually cooked, processed and refrigerated. The knowledge about thermal properties of meat and meat products is very important because of denaturation of proteins during thermal treatment of foods (Fernández-Martín et al., 1997). Kemp et al. (2009) determined the apparent heat capacity of pork, lamb and beef samples. Hill et al. (1967) measured thermal conductivity values of frozen and fresh pork. Thermal diffusivity of pork meat was also determined (Zhang et al., 2004).

The objective of the investigation described in this paper was to apply FPPE method and determine how thermal effusivity of egg blends and of pork depends on the fat content of the same samples.

THEORETICAL BACKGROUND

Thermal effusivity e (often called as heat penetration coefficient) depends on the thermal conductivity κ, density ρ and the volume specific heat c at constant pressure of the sample. It is defined as $e= (\kappa\rho c)^{½}$ and can be determined directly by one single FPPE measurement.

In the FPPE method the sensor is a pyroelectric foil made from polyvinylidene fluoride (PVDF) provided on both sides with metal coating. When the pyroelectric foil is heated, the polarized charge is generated on both sides of the foil. Such heating can be accomplished by a modulated laser beam. In the FPPE

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configuration the modulated laser beam is absorbed at the blackened rear side of the pyroelectric foil which leads to the periodic heating. Due to the temperature change the polarised charge density differs at the two surfaces of the foil and leads to the polarised current (I_p) across the two sides of the foil given by (Mendelis és Zver, 1985):

$$I_p = \frac{\Delta q_p \cdot A}{\Delta t} \qquad (1)$$

where Δq_p is the polarised charge density change, A is the area of the foil and Δt is the interval. Since the pyroelectric foil is heated by means of the periodic light beam, the charge densty will vary with the same periodicity. Generated voltage at the same frequency (FPPE signal) can be detected by a phase sensitive amplifier (Marinelli et al., 1992) and is determined by the following expression (Azmi et al., 2003):

$$V(\omega) = \frac{pL_p\Theta_p}{\varepsilon\varepsilon_0} \qquad (2)$$

where p is the pyroelectric coefficient, θ_p is the generated heat mass in the PVDF foil, L_p is the thickness of the PVDF foil, ε is the dielectric constant of the pyroelectric detector and ε_0 is the dielectric constant of the vacuum.

The FPPE method applied here is a relative approach. Initially the FPPE signal V_r of a sample having a well known thermal effusivity e_r (usually distilled water) is measured. Then, the FPPE V_s signal from the test sample is recorded and the unknown sample's effusivity e_s calculated from:

$$e_s = \frac{e_r \cdot V_r}{V_s} \qquad (3)$$

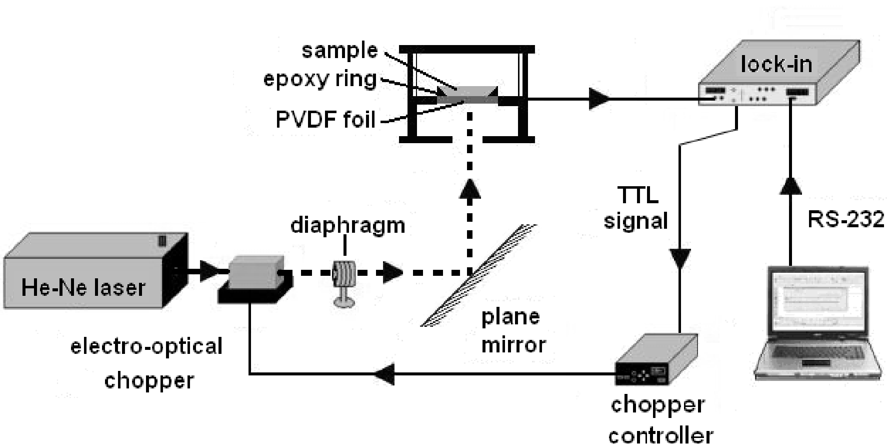

Figure 1
The schematic diagram of the home-made apparatus for measurement of thermal effusivity by FPPE method

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MATERIALS AND METHODS

Thermal effusivity measurements were conducted with a home-made FPPE set-up (Fig. 1). The light source was a Melles Griot He-Ne laser emitting 3.6 mW power at 632 nm. The beam of this laser was modulated by an electro-optical modulator and directed to the blackened side of the PVDF foil. The FPPE signal was amplified by the lock-in amplifier (SR-530) and connected to a computer for automatic data acquisition. The average of 128 successive readouts of the lock-in amplifier was selected as representative for a single sample load. Measurements were made in triplicate and the average taken as indicative for repeatability.

As mentioned above two kinds of samples were investigated in this study, the first one includes liquid egg prepared from hen eggs containing different amounts of egg yolk and egg white. The mass fraction of the hen's egg yolk in the blends varied from 0% (sample W1) to 100% (W6) (23% (W2), 32% (W3), 47% (W4), 70% (W5)). For the reasons of clarity, W1 is the egg white itself and hence the amount of egg yolk in the blend is 0%; likewise W6 is the pure (100%) egg yolk. In order to eliminate air bubbles which may influence the thermal contact between the sample and the pyroelectric foil the blends were manually agitated for three minutes at room temperature. The quantity of samples used for the analysis was consistently the same (400 µl).

The second series of samples were prepared from pork meat and lard. Overall, eleven samples with different fat content have been studied. The fat content of spare rib is 4.5 % in g/g. Varying amounts of meat and lard were homogenized with ultra-Turrax blender. The fat content (controlled by a butilométer) of the samples is as follows: 14.5, 23.6, 33.15, 42.7, 52.25, 61.8, 71.35, 80.9, 90.45 and 100 %.

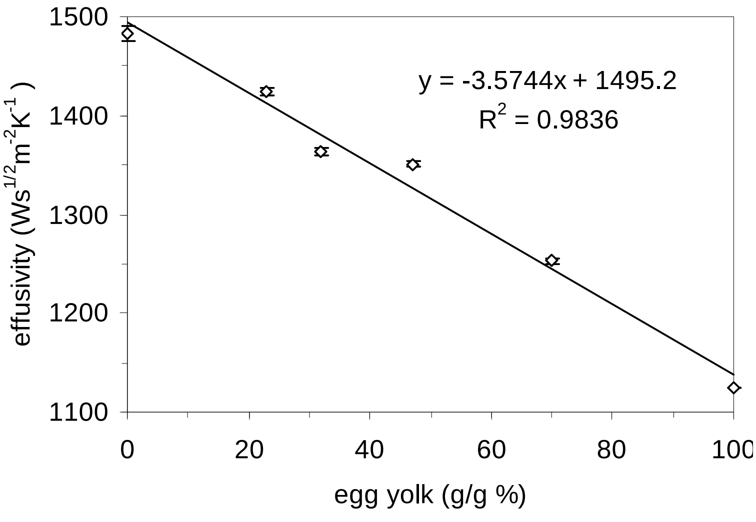

Figure 2
Thermal effusivity of egg blends plotted versus the egg's yolk content.

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RESULTS AND DISCUSSION

To calibrate the set-up one has measured the amplitude of the IPPE signal from distilled water as a function of the modulation frequency. The measured signal was linear between 0.1 and 1.5 Hz and 0.5 Hz was chosen for further experiments. The effusivity value of distilled water is 1580 $Ws^{½}m^{-2}K^{-1}$ which was taken from the literature *(Bicanic et al., 1992)*.

As the next step the FPPE signal from egg samples has been measured. Thermal effusivity of egg yolk and egg white is 1122±31 $Ws^{½}m^{-2}K^{-1}$ and 1511±21 $Ws^{½}m^{-2}K^{-1}$ respectively (Szafner et al., 2012). The effusivity of blends ranges between the values for egg's white and egg's yolk. It decreases linearly (R^2=0.98) with the increasing fraction of egg yolk in the sample as shown in (Fig. 2). The one percent increase in the amount of egg yolk results in -3.57 $Ws^{½}m^{-2}K^{-1}$ drop in effusivity.

The effusivity of spares rib without added lard and of pure lard is 1226±12 and 591±10 $Ws^{½}m^{-2}K^{-1}$ respectively. The relationship between effusivity of premade mixtures and their fat content is linear; increasing the lard content by one percent decreases the effusivity by 6.65 $Ws^{½}m^{-2}K^{-1}$ (Fig. 3).

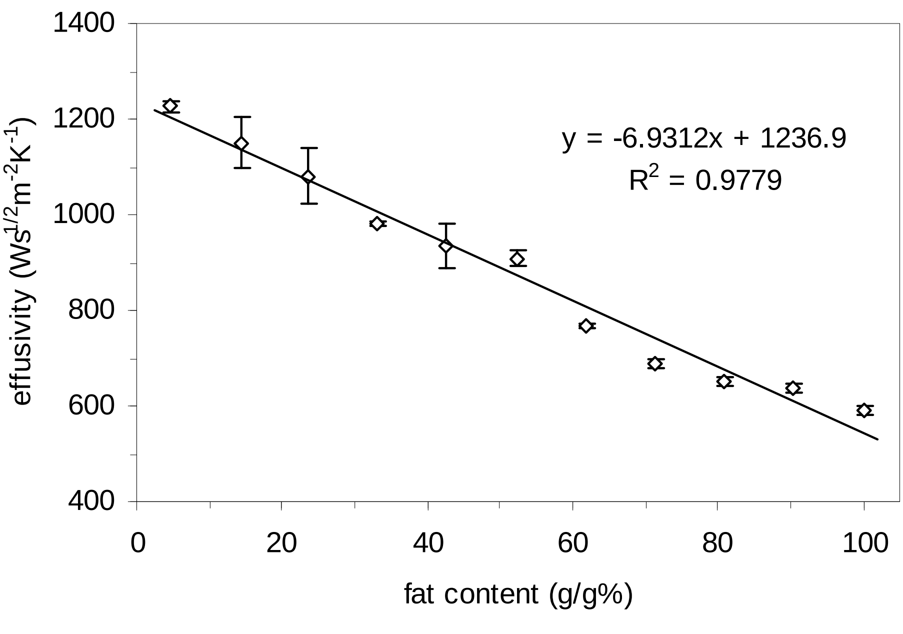

Figure 3
Thermal effusivity of pork (meat) versus the fat content

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CONCLUSIONS

The results obtained confirm the assumption that the ratio of water and fat content in foods affects the effusivity. The water content of egg white and yolk is typically above 80 % and about 50 %. On the other hand fat content is 1-2% and 30% respectively. The water content increases the effusivity while the fat content reduces it.

The relationship between thermal effusivity and the content of egg yolk in liquid eggs (blends) is linear. This offers an opportunity to assess the content of the egg yolk in the blend via effusivity measurement of the latter. This is important in the confectionery industry where eggs rich in egg's white are preferred. Other examples include the preparation of foam and production of dried pastas.

The relationship between the amount of lard and the effusivity of pork confirms that the fat decreases the effusivity. In addition the results obtained offer a relatively simple possibiliy for measuring the content of fat in pork (meat).

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