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Development of a novel approach to determine heating pattern using computer vision and chemical marker (M-2) yield

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Abstract

In this study, a novel approach to determine heating patterns using chemical marker (M-2) yield and computer vision was developed for packaged foods after microwave sterilization. Due to various constraints of temperature measurement devices such as fiber-optic temperature sensors, thermocouples, and infrared sensors, there is a need to develop an accurate and rapid method to determine heating patterns in packaged food trays after microwave sterilization. Yield of a heat sensitive chemical marker (M-2) was used as a coloring agent and digital images of the processed trays were analyzed using a computer vision system. A script in IMAQ vision builder software was written to obtain a 3-D heating pattern for the sterilized trays. Relationship between chemical marker (M-2) yield and cumulative thermal lethality (F_0) was also studied. Validation of the locations of cold and hot spots determined by computer vision were performed by fiber-optics temperature measurement sensor. Results show that computer vision in combination with chemical marker M-2 and other accessories can be used as a rapid, accurate and cost efficient tool to specify the location of cold and hot spots after microwave sterilization.

Keywords: IMAQ vision builder; Chemical marker M-2; Computer vision; Machine vision; Digital image processing; Cold and hot spots; Microwave heating; Sterilization

1. Introduction

Computer vision is a technology for acquiring and analyzing a digital image to obtain information or to control processes. Computer vision can be a successful tool for online measurement of several food products with applications ranging from routine inspection to complex vision monitoring (Gunasekaran, 1996). Du and Sun (2004) presented a review about recent developments in the application of image processing techniques for food quality evaluation and pointed out many opportunities for image processing in the food industry. Computer vision includes capturing, processing and analyzing images to assess the visual quality characteristic in food products (Gonzalez & Wintz, 1991). It is the construction of an explicit and meaningful description of physical objects from images (Ballard & Brown, 1982). Computer vision is a branch of science that develops the theoretical and algorithmic basis by which useful information about an object or scene can be automatically extracted and analyzed from an observed image, image set or images sequence (Haralick & Shapiro, 1992). The technology aims to duplicate and augment human vision by electronically perceiving and understanding an image (Sonka, Hlavac, & Boyle, 1999). Recent advances in hardware and software have expanded this technology by providing low cost powerful solutions, leading to more studies on the development of computer vision systems in the food industry (Locht, Thomsen, & Mikkelsen, 1997; Sun, 2000).

The increased awareness and sophistication of consumers has created the expectation for improving quality in

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Nomenclature

C	marker yield (mg/g of sample)	LUT	look up table
C_0	initial marker yield at saturation (mg/g of sample)	R	universal gas constant at reference temperature (cal/mol K)
C_∞	marker yield at saturation (mg/g of sample)	t	time (min)
E_a	activation energy (kcal/mol)	T_0	reference temperature
F_0	cumulative thermal lethality (min)	T	temperature (K)
k_0	reaction constant at reference		

food products. This in turn has increased the need for enhanced quality monitoring. Microwave sterilization is a thermal method that has promise to produce high quality and shelf stable foods (Guan et al., 2003; Zhang, Datta, Taub, & Doona, 2001). To design new thermal processes that ensure adequate sterility for shelf stable foods, it is necessary to determine the locations of cold and hot spots during microwave sterilization. The cold spot is the region which receives the lowest thermal energy and the hot spot is the region of highest thermal energy reception. In order to meets the stringent requirement of food regulation bodies, there is a need to develop reliable and rapid methods to determine the heating pattern, especially the location of cold spots.

A chemical marker method was developed at the United States Army Natick Research Center (Kim & Taub, 1993) to correlate heating intensity with development of brown color through the Maillard reaction. The chemical marker M-2 (4-hydroxy-5-methyl-3(2*H*)furanone) is formed by reaction between D-ribose and amines through non-enzymatic browning reaction after enolization under low acid condition (pH > 5). The yield of M-2 can be used as means to detect the degree of thermal treatment at any location of processed homogeneous foods.

High performance liquid chromatography (HPLC) can be used to determine the chemical marker yield (M-2 yield) at different locations of microwave-sterilized food (Pandit, Tang, Mikhaylenko, & Liu, in press). It was observed that HPLC analysis is a costly and time consuming method to determine the heating pattern. A rapid analysis of the heating pattern for different layers of processed foods was not possible by HPLC method. Automated visual inspection may be the best possible option because of its cost effectiveness, consistency, superior speed and accuracy.

This study deals with the application of Image Acquisition (IMAQ) Vision Builder software, digital imagine systems, and chemical marker M-2 yield as a tool to map heating patterns of thermally treated homogeneous food products. Specific objectives of this study were as follows: (1) to establish a relationship between thermal cumulative lethality (F_0) and chemical marker (M-2) yield, (2) to develop a novel method using computer vision systems and chemical marker (M-2) yield to locate the cold/hot spots, (3) to verify the specified cold/hot spots locations.

This information will help in evaluating the heating uniformity as well developing a monitoring procedure to ensure safe level of microwave sterilization.

2. Materials and methods

2.1. M-2 marker yield as a coloring agent

Instant mashed-potato flakes acquired from Oregon/Washington Potatoes Co. (Boardman, OR) was selected as the model food and the accumulation of M-2 marker yield as a coloring agent to quantify the amount of thermal energy at a point. The mashed potato sample was prepared with 1.5% D-ribose and a moisture content of 83.12% (wb). Polymeric trays $14 \times 9.5 \times 2.67$ cm (7 oz) were filled with 200 g of mashed potato and vacuum-sealed at 18 in. of Hg vaccum. Each tray was fitted with a thermo well located in the middle to monitor temperature at the single point using a fiber-optic temperature sensor. The single-mode 915 MHz microwave sterilization system developed at Washington State University, Pullman, WA was used a source of energy and trays were kept in stationary at the center of pressurized microwave cavity. Trays were heated to various F_0 values ranging from 3.7 to 18.

F_0 is a quantitative measurement of the degree of cumulative thermal lethality which is explained as (Holdsworth, 1997):

$$F_0 = \int_0^t 10^{\frac{T-T_{\mathrm{ref}}}{z}} \mathrm{d}t \tag{1}$$

where z is defined as change in temperature to increase the rate of inactivation by a factor of ten (Holdsworth, 1997). T is a temperature in °C at any time t during microwave heating. For thermal processes to produce shelf-stable low acid foods, *Clostridium botulinum* type A and B are the targeted bacteria, z for this bacterium is about 10 °C and T_{ref} is considered as 121.1 °C (Prescot, Harley, & Klein, 2002). Typically, in commercial canning practices, F_0 varies between 3 and 12 min depending upon raw material and storage conditions for the processed foods.

The temperature history of the monitored point was saved at 2 s intervals in each experiment. A sample weight between 0.20 and 0.21 g was taken out precisely from the region around the sensor tip for HPLC analysis. M-2 marker yield for each F_0 at any given power level was calculated from M-2 peak area obtained after HPLC analysis. Chemical marker (M-2) yield was expressed as mg/g of sample using slope of the calibration curve established for a commercial chemical marker sample by Givaudan Flavor Corporation (Cincinnati, Ohio). Mathematically yield of chemical marker (M-2) during heating process is expressed as:

$$C(t) = C_\infty - (C_\infty - C_0) \times \exp\left\{\int_0^t -k_0 \exp\left(-\frac{E_a}{R}\left[\frac{1}{T(t)} - \frac{1}{T_0}\right]\right) dt\right\} \quad (2)$$

where $C(t)$ is marker yield at any time, C_∞ is marker yield at saturation, E_a is energy of activation, R is molar gas constant, $T(t)$ is recorded temperature–time history at the measured point, T_0 is reference temperature. Initial marker yield before heating, C_0, was determined as zero for mashed potato sample with 1.5% D-ribose. Kinetic parameters were calculated using statistical analysis (Lau et al., 2003; Pandit et al., in press; Wang, Lau, Tang, & Mao, 2004) software SAS System Release 8.1 (SAS Institutes, CARY, NC, 2000).

Experiments were also conducted to correlate the intensity of color measured using IMAQ vision builder software and degree of thermal lethality (F_0) during microwave sterilization. Mashed potato with 1.5% D-ribose in 7 oz trays with fiber-optic temperature sensors fitted in the center of trays were sterilized for various level of F_0. IMAQ vision builder software was used to determine the color value at the tip of the fiber-optic probes for each level of F_0.

2.2. Microwave as a source of energy

Ten ounce trays ($14 \times 9.5 \times 3.3$ cm) were selected for studying the heating pattern of the sterilization process in the pilot-scale 915 MHz microwave sterilization system. The system configuration was specially designed to ensure that the cold spot was located in the center of the 10 oz tray of mashed potato by adjusting phase difference of microwave from top and bottom of the tray. Mashed potato samples with 1.5% D-ribose were prepared with three different salt content levels: 0%, 0.5% and 1%. Salt concentration was changed to alter the dielectric loss of the mashed potato so that the study can be applied to a broad range of homogenous foods with different dielectric properties. Trays were heated at 2.67 kW power levels with a repeatable heating pattern. Fiber-optic sensors were fitted at the center of each tray and the trays were heated to a temperature of 121 ± 2 °C. After heating up to the set temperature, trays were rapidly cooled down to room temperature and taken out from the microwave cavities. To stop further chemical marker formation as well as to harden the processed mashed potatoes, the processed trays were cooled in the deep-freezer at -35 °C for 30–45 min. Hardening of the processed trays in the deep-freezer made it easy to cut the mashed potatoes into layers. In this study, the mashed potatoes were cut into vertical and middle layers and pictures of each layer were taken to analyze the results.

2.3. Image processing system configuration

Computer vision systems generally consist of five basic components: a digital camera, an image capturing box, illumination, computer hardware and software as shown in Fig. 1. A digital camera (Olympus C-750 Ultra Zoom) was set on top of a wooden box ($40 \times 30 \times 24$ cm) and an illuminating round light was mounted inside the box. The resolution of digital camera was 2288×1712 pixel. Even illumination is an important prerequisite in image acquisition for food quality evaluation. A wide variety of light sources and lighting arrangements are available (Tao, Chance, & Liu, 1995). The quality of the captured image can be greatly affected by the lighting condition and a

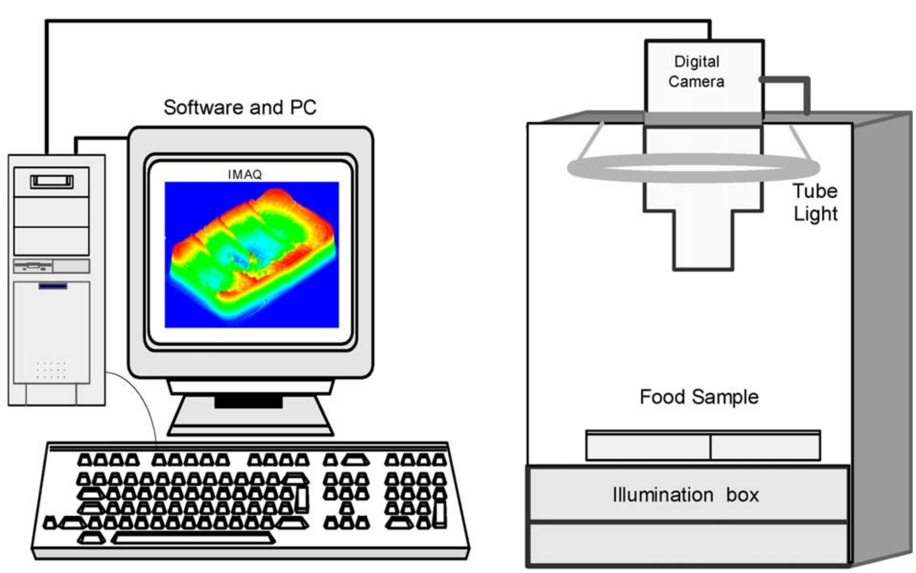

Fig. 1. Components of a computer vision system.

well-designed illumination system can help to improve the success of the image analysis by enhancing the image contrast (Novini, 1995). The camera was mounted perpendicular to the surface of the tray. The lighting system was arranged to provide the contrast necessary between the object under inspection and the background. The used camera provided adequate resolution to meet the minimum requirements of the software. National Instrument software Image Acquisition Vision Builder version 6.1 was installed on 80 GB Pentium IV of RAM 1 GB dell desktop system.

2.4. IMAQ vision builder to locate cold and hot spots

Image processing analysis with the above-mentioned system consisted of six steps (Fig. 2): (1) sample preparation, (2) image acquisition, (3) system calibration, (4) noise filtering, (5) script development, and (6) result analysis.

Image acquisition, that is the capturing of an image in digital form, is the first step in any image processing system. IMAQ Vision is a library of LabVIEW (National Instrument product, Austin, TX) that can be used to develop a computer vision work. Through interactive programming on sample trays, the following batch script was developed:

(i) *Simple calibration*—when camera axis is perpendicular to the image plane and lens distortion is negligible, a simple calibration is used to calibrate the image setup. In the sample calibration, a pixel coordinate is transformed to a real-world coordinates through scaling in the x and y directions. To express measurements in real-world units; a coordinate system was defined by specifying origin, angle, and axis direction.

(ii) *Extract color planes: HSL*—saturation breaks down a color image into various set of primary components such as HSL (Hue, Saturation, and Luminance). Each component becomes an 8-bit image that can be processed as gray scale image. Two principal factors—the coupling of the intensity component from the color information and close relationship between chromaticity and human perception of color makes the HSL space ideal for developing machine vision applications.

(iii) *Image mask-from ROI*—region of interest (ROI) is an area of an image in which we want to focus our image analysis. ROI can be defined interactively, programmatically, or with an image mask. An area of the image that is graphically selected from a window displaying the image.

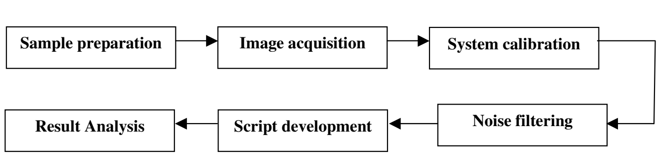

Fig. 2. Major steps involved in heating pattern analysis using computer vision.

(iv) *Look up table (LUT) equalize*—to highlight image details in an area containing significant information at the expense of the other areas. A LUT transformation converts input grayscale values in the source image into other grayscale values in the transformed image. IMAQ Vision provides four VI's that directly or indirectly apply lookup tables to images. IMAQ Equalize distributes the grayscale values evenly within a given grayscale range. This is used to increase the contrast in image.

(v) *Gray morphology-Dilate*—grayscale morphology helps in removing or enhancing isolated features. Grayscale morphological transformations compare a pixel to those pixels surrounding it. The transformation keeps the smallest pixel values when performing erosion or keeps the largest pixel values when performing dilation. Dilation increases the brightness of pixels surrounded by neighbors with a higher intensity. They mainly are used to delineate objects and prepare them for quantitative inspection analysis.

(vi) *FFT filters-truncate low pass*—Fast Fourier Transform (FFT) is used to convert an image into its frequency domain. An image can have extraneous noise, such as periodic stripes, introduced during the digitization process. In the frequency domain, the periodic pattern is reduced to a limited set of high spatial frequencies.

A low pass frequency filter attenuates or removes high frequencies present in the FFT (Fast Fourier's Transforms) plane. This filter suppresses information related to rapid variation of light intensities in the spatial image i.e., frequency components above the ideal cut-off, frequency are removed, and the frequency component below it remains unaltered. This generally helps in smoothing the sharp edges.

(vii) *Advance morphology—remove small objects*—morphological transformations extract and alter the structure of objects in an image. We can use these transformations to prepare objects for quantitative analysis, observe the geometry of regions, and extract the simplest forms for modeling and identification purposes. The advanced morphology functions are conditional combinations of fundamental transformations such as the binary erosion and dilation. This function eliminates tiny holes isolated in objects and expands the contour of the objects based on the structuring element.

(viii) *Image-3D View*—this function gives a pictorial color base three-dimensional heating pattern. IMAQ Vision has several color scales to depict the heating pattern. Under this study, the program was set so that the red color of the spectrum represents the hot area having higher microwave thermal treatment and this region was shown as ridge region. Similarly the deep blue color represents the cold area having less thermal treatment and was shown as depressed region.

(ix) *Quantify*—the grayscale quantify tool provide a numeral value for the color intensity. Interpretations of the numerical value depend on the selection of color palette. For *Rainbow* color palette the number zero is assigned to deep blue and 255 to dark red. These dimensions less numbers relatively compares the degree of color intensity varying from deep blue to dark red.

System calibration and noise filtering were done to improve the accuracy and visibility of the trays. After running the script for each layer results were analysed to locate cold and hot spots.

3. Results and discussion

For a 2.67 kW power level, experiments were conducted for various values of F_0. At each F_0 the M-2 marker yield was obtained using HPLC method. A linear correlation ($R^2 = 0.97$) was obtained between the accumulated marker yield and F_0 (Fig. 3). The linear relationship between F_0 and the marker yield suggests that darker regions of the tray had higher marker yield and higher degrees of thermal treatment. Similarly, lighter regions had lower marker yield and lower degrees of thermal treatment. Increases in marker yields for selected points were best fitted with linear relationship.

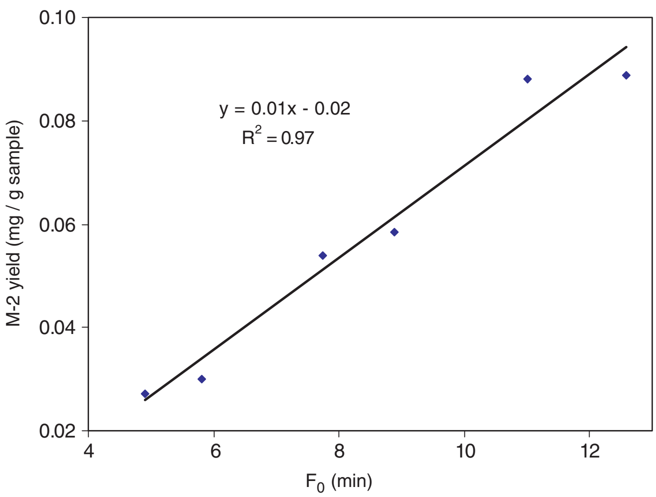

Fig. 3. Relationships between M-2 yield and F_0 accumulation in mashed potato during microwave sterilization, each point represents the mean of two replicates.

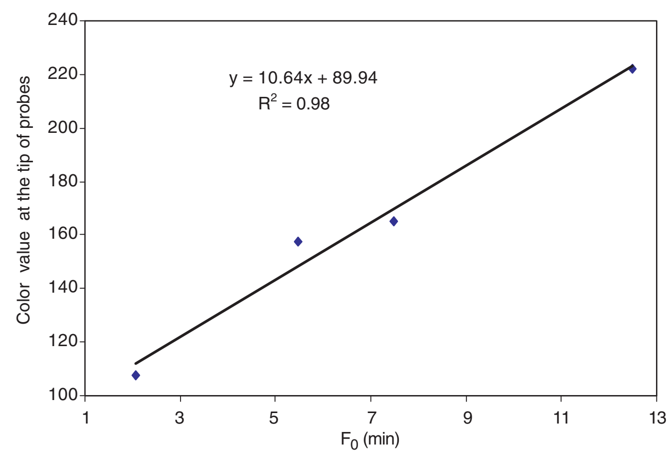

Fig. 4. Relationships between color values obtained by IMAQ vision builder and F_0 for processed sample, each point represents the mean of two replicates.

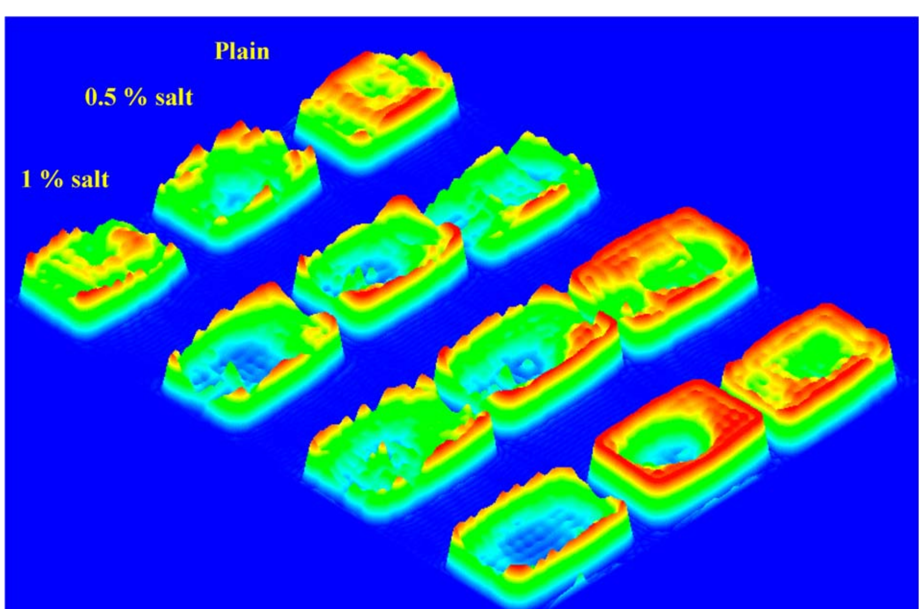

Fig. 5. Comparison of heating patterns of 10 oz trays with three levels of salt content after microwave sterilization, tested in replicates.

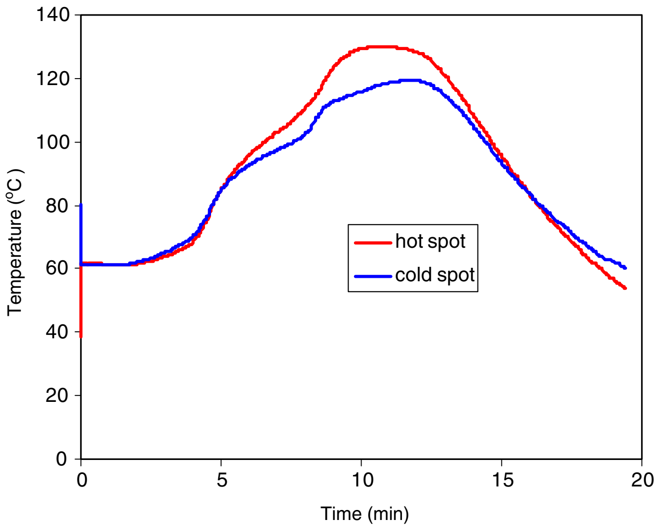

Fig. 6. Heating profile of hot and cold spots locations in 10 oz trays during microwave sterilization at 2.67 kW, tested in two replicates.

A linear relationship ($R^2 = 0.98$) was also observed between color value at the tip of fiber-optics probes (Fig. 4) and F_0. The deep red color has the highest color value and the deep blue has the lowest color value. This result suggests that the degree of the color intensity increases with level of the thermal treatment.

The deep blue color shows cold spot location and dark red color shows the hot spot location (Fig. 5). It was observed that center of the middle layer in the packaged food was less processed than the edges in each tray (Fig. 5). Cold spot was specified at middle of middle layer and hot spot at the location close to right farther corner in 10-oz tray. Locations of cold and hot spots were independent to the levels of salt content.

4. Validation of locations specified by computer vision

In order to evaluate the accuracy of the cold and hot spot locations determined by computer vision, experiments were conducted using microwave as a source of energy. Experiments were carried in two replicates to test the repeatability of heating profile and temperature difference between cold and hot spots identified by the computer vision method at 2.67 kW power levels. Fiber-optic temperature sensors were inserted at those two selected locations and experiments were carried at 2.67 kW power level. The measured temperature confirmed the hot and cold spots for each replicate (Fig. 6). To further confirms the location of the cold spot in relationship with other parts of the tray additional 13 tests were conducted. In each of the test four fiber optic sensors were placed in the sample tray during sterilization process. One of the sensor was always inserted at the cold spot identified by the computer vision method while the other three were placed in the three different locations. Compiling the temperature measurement for 13 tests provided temperature of 40 points (8×5) evenly distributed in the middle layer of the tray. Computer vision heating patterns and temperature mapping obtained using fiber-optics are compared in Fig. 7. Results show that heating pattern and cold spot location obtained by both methods are in good agreement. This indicates that the novel method can indeed be used to study general heating patterns in homogeneous foods after microwave sterilization processes.

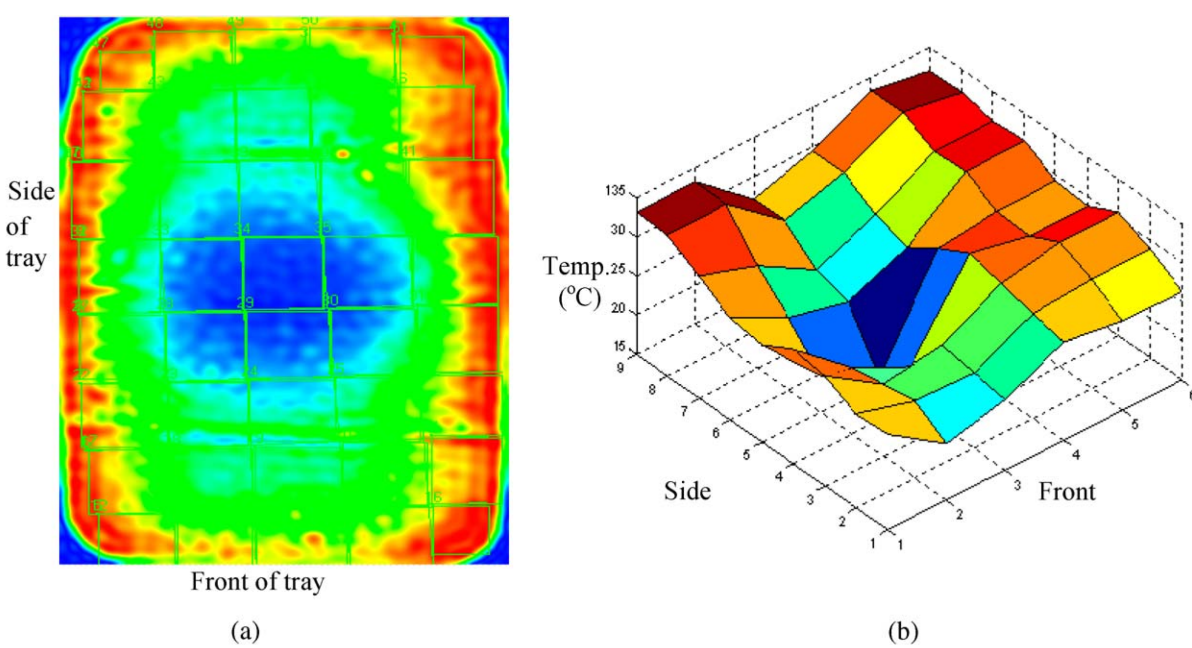

Fig. 7. Comparison of computer vision heating patterns and actual temperature mapping for 10 oz trays: (a) IMAQ heating pattern, (b) actual temperature profile.

5. Conclusions

In this paper, a novel approach has been developed to determine the heating pattern using the chemical marker M-2, digital imaging, and computer vision software (IMAQ) vision builder. A linear correlation was obtained between the M-2 marker yield and the degree of thermal treatment (F_0), which suggests that darker color corresponds to higher thermal lethality. Relationship between color at the tip of fiber-optics probe and F_0 was observed as linear. Locations of cold and hot spots obtained after image processing were also verified using fiber-optic temperature sensors. Locations of the cold and hot spots specified by computer vision matched well with temperature measurements using fiber-optics probes. The experiments prove that computer vision (IMAQ Vision Builder) with the chemical marker M-2 and other accessories can be used as an effective tool to identify the location of cold and hot spots in microwave processed foods. Due to its cost effectiveness, consistency, fast speed and accuracy in comparison to HPLC, this method can be considered as the best option to determine the heating pattern.

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