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Estimation of surface temperature and thermal load in short-time heat treatment of surimi through reflectance spectroscopy and heat transfer modeling

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ABSTRACT

Documentation of surface temperature is challenging for short food surface pasteurization treatments, particularly in steam environments. In this study a spectroscopic approach is investigated for estimating thermal load while heat transfer modeling is used to estimate the surface temperature of a model fish product when heated in steam or immersed in water. Reflectance spectroscopic measurements show that visible spectroscopy (400–550 nm) has potential for assessing the thermal load of surimi heated in water in the temperature range between 70 and 95 °C. For treatment times >10 s, robust models ($r^2 \geqslant 0.9$) with acceptable prediction errors (<3 °C) were achieved. A similar development in the absorption was seen in steam treated surimi, for short (<10 s) processing times. Heat transfer modeling confirmed the thermal load indicated by the measurements, and demonstrated the large temperature gradients that occur with short time, high temperature treatments.

1. Introduction

Fish is very sensitive to thermal processing and will often become tough and dry when exposed to excessive heat, e.g. when reheated prior to consumption (Rosnes et al., 2011). Technologies that can ensure extended shelf life and food safety, while maintaining optimal sensory properties, are therefore of great interest. The interior of a fish muscle is sterile (Herborg and Villadsen, 1975), hence the target area for decontamination, immediately after cutting, is the surface. This may also be the case for heat processed products that could be exposed to potential recontamination prior to packaging. A number of technologies have been used for surface decontamination of seafood (e.g., organic acids, chlorine dioxide, electrolyzed oxidizing water) (Skåra et al., 2012). Surface decontamination with heat hasseveral benefits over other methods. Most importantly it does not leave chemical residues on the surface, which is in compliance with current EU-regulation (Anonymous, 2004a,b).

In order to assess the efficacy of these treatments, accurate knowledge of the temperature on and just below the surface is necessary to accurately estimate the time–temperature process history (Kondjoyan and Portanguen, 2008). The use of a thermocouple is practically impossible for several reasons; it is difficult to secure a thermocouple probe in the food, and its placement will greatly affect the temperature measurement. Moreover, since the thermal conductivity of the metal probe is much higher than that of food, heat may be conducted through the metal, leading to erroneous measurement. With rapid treatments, a temperature gradient of around 10 °C/mm can be observed near the surface (Techasena and Flick, 1995). Currently available temperature measurement methods require meticulous calibration. Infrared (IR) measurements must take intoaccount the effect of steam on the IR-signal. The inverse method, deriving the surface temperature from temperatures recorded at two different depths requires accurate positioning of thermocouples (Techasena and Flick, 1995). Determining the thermal load by measuring the changes on the product surface induced by temperature changes is a more versatile and less labor intensive approach. One potential technology could be near infrared spectroscopy (NIR), a non-destructive, on-line analytical tool, which is increasingly used in the food industry for rapid product characterization (Xiaobo et al., 2010).

Surimi represents a suitable model system for spectroscopic studies of fish product surfaces, with a composition and properties that resemble both shellfish analoges and lean fish. Surimi is a sta-

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ble (Moosavi-Nasab et al., 2005) and rather homogeneous aggregation of uncooked fish proteins. A number of studies have been published describing the mixing process (Ducept et al., 2012) and the subsequent gelling procedures and properties (Bouraoui et al., 1998; GomezGuillen et al., 1996) for the manufacturing of kamaboko from surimi.

Efforts have been made to use NIR spectroscopy to determine end-point temperature (EPT) in surimi (Uddin et al., 2002a,b). Some correlations were found between EPT and absorption in the NIR region, but spectral absorption in this region is highly dominated by water. Controlling the presence and amount of water in an industrial processing environment may not be feasible. Stormo et al. (2012) developed a method for determining endpoint temperature using wavelengths from the visible range of the spectrum (400–700 nm) where water absorption is negligible. These authors assigned this spectroscopic response to an increased light scattering effect caused by the denaturation of major muscle proteins, like myosin and actomyosin (Kimura et al., 1980). A temperature induced scattering effectshould be taken into account and corrected for in other NIR-prediction models, e.g. for protein content determination (Zhang et al., 2010). The increase in scatter that can be associated with aggregation (Brenner et al., 2009), and denaturation (Chanthai et al., 1998), could also be monitored in order to quantify surface denaturation. In surimi, a gel is formed as temperature reaches about 70 °C (Su et al., 1999). As denaturation processes, a protein gel, such as surimi, becomes whiter, and the inhomogeneity of the surface produces the light scattering effect. Heat processing conditions above this temperature are highly relevant for reduction of food pathogens such as *Listeria monocytogenes*, and hence the monitoring of spectralchanges could be used to indicate/document thermal load. Whereas Stormo et al. (2012) developed models for 120 s treatments up to 74.4 °C, this work aims to further quantify the scattering effects caused by temperature and denaturation, into higher temperatures. It also aims at studying these changes in an industrially relevant steam surface heating application.

Realizing the limitations of surface temperature measurement for surface steam treatments, heat transfer modeling needs to be used to support the spectroscopic changes. Heat transfer modeling has been used to describe steam surface heating processes for hot dogs (Huang, 2004, 2005), as well as for poultry (Kondjoyan and Portanguen, 2008). Huang (2004) suggested to heat the outer 1 mm to a temperature of >80 °C in order to achieve a 'complete' destruction of *Listeria monocytogenes* on hot dogs. Hence the design of a surface heating process with a desired lethal effect requires some understanding of the governing heat transfer process. Except for the work of Stormo et al. (2012), few surfaceheat transfer studies are available for fish products, and none in the steam temperature (≈100 °C) region.

Hence, based on studies with heating surimi the aim of this research was to (i) evaluate the heat transfer process during water immersion heating and steam treatment, (ii) develop heat transfer models to predict the thermal load on a (surimi) fish product surface subjected to high temperatures – short time (2–30 s) treatments in water bath and under steam, (iii) use spectral measurements to determine the thermal load and monitor the heating process during cooking.

2. Material and methods

2.1. Surimi samples

In order to obtain a relevant imitation of both lean fish and minced fish products like shellfish analoges, surimi was chosen as a model product, mainly for its homogeneity, stability and the availability of physical properties similar to that of lean fish. The focus area of the study was the surface, and potential indigenous bacterial load was irrelevant. Cylindrical disks of surimi were made from frozen Alaska Pollock (*Therangra chalcogramma*) surimi (grade A, American Seafood Company, Seattle, USA). Moisture content was stated to be 74.5 ± 0.3%. Surimi-slices (approx. 3 mm thick) were cut from frozen surimi blocks (10 kg) using a band saw. The frozen slices were immediately vacuum packed and kept frozen at −30 °C. Prior to treatment and analyses, vacuum packaged samples were thawed in water at approx. 5 °C, and left to equilibrate at room temperature. After equilibration, the pouches were cut open and cylindrical surimi disks (Ø = 30 mm) were stamped using a cork borer.

2.2. Heating and cooling

2.2.1. Water immersion

The surimi disks were placed in a metal grid and directly immersed in a water bath (Haake D8, Thermo Haake, Karlsruhe, Germany) using a programmable motorized linear stage elevator device (Long Travel Motorized Linear Stage 8MT195, Standa Ltd., Vilnius, Lithuania) to ensure reproducible immersion time. The samples (n = 10) were heated at temperatures between 70 and 95 °C for different time intervals (2–30 s). After heating, the samples were immediately transferred to ice water (10 min), and subsequently left tilted at an angle of 45° at room temperature (5 min) for removal of excess water and temperature equilibration, prior to spectroscopic measurement.

2.2.2. Steam treatment and cooling

A modified version of the BugDeath test rig, originally described by Foster et al. (2006), was used for steam treatments. The original test rig was designed with four chambers (quadrants) and the heating or cooling medium introduced perpendicular to the surface of the sample. The inlet steam supply was connected to an industrial scale steam generator. The steam pressure was reduced from 4 bar to 2 bar through 2 regulator valves. The outlet of the steam was modified to 22 mm. The amount of steam supplied to the unit was measured by the volume of the condensate formed during heating, and the calculated velocity of steam at the outlet was approximately 22 m/s. The sample was placed 50 mm below the steam outlet.

The surimi disk sample was placed on a sterile Teflon insert (h = 8 mm) in a glass petri dish (Ø = 30 mm). The top surface of the surimi disk was ~2 mm above the petri dish wall. The sample was placed in a holder, exposed to steam heating for pre-designated heating time, and moved to a separate cooling chamber, in which a continuous flow of air was supplied to approx. −2 °C, for 20 s.

2.3. Reflectance spectroscopy

Reflectance spectra were recorded using a XDS Rapid Content Analyzer (FOSS NIR Systems, Inc., Laurel, MD, USA) in the wavelength range of 400–2500 nm. Immediately after the described cooling phase, the samples were placed in a 35 mm quartz cuvette. 32 spectra were recorded per sample. The resolution was 0.5 nm and the field of view, 17 mm. The spectra were collected using Vision software packages (NIRSystems, Silver Spring, USA) and stored in optical density units (absorption), log (1/R), where R was the reflected fraction of the incident light. All spectra were recorded at room temperature. Partial least square (PLS) was used to develop linear regression models of absorption and processing temperature. One data set was not used in the model developed, but set aside for model validation and evaluation. All data analysis was