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The Effects of Airflow on Oven Temperatures and Cakes Qualities

Shahapuzi, N. S., Taip, F. S.*, Ab. Aziz, N. and Ahmedov, A.

Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

ABSTRACT

The presence of airflow during heating process is expected to increase heat uniformity in a closed heating chamber. Circulation of hot air increases the percentage of convective heat transfer. In this study, effects of airflow on oven temperature, cake temperature and several cake qualities were investigated. Experimental studies were conducted in convective oven using two different baking modes; with and without airflow. During baking, oven temperatures and internal cake temperature were measured, and images of cake expansion were captured. Results of the study showed that the presence of airflow could maintain the oven temperature within a small range of set point temperature. Temperature in the oven exhibited ±5.5°C fluctuation, approximately 3.5% overshoot that occurred continuously during baking with airflow. On the contrary, higher overshoot (ranging from 15 to 30%) was observed in oven temperature without airflow. Airflow also showed a significant effect ($p<0.01$) during the second stage of baking. The presence of airflow increased the heating rate and resulted in a faster volume expansion, which was 3.21mm/min, as compared to 2.88mm/min without the airflow. However, airflow dried off the cake surface, resulted in quicker browning, higher weight loss and lower moisture content of cakes.

Keywords: Cake baking, airflow, heat transfer, internal cake temperature, volume expansion

INTRODUCTION

Oven conditions contribute to effectiveness of heat transfer to the product. Appropriate oven temperature, air circulation, humidity, baking time and oven load should be determined before setting up oven condition. There are a series of physical, chemical and biochemical changes involved during baking process. The changes can be seen on cake expansion, moisture content, surface colour and texture. These changes are usually evaluated as the final product quality.

During baking, heat is mainly transferred to the product surface through three mechanisms of heat transfer. The first mechanism is the radiation from oven walls, followed by the convection of hot air flowing inside the oven, and finally the conduction

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E-mail addresses:
nursyafikah@upm.edu.my (Shahapuzi, N. S.)
farahsaleena@upm.edu.my (Taip, F. S.)
norashikin@upm.edu.my (Ab. Aziz, N.)
anvar@upm.edu.my (Ahmedov, A.)
*Corresponding Author

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from the surface to the core of the product. A homogenous heating of product is crucial to prevent microbial risk and to maintain the uniformity of product quality (Verboven *et al*., 2000). For that reason, a uniform heating medium is required to obtain a homogeneous heating to the product. Thus, operating the oven with airflow mode could be a reasonably good option to accomplish a uniform oven temperature (Spence *et al*., 2007; Therdthai *et al*., 2004; McFarlane, 2006; Xue & Walker, 2003).

The presence of airflow generally influences heat exchange in the oven chamber, in which the percentage of convective heat transfer will be increased to some extent. Therefore, it is interesting to distinguish how these changes may influence oven temperature, baking process and finally product properties. Some previous studies have reported the effects of process condition in tunnel type oven (Baik *et al*., 2000a), pilot plant oven (Zareifard *et al*., 2009; Khatir *et al*., 2012), electric oven (Lostie *et al*., 2002) and infrared-microwave combination oven (Turabi *et al*., 2007), to name a few. However, the effects of the airflow to the oven temperature, process condition and product quality during cake baking have not been substantially reported.

The present study investigated how the variations in temperature and the presence of airflow affect the profile of oven temperature. This study also evaluated the effects of oven temperature and internal cake temperature towards cake expansion and product qualities.

MATERIALS AND METHODS

Cake batter was prepared by means of standard creaming method using a hand mixer (Panasonic, MKGH1, Osaka). Major ingredients are listed in Table 1. An aluminium baking pan with dimension of 15 cm x 15 cm x 7.5 cm (L x W x H) was modified to have transparent glass at the front side. The batter (ranged from 444 g to 448 g) was poured into the baking pan, and tapped three times before the top surface was smoothed with an offset spatula. The initial height of cake batter ranged from 28 mm to 30 mm.

TABLE 1: Major ingredients of butter cake based on flour weight

Ingredients	Wt. (%)
Butter	65.5
Castor sugar	87.0
Sifted cake flour	100.0
Baking powder	3.5
Eggs	67.8
Fresh milk	69.6
Vanilla essence	4.3

Baking experiments were carried out in an electrical convective oven Brio-Inox (Gierre, Milano). The cake was baked at three different oven temperatures (160°C, 170°C and 180°C) under forced convection (with airflow mode) and static air (without airflow). The overall schematic diagram of the experimental apparatus is illustrated in Fig.1. Wire K-type thermocouples were used to measure the temperature at four different positions identified as

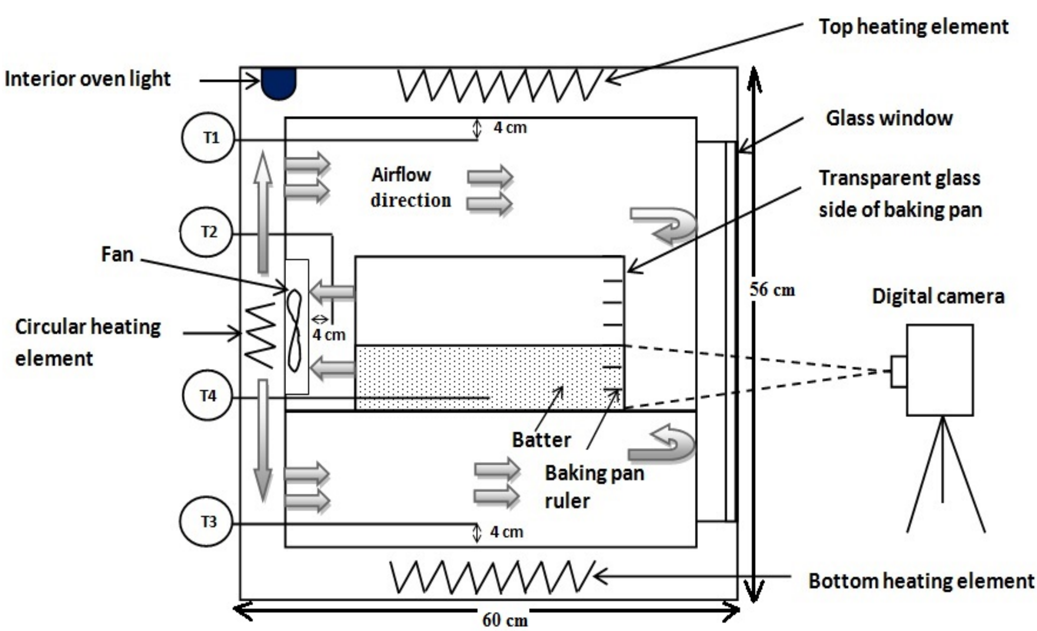

Fig.1: Experimental baking apparatus

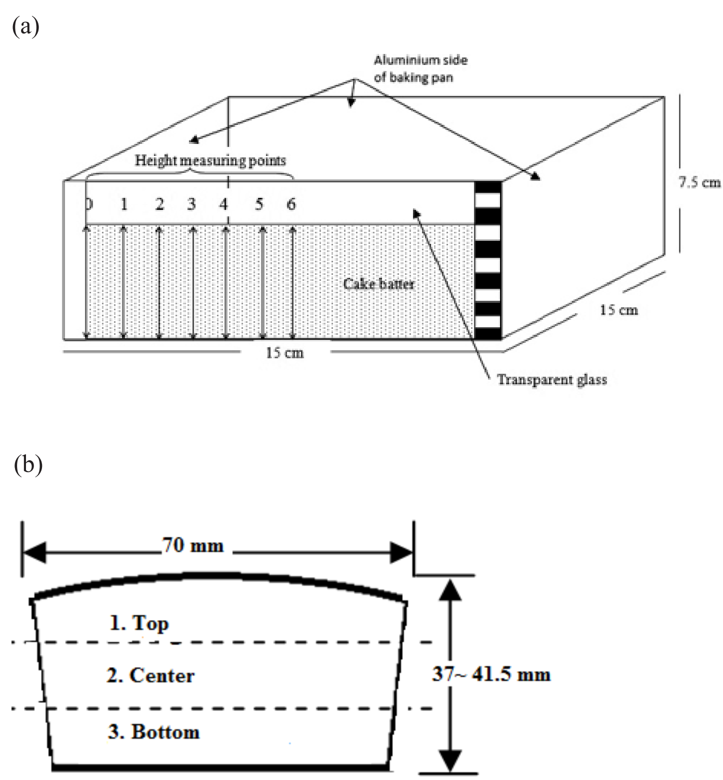

Fig.2: Experimental cake baking pan and sectioning of cake samples for the analysis of moisture content

T1 (top), T2 (center), T3 (bottom) and T4 (internal cake temperature). All thermocouples are connected to a data logger (Monarch Instrument, Monarch 309, USA) for temperature display and recording.

A digital camera (Sony, DSC-H50) was used to photograph the cake at 3 min intervals during baking. The distance of the camera tripod was 0.5 m from the oven glass window. Height of the cake was measured at every 1 cm interval from the left side until the centre point, as shown in Fig.2a. The measurement of the height of the cake was done from the digital image after the calibration of the images using the stainless steel ruler marking at the right side of the baking pan. Shrinkage during baking was calculated as the difference in height at its maximum height and the final height at the end of baking for each point. The difference in the cross sectional area of the sliced cake after baking and after 1 hour of cooling was measured to calculate the shrinkage during the cooling. This method was adopted from the previous work of HadiNezhad and Butler (2010). The crust and crumb thickness were also measured for every baked cake. The data of three replicates were recorded for each experiment.

The initial and final moisture contents of cake were analyzed by means of moisture analyzer (Infrared moisture balance, MX-50 AND Weighing, Adelaide) under standard drying, medium accuracy (0.05%/min) based on wet sample mass. The initial moisture content of batter was analyzed by spreading 2 g batter sample evenly on the aluminum foil before the start key was pressed to heat it. The cake was then cut into halves and a 2-mm sample was sliced from the centre part of the first half. The sample was then divided into three portions; top crust, crumb center and bottom crust, as shown in Fig.2b. The samples were placed in an air tight container to prevent moisture loss prior to the analysis. The moisture content was measured according to the sample portion.

Statistical analysis was conducted to study the effects of airflow and temperature on the oven temperatures profile and the quality of the final cake using GraphPad Prism 6 (GraphPad Software, Inc., 1992-2014). The data were analyzed using a two-way ANOVA analysis of data.

RESULTS AND DISCUSSION

Effects of Airflow on Oven Temperatures

The temperature profiles in the oven chamber during the cake baking process for with and without airflow at the set point temperature 170°C are shown in Fig.3. The oven temperatures were measured at the top, centre and bottom of the oven chamber, and identified as T1, T2 and T3, respectively. Three different points were chosen to measure the oven temperatures.

A distinct temperature difference could be seen between the top, centre and bottom of the oven during the baking process without the airflow mode. The temperature at the top (T1) was always higher than the bottom (T3), followed by the centre of oven (T2), giving the standard deviation range of 1.7°C to 10.2°C. This could be due to the location of the thermostat in the oven and the ineffective heat transfer that resulted from the lack of air circulation. On the contrary, with the presence of airflow in the oven chamber, all the three measured locations showed relatively similar temperature ($p<0.05$), whereby the standard deviation was between 0.4°C and 2.9°C.

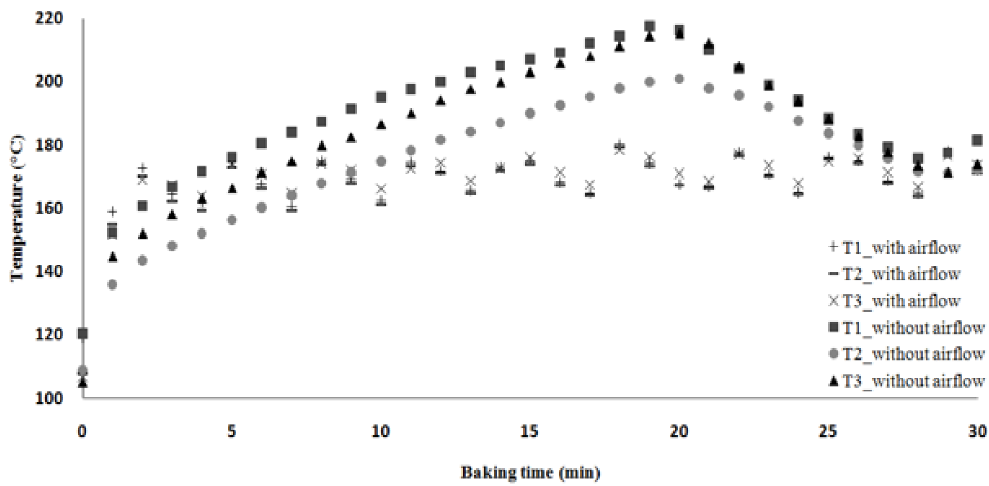

Fig.3: Oven temperature profiles during cake baking in convective oven for with and without airflow modes. T1, close to the top oven surface, T2, the centre location of oven, T3, close to the bottom oven surface

Although the set point is 170°C, the actual temperatures in each location were higher with overshoots between 19-30% without the airflow mode. The temperature at the top (T1) reached up to 217°C, which was 47°C higher than the set point (see Fig.3). A smaller overshoot (3.54%) was observed with the presence of airflow. The average temperature of the oven during baking with airflow was nearly to the set point temperature even though there was a fluctuation (±5.5°C) in the oven temperature.

The presence of airflow can also maintain the temperature within a small deviation of the set point. However, the temperature varied according to the locations. The bottom part of the oven chamber showed a slightly higher temperature than the centre and the top surface. This could be due to the variation in the circulation pattern of hot air in the oven chamber, as shown in Fig.1. Initially, the air in the oven chamber was sucked into the fan. Then, the air was heated by a circular heating element before travelling behind the panel to re-enter the oven chamber. The measurement of air velocity at the top, the centre and the bottom of the oven's right rear panel showed average readings of 0.34 m/s, 0.35 m/s and 1.88 m/s, respectively, measured by the thermal anemometer (Testo 425, USA). Higher hot air velocity at the bottom of the oven chamber generated the turbulence air condition in the oven, hence increased the convective heat. A relatively similar result was found by Spence *et al* .(2007) for the flow field in the domestic kitchen oven.

Effects of Baking Temperature on Oven Temperature

The oven temperature was affected by the variation of the set point temperature for both baking modes. Fig.4 shows the oven temperature profile at the top (T1) during the baking temperature of 160°C, 170°C and 180°C. The temperature variations during baking without airflow required a longer time to reach the maximum oven temperature than baking with airflow ($p<0.01$). In contrast, the increasing temperature during baking with airflow mode had slightly decreased the time taken to complete one cycle. This could be due to the physical properties of air that varied with temperature. Increasing the baking temperature would increase the velocity of hot air. It therefore caused the heat transfer mechanism to speed up. Thus, the maximum temperature could be reached faster. Hence, a complete cycle was accomplished earlier.

In contrast to baking with airflow, the temperature variation during baking without the airflow mode resulted in a quite a high percentage of overshoots ($p<0.01$). The maximum temperature overshoots were in the ranged of 28-30% for the top of the oven chamber, 16-19% for the centre of the oven chamber and 25-28% for the bottom of the oven chamber.

Effects of Baking Temperature on Internal Cake Temperature

The internal cake temperature for the three different baking temperatures is illustrated in Fig.5. There were three distinct stages during cake baking, namely, initial heat penetration, heating up and crust and crumb formation. The initial heat penetration stage occurred in the first one sixth of baking time. There was a relatively small temperature gradient. This was followed by a heating up stage where cake temperature increased rapidly. The internal cake temperature reached a pseudo-plateau during crust and crumb formation at an approximated temperature of 99.9°C. By increasing the baking temperature, shorter time was needed to reach pseudo-plateau temperature. The pseudo-plateau temperature occurred as a result of structure stiffening and formation of superficial dry crust layer that limit heat transfer through the crust and water vaporization (Fehaili *et al*., 2010; Lostie *et al*., 2002; Ousegui *et al*., 2010). Therefore, the temperature of crumb would not exceed the water boiling point temperature.

Temperature variation did not have significant effects on the internal cake temperature during the first and third stages ($p>0.05$). This was closely related to the slow heat penetration mechanism in the first stage and maximum heat occupancy in the cake during the third stage. Nevertheless, the temperature variation had given a direct impact on the second stage of baking ($p<0.01$). This could be due to the linear relationship between the oven temperatures to the heating rate in the cake. Higher oven temperature means more heat is transferred to the cake surface. Therefore, a steeper slope representing higher rate could be seen as the oven temperature increased from 160°C to 180°C, as shown in Fig.5. The temperature increment

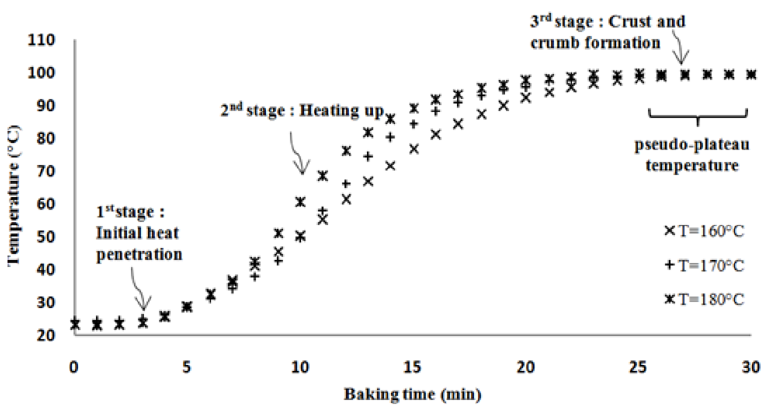

Fig.5: Internal cake temperature for the increasing of baking temperature with airflow mode

during the second stage of baking is critical since it is responsible to initiate several reactions such as caramelization, Maillard reaction, starch gelatinization, protein denaturation, water movement, cell structure formation and enzyme activities (Chang, 2006).

The findings from the present study corroborate with the results obtained by Lostie *et al*. (2002) who found that increasing the baking temperature would increase the rate of internal cake temperature during the second stage of baking. The heating rate during second stage increased more than half, i.e. from 5.17°C/min to 7.96°C/min, as the temperature was increased from 160°C to 180°C.

Effects of Airflow on Internal Cake Temperature

Fig.6 shows distinct three stages of internal temperature of the cake baked with and without airflow modes. The significant difference ($p<0.01$) could be seen on the thermal gradient during the second stage. The airflow significantly influenced the second stage by increasing the thermal gradient thus produced a sharper slope and hence shorter time to accomplish the second stage. The circulation of hot air increased the convective heat transfer to the cake surface. On the contrary, the second stage of baking without airflow mode showed slow but steady increase in the temperature until it reached a plateau in the third stage.

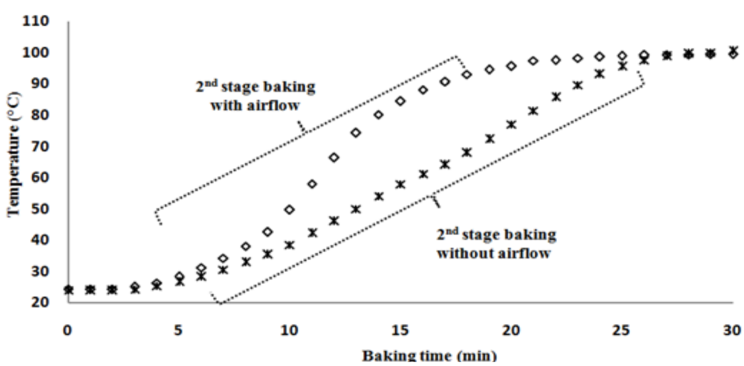

Fig.6: Internal cake temperature for baking in different modes at 170°C

TABLE 2: Heating rate of cake baking at 170°C

Time (min)	Without airflow mode(°C/min)	With airflow mode(°C/min)
0	0.33	0.48
5	2.10	3.20
9	3.74	7.52
14	3.45	3.20
18	4.36	1.04
23	2.63	0.33
26	0.70	0.05

The heating rates in both baking modes are tabulated in Table 2. Slower heating rate occurred at the first stage of baking in both the baking modes. The second stage started approximately at minute 5, where batter temperature started to increase gradually. Rapid heating could be seen in baking with airflow mode where the heating rate was doubled from 3.2°C/min to 7.52°C/min, as compared to without the presence of airflow. The presence of airflow reduced the total baking time by 20% as compared to without airflow.

Effects of Baking Temperature and Airflow on Cake Expansion

The images of a typical cake expansion that occurred during baking at 170°C with airflow mode are shown in Fig.7. The appearance of the brown surface colour gave an indication that the expansion process was slowing down and would end soon.

The profile of cake height changes during baking is plotted in Fig.8 based on the centre point of the cake height. Increasing the baking temperature slightly increased the percentage of height increment. This is similar to the findings in Fig.5 which showed that the increasing of baking temperature did not have any significant effect on the gradient of internal cake temperature.

The percentage of cake shrinkage after baking with airflow for 160°C, 170°C and 180°C are 11%, 14.9% and 17%, respectively. These results are based on the total cross sectional area of a sliced cake. In contrast, the cake shrinkage after baking without airflow was 12.5%, 21.9% and 22.7% for 160°C, 170°C and 180°C, respectively. Cake baked at a high temperature shrank the most after cooling. This might be the results of cake contraction during cooling which was caused by the release of gas in the bubbles. Higher baking temperature produced a higher pressure of gas in the bubble, and therefore caused greater cake contraction.

Apart from baking temperature, the airflow inside the oven chamber resulted in significant differences in the expansion of cakes ($p<0.05$). Cakes expanded at different rates during the second stage of baking period in both the baking modes (see Fig.9). Higher percentage of height changes could be seen in the baking process with the airflow mode. In particular, the rate of cakes height increased approximately 3.21mm/min during the second stage of baking with airflow as compared to 2.88mm/min while baking without airflow.

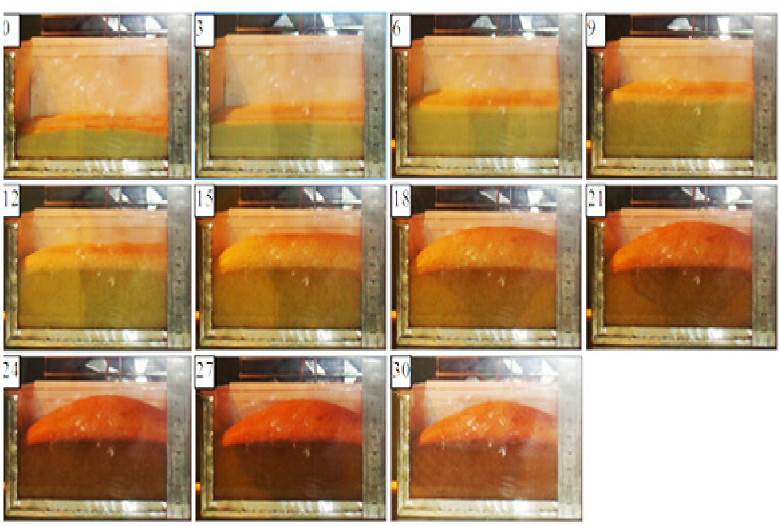

Fig.7: Successive images taken during batter expansion. The number on each image represents the time (min) of baking at which the image was taken

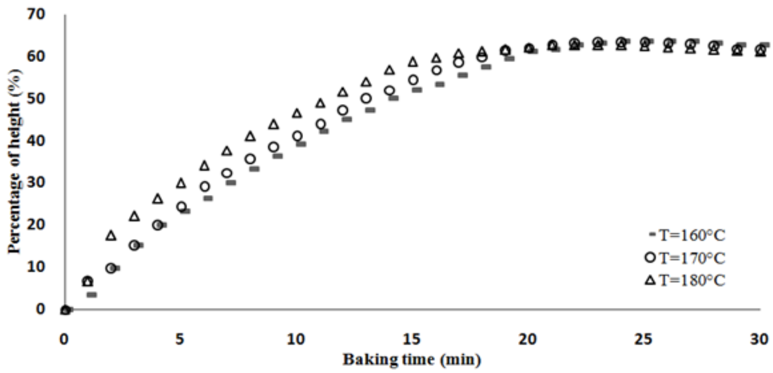

Fig.8: The profile of cake height changes for low (160°C), medium (170°C) and high (180°C) baking temperature baking with airflow mode

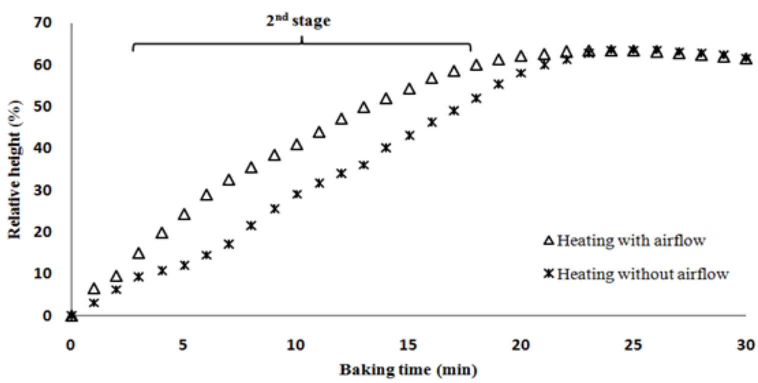

Fig.9: The profile of cake height changes for different baking modes at baking temperature 170°C

Fig.8 and Fig.9 can be used to emphasize the findings on the effects of temperature variation and baking mode towards baking process. Hence, airflow plays an important role in cake baking by having a higher percentage of cake height increment.

Moisture Content of Cakes

Water movement during cake baking process occurs when the moisture in the batter moves to its surrounding and then evaporates. Water movement also contributes in heat transfer and diffusion. However, cake will become dry and large crust portion will be formed if too much water evaporates and thus reduces the taste and cake quality. Therefore, the moisture content becomes one major concern since it greatly influences the quality and acceptance of a product (Chang, 2006).

The initial moisture content of batter was 34.06± 0.12% in wet basis. Table 3 shows the percentage of moisture content of cake after baking ended with the range of 25.27% to 33% in this experiment. Generally, the moisture content was lowest on the top surface (portion 1), highest in the middle (portion 2) and intermediate moisture content in the bottom portion (portion 3) where the significance level is $p<0.01$. This is approximately similar to that found in Baik *et al*. (2000b) for thick cake layer baked in a tunnel type industrial oven. Therefore, the findings in this study can support the theory that temperature distribution in the product (generally, surface>bottom>centre) can affect moisture movement, as suggested by Baik *et al*. (2000b).

TABLE 3 : Percentage of moisture content in wet basis of cake after baking

Portion	Baking without airflow mode (%)			Baking with airflow mode (%)		
	160°C	170°C	180°C	160°C	170°C	180°C
Top	25.49±1.56	27.19±0.93	27.27±3.21	26.12±0.85	25.27±0.45	25.27±0.01
Center	32.08±2.18	33±0.44	32.38±0.32	31.92±0.54	32.33±0.94	32.1±0.38
Bottom	29.06±0.95	29.45±0.73	27.97±0.19	29.05±0.01	27.69±0.12	27.14±0.02

Cakes baked with airflow showed a lower percentage of moisture content as compared to baking without airflow ($p<0.05$). The thermal gradient in cake might influence the percentage of the final moisture content. As shown in Fig.6, baking with airflow resulted in a higher thermal gradient. The higher thermal gradient in the cake might enhance the migration of moisture from the hotter to colder region.

The moisture loss during baking might contribute to the weight loss of cake. By increasing the baking temperature, it causes the higher percentage of weight loss, as illustrated in Fig.10. Besides, the cake baked with airflow mode resulted in a higher weight loss compared to those without airflow mode ($p<0.05$). This might be due to the enhanced airflow velocity by the fan to distribute heat throughout the oven chamber and thus increased heat penetration to the cake.

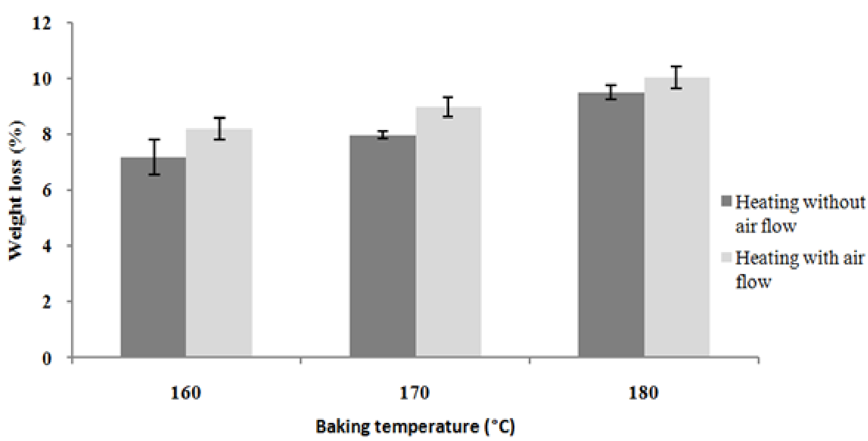

Fig.10: The percentage of weight loss with an error bar for low (160°), medium (170°C) and high temperature (180°) under different heating modes

Cake Properties and Qualities

Several factors have effects on the texture of cake such as ingredient, mixing process, baking temperature, baking time, air velocity and type of oven. The variation in the baking temperature caused the surface colour to become dark brown and resulted in thick cake crust. The presence of airflow during baking resulted in a uniformly brown surface colour of the cake. In contrast, baking without airflow mode produced a cake that has a pale surface colour with some dark spot, cracked surface and compact texture.

After cooling to room temperature for an hour, the cakes undergoes a slight shrinkage. Cakes baked with airflow mode shrunk lesser (about 11%-17%) than those without the airflow mode (12.5% to 22.7%), while higher baking temperature increased shrinkage in both the baking modes. The final height of the cake baked with airflow was also lower. The reduction in the cake height is mainly due to the contraction of cake. Baking with airflow causes bubble expansion to become faster and gas pressure in the bubbles becomes higher, causing the cake contraction to occur earlier.

CONCLUSION

The presence of airflow during baking process highly influences the oven temperature as the hot air can be circulated throughout the oven chamber resulting in a uniform oven temperature profile. It can also maintain the temperature of the oven very closely to the set point temperature. A uniform heat in the oven chamber increases the heat received by the product and affects its end quality. The cake baked with airflow showed a higher rate of volume expansion but a lower percentage of moisture content as a result of the higher heating rate in the cake.

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