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NON-CONTACT TEMPERATURE MEASUREMENT BASED ON INFRARED RADIATION FOR BREAD BAKING PROCESS

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Abstract

The control of baking temperature is prime important for bread making since it directly affects the quality attributes of bread products and the efficiency of energy utilization. This study proposes a technique to measure the product's surface temperature based on infrared radiation (IR) for the bread-baking process.

Wheat dough samples were baked with different three-step temperature settings (180 ^{0}C - 120 ^{0}C - 170 ^{0}C C, 180 ^{0}C - 120 ^{0}C - 180 ^{0}C, and 180 ^{0}C - 120 ^{0}C - 190 ^{0}C). A thermal image camera and an infrared sensor were used to determine the values of emissivity (ε). The total weight loss was calculated by the weight difference between the dough and bread product. Data were analyzed using the analysis of variance (ANOVA) and the Turkey test at 0.05 level of significance.

It was found that the weight loss of bread products obtained from different baking temperature settings differed significantly ($p < 0.05$). The total weight loss of samples was in the range of 10.5% - 12.6%. During the first stage, where the core temperature (TCore) and the surface temperature (TSurf) increased to 40 ^{0}C, and 98 ^{0}C, respectively, a slight volume expansion was observed while weight loss was not detectable. In the second stage, TCore and TSurf respectively increased to 60 ^{0}C, and 113 ^{0}C. The volume expansion was obvious, and the weight loss could be observed. Finally, when TCore and TSurf increased to 98 ^{0}C, and 140 ^{0}C, respectively, in the last stage, most of the weight loss was found, primarily due to moisture evaporation and the crust turned brown with slightly darker shades upon increasing the baking temperature from 170 ^{0}C to 190 ^{0}C. The emissivity (ε) values inferred from the measurements tended to decrease from 0.95 to 0.87. By considering ε as a constant value for a 10 ^{0}C -interval within this baking stage, a good agreement between the product's surface temperature measured with the IR sensor and that measured with a thermocouple was found, with a correlation coefficient (r) of 0.99.

This finding suggests the potential of the infrared radiation technique for real-time, non-contact temperature measurement to monitor and control the bread-baking process.

***Key words**: Bread, Baking, Emissivity, IR sensor.*

1. Introduction

Bread is among staple foods that have long been consumed worldwide with a current market size of USD 208.7 Billion. The size of the bread market is expected to continually grow at a compound annual growth rate (CAGR) of 3.6% during 2023 - 2029. While bread consumption has been leading in North America and Europe, the increasing demand for bread products has been reported in other emerging economic regions of the globe, primarily in China [1, 2].

Consumer acceptance of bread products mainly depends on certain physical characteristics including texture, flavor, and crust color. These characteristics are mostly developed during baking. Bread baking is a complex process in which multiphase heat and mass transfers occur simultaneously coupled with other phenomena like starch gelatinization, volume expansion, crust development browning reaction, and water evaporation. The evaporation front divides the crumb and the crust. For the most part, water evaporation is responsible for the total weight loss of bread. As a result, baking is considered to be crucial in bread making since the process conditions could directly affect the final quality of bread product, and so the consumer acceptance. Such important characteristics of bread being developed during baking have been found to be strongly influenced by baking temperature. An extensive list of research studies about the effects of baking temperature on moisture content, crust thickness and color, volumetric expansion, porosity, and crumb structure could be found elsewhere [3].

According to Swortfiguer [4], cited by Therdthai *et al*., [5], the baking process could be divided into three stages. The first stage takes part up to the point where the outer crumb temperature reaches 60 ^{0}C. Enzymatic activities are enhanced, volume slightly increases, and the outer surface begins to turn brown. This stage takes approximately 26 min. which accounts for roughly one-fourth of the total baking time. In the second stage, crumb temperature increases to approximately 98 - 99 ^{0}C and remains unchanged throughout the stage. All activities occur at their peak rate. This stage covers approximately one-half of the total baking time. When the crust temperature reaches 150 - 205 ^{0}C, the Maillard reaction causes the crust to turn dark brown [6]. Finally, in the last stage, the volatilization of organic substances leads to some additional weight loss, known as bake-out-loss [4].

Therdthai *et al*., [5], developed a quadratic model to describe the influences of baking temperature and time on crust color, crumb temperature, and weight loss. Based on the obtained model, an optimum baking temperature profile could allow the weight loss to be minimized while maintaining crust color and crumb temperature within an acceptable range. Recently, Silva *et al*., [3], developed an experimental setup that could precisely monitor the changes in physical properties during bread baking. The results clearly showed the effects of baking temperature on weight loss, moisture content, volumetric expansion, crumb structure, and crust color.

It would be clear that the control of baking temperature is key to obtaining bread products with desirable final quality attributes. Accordingly, the baking temperature should be continuously monitored and controlled throughout the baking process, preferably in a real-time manner. In addition, from the food safety point of view, the concerns about biological, physical, and chemical hazard food contamination, should also be taken into account. Any contact surface or spot in the food processing line could cause contamination. Generally, the contamination from a sensor or a measuring device could be minimized or limited by using noncontact-type equipment.

Infrared thermography has been successfully adopted for noncontact temperature measurement [7 - 13]. Theoretically, all kinds of objects can absorb, radiate, and reflect energy. The total amount of energy detected by an infrared sensing device includes both the direct emission from a material surface and a reflected portion of energy originating from the surroundings. The ability of a material's surface to radiate energy in the form of infrared is known as emissivity (ε) - a material's surface property having a value ranging from 0 to 1. Knowing the total amount of detected infrared energy and the emissivity value, the surface temperature could be inferred.

This study aimed to explore the possibility of using infrared thermography techniques to measure the crust and crumb temperatures of bread during baking.

2. Materials and Methods

2.1 Sample preparation

Dough samples were prepared with wheat flour (50%), water (25%), table sugar (10%), margarine (5.8%), chicken egg (3%), milk powder (2.5%), butter (1.8%), salt (0.85%), and dried yeast (0.75%). All ingredients were thoroughly mixed, kneaded, and rested at 25 ^{0}C for 40 min. allowing the bulk dough to ferment. The dough was cut into 70-g dough pieces, kneaded to form a ball-shape sample, and proofed under the cover of a moist cloth at 25 ^{0}C for 150 min before baking. Samples were baked using a commercially available electric oven (Zanussi, Model ZOT103KX).

2.2 Instrumentation

Digital thermometers (Fluke 52-II) equipped with type-K thermocouples were used to measure the oven temperature and the core and surface temperatures of a sample. The junction of a thermocouple was placed at the center inside the dough samples to measure the core temperature. The oven temperature was the average value of the temperature measured from 4 spots vertically along the wall of the oven. The intensity of infrared energy emitted from the sample was measured using the miniature infrared sensor, with a spectral response of 8 - 14 μm, (MI, Raytek Corporation) installed at the middle top position of the oven. This was a proper position for capturing the infrared energy emitted from the sample since the top surface of the sample was considerably flat and smooth without much of the angle changing throughout the baking process. In addition, a thermal image (TI) camera, (Model TI 32, Fluke) was also used to determine the emissivity value of a sample. Though the TI camera could offer an advantage over the IR sensor in that the former can compensate for the reflected energy or background temperature (T_{BG}) allowing the measurement to be more accurate, it might not be practical to use the TI camera for a process control purpose.

2.3 Baking experiment

The baking experiment was conducted with two different temperature settings. Baking was done at a fixed temperature of 180 °C in the first setting. For the second setting, the baking temperature was varied sequentially for three different baking stages, referred to as "temperature zones," according to Therdthai *et al.*, [5]. This was to simulate the different spatial zones that the bread experiences while moving through a continuous industrial oven. The oven was allowed to equilibrate at a setpoint temperature of Zone 1 for 10 min. before each test run. The boundary of each zone was justified based on the core temperature of the dough. Zone 1 ended when the core temperature reached 40 °C. The baking temperature was varied within a range of 180 °C to 210 °C. Zone 2 covered a period that the core temperature increased from 40 °C to 60 °C. The baking temperature in the range of 90 °C to 120 °C was considered. In the final zone, the core temperature was increased from 60 °C to 98 °C and was then maintained at this temperature for 10 min. The baking temperature was varied from 90 °C to 120 °C. Preliminary baking test runs were made to determine three baking temperature schemes. The proper baking temperature schemes were chosen by varying the temperature in each zone, according to the ranges mentioned above, so that the dough was properly cooked, and the weight loss and crust color based on visual inspection, were at acceptable levels.

2.4 Emissivity determination

In this study, the emissivity value (ε) of a sample was determined using both the TI camera and the IR sensor.

To determine the value of with the TI camera, the possible value was keyed in as input, then adjusting the value of T_{BG} in the TI camera until the reading temperature was similar to that measured with a thermocouple. This T_{BG} represented the reflected energy from the surroundings under the experimental condition being studied. Next, this T_{BG} was used as an input for the TI camera, and by varying the value of ε in the TI camera until the reading temperature was equal to that read from a thermocouple, the true value of ε was obtained.

With the IR sensor, ε value was determined by adjusting this value, as an input, for the IR sensor until the reading temperature from the IR sensor was equal or closest to that from the thermocouple attached at the top surface of the sample.

2.5 Weight loss calculation

The percentage weight loss of bread product was calculated using equation (1):

$$\%Weight\ loss = \left(\frac{(m_{dough}) - (m_{bread})}{m_{dough}}\right) \times 100 \qquad (1)$$

Where: m_{dough} is the mass of a dough sample, and m_{bread} is the mass of a bread product.

2.6 Statistical analysis

The experiment was carried out using a completely randomized design with three replicates. Analysis of variance (ANOVA) and multiple comparisons (Turkey test) were performed on weight loss data. The relationship between the surface and core temperatures of the sample was obtained using a linear regression. All statistical analyses were made at a 0.05 level of significance using the SPSS statistical package for Windows (Armonk, NY: IBM Corp).

3. Results and Discussion

3.1 Temperature settings for a step-change temperature baking scheme

From preliminary tests, three baking temperature schemes chosen according to Therdthai *et al.*, [5], were obtained as shown in Table 1.

Table 1. Bread weight loss from different baking schemes

Baking schemes	Weigh loss(%)*
180 °C - 120 °C - 170 °C	10.81 ± 0.34^{a}
180 °C - 120 °C - 180 °C	12.56 ± 0.47^{c}
180 °C - 120 °C - 190 °C	11.85 ± 0.78^{b}

Legend: *Obtained from the 2nd and the 3rd stages of baking. Data are mean ± SD (n = 3). Figures with different letters differ significantly ($p < 0.05$).

During stage 1 of baking, a slight volume expansion could be visually observed since enzymatic activity and yeast growth were enhanced.

With a baking temperature of 210 °C, the surface temperature was increased at rather a high rate to 110 °C at the end of the stage where the core temperature reached 40 °C. The crust formed up rapidly and the surface got slightly burned. Once formed up, the crust structure would prevent further water evaporation in subsequent stages of baking which is undesirable. It can be seen from Table 1 that the proper baking temperature for the first stage of all baking schemes was 180 °C. This was the baking temperature that allowed the core and the surface temperatures of the dough to gradually increase to 40 °C and 90 - 95 °C, respectively, at the end of the stage. Without the formation of crust, the surface layer would still allow water vapor to diffuse through it. However, the water vapor pressure at the surface was still low so the evaporation was not present or was undetectable if there was. As a result, weight loss was presumably negligible. This stage took approximately one-fifth of the total baking time.

During stage 2 where the core temperature of the dough was increased from 40 °C to 60 °C, volume expansion was clearly observed. Once the temperature at stage 1 was fixed at 180 °C, it was found from this experiment that different settings of temperature in this stage - 90 °C, 110 °C, and 120 °C, did not significantly impact the percentage weight loss. However, only the baking condition with 120 °C could allow the dough sample to be properly cooked which would otherwise remain uncooked at the end of the baking process, and so this temperature level was chosen. This stage took approximately one-tenth of the total baking time.

In the last baking stage, the core temperature was raised from 60 °C to 98 °C and additionally kept at this level for 10 min. to allow the crust to turn brown properly and, the desirable aromatic profile to be developed. All activities proceeded at the maximum rate [5]. It was evident that water evaporation during this stage contributed to the largest portion of weight loss. This was the longest baking stage from the total baking time of 28 min. Apparently, it was possible to set the temperature for this stage to be any level between 170 °C, 180 °C, and 190 °C since the only visually different quality attribute was crust color. In addition, color preference is subjective, so the final judgment among these temperature settings should not be made particularly without systematic assessment like sensory evaluation. As a result, the baking scheme was chosen for this study as presented in Table 1.

3.2 Effects of baking scheme on bread weight loss

The three chosen baking schemes resulted in a significant difference in percentage weight loss (Table 1). Since the baking temperatures for stages 1 and 2 were similar for all baking schemes, it would be perceivable that this difference was due to the temperature in the last stage of baking. Noted, this was the longest stage which covered around 71% of the total baking time. In addition to water evaporation, the volatilization of organic substances, known as bake-out-loss [4, 5], would be the reason for the difference in weight loss. Bread weight loss obtained in this study was in a range of approximately 10.8% - 12.6% which was comparable to literature values [3, 14].

3.3 The emissivity of bread obtained with a thermal image camera

A typical thermal image of baking samples captured with the TI camera is given in Figure 1.

As to compare between baking conditions, the measurements were made for the baking process with a constant temperature of 180 °C and the process with a step-change temperature scheme (180 °C - 120 °C - 170 °C). The result is given in Figure 2.

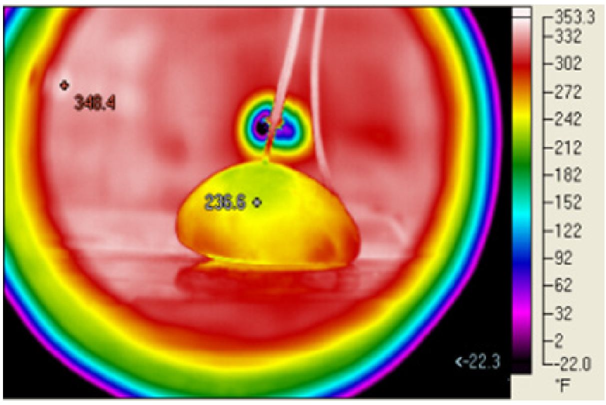

Figure 1. The thermal image of the bread sample during baking

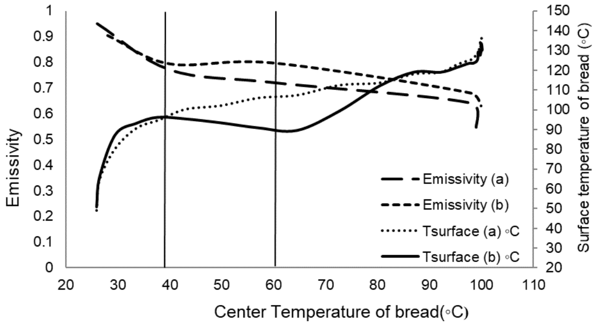

Figure 2. The evolution of emissivity with sample temperatures was observed from two different baking conditions: a) baking with a constant temperature of 180 °C, and b) baking with a step-change temperature scheme (180 °C - 120 °C - 170 °C)

Numerical values of the diffusivity values were also summarized in Table 2.

Table 2. Data on emissivity values and the core temperature of bread loaf obtained with two different baking temperature settings

Core temperature (°C)	Emissivity (ε)	
	(a)	(b)
25 - 40	0.770 - 0.950	0.793 - 0.903
40 - 60	0.720 - 0.770	0.793 - 0.797
60 - 98	0.545 - 0.720	0.630 - 0.800

Legend: (a) Constant-temperature baking at 180 °C, and (b) 3 stages of temperature baking (180 °C - 120 °C - 170 °C).

The results showed that the emissivity values of bread during baking fell in the range of 0.55 - 0.95, which was similar to the range reported by Rogers and Brimelow [15].

A close examination revealed that the emissivity values obtained from the two different baking processes were not much different for the same surface temperature. The relationship between the emissivity value of bread and the surface temperature during baking is shown in Figure 3.

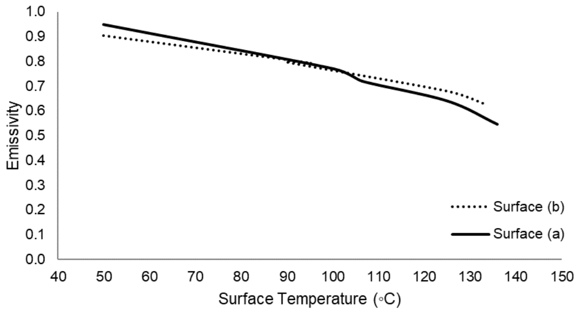

Figure 3. The relationship between emissivity and surface temperature: a) a) baking with a constant temperature of 180 °C, and b) baking with a step-change temperature scheme (180 °C - 120 °C - 170 °C)

3.4 Temperature measurement using infrared sensor

Table 3 provides information on experimental values of emissivity at various stages of baking along with the temperatures of bread measured with the IR sensor and a thermocouple.

Since the variation of emissivity with temperature was quite small, so in this table the emissivity was assumed to be constant over a 10 °C-interval. Accordingly, the emissivity values were in a range of 0.87 - 0.95. It could be seen that, based on these values of emissivity, the reading values of surface temperature from the IR sensor during stages 1 and 2 of the baking process were quite different from those measured with a thermocouple. However, in the last and the longest stage of baking, the surface temperatures measured with the IR sensor and a thermocouple were very close. Nevertheless, if weight loss is a matter of concern, the IR sensor could be used as a sensing device in a control system for the bread-baking process since most weight loss occurs during the last stage of baking.

3.5 Relationship between the surface and the inner crumb temperature

While infrared thermography could be used to measure the temperature at the surface of an object, the quality control of bread during the baking process focuses on the inner crumb temperature. The IR sensor could still be applicable for this process if a relationship between the surface and the core or inner crumb temperatures could be established.

In this study, a very high correlation coefficient between the core and the surface temperature was found yielding a correlation coefficient (*r*) of 0.99. By using a simple regression to fit data on the core and the surface temperatures of the bread sample during baking, the linear relationships for the three baking stages were obtained as shown in Table 4.

Table 4. Relationship between inner crumb and surface temperatures

Inner crumb temperature (°C)	Fitted linear relationship	R^2
25 - 40	$y = 0.152x + 19.55$	0.926
40 - 60	$y = -3.020x + 330.48$	0.992
60 - 98	$y = 0.887x - 19.09$	0.818

Legend: *x* and *y* are inner crumbs and surface temperatures, respectively.

The high R^2 values suggest that the application of these relationships for the control of bread baking process should yield satisfactory results.

4. Conclusions

- The weight loss of bread products obtained from different baking temperature schemes differed significantly. Most of the weight loss occurred primarily due to moisture evaporation in the third stage of baking.
- The emissivity () values of bread inferred from the measurements tended to decrease from 0.95 to 0.87 when the surface temperature of bread increased from 98.0 °C to 140 °C. A good agreement between the product's surface temperature measured with an IR sensor and that measured with a thermocouple was found, with a correlation coefficient (*r*) of 0.99.
- The infrared radiation technique for a real-time, non-contact temperature measurement has the potential to monitor and control bread baking process.

Table 3. The variation of experimental values of emissivity at various stages of baking with the surface temperature of bread samples

Baking stage	Emissivity	Temperature measured by thermocouple (°C)		Temperature measured by IR sensor (°C)
		Core temperature	Surface temperature	
1	0.95	31 - 40	98.0	110.8
2	0.95	41 - 50	99.5	113.9
	0.95	51 - 60	113.0	124.2
3	0.95	61 - 70	125.3	125.2
	0.94	71 - 80	126.0	126.1
	0.93	81 - 90	137.0	136.4
	0.87	91 - 100	140.0	139.0

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