Influence of electrical and hybrid heating on bread quality during baking

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Abstract Energy efficiency and product quality are the key factors for any food processing industry. The aim of the study was to develop energy and time efficient baking process. The hybrid heating (Infrared + Electrical) oven was designed and fabricated using two infrared lamps and electric heating coils. The developed oven can be operated in serial or combined heating modes. The standardized baking conditions were 18 min at 220°C to produce the bread from hybrid heating oven. Effect of baking with hybrid heating mode (H-1 and H-2, hybrid oven) on the quality characteristics of bread as against conventional heating mode (C-1, pilot scale oven; C-2, hybrid oven) was studied. The results showed that breads baked in hybrid heating mode (H-2) had higher moisture content (28.87%), higher volume (670 cm³), lower crumb firmness value (374.6 g), and overall quality score (67.0) comparable to conventional baking process (68.5). Moreover, bread baked in hybrid heating mode showed 28% reduction in baking time.

Keywords Bread · Infrared heating · Hybrid heating oven · Volume rise · Crumb firmness

Introduction

Baking ovens play a vital role in deciding the final product quality of any baking process. Ovens are the integral part of

the baking process as an energy source. The success or failure of baking operation is determined by the oven and its operating conditions (Zhou and Therdthai 2007; Chhanwal et al. 2012). Ovens are mainly classified based upon operational mode (batch or continuous), heating source (electrical or hot air heating) and mode of heating (conductive, convective, radiative). Electrical heating ovens are widely used for batch baking process due to their process flexibility for different bakery products. Bread baking is a very complex process where, temperature inside the oven is responsible for the various physiochemical and biological processes that occurs during transformation of dough into bread. These processes are mainly influenced by oven air temperature. Non-uniform temperature distribution inside the oven causes variations in overall bread quality. Variations in the product quality can be controlled or minimized by optimizing processing conditions (Chhanwal et al. 2012).

At present, baking industry is looking for alternate heating oven to accelerate process, increase the production rate, and improve the product quality with reduction in processing cost. Baking time is the key factor influencing all these benefits and its reduction can increase energy efficiency of the baking operation. Use of rapid heating methods such as microwave, jet impingement or infrared helps to reduce baking time. Infrared radiations have higher thermal efficiency and rapid heating rate than the conventional heating modes (electrical heating) (Krishnamurthy et al. 2008). Infrared heating provides significant advantages over conventional heating such as, reduced heating time, uniform heating, reduced quality losses, inexpensive infrared source and significant energy saving (Ratti and Mujumdar 2006; Krishnamurthy et al. 2008). Therefore, use of infrared radiation heating for baking process can help to achieve rapid heating. However, rapid heating by infrared alone may cause deterioration in bread quality such as higher browning and charring of bread surface, insufficient baking of bread, etc. Apart from these, bread baking with infrared heating mode produces breads with a

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thicker crust, lower specific volume and higher crumb firmness than conventionally baked ones (Sumnu and Ozkoc 2010). These problems can be overcome by the use of hybrid heating mode (combination of different heating modes such as microwave, infrared, jet impingement or electrical heating). This hybrid heating pattern yields quality baked product with reduction in baking time (Datta and Rakesh 2013).

Hybrid heating or combination of two or more heating modes, compliment to each other and thus reduces the process time (Datta and Rakesh 2013). Rakesh et al. (2009) reported that the heating rate is faster in combination ovens compared to heating with only one mode i.e. microwave or forced convection. Major studies used microwave as one of the heating mode combined with conventional, infrared or jet impingement. Keskin et al. (2004) studied the bread baking process with different heating configuration such as halogen lamp (infrared); microwave, halogen lamp-microwave combination and conventional (electric heating coil). The author opined that, the use of halogen lamp-microwave combination reduces conventional bread baking time by 75%. In halogen lamp-microwave combination oven, microwave heating adversely affected the moisture and texture of bread. Moreover, on increasing the halogen lamp power volume decreased and crumb firmness increased. Baking time, halogen lamp power and microwave power were most significant factors that decide bread quality (Demirekler et al. 2004).

In another study, effect of microwave-infrared combination oven on wheat cake and gluten-free rice cake quality was studied by Sumnu et al. (2005) and Turabi et al. (2008) respectively. However, bread baking using microwave heating has some quality problems such as reduced bread volume, gummy texture and crumb hardness (Sumnu 2001). Hence, there is need for infrared heating in combination with conventional heating to obtain a better product quality. Moreover, the increase in use of infrared may affect product quality and that needs to be optimized. Only few studies reported the use of hybrid heating oven for reduction in baking time. Biscuit baking in infrared oven shows 40-50% reduction in baking time with a comparable product quality (Wade 1987).

Skjoldebrand (2002) suggested the use of short wave infrared radiation along with convection for rapid baking. Moreover, the difference in heating mode and baking time may alter the product quality which needs to be evaluated.

The main objective of the present study was to design and develop a hybrid heating oven for the bread baking process. This study was further extended to compare the physico-sensory characteristics and energy efficiency of bread obtained by hybrid heating mode with bread baked in a conventional mode.

Materials and methods

Design of hybrid heating oven

The common, domestic electrical heating ovens have two heating elements i.e. one is at the top, and another at the bottom of the oven. The bottom heating element is used for baking, mainly by convection and conduction modes of heating to the food and the top one provides radiation mode of heating for broiling or grilling (Chhanwal et al. 2010). Energy consumption of this oven can be reduced by replacing top electrical heating mode by infrared heating i.e. hybrid heating mode. This allows the baking time reduction and thus save energy consumption.

A hybrid heating oven (size $41 \times 41.5 \times 35$ cm) was fabricated for conducting experiments (Fig. 1). The fabricated oven had two infrared lamps (500 W, each) and two electrical heating coils (1000 W, each). The infrared lamps were made up of quartz halogen envelope with a tungsten filament to produce infrared radiations and were placed at the top portion of the oven. For the electrical heating, two heating coils were placed inside the oven (one at the top and other at the bottom). Three controllers were used to regulate ON/OFF of two heating coils and infrared lamps. Using these controllers, the baking oven can be operated separately in hybrid and conventional heating mode. Oven temperature was maintained at $220 \pm 5^\circ\text{C}$ during baking process. Bottom heating coil was kept ON throughout the baking process, and top heating coil was

Fig. 1 Hybrid heating baking oven

‘ON’ once the infrared lamp was turned OFF. Baking process was carried out in both hybrid and serial heating modes. Hybrid heating oven conditions were optimized in terms of baking temperature, time, serial and hybrid heating modes.

Raw material

Commercial wheat flour (PBW 175 variety) having 12% moisture, 0.49% ash, 10.5% dry gluten and 25 ml zeleny’s sedimentation value; compressed yeast (Tower brand, AB Mauri, India Pvt. Ltd. Chennai, India), salt (common food grade sodium chloride), sugar (from local market), and hydrogenated fat (Bunge India, Pvt. Ltd. Mumbai, India) were used for the studies.

Bread baking

Bread samples in triplicate were prepared using standard recipe consisting of wheat flour (100%), water (62%), compressed yeast (2%), salt (1.5%), sugar (12%), and hydrogenated fat (3%). The dough was prepared by mixing all the ingredients in a mixer (Hobart, GmbH, Offenburg, Germany) and fermented in a proofing chamber (at 30°C and 75% RH) for 90 min. Then fermented dough was remixed, rounded, relaxed for 15 min, molded, placed in bread pan and proofed (30°C with 85% RH) for 55 min in a proofing chamber (Anishaparvin et al. 2010). There were four different sets (C-1, C-2, H-1 and H-2) of baking conditions used for the bread baking process as shown in Table 1. The first set of bread (C-1) was baked in a pilot-scale electric heating baking oven (Rotel, APV Inc., Queensland, Australia), where the temperature was controlled by a thermostat, which keeps the heating element under ON/OFF according to the pre-determined set temperature (i.e. 220±2°C). The fabricated oven was used for the remaining three trials (C-2, H-1 and H-2). The second set of bread (C-2) was baked in the fabricated oven with only conventional heating mode (infrared lamp was switched OFF and both heating coils were turned ON) for 25 min at 220°C. The third set of bread (H-1), baked in hybrid heating mode, was operated for first 8 min with infrared lamps and bottom heating coil ON and for next 10 min both heating coils i.e. top and bottom was ON with infrared lamp switched OFF. Bread was baked for only 18 min

and removed based on visual inspection. Similarly, the fourth set of bread (H-2) was baked for 10 min in hybrid heating and 8 min electrical (conventional) heating. Subsequently, after the baking process breads were removed from the oven and cooled to room temperature. Further, breads were evaluated for quality aspects such as moisture content, volume, crumb firmness, color values and sensory characteristics.

Evaluation of bread

Moisture analysis

Moisture content of the bread was determined using two stage (air drying and oven drying) AACC (American Association of Cereal Chemists) method 44-15A. Breads were cut into the small pieces, and air dried for 14–16 h. Then air dried sample was powdered and heated in hot air-oven at 130°C for 60 min. These samples were transferred to desiccators and weighed for moisture calculation (AACC 2000).

Total moisture content of the bread samples was determined by the formula:

$$\% \text{ of total moisture} = \frac{A + (100 - A)B}{100} \quad (1)$$

where, A is the moisture content by air drying stage and B is moisture content of oven drying stage.

Volume analysis

Volume of bread samples in duplicates were determined by the rapeseed displacement method using standard volume-measuring apparatus (National manufacturing co., Lincoln, Netherland). The apparatus was calibrated initially by the following procedure. Initially, 400 cm³ standard block was placed at the bottom chamber of the volume measuring apparatus. Slit plate located at the end of the shaft was moved on closing the instrument. Volume of the block was read from the height of the rape seed collected in the shaft. Similarly, instead of standard block, bread samples were placed and analyzed for their volume.

Table 1 Operational conditions for the sets of bread baking experiments*

Experimental Trails	C-1	C-2	H-1	H-2
Oven	Pilot oven	Hybrid oven	Hybrid oven	Hybrid oven
Heating mode	Conventional	Conventional	Hybrid	Hybrid
Infrared Lamps (min)	-	-	8	10
Top coil (min)	25	25	10	8
Total Baking time (min)	25	25	18	18

*Bottom heating coil is ON during the entire baking process and hence not mentioned in table

Crumb firmness

The crumb firmness was determined according to AACC, (2000) standard method using a texture analyzer (Model Tahdi, Stable Microsystems, Surrey, England) which was equipped with plunger diameter of 35 mm, plunger speed of 100 mm per minute, load cell 10 kg. For firmness analysis, 25-mm thick bread slices were force tested against 25% compression. Crumb firmness were carried out in duplicates for each bread sample and analyzed on both sides of two bread slices. The average of four firmness values was considered as final crumb firmness.

Sensory analysis

Sensory evaluation of bread was carried out by a 10 member panel consisting of semi trained panelists. The panelist were asked to score for the sensory attributes such as crust color (1= very pale/very dark brown and 10 = golden brown), shape (1 = flat and uneven and 10 = convex shape), crumb color (1 = brown and 10 = creamish white), grain (1 = very coarse and 15 = very fine), texture (1 = hard and 15 =very soft), and eating quality (1 = foreign and 10 = typical and pleasant). The overall quality score (maximum of 70) was computed by combining scores of all the above mentioned sensory characteristics (Indrani et al. 2003).

Color analysis

The crust and crumb color of bread samples were analyzed using Hunter Lab color measuring system (Labscan XE, Hunter Associates Laboratory Inc., Reston, Virginia, USA). Approximately, 10 g sample was placed in a small glass bowl with a glass cover in order to provide uniform flat surface. Measured values were expressed as luminosity (L^*), red versus green (a^*), yellow versus blue (b^*) and the total color difference (ΔE). The L^* , a^* and b^* values of white standard tile used as reference were 92.47, -0.8 and 1.14 respectively. Each test was carried out in duplicate and analyzed on both sides of bread slices.

Statistical analysis

Results were statistically analysed by the t-test (test of significance for the difference between two means) using Microsoft excel software. The differences at $P < 0.05$ were considered significant.

Result and discussion

Comparison of bread baked in conventional and hybrid heating oven

Crust and crumb portion of bread samples baked through conventional heating and hybrid heating are shown in Fig. 2 (a-b). It is clear from the figure, that appearance of C-2, H-1 and H-2 breads are same. Visually, the overall appearance of breads baked in hybrid mode was similar to bread baked in conventional heating mode except for the bread volume. Moreover, there was not much difference in bread crust color, besides, the less baking time of H-1 and H-2 breads. Breads baked with hybrid heating mode (H-1 and H-2) had higher volume compared to the bread baked in a conventional oven (C-1 and C-2) due to more heat supplied in the initial stage of baking through infrared heating mode. Contradictory to the above findings, Keskin et al. (2004) reported a decrease in specific volume, moisture content and an increase in crumb firmness value with an increase in halogen lamp power (infrared source) of microwave-halogen lamp combination oven. Moreover, this may be due to use of halogen lamp-microwave combination heating; whereas, in this study infrared-electric heating was used. According to, Skjoldebrand and Andersson (1989) during infrared bread baking, crust formation and baking of crumb takes place simultaneously. Therefore, crust formation and volume rise might have occurred simultaneously in this study.

Apart from the product quality, the energy efficiency of the baking process increased due to the hybrid heating mode. Energy demand of hybrid heating baking process was less than the conventional baking process due to reduction in baking time, as energy requirement of two infrared lamps was same as that of one heating coil. Therefore, 7 min reduction in baking process saves 28% of energy in hybrid heating baking process compared to conventional electrical heating baking. Keskin et al. (2004) reported that, bread baked in microwave-halogen combined oven reduced baking time drastically (75%), however, its product quality was altered. Demirekler et al. (2004) also reported a reduction in baking time by 60% on using halogen-microwave heating compared to convention heating with a comparable product quality.

Moisture content

Moisture content of bread samples is given in Table 2. It clearly shows that bread samples prepared through hybrid heating (H-1 and H-2) mode had slightly higher (statistically insignificant) moisture content than the conventional heating. The water loss is strongly related to the temperature in the crust and as the crust dehydrates, temperature increases. The mass transfer mechanisms inside the dough were due to

Fig. 2 Breads baked in conventional and hybrid heating oven (a) crust (b) crumb

(a)

(b)

diffusion along with evaporation and condensation (Thorvaldsson and Janestad 1999). The moisture loss in breads due to these mechanisms in turn depends on the heating mode and the baking conditions used. Higher moisture retention in H-1 and H-2 breads can be explained as a consequence of quicker crust formation due to infrared heating which restricted further moisture loss from the bread during baking.

Moreover, there was significantly less variation among the bread samples on overall moisture retention (27.11 to 28.87%). Wade (1987) also reported higher moisture content in biscuits baked with infrared heating. Keskin et al. (2004) reported a linear increase in moisture loss of bread with baking time irrespective of heating mode. They also reported a higher moisture loss of bread in microwave-halogen heating compared to conventional heating. However, bread baked in

microwave-infrared oven had higher moisture loss compared to jet impingement and microwave-jet impingement oven due to higher temperature during baking process (Sumnu et al. 2007).

Volume

The breads baked through hybrid heating (H-1 and H-2) had higher volume than the conventional heating (C-1 and C-2) due to the effect of infrared application in hybrid heating oven (Table 2). Among different breads, H-2 had the highest volume (670 cm^3) due to maximum exposure of 10 min to infrared which helped to raise the bread volume. On comparison between the breads baked through conventional heating, it was observed that C-2 had slightly higher volume (630 cm^3) than the C-1 (590 cm^3). Keskin et al. (2004) reported lower

Table 2 Quality characteristics of bread

Bread samples	Moisture content (percent)	Volume (cc)	Crumb firmness (g)	Overall quality score (70)
C-1	27.11 ± 0.78	590 ± 11.54	650.8 ± 24.14	67.5 ± 4.38
C-2	27.69 ± 1.2	630 ± 12.5	626 ± 20.25	68.5 ± 5.69
H-1	28.01 ± 0.89	655 ± 15	423.6 ± 23.08	66.2 ± 5.6
H-2	28.87 ± 0.96	670 ± 5	374.6 ± 28.29	67.0 ± 4.56

C-1, Conventional- 1; C-2, Conventional- 2;
H-1, Hybrid -1; H-2, Hybrid -2

specific volume in breads baked through halogen lamp and halogen lamp-microwave combination due to early crust formation, which restricts further volume expansion. However, in our study, use of infrared along with the conventional heating have resulted in higher volume rise due to simultaneous occurrence of crust formation and crumb baking as indicated earlier.

Crumb firmness

The breads baked in hybrid heating (H-1 and H-2) mode had significantly lower firmness value (Table 2) than the breads baked in conventional heating (C-1 and C-2). It may be due to the infrared heating which had improved the softness of bread as a result of an increase in volume and moisture retention that reduced the crumb firmness value. On comparison among them, H-2 had the lowest firmness value indicating softer crumb texture due to longer exposure (10 min) to infrared during hybrid heating. These results were also qualitatively supported by overall quality scores (Table 2). Apart from this, it was interesting to note that as the moisture content of the bread sample increased, the crumb firmness value decreased (Table 2). The moisture content of the crumb has some mechanical and qualitative implications, in relation with the gelatinization of starch in the dough during the baking process and correlates with crumb softness (Zghal et al. 2002). The degree of gelatinization depends on the available water and temperature during baking (Blanshard 1987). A negative correlation was observed between volume and firmness of bread; as volume increased, crumb firmness decreased.

Keskin et al. (2004) also reported a decrease in crumb firmness during baking with halogen lamp alone. They also

observed negative correlation between volume and crumb firmness for conventional and only halogen lamp baking. However, microwave and microwave-halogen lamp baking does not show such correlation. Moreover, Patel et al. (2005), reported higher crumb firmness value due to higher heating rate (forced convection and microwave heating) during bread baking. However, in our study bread baked in hybrid heating oven having higher heating rate resulted in lower crumb firmness. Shyu et al. (2008) compared bakery products (bun bread, toast, pound cake, and sponge cake) baked in the far-infrared oven with conventional oven. They found that, softer sponge cake obtained with far-infrared oven had similar sensory quality and volume as that of cake in conventional oven.

Color

The color values, L* (luminosity), a* (redness versus green), b*(yellowness versus blue) and ΔE (total color difference) for the crust and crumb of bread samples is given in Table 3. The color of bread was related to physicochemical characteristics of raw dough and chemical reactions (Maillard reactions and caramelization) during baking that produced browning (Tong et al. 2010). Hybrid heating breads (H-1 and H-2) had darker crust color due to infrared application and showed lower luminosity (L value), lower a and b value and higher total color difference (ΔE values) than conventional heating breads (C-1 and C-2). This can be due to the infrared heating that provided higher surface heating with low penetration depth. Moreover, there was no significant difference between the crust color of breads samples of hybrid heating (H-1 and H-2). Comparatively, the crumb portion has light coloration due to less temperature and high water activity than crust. The

Table 3 Color analysis value of bread samples

Bread samples	Crust portion				Crumb portion			
	L*	a*	b*	ΔE	L*	a*	b*	ΔE
C-1	24.56 ± 0.67	2.64 ± 0.39	2.83 ± 0.10	66.82 ± 0.72	70.93 ± 1.11	-1.34 ± 0.04	11.39 ± 0.78	22.54 ± 0.70
C-2	18.74 ± 0.37	2.34 ± 0.39	2.23 ± 0.52	72.06 ± 0.34	71.85 ± 0.80	-1.34 ± 0.04	11.65 ± 0.53	21.84 ± 0.62
H-1	17.11 ± 0.22	1.09 ± 0.04	0.84 ± 0.12	73.61 ± 0.21	72.86 ± 0.29	-1.35 ± 0.09	11.94 ± 0.34	21.13 ± 0.17
H-2	17.80 ± 0.70	1.00 ± 0.10	1.35 ± 0.30	72.92 ± 0.70	73.71 ± 0.78	-1.38 ± 0.05	11.85 ± 0.40	20.36 ± 0.82

C-1, Conventional- 1; C-2, Conventional- 2; H-1, Hybrid -1; H-2, Hybrid -2

bread crumb samples of hybrid heating (H-1 and H-2) had slightly (statistically insignificant) higher luminosity (L^* value) and lower total color difference (ΔE values) than the conventional heating bread samples. However, their, a^* and b^* values were almost similar to conventional heating bread samples (C-1 and C-2). Similarly, Keskin et al. (2004) reported higher ΔE values for the cake baked in halogen lamp than conventional baking. Moreover, ΔE values of cake increased with increase in halogen lamp baking time (Sevimli et al. 2005). The above results made clear that, only the crust color of the hybrid heating bread samples were slightly altered and not the crumb color (Fig. 2 and Table 2).

Sensory analysis of bread

The average scores for sensory attributes of the bread samples are depicted in Table 2. The results showed that there was no statistically significant variation between the bread samples on overall quality scores (just varied from 66 to 69). On comparison, bread samples of conventional heating (C-1=67.5 and C-2=68.5) had slightly higher overall quality scores than the hybrid heating bread samples (H-1=66.2 and H-2=67.0). This can be explained as consequences of darker crust color and slight gummy mouth feel of the hybrid heating bread samples (H-1 and H-2). Moreover, C-2 (68.5) had slightly higher sensory score than all the other samples. Hence, it can be concluded that sensory attributes of hybrid heating bread were desirable and not affected to a large extent.

Conclusions

The fabricated hybrid heating baking oven had two infrared lamps and heating coils. Optimum bread quality was obtained by coupling infrared heating (provides high heat density) with the electrical heating. The breads baked in hybrid heating oven were comparable with breads baked in conventional electrical heating for various quality attributes such as crumb firmness, volume, moisture content and color. On overall comparison, H-2 had better qualitative characteristics in terms of volume and texture than all other breads (C-1, C-2, H-1). Moreover, breads baked in hybrid heating mode (H-1 and H-2) required 18 min of baking time as against 25 min in conventional electrical heating oven, resulting in 28 % reduction in baking time along with improved quality characteristics. Reduction in baking time reduces energy consumption and lowers its manufacturing cost. Thus, hybrid heating baking process produces improved quality bread in terms of more softness and volume rise than conventional heating with proper browning of bread surface. It can be concluded that use of hybrid heating oven for the manufacture of bread by the baking industries is advantageous as it reduces energy consumption, lowers manufacturing cost and produces bread comparable to

conventional heating oven. The simple architect and economical cost of hybrid heating oven facilitates scale-up.

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