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Characterization of dough baked via blue laser

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ABSTRACT

Depth of heat penetration and temperature must be precisely controlled to optimize nutritional value, appearance, and taste of food products. These objectives can be achieved with the use of a high-resolution blue diode laser—which operates at 445 nm—by adjusting the water content of the dough and the exposure pattern of the laser. Using our laser, we successfully cooked a 1 mm thick dough sample with a 5 mm diameter ring-shaped cooking pattern, 120 repetitions, 4000 mm min^{-1} speed, and 2 W laser power. Heat penetration in dough products with a blue laser is significantly higher compared to with an infrared laser. The use of a blue laser coupled with an infrared laser yields most optimal cooking conditions for food layered manufacture.

1. Introduction

The heating mechanism used in food layered manufacture (FLM) must be highly controllable and precise to guarantee that a cooked food product meets the taste and appearance requirements (Zoran and Coelho, 2011). The heating mechanism must also accommodate different food shapes and recipe variances, while allowing for custom texturization of food products (Sun et al., 2015). Our laser heating mechanism can be parameterized by a number of variables including speed, power, and spot size, and the heat can be controlled spatially making laser heating ideal for high-resolution food processing. As, to the best of our knowledge, the specific effects of laser wavelength, speed, and power during cooking have not been experimentally studied; this is the objective of the present investigation. Specifically, to explore the effects of a shorter wavelength on the cooking outcomes, we used a blue diode laser that operates at a wavelength of 445 nm, resulting in low water absorbance (Pope and Fry, 1997).

Starch gelatinization is used to assess satisfactory completion of the baking process (Wang and Copeland, 2013). In dough-based products, this phenomenon plays an important role in the transition from raw to baked dough with crumb-like texture, and thus determines product digestibility (Wang and Copeland, 2013; Zanoni et al., 1995a). Starch gelatinization is essential for ensuring that soft baked products have pleasurable appearance and texture (Purlis, 2012). The process begins with starch granules swelling at a temperature in the 60–70 °C range (Olkku and Rha, 1978). With continued heating, starch granules swell and erupt into fragments (Olkku and Rha, 1978). Because this fragmentation occurs on a micron scale, a scanning electron microscope (SEM) can be used to qualitatively assess starch gelatinization (Almeida and Chang, 2013; Huang et al., 1990). Huang et al. (1990) uses SEM to qualitatively characterize changes in potato starch granules during heating. A temperature of 96 °C in the dough core is often used to determine completion of the gelatinization process (Mondal and Datta, 2008; Zanoni et al., 1995b).

Additive manufacturing (AM) technology is a revolutionary way to cook and combine food products. This technology adds layer-upon-layer of material to an object—in this case an edible product—to create complex 3D forms. Some foods that have been printed via this method include chocolate, dough, scallops, meat, sauce, and cheese (Lipton et al., 2015). Combining AM technology with FLM can produce novel food geometries, ingredient combinations not possible with conventional cooking processes, and the

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need for high-resolution (millimeter scale) customizable cooking methods for targeted heating of food products (Zoran and Coelho, 2011). Laser beams provide customizable heating favorable in an FLM application since their power, speed, and beam resolution can be precisely controlled digitally (Zoran and Coelho, 2011).

We investigate the applicability of a blue diode laser in dough baking using a simple dough as a food system model. The water content of the dough was altered to determine the effect of degree of saturation on the heating process. Multiple laser-cooking patterns and repeat exposures were used to assess their effects on the temperatures achieved in the dough products. The main objective was to establish the point of complete starch gelatinization in a 1.0 mm thick layer of dough, a common food thickness in FLM.

2. Materials and methods

2.1. Sample preparation

Commercial all-purpose flour (Gold Medal, General Mills, Minneapolis, USA) was used for all experiments involving dough. According to the manufacturer label, 100 g of this flour contains 10 g of protein and 73 g of carbohydrate. The dough was prepared by mixing flour with water (at a 5:3 ratio) in a food processor (FP-8FR series, Cuisinart, East Windsor, USA) for 60 s at low speed in ambient conditions (23 °C). After mixing, the dough was left to rest at 4 °C for at least 15 min. No yeast was added to prevent fermentation and expansion of the dough during storage and further processing. Prior to processing, the dough was laminated into a thickness of 3 mm (±0.1 mm) and square shape with side length 30 mm; only a small portion of this area was treated with a laser (Fig. 3).

2.2. Laser setup

A 3.8 W (445 nm wavelength) blue diode laser (J Tech Photonics, Inc., Kemah, USA) was used for laser cooking. The laser was mounted to a custom acrylic mounting plate that was fastened to the Z-Cart of a vertically mounted screw table, attached to the X Carriage on an X-Carve Gantry (Inventables, Inc., Chicago, USA). To adhere to the health and safety regulations, the apparatus was placed in a custom enclosure made from a 250–520 nm laser shielding acrylic (Fig. 1). Cartesian motion and feed rate—or speed—of the blue laser was controlled by inputting the G-code on an SD card.

The laser power was kept constant at the manufacturer-recommended 2.0 W to avoid overheating and to increase duration of the laser diode operation. The height (the *z* coordinate) is defined as the perpendicular distance between the laser head and the food sample surface. The approximate focal length of the blue laser is 28 mm. Thus, when the height increases above 28 mm the beam diverges, resulting in a larger beam spot size that creates a more diffuse energy profile since the beam is not collimated. Fig. 1 shows an unfiltered dough sample subjected to blue laser processing.

2.3. Laser-cooking patterns

Controlling the laser motion via G-code made it possible to experiment with six different cooking patterns (Fig. 2). Interpolated circular patterns, such as the spiral, ring, and Archimedean spiral (which resulted in a decreased exposure of the sample center), were also explored. However, curved patterns were preferable, since they did not induce significant changes to the laser velocity during scanning. Sharp corners—as opposed to round corners—in a cooking pattern impart a rapid acceleration on the motors in order to maintain a constant velocity, thereby making it difficult to maintain a constant speed throughout the cooking process. The Hilbert curve, a continuous fractal space-filling pattern more commonly used in computer science applications, was also explored, since it offers another efficient means of traversing a 2D dough sample. Moreover, a pattern of interlaced circles was tested to allow for continuity as well as repeated exposure of the sample area.

Images were acquired using a digital single-lens reflex camera (EOS Rebel T5i, Canon, Tokyo, Japan). The images were taken in uncompressed form as a “Canon Raw Version 2” to allow for the highest resolution. Image post-processing was limited to color balancing with a white color swatch, which was placed into the photo-shooting environment. Adobe Photoshop CS6 was used to correct the images.

2.3.1. Calculating energy efficiency

The efficiency of each laser-cooked pattern was estimated by comparing the energy delivered by the laser to the degree of heating exhibited by each cooked dough sample. The following assumptions were made in calculating the efficiency of each pattern: 1) the feed rate remained constant, 2) the laser power remains constant, and 3) the dough was treated as a lumped

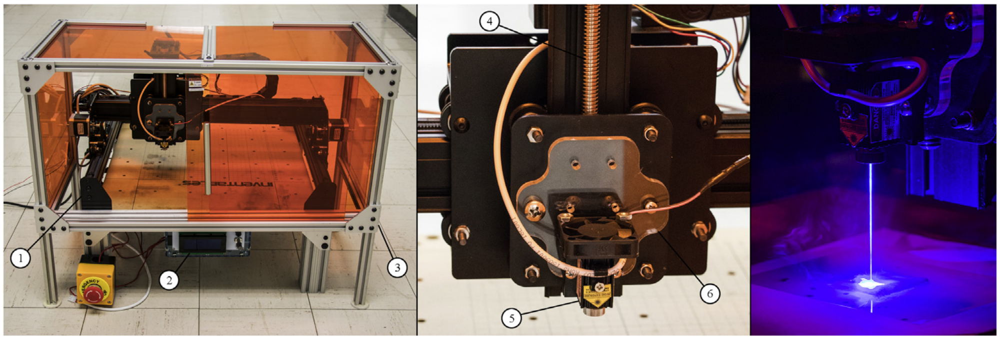

Fig. 1. Experimental setup for the blue diode laser. The diode laser (5) is mounted to the X-Carve gantry (1), which has three degrees of freedom (motion is permitted along the x, y, and z axes, with the latter pertaining to the height above the sample). The apparatus is enclosed in a laser shielding orange acrylic case (3) that has a sliding door that facilitates easy access during experimentation. The optical density of this 250–520 nm laser shielding acrylic is rated at OD 4+. 2: Controller for implementing Gcode, 4: z-axis screw table, 6: custom acrylic mount for diode laser. Right: Dough sample subjected to blue diode laser heating. The beam appears white in the image due to the vibrancy of the light source and camera limitations. The square-shaped dough sample is visible where it comes into contact with the beam and distorts the beam shape. The lack of beam collimation can be observed in this image, as the beam waist occurs just prior to interacting with the dough sample. The contrast and brightness of the image were altered in order to allow the smoke that results from the laser-cooking process to be visualized. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)