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Thermal gelation of Pacific whiting surimi in microwave assisted pasteurization

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ABSTRACT

This research invetigated the potential of microwave assisted pasteurization systems (MAPS) for production of molded or thick sheeted products from Pacific whiting (PW) surimi. Prior to MAPS processing, a systematic study was conducted to evaluate the effect of heating rate on textural properties of PW gels by heating surimi paste from 3 °C/min to 24 °C/min. No gel was formed at a slow heating rate (3 °C/min). Gels with greater strength were achieved with higher heating rates. The heating pattern for the surimi pastes in microwave heating was predicted using a gellan gel model food in which 2% salt and 40% sucrose were added to adjust the dielectric properties. Prepackaged PW surimi paste in pouches were pasteurized to a similiar leathal lethalty for non-proteolytic *Clostridium botulinum* spores with MAPS or water bath as control. The breaking force and penetration distance of the PW surimi gels were significantly ($P < 0.05$) higher when processed in MAPS as compared to water bath.

1. Introduction

Surimi is a primary material for various surimi seafood products formed and cooked with different flavor extracts (crab, shrimp, or lobster). By refining myofibrillar proteins from fish mince, surimi is commercially made from various species, such as Alaska pollock (*Gadus chalcogrammus*), various whitings (*Merluccius* spp), cods (*Gadus* spp.), croakers (Family *Scidenidae*), bream and carps (Family *Sparidae* and *Cyprinidae*) and milkfish (*Chanidae* spp). Among them, Alaska pollock and Pacific whiting (PW) are the two main fishery resources for surimi production in the United States (Park, 2014a). Compared to Alaska pollock, PW is more competitive because of its lower price (Lin and Park, 1996). Proteolytic enzymes in the muscle tissue of PW degrade myofibrillar proteins and impede their gel formation, especially when a slow rate of heating is used (Klesk et al., 2000). Washing and rinsing control endogeneous cysteine proteases by removing the entire cathepsin H and almost all of cathepsin B during surimi manufacturing. But cathepsin L bound tightly to myofibrillar proteins remains in the muscle tissue and is difficult to be removed during washing (An et al., 1994). Consequently, severe textural degradation of surimi gel (or incapability to form a gel) occurs if not cooked fast enough or if not heated with appropriate enzyme inhibitors (Park et al., 2014b).

Cathepsin L is a heat activated protease with high specific activity at 55 to 60 °C (Seymour et al., 1994; Visessanguan et al., 2003). Yongsawatdigul et al. (2014) notes that proteases in cold water fish species, such as PW, have optimal activity between 40 and 60 °C, with intramuscular proteases from warm water species having optimal enzyme activity between 50 and 70 °C. Rawdkuen et al. (2007) incubated PW surimi at 55 °C for up to 180 min before heating it at 90 °C for 20 min and observed a degradation of myofibrillar proteins, especially the myosin heavy chain (MHC). The MHC was totally lost when incubated at 55 °C for 30min. Similar results were also found when PW surimi was heated at 60 °C for 30 min (An et al., 1995). Seymour et al. (1994) found that PW endogeneous muscle proteases were denatured at 70 °C. Thus, the time during which surimi is exposed to a temperature range of 40–70 °C greatly influences the final textural properties of the surimi and the surimi seafood products when significant levels of residual endogeneous proteases are present.

Adding food grade protease inhibitors and applying rapid cooking are the two possible solutions to minimize the protease impact on gelation. Beef plasma protein, egg white, whey proteins and potato extracts are effective protease inhibitors (Lanier et al., 1981; Wasson et al., 1993; Weerasinghe et al., 1996). But the addition of protease inhibitors cannot totally control the function of proteases. Thus, rapid cooking methods are recommended to achieve optimal quality of protease-laden surimi gels (Yongsawatdigul et al., 1995). Ohmic heating

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has been proposed as an effective tool to yield high gel strength due to its rapid and uniform heating (Yongsawatdigul et al., 1995, 2014). A heating rate as high as 160 °C/min has been achieved in a laboratoy scale ohmic heating apparatus (Moon et al., 2017). Limited attempts were made to examine microwave heating for the formation of heat induced surimi gels, although microwave or radio frequency heating is a common technique used in the meat industry for tempering frozen blocks. Fu et al. (2012) investigated the effect of microwave heating on silver carp surimi gels, and the mechanical and functional properties of surimi products were improved by microwave heating compared to conventional heating. Riemann et al. (2004), Stevenson et al. (2012) and Liu et al. (2013) studied the gelation response of Alaska pollock surimi heated using microwave heating (Industrial Microwave Systems, Morrisville, NC, USA) (Lanier et al., 2007). For Alaska pollock surimi, which is known to contain limited amounts of proteolytic enzymes, their results indicated that slow heating produced stronger texture than rapid heating. Limited influence of proteolytic enzymes occurred during the heating of the Alaska pollock surimi, so rapid heating did not show any advantages in this case. Also, no real-time temperature was reported during heating nor information about the location of cold and hot spots in the above studies. Thus, a more defined study is required to estimate the potential of using the microwave technology in cooking and further pasteurizing surimi and surimi seafood.

At Washington State University (WSU), Tang and his group have developed a single-mode 915 MHz microwave-assisted thermal sterilization (MATS) technology and a single-mode 915MHz microwave-assisted thermal pasteurization system (MAPS) for production of shelf-stable low acid foods and chilled foods, respectively (Tang, 2015). Typical target process temperatures for MATS are 120–130 °C, and for MAPS are 70–90 °C. By adjusting the microwave power and conveyor speed, WSU pilot-scale MAPS can raise the temperature of different food products to between 70 °C and 90 °C within a short time (1.5–4 min) for control of pathogenic bacteria and viruses (Tang, 2015). However, due to the inherent non-uniform heating associated with microwave heating, the cold spot must be identified to ensure the safety of the pre-packaged foods. A chemical marker-model food system was developed by WSU to determine the heating pattern of MAPS (Wang et al., 2018a). Based on the caramelization reaction, D-ribose and NaOH are commonly used as reactants to produce a chemical marker (Namiki, 1988) that can visually indicate localized heating. A brown color is produced in the model food when heated above certain temperature and heating time, the intensity of the collor increases with temperature and time.

A firm and clear gellan gel formulated by low-acyl gellan gum and $CaCl_2$ was used as a carrier for chemical markers in the heating pattern determination for MAPS (Zhang et al., 2015). The gelation temperature and mechanical properties of gellan gel can be adjusted with different polymer and cation concentrations (Morris et al., 2012; Tang et al., 1997a, 1997b). Also, the dielectric properties can be controlled by adding salt and sugar (Luan et al., 2015a). The heating pattern of the chemical marker-model food system provides the locations of cold and hot spots in microwave heating. Temperature history at the cold spot is then measured for process development (Tang et al., 2018).

Our goal was to explore the potential of using the MAPS to pasteurize packaged PW surimi seafood. The specific objectives were to: 1) study thermal gelation properties of PW surimi gels as affected by heating rates, 2) develop a model food for PW surimi and use the model food to develop a pasteurization process based on MAPS, and 3) compare textural properties of PW surimi gels after processing in MAPS or in a hot water bath.

2. Materials and methods

2.1. Materials

Pacific whiting (*Merluccius productus*) surimi (Grade A) manufactured using 4% sugar, 4% sorbitol, and 0.3% sodium tripolyphosphate was obtained from Pacific Surimi (Newport, OR). Frozen surimi was transported from Oregon State University (Astoria, OR, USA) to Washington State University (Pullman, WA, USA) in a styrofoam container filled with dry ice overnight. The frozen surimi was stored in a freezer at −30 °C before treatment.

2.2. Surimi gel preparation

Surimi samples were prepared according to Yongsawatdigul et al. (1995) to minimize quality degradation. Frozen Pacific whiting surimi was kept at room temperature (23 °C) for 1 h to obtain a core temperature of approximately −5°C, then cut into about 30 mm cubes. A silent cutter (UM 5 Universal, Stephan Machinery Corp, Columbus, OH, USA) equipped with a vacuum pump (to remove air bubbles during mixing) and an ethylene glycol temperature control system (to keep temperature low during mixing) was used for chopping the surimi cubes into a paste. Four chopping steps were followed: first, surimi cubes were chopped at 1800rpm for 1min; second, 1% salt was added into the chopped surimi, then continue chopping at 1800 rpm for 1 min; third, ice water (0 °C) was added to adjust the final moisture content to 76%, then chopping at 1800 rpm for 1 min; then, chopping was conducted at 3600 rpm for 3min under vacuum (0.5–0.6 bar). The prepared surimi paste was packed into a polyethylene bag and then air pockets introduced while placing the paste into the bag were removed using a vacuum packaging machine (ULTRAVAC-225, KOCH Vacuum Packaging, Kansas City, MO, USA).

To study the influence of heating rate on textural properties of surimi gels, the surimi paste was stuffed into custom-built aluminum thermal kinetic testing (TKT) cells (Wang et al., 2018b). The TKT aluminum cell was designed with a 50 mm inner diameter, 5 mm inner height, and 2 mm cell thickness. The top surface of the lid and bottom surface of the base were machined to provide maximum contact with the surfaces of aluminum plates in a heating block system. TKT cells with surimi paste were heated in a computer-controlled heating block system developed at WSU. The heating block system consisted of two aluminum heating plates, each was attached with a heating pad on the side of the plate opposite from the contacting surface with the test cells (Ikediala et al., 2000). Heating rate could be precisely controlled from 0.2 °C/min to 28 °C/min by setting selected number of heating pulses in microsecond time intervals into the data acquisition and control system. For cooking tests, one TKT cell with the surimi paste prepared as described above was placed between the two heating plates in the heating block system. The surimi pastes were preheated to 30 °C, then heated from 30 to 90 °C at one of three heating rate settings: 3, 12 and 24 °C/min. To achieve higher heating rates, surimi pastes were also heated in the heating block system or a water bath (Model HAAKE DC 30, Thermo Electron Corp., Waltham, MA, USA) pre-set at 90 °C. The TKT cells were cooled by submerging into ice water for 5 min immediately after the core temperature reached 90 °C. The surimi samples were removed from the TKT cells and sealed in plastic bags and stored overnight at 4 °C before texture measurement.

For thermal gelation tests in MAPS and water baths, 227.8 g surimi paste prepared as described above was stuffed into a polyethylene pouch and sealed in a vacuum packaging machine (ULTRAVAC-225, KOCH Vacuum Packaging, Kansas City, MO, USA). The final dimension was 140 mm long, 90 mm wide, and 20 mm high. Surimi paste were equilibrated to room temperature before processing in MAPS and water bath.

2.3. Temperature measurement and prediction of surimi in TKT cells

The temperature of surimi paste in the TKT cells was measured using a thermocouple (Type-T, Eutech Instruments, Vernon Hills, IL, USA). For surimi paste processed in the heating block system, the thermocouple was inserted through the side of a TKT cell. For surimi

pastes processed in the water bath, the thermocouple was installed in the middle of the TKT cell lid. In both processes, the endpoint of the sensor was placed in the geometric center of the TKT cell to obtain the temperature history of the slowest heating point of surimi paste. The real-time temperature during heating was recorded using an external Hioki Multichannel Data Logger (Memory Hillogger LR8400, Hioki, Cranbury, NJ, USA).

As a biological material, surimi paste has a low thermal diffusivity leading to thermal lag during heating, especially at high heating rates. Thus, a theoretical estimation of the temperature distribution within the sample during heating was correlated with the accuracy of the temperature measured by the thermocouple. The difference of temperature between the sample surface and sample geometric center during heating at a constant rate can be calculated using the following equation (Carslaw and Jaeger, 1959; Tang et al., 1991):

$$\Delta T = T_s - T_c = \frac{\beta (L^2)}{2\alpha}\left\{1 - \frac{32}{\pi^3}\sum_{0}^{\infty}\frac{(-1)^n}{(2n+1)^3}\, exp\left[\frac{-\alpha(2n+1)^2\pi^2 t}{4L^2}\right]\right\} \quad (1)$$

where T_s is the sample surface temperature, T_c is the sample geometric center temperature, β is heating rate (°C/min), α is thermal diffusivity (m^2/s), L is a half of the sample thickness (m), t is time (s).

The thermal diffusivity of surimi paste was measured using a thermal property analyzer (KD2 Pro Sensor, Decagon Devices, Pullman, WA, USA).

2.4. Model food system preparation for MAPS processing

The standard procedure for developing a microwave assisted thermal process includes determination of cold spots based on thermally induced color changes in a model food containing chemical precursors (Tang, 2015). In this study, gellan gels studied in Wang et al. (2018a) were used as the model food to develop the MAPS process for surimi. Gellan gel model food was prepared by slowly adding 1% (w/v) low-acyl gellan gum (CP Kelco Inc. Atlanta, GA) into distilled de-ionized (DDI) water (23 °C). The mixture was stirred using a magnetic stirrer for 1 h, and then slowly heated to 90 °C. 20 mM $CaCl_2{\cdot}2H_2O$ and 1% (w/w) D-ribose were added into the gellan gum solution (90 °C) with continuous stirring for 5 min. Salt was added to make the final salt concentration 0, 0.2, 0.4, 0.6, 0.8 or 1.0%. Sucrose was also added to make the final sucrose concentration 10, 20, 30 or 40%, and stirred at 90 °C for 5min. Titanium dioxide (0.5%, w/v) was added into the solution (90 °C) and stirred for 15 min. The solution was cooled to 60 °C before NaOH was added and stirred for 1 min to obtain a final NaOH concentration of 30 mM. Gellan solution was poured into 50 mL plastic centrifuge tubes and cooled in a refrigerator (4 °C) prior to measurement of dielectric properties. Gellan solution (226.8g) was poured into 295.7 mL (10 oz) tray and cooled in a refrigerator (4 °C) for 1 h to obtain a gel. This gellan gel model food was placed into a pouch, then vacuum-sealed and equilibrated to room temperature before processing in MAPS.

2.5. Dielectric properties measurement

The (relative) dielectric constant (ε') represents a material's ability to store electric energy, and the (relative) loss factor (ε'′) represents the ability to dissipate the electrical energy into heat. The two dielectric properties are used to evaluate the thermal behavior of food in microwave heating. To match the dielectric properties of surimi paste, salt and sucrose were mixed with a gellan solution adjust the loss factor and the dielectric constant of the model food.

An HP 8752 C network analyzer with 85070B open-end coaxial dielectric probe (Agilent Technologies, Santa Clara, CA, USA) as described in Guan et al. (2004) was used to measure the dielectric properties. Surimi paste or gellan gel model food samples were placed in a jacketed testing cell with an inner diameter of 21 mm and a height of 94 mm; the testing cell was heated through the jacket by a circulating oil bath up to 100 °C, while the corresponding dielectric constant and dielectric loss factor were measured at every 10 °C between 20 and 90 °C. Detailed information of the testing cell is described in Wang et al. (2003). The testing cell was cooled to a temperature lower than 20 °C using a circulator (VWR 1157, VWR Science Products, Radnor, PA, USA). Two samples were tested from each treatment (n = 2) and the average values are reported.

2.6. Penetration depth

Information on the penetration depth of the microwave energy into foods is important for designing the size, especially the thickness, of the packaged food samples in microwave-assisted thermal processes. It is defined as the depth where the incident power decreased to 1/e (Euler's number e ≈ 2.718) of the power entering the material's surface (Von Hippel, 1995), and is calculated from:

$$D_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 + 1} - 1\right]}} \quad (2)$$

where c is the speed of light in free space (3×10^8 m/s), and f is the frequency, which in this study is 915 MHz.

2.7. Microwave-assisted pasteurization process

A pilot-scale single-mode (915 MHz) microwave-assisted pasteurization system was used to process gellan gel model food and surimi samples in 236.6 mL (8 oz) pouches. The MAPS consisted of four sections: preheating, microwave heating, holding and cooling (Fig. 1).

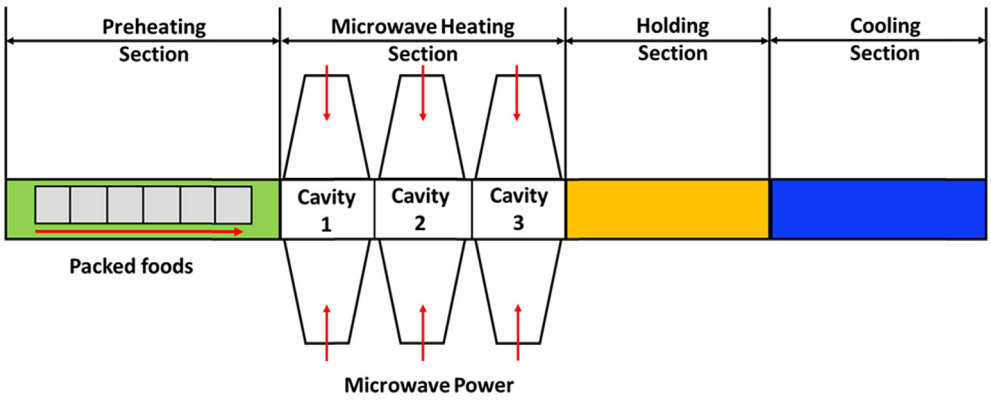

Fig. 1. Schematic diagram for microwave assisted pasteurization system (MAPS).

Three microwave cavities were installed in the microwave heating section, which allowed the sample temperature to increase rapidly. Since microwave heating is not uniform, determination of the heating pattern is required to locate the cold and hot spots for process design (Details refer to Section 2.8).

Eight pouches of gellan gel model food were placed into a carrier and pre-heated in the preheating section for 15 min with a water temperature of 30 °C. The pouches were moved to the microwave heating section where 5.0 kW, 4.4 kW, 4.4 kW microwave power were applied in the first, second and third cavities, respectively. The conveyor moving speed in the was set at 40 inches/min. In this section, water immersion was applied to reduce edge heating (Tang, 2015). Following microwave heating, the pouches were moved to the holding section and held for 100s where the temperature was maintained at 90 °C with circulating water. After that, the pouches were moved to the cooling section and held for 5 min with a water temperature of 25 °C. The processed pourches of model food were then unloaded for heating pattern determination.

Similar to the processing procedures of gellan gel model food, packaged 226.8 g surimi pastes were placed in the carrier and pre-heated at 30 °C for 15 min. To achieve desired level of pasteurization the conveyor speed was adjusted to 26 inches/min with 5.0 kW, 4.4 kW, 4.4 kW microwave power applied in the first, second and third cavities, and holding time was increased to 360 s. In the cooling section, cooling time increased to 10 min to collect more data for thermal lethality calculations. The process was designed to achieve a minimum temperature of 90 °C for 10 min at the cold spot to obtain more than 6 log reduction of non-proteolytic *Clostridium botulinum* (Wang et al., 2018b, Peng et al., 2017). The processed surimi samples were stored overnight at 4 °C before gel textural properties measurement.

2.8. Heating pattern determination and validation

Previous studies indicated that the cold spot was located in the middle layer of the food sample in the microwave assisted thermal process (Resurreccion et al., 2013; Tang et al., 2008). Thus, the processed gellan gel model foods were cut horizontally along the middle plane. A Computer Vision System (CVS) was used to take images of the middle layers (bottom part). Detailed information about CVS was described in Zhang et al. (2014). Based on the image of the middle layer, the heating pattern was analyzed by CS6 Photoshop software (Adobe Systems, Inc., San Jose, CA, USA) and IMAQ vision builder (National Instrument Product, Austin, TX, USA) with a script designed by Pandit et al. (2007).

Validation of the heating pattern was conducted by measuring the temperature history of the cold and hot spots of packaged 226.8 g surimi paste. The locations of the cold and hot spots were determined by comparing the average value of the prominent temperature zones. A mobile metallic temperature sensor (TMI-USA Inc., Reston, VA, USA) is a reliable and accurate method to measure the temperature profile of cold and hot spots in microwave assisted thermal processes (Luan et al., 2013, 2015b). In operation, the mobile metallic sensors with a protective metal tube (diameter 2 mm, length 50 mm) were horizontally inserted into the middle layer of the surimi paste, the end points of the sensors were placed at the location of the cold and hot spots. Temperature profiles were generated to validate the heating pattern, also as a reference for processing design to meet the requirement of pasteurization. The difference of the cold and hot spot was around 10 °C after the microwave heating section.

2.9. Thermal gelation of surimi paste in a water bath

To simulate conventional heating, 226.8 g surimi paste in sealed pouches was heated in a water bath. The paste was equilibrated to room temperature (23 °C) before being immerged in the water bath at 30 °C for 15 min which was the same preheating procedure used for MAPS. After preheating, the packaged surimi pastes were moved to 90 °C water bath holding for 38 min to achieve a similar lethality (equivalent to 90 °C-10 min) at the cold spot as that of the MAPS process. After that, the samples were cooled by immersing into water at 23 °C. Cooked surimi gels were stored overnight at 4 °C before measuring gel texture. To measure the temperature of the cold and hot spots, the TMI mobile metallic temperature sensors were inserted into the surimi paste before sealing the pouch. The cold spot for the sample was located at the geometric center, and hot spot was in the middle layer of any corner within 5 mm to the edge of the sample. The end points of the TMI mobile sensors were placed in the exact locations of cold and hot spots.

2.10. Gel textural properties evaluation

Gel textural properties evaluation was conducted using a TA-XT2 Texture Analyzer (Stable Micro Systems Ltd., Surrey, U.K.) with a 5 kg load cell. A 5 mm diameter spherical probe (Stable Micro Systems, TA-8B) was used for the puncture test. The probe moving speed was set at 1 mm/s to a depth of 15 mm, and the breaking force (g) and penetration distance (mm) were recorded by the Texture Expert software (version 1.15, Stable Micro Systems Ltd).

All cooked gels were equilibrated at room temperature (23 °C) for 2 h prior to testing. A sample holder was designed to hold the surimi following cooking in TKT cells. The sample holder had the same dimension as that of the TKT cells. In addition, the top lid and bottom base had a 10 mm diameter opening to allow the probe to penetrate (Fig. 2a and b). In the gel textural properties measurement, a surimi sample was carefully moved to the sample holder. The sample holder was placed on a cylindrical stand with a 30 mm height cavity. During the measurement, a spherical probe penetrated the sample through the center of the opening. The breaking force and penetration distance were recorded. Ten surimi samples were tested from each treatment (n = 10) and the average values were reported.

For textural property measurement of the surimi samples processed

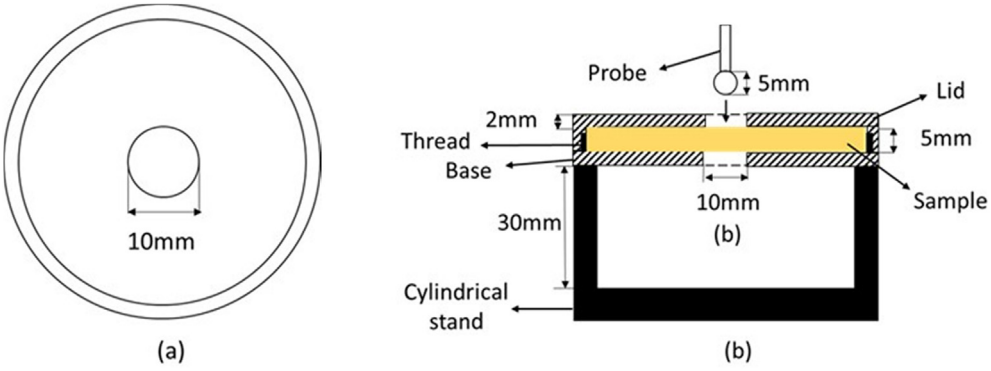

Fig. 2. (a) Sample holder for texture analyses (b) cross-section of sample holder and cylindrical stand.

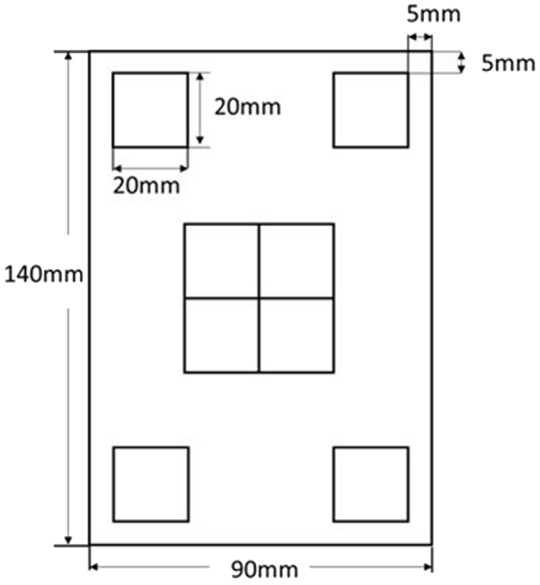

Fig. 3. Sampling from cold and hot spots of the 226.8 g surimi sample.

in the water bath, 20 mm cubes were cut out of the cold and hot spot zones as indicated in Fig. 3. The hot spots in the surimi were located in the four corners of the sample, and the cold spot was located in the geometric center of the sample. Similar to the sampling of surimi processed in the water bath, 20 mm cubes were also cut out of the corresponding cold and hot spot zones in samples processed with MAPS for surimi gel textural properties measurement. Ten surimi samples were tested from each treatment (n = 10) and the average values were reported.

2.11. Data analyses

Analysis of variance (ANOVA) was conducted by using SAS (SAS Institute Inc., Cary, NC, USA) and the significance level P was set at 0.05 probability level.

3. Results and discussion

3.1. Temperature profiles of surimi processed with different heating rates

Temperature differences between the surface and geometric center (cold spot) of PW surimi heated using the heating block system are illustrated in Fig. 4. Thermal diffusivity of surimi was 0.152×10^{-6} m^2/s measured by the KD2 Pro Sensor. The predicted temperature profiles of the samples in the heating block system set a ramping rate of 3 °C/min, 12 °C/min and 24 °C/min were very close to the temperatures measured by the thermocouple (Fig. 4a, b and c). The time required for the surimi geometric center to reach 90 °C were 21.1, 5.2 and 3.5 min. The higher the heating rate, the larger the thermal lag between the surface and center (Carslaw and Jaeger, 1959; Tang et al., 1991). For surimi paste processed in the heating block and water bath with the temperature maintained at 90 °C, the time required for the center to reach 90 °C were 2.9 and 2.3 min (Fig. 4d). Thus, the time required to reach to 90 °C from low to high were 3 °C/min, 12 °C/min and 24 °C/min, heating block at 90 °C and water bath at 90 °C.

3.2. Textural properties of surimi gel processed at different heating rates

Effects of heating rate on the breaking force and the probe penetration distance (brefore breaking) of PW surimi gels are shown in Fig. 5. No gel was formed of surimi processed with heating rate at 3 °C/min. Gel was formed after heating at and above 12 °C/min. Both the breaking force and the penetration distance significantly increased ($P < 0.05$) with the increasing heating rate, demonstrating that a stronger gel was obtained with the higher heating rate. Textural properties of the surimi pastes heated at 24 °C/min, in heating block at 90 °C and water bath at 90 °C were similar with no significant loss in gel strength. The texture of the 5 mm thick samples heated in 90 °C water bath was comparable to thatat 24 °C/min or in 90 °C heating block. This is because proteolytic enzymes in Pacific whiting surimi was inactivated quickly in 5 mm thick samples.

Myofibrillar proteins constitute 66–77% of total proteins in fish mince (Suzuki, 1981). During the thermal process, heat induced the association of unfolded proteins, allowing neighboring protein molecules to interact each other, and bond together into a three-dimensional network (Park, 2014b). The main reason for no gel formed at 3 °C/min was that the myofibrillar proteins were degraded by proteoylytic enzymes during slow heating. In the current study, the time required from 40 to 70 °C for surimi processed with 3 °C/min, 12 °C/min, 24 °C/min, heating block at 90 °C and water bath at 90 °C were 10 min, 2.5 min, 1.3 min, 0.7 min and 0.4 min, respectively. No gel formed at a heating rate of 3 °C/min demonstrating that the 10 min taken to traverse 40 to 70 °C was long enough for the residual proteases to degrade myofibrillar proteins. The breaking force and penetration distance for surimi pastes heated at 24 °C/min were almost twice of those heated at 12 °C/min. But no significant difference ($P > 0.05$) was found for surimi paste sample heated at a rate among 24 °C/min, heating block at 90 °C and water bath at 90 °C (Fig. 5). This indicates that protease inactivation was insufficient at 12 °C/min heating rate and a higher rate was needed to reach the enzyme inactivation temperature quickly enough to reduce proteolytic degradation. Similar results were observed by Yongsawatdigul, and Park (1996) that PW surimi gels were very soft and mushy with heating rates at 1 and 5 °C/min, but rheological properties were measurable starting 10 °C/min. Shear stresses and shear strains for samples heated at 20 and 30 °C/min were higher than that heated at 10 °C/min, but no difference in shear stress between 20 and 30 °C/min. The results demonstrate that rapid heating is an effective approach to achieve stronger gels for PW surimi. However, gel textures were similar once the heating rates are higher than a certain point where residual proteases are completely inactivated.

3.3. Effect of salt and sucrose on dielectric properties and penetration depth

In dielectric heating, similar temperature rises can be achieved if different foods have similar thermal and dielectric properties (Ryynänen, 1995). To determine the heating patterns of different foods, the dielectric properties of the gellan gel model food should be adjustable. As common food ingredients, salt and sucrose have been used to adjust the dielectric properties of the gellan gel model food (Luan et al., 2015a).

Adding salt significantly increased the dielectric loss factors but had limited effect on dielectric constant of the gellan gel model food (Fig. 6). However, adding sucrose has a significant effect on the dielectric constant, in agreement with previous studies (Guan et al., 2004; Morris et al., 2012; Stogryn, 1971). At a sucrose concentration of 40%, the dielectric constant of the gel model food matched that of surimi, including its temperature dependence. A combination of the addition of 40% sucrose and 2% salt in model food was appropriate for heating pattern determination of surimi in thermal processes with MAPS. It is clear from Fig. 7, 915 MHz microwaves have the same penetration depth in the gellan gel model food with 40% sucrose and 2% salt and in surimi between 20 and 90 °C. Schiffmann (1995) suggested that the thickness of the food samples less than two times of the penetration depth could achieve more uniform heating (along the depth of a food tray) in a dielectric heating system. Since equal amount of 915 MHz microwave was applied in phase from both the top and bottom horn of the cavities (Tang, 2015) in a MAPS, the thickness of the sample should be less than four times of the penetration depth. In this study,

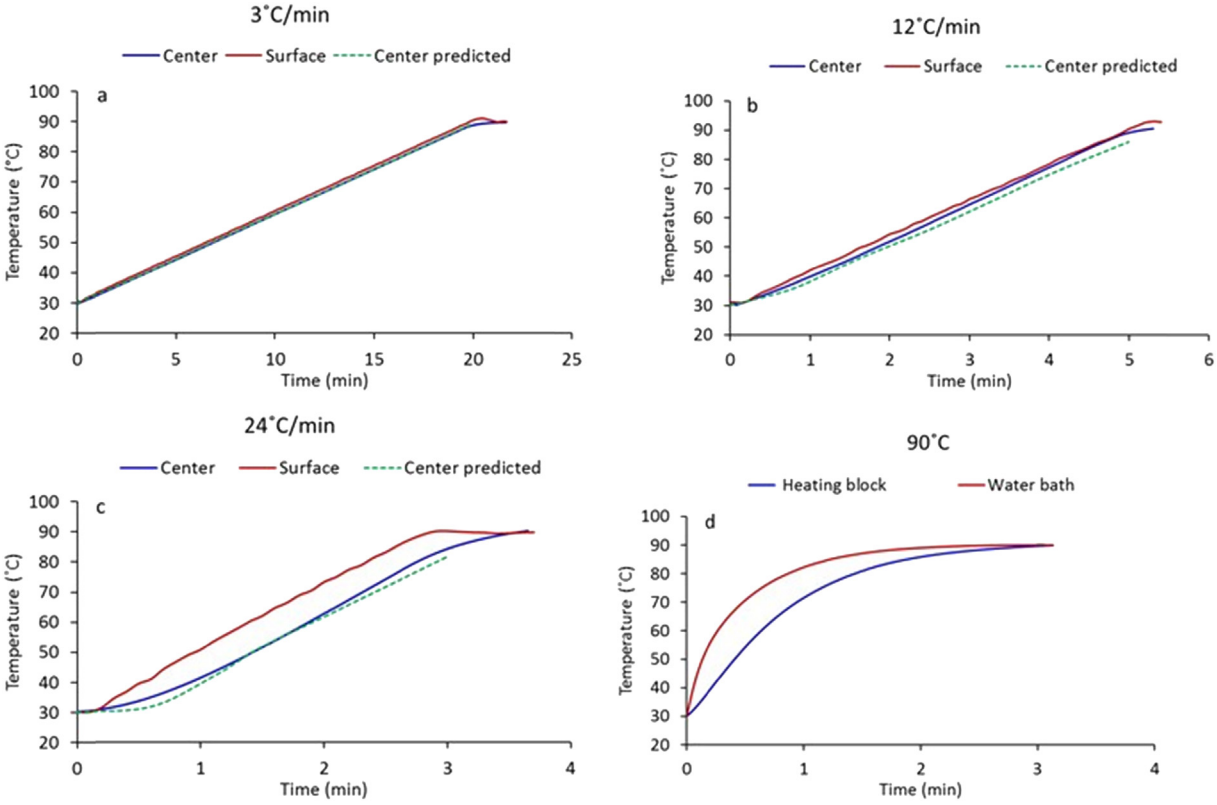

Fig. 4. Temperature profiles of PW surimi processed at three different temperate ramping settings in the heating block system a). 3 ˚C/min, b). 12 ˚C/min, c). 24 ˚C/min, and d). direct heating in 90 ˚C heating block and water bath.

thicknesses of the packaged surimi paste in pouches ranged from 20 to 22 mm, which were less than 28 mm (4 × 7 mm) when the samples were heated to 90 ˚C.

3.4. Heating pattern in MAPS process

After processing in MAPS, the heating pattern in the gellan gel model food is shown in Fig. 8. The color from red to blue represented the thermal intensity from high to low. In Fig. 8, zone 1, 2, 3 and 4 shown in red correspond to hot zones, and received high thermal energy. Zone 5 in blue corresponds to the cold zone, and received the least thermal energy. Among all four hot zones, the zone 4 had the most intensive red color. Thus, the exact locations of the hot and cold spots were in zone 4 and 5, respectively. The CVS was used to divide the zone 4 and 5 into many small grids, and the most red and blue spots were located. The length and width of the packaged sample were measured as 140 mm and 90 mm, respectively. The geometric center was defined as (0, 0), the numeric locations of cold and hot spots were measured and presented as relative coordinates. The cold spot and hot spot were found at 1.7 mm, −22.5 mm and 32.5 mm, −52.4 mm, respectively. The numeric locations were used as reference for the following discussion of the temperature histories at the cold and hot spots.

3.5. Surimi paste pasteurized in MAPS and water bath

The United States Food and Drug Administration (FDA) suggests a minimum 6 log reduction of *Listeria monocytogenes* and nonproteolytic *Clostridium botulinum* types B and E by equivalent thermal treatment of 70 ˚C for 2 min and 90 ˚C for 10 min, respectively, for the pasteurization of chilled, vacuum packed surimi seafood (FDA, 2011). Thus, the $F_{90˚C}$

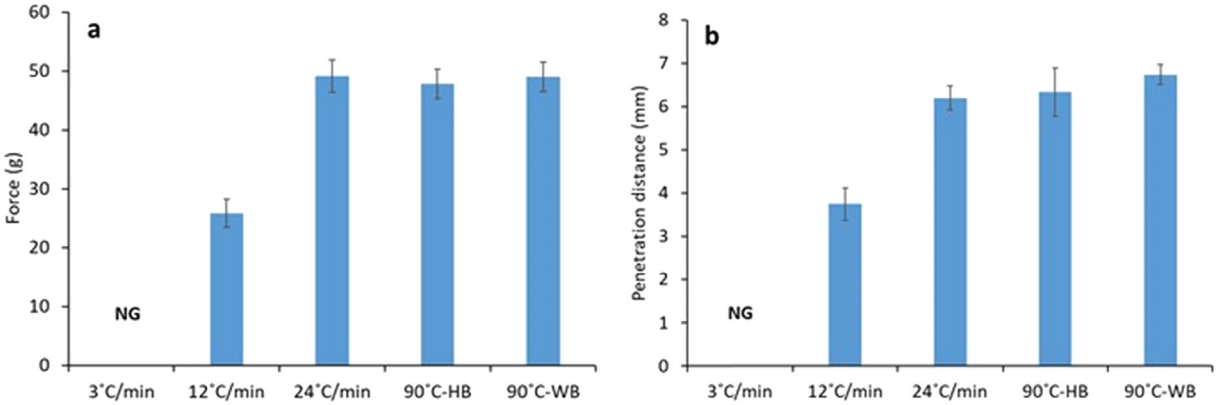

Fig. 5. Breaking force (a) and penetration distance (b) of surimi processed at 3 ˚C/min, 12 ˚C/min, 24 ˚C/min, 90 ˚C -HB (heating block) and 90 ˚C -WB (water bath). NG- No gel formed. The data represent average of ten replicates.

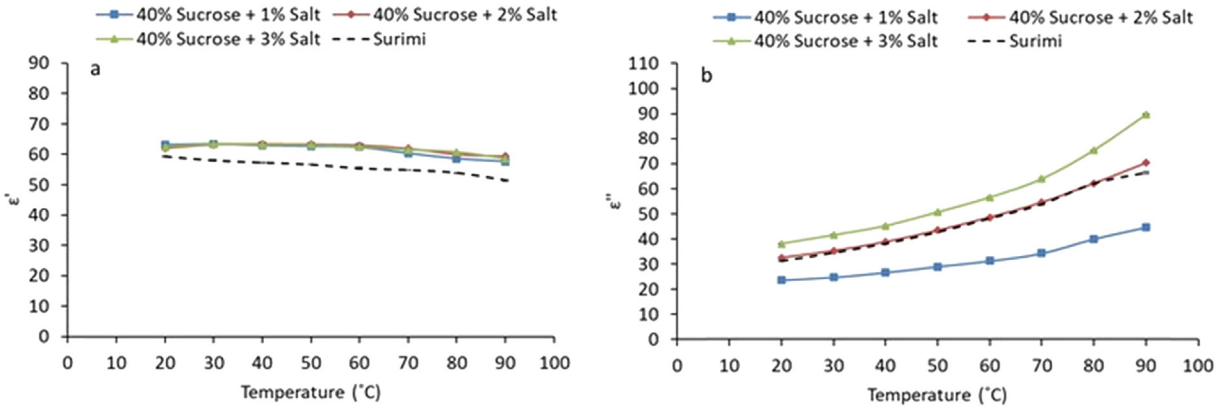

Fig. 6. The effect of salt and sucrose on the dielectric constant (a) and dielectric loss factor (b) of a gellan gel at 915 MHz between 20 and 90 °C. The data represent average of two replicates.

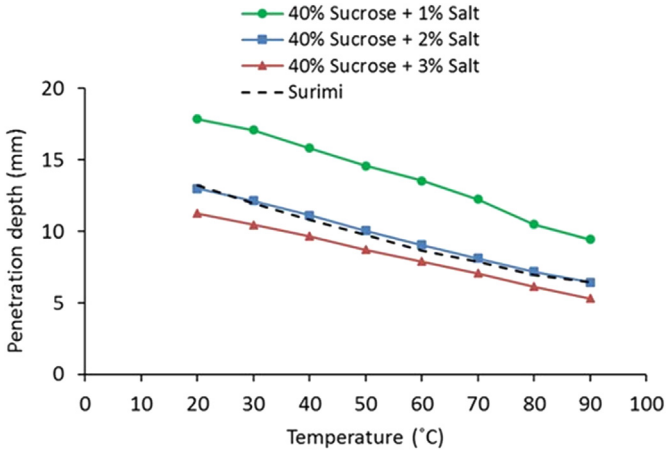

Fig. 7. Effect of salt and sucrose on penetration depth of gellan gel model food at 915 MHz between 20 and 90 °C.

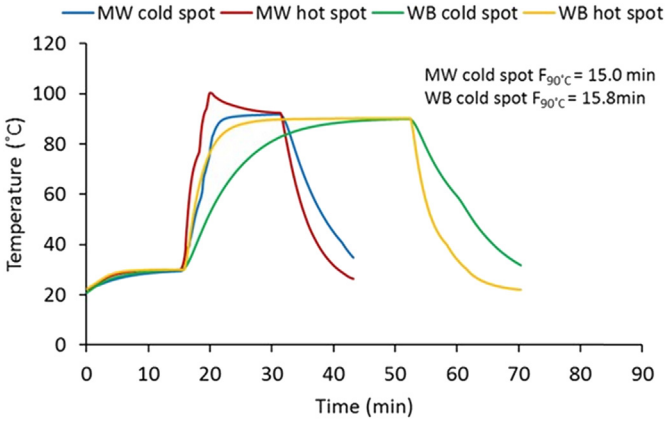

Fig. 9. Temperature profiles at the cold and hot spots of 226.8 g surimi in MAPS and water bath. WB: Water bath; MW: Microwave.

value higher than 10 min was the target for the surimi paste pasteurization. The temperature profiles at the cold and hot spots of the packaged surimi paste in the MAPS process are shown in Fig. 9.

For surimi pastes processed in the MAPS, the temperature of both cold and hot spots reached 30 °C after preheating at 30 °C for 15 min. In the following microwave heating section, the temperature of both the cold and hot spot increased quickly. The temperature of the cold spot reached close to 90 °C, and the hot spot surpassed 90 °C to the highest 99 °C after the microwave heating section. The temperature of the hot spot was consistently higher than the cold spot in the microwave heating sections. Such differences validated the locations of cold and hot spots determined from the heating pattern using the gellan gel model food.; temperature of cold spot was maintained at 90 °C during the holding section, then decreased to around 30 °C after cooling in 25 °C for 10 min. The overall $F_{90°C}$ of the cold spot in MAPS was

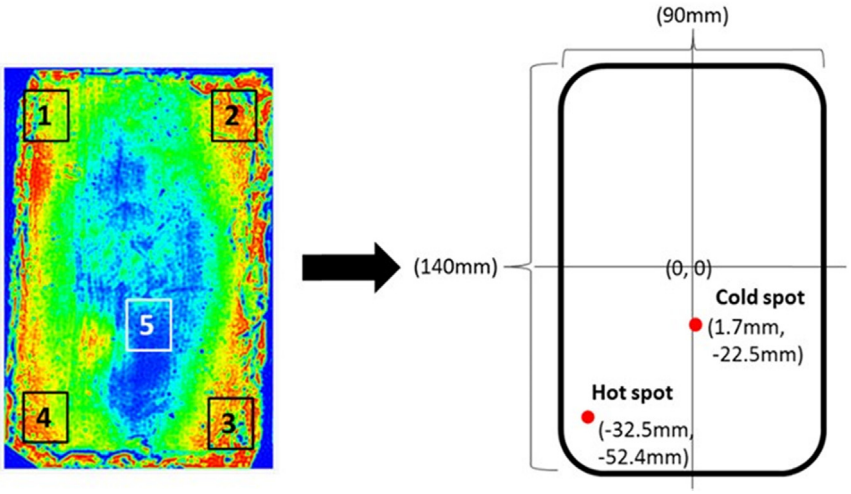

Fig. 8. Heating pattern (a) and cold/hot spot location (b) of 226.8 g gellan gel model food in MAPS.

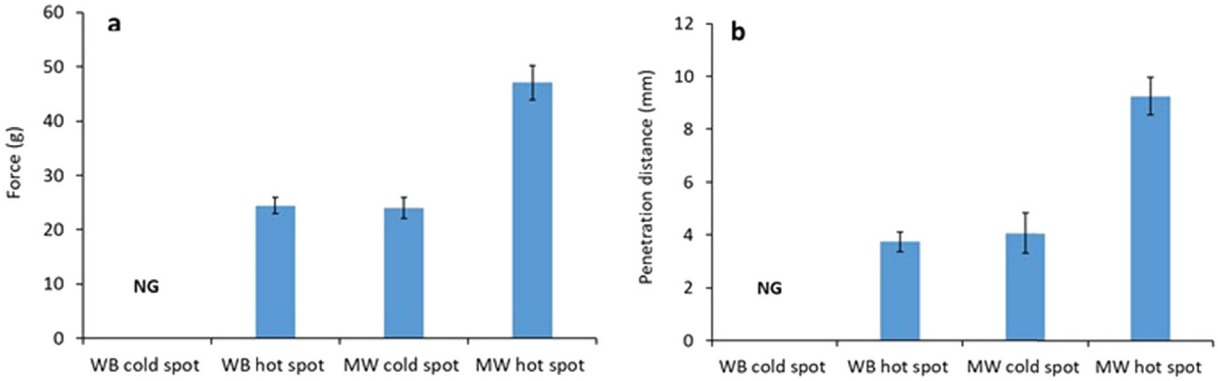

Fig. 10. Textural properties of surimi processed in MAPS and water bath. WB: Water bath; MW: Microwave. The data represent average of ten replicates.

15.0 min. For surimi paste processed in the water bath, both the cold and hot spots reached 30 °C after preheating. Surimi pastes were moved to water bath at 90 °C. Both the temperature of the cold and hot spots increased with time. The cold spot took around 30 min, and hot spot took less than 10 min to reach close to 90 °C. The overall $F_{90°C}$ of the cold spot in the water bath was 15.8 min.

The breaking force and the penetration distance for the surimi processed in MAPS and water bath are shown in Fig. 10. No surimi gel was formed in the cold spot zone when heated in a water bath. This can be contributed to the activity of cathepsin L which degraded the myofibrillar proteins in slow cooking (An et al., 1994). The average breaking force of surimi gel located at the hot spots in water bath was 25 g and penetration distance was 4 mm, which is significantly higher compared to that at the cold spot. Gel was formed at the cold spot of surimi paste processed in MAPS. The average breaking force and penetration distance was 24 g and 4 mm, which were similar to ($P > 0.05$) the textural properties of surimi hot spot in water bath. Both the breaking force (47 g) and penetration distance (9 mm) significantly increased for gels heated at the hot spot compared to the cold spot of surimi processed in MAPS or for those processed in the hot water bath.

As discussed in section 3.2, rapid heating is an effective approach to overcome the influence of proteolytic degradation in PW surimi. The heating rates of the sample cold spot and hot spot in water bath , the sample cold spot and hot spot in MAPS were approximately 4°C/min, 12 °C/min, 11.5 °C/min and 23 °C/min, respectively. In particular, it took 7 min for the temperature of the sample cold spot in water bath to increase from 40 to 70 °C, such slow heating resulted in no gel formation. Microwave heating significantly increased the heating rate during thermal gelation of surimi paste. The heating rate of the cold spot was about half of the hot spot in MAPS, which resulted in a gel of half the strength. A stronger gel at the cold spot could be achieved by increasing the microwave power and reducing the conveyor speed of MAPS. Although the heating rate of the hot spot will also increase correspondingly, but a heating rate higher than 23 °C/min had limited effect on textural properties once the surimi gel was formed (Fig. 5). Therefore, stronger gels could be formed from PW surimi paste by MAPS as compared to that processed with a conventional water bath heating, since the much shorter time it takes for MAPS to bring product temperature a level at which proteases are inactivated. Current research may be applied for the pasteurization of surimi seafood and further for the heating process of thick filament sheets or blocks made using protease-laden surimi like PW surimi.

4. Conclusions

Heating rate greatly influenced thermal gelation of surimi samples. No surimi gel was formed with heating rate at 3 °C/min. Surimi gels started to form when heated at 12 °C/min. The gel strength increased as the heating rate increased from 12 °C/min to 24 °C/min. No further increase in gel strength was observed when heated at 24 °C/min in heating block pre-set at 90 °C and or in a water bath at 90 °C. Thus, the heating rate of 23 °C/min at the geometric center of surimi in 8 oz pouches in a MAPS process was fast enough to overcome the influence of proteolytic enzymes in PW surimi. The dielectric properties of a gellan gel model food with 2% salt and 40% sucrose matched that of PW surimi. A clear heating pattern was obtained and cold and hot spot locations were determined in the 226.8 g surimi samples for MAPS. After thermal processing with MAPS to reach 90 °C −10 min at the cold spot in the 8 oz pouches, the breaking force of the surimi gel at the hot spot were twice as high as the cold spot. But no gel was formed at the cold spot of surimi samples in 8 oz pouches when heated in a water bath. Thus, MAPS is effective in producing strong surimi gels from PW surimi paste. More research is needed to improve the heating uniformity of MAPS which would benefit the texture uniformity of PW surimi and potentially other gel based food products.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfoodeng.2019.04.001.

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