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Continuous measurement of contact heat flux during minced meat grilling

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ABSTRACT

Few studies concerning contact heating of food products were found in the literature despite the importance of this mode of heat transfer in many operations (grilling, pan-frying) and its drastic impact on product quality change during heating. An original heating device to measure continuously contact heat flux and heating surface temperature was therefore developed and applied to the contact heating of turkey meat with a heating surface at 128°C, 215°C and 255°C. Based on the experimental results obtained, a simplified heat transfer model was developed and allowed the calculation of the parts of the total energy received by the product (i) used to raise its temperature (ii) used to evaporate water exuding from its lower surface during heating and (iii) lost by heat exchange with the surroundings. In the experimental conditions covered by our experiments, the part of energy used to evaporate water exuding from the product was found to vary between 55% and 67% of the total energy received. The precise evaluation of the kinetics of variation of the contact heat transfer coefficient (quantifying the quality of thermal contact between the lower surface of the meat sample and the heating plate) was also made possible. At 215°C and 255°C, this coefficient ranged from 500 to 100 $W \cdot m^{-2} \cdot K^{-1}$ between the start and the end of the cooking, these values being in the same order of magnitude as those measured in previous studies concerning single-faced grilling of meat.

1. Introduction

From industrial production to final preparation in the kitchens of consumers, food products undergo a large number of heat treatments. Different technologies may be used, including hot air or vapour heating, deep- or pan-frying, grilling, dielectric heating (microwave, high frequency), resistive (ohmic) heating or water cooking, etc. With the exceptions of dielectric and resistive heating, all these technologies are based on the implementation in a thermally-controlled environment of three elementary modes of external heat transfer: thermal convection, thermal radiation and contact heat transfer, the latter mode occurring when two solids at different temperatures are placed in contact.

Although many studies in the literature have been devoted to convection and radiation during the heating of food products (Erdoğdu, 2008; Rastogi, 2012), very few have focused on contact heat transfer. This seems paradoxical because contact heat transfer is the principal mode of heat transfer in many operations (single- or double-faced grilling, pan-frying) and is known to induce drastic quality changes in the zone of the product close to the heating surface, as studied for example by Kalogeropoulos et al. (2006), Sioen et al. (2006), Haak et al. (2007) and Clerjon et al. (2012) with respect to pan-fried meat or fish and Boskou et al. (2006) for pan-fried potatoes.

The experimental and theoretical study of contact heat transfer on food products is rare because it is a complex matter. Firstly, the surface of a solid material will always present irregularities at the microscopic (roughness) or macroscopic scales (flatness anomalies, corrugations). As a result, the interface between these two solids in contact must always be envisioned as a series of contact spots interspersed with gaps, leading to an actual contact surface that is always smaller than the apparent contact surface (Madhusudana, 1996). As proposed by Incropera et al. (2007), the effect of the geometry of this complex interface upon heat transfer between the two solids in contact can be globally described by the use of a thermal contact resistance R_{ct} defined according to equation (1):

$$R_{ct} = \frac{T_A - T_B}{\dot{q}_{ct}} \quad (1)$$

where $T_A - T_B$ is the temperature across the interface and $\dot{q}_{ct}$ is the resulting heat flux exchanged between the two solids.

When a food product is put in contact with a hot surface numerous

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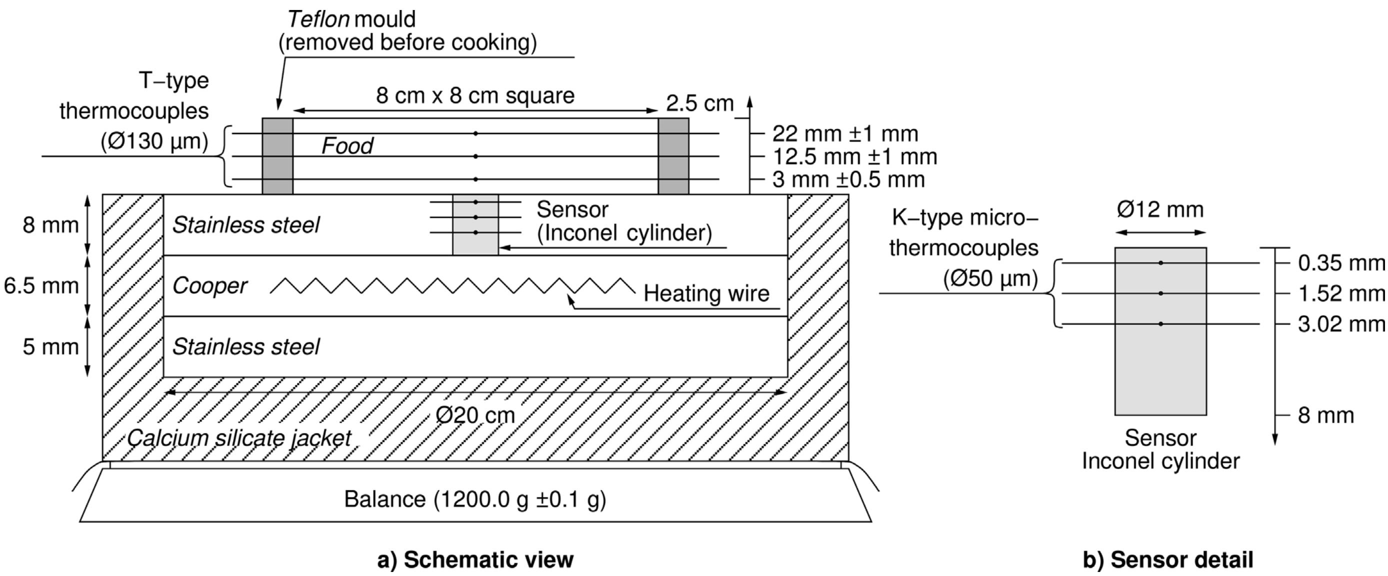

Fig. 1. Experimental contact heating device.

thermally-induced physicochemical transformations occur in the heated product, leading to variations in the quality of the physical (and hence thermal) contact between the two surfaces. These interfering phenomena may occur continuously during heating or can happen very suddenly (boiling, detachment, etc.) They consist mainly in the formation of a crust on the lower surface of the product, followed by possible deformation or contraction of this surface and the potential release of cooking exudates from the heated product into the interstitial zone between the product and heating surface (Kondjoyan et al., 2014).

Concerning crust formation and deformation of the heated surface (as studied in meat by Portanguen et al., 2014, in bread by Vanin et al., 2013 and in pancakes by Sanz-Serrano et al., 2017), this phenomenon is likely to occur when the product surface is exposed to a high heat flux. This then leads to abrupt water evaporation at this exact location, the internal diffusion of moisture within the product being insufficient to compensate for this moisture loss. Once formed, this mechanically rigid crust causes the heated material to contract, thus tending to reduce the overall contact surface area between the product and heating surface. The crust also acts as a barrier layer to heat and mass transfer between the product and its surroundings.

Concerning the release of cooking exudates during heating or, by extension, the part played by an additional layer of oil between the product and heating surface, this allows the replacement of air as an interstitial medium between the two surfaces with a liquid medium which may improve the quality of the thermal contact between the two surfaces. However, study of the influence of cooking exudates during contact heating remains highly complex because most of these exudates vaporise when they come into contact with the heating surface, thus limiting overall heating of the product (Cernela et al., 2015).

Faced with this complexity, the most common method used to measure contact heat flux during the heating of solid food products consists in placing a surface heat flux sensor between the heating surface and the heated product (Houšová and Topinka, 1985; Pan and Singh, 2002; Pan et al., 2000; Wichchukit et al., 2001). This flux measurement, supplemented by two temperature measurements in the product and heating surface (as close as possible to the interface) enables the calculation of continuous variations in the contact heat transfer coefficient. This method provides an on-line and instantaneous measurement of thermal contact quality but (i) a small location error of the thermocouple in the product may lead to a major error regarding the surface temperature because very high temperature gradients are expected in the zone of the product close to the heating surface, (ii) product temperature is only measured at a local level that is not necessarily representative of the average lower product surface temperature, particularly for products presenting macroscopically noticeable surface irregularities, and (iii) positioning a surface heat flux sensor between the two materials will necessarily cause a local disturbance of heat and mass transfer phenomena at this location. More, it provokes (i) the addition of two supplementary resistances to heat transfer between the sensor and the product and between the sensor and the heating surface and (ii) the modification of mass transfer phenomena at the location of the sensor such as release and potential vaporisation of cooking exudates.

The aim of the present study was therefore to adapt, in order to measure precisely the contact heat transfer between a pan and a minced meat block, an original experimental device developed by Cernela et al. (2015) and precisely described in the following section. This device allowed the continuous measurement of the heating surface temperature whereas the heating device presented here allows also, after adaptation, the continuous and non-invasive measurement of the contact heat flux exchanged between the heating surface and heated product. The product chosen for this study was turkey meat since this product is commonly cooked by contact heating and exhibits complex phenomena during heating (crust formation, deformation, release of cooking exudates …) The meat was minced before heating not to take into account the muscle anisotropy and to have a product whose structure is more repeatable for the heating test. A simplified heat and mass transfer model was also developed during this study in order to calculate continuous variations of the product's lower surface temperature and the contact heat transfer coefficient between the product's lower surface and the heating surface.

2. Materials and methods

2.1. Contact heating device

In order to perform contact heating experiments under controlled conditions, a contact heating device previously developed in our laboratory by Cernela et al. (2015) was modified in order to meet the objectives of the present study, which included continuous measurement of the contact heat flux exchanged between the heating surface and the heated product.

As shown in Fig. 1(a), the heating device was composed of three 20 cm diameter cylindrical metal discs placed inside a calcium silicate insulation jacket (Silicate L, Sored UPM, Messein, France). From bottom to top, the first disc was made of 5 mm thick stainless steel (Type 304),