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EXPERIMENTAL STUDIES ON THE EFFECT OF AIRFLOW ON OVEN TEMPERATURE AND PRODUCT QUALITIES IN CAKE BAKING PROCESS

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ABSTRACT

Convection oven offers a uniform heating process by increasing airflow and circulating air inside oven chamber has overcome the static air and dominant radiant heat that encounter in conventional oven. Consequently uneven cooking and surface browning on the product can be avoided. Therefore, the purpose of this study is to investigate the effect of air flow on oven temperature and product qualities in cake baking process. Experimental study is conducted within two different baking conditions; with and without airflow in convective oven. The parameters measured are internal oven temperatures and internal cake temperature whereas the output product qualities are measured in terms of height increment, moisture content and texture properties. Significant differences can be seen on the oven operating temperature and the product itself such as internal temperature, percentage of height increment, percentage of final moisture content and texture properties. Baking process with airflow condition showed a uniform heat distribution in the oven chamber, higher heating rate of internal cake temperature (6.7°C/min compared to 3.9°C/min for without airflow condition) and higher percentage of height increment of cake (3.21mm/min compared to 2.88mm/min for without airflow condition). Nevertheless, weight loss further ensues if cake baking process carried out with the present of airflow, compared to heating without airflow which the baked cake retains higher percentage of moisture content.

Keywords: *Convective oven, Cake baking, Internal cake temperature, Height increment, Moisture content.*

INTRODUCTION

A series of physical, chemical and biochemical changes such as volume expansion, evaporation of water, formation of porous structure and browning reaction take place in the product throughout the baking process. All of these changes determining the quality of final product. During baking heat energy is mainly transferred to the product surface by radiation from oven walls and by convection from hot air flowing inside the oven, and by conduction from the surface to the core of the product. The percentage of heat transfer differs according to the type of product and oven chamber design and operation. Meanwhile heat distribution in the oven chamber is influenced by the airflow, the heat supply, the humidity, the oven load and the baking time [1].

Non-homogeneous heating of food might cause considerable microbial risk and a large non-uniformity of the food quality [2]. The non-uniformity might attribute to a bad distribution of the heating medium. Hence optimization of oven operating conditions ought to be considered to achieve a reduction in energy consumption as well as an improvement in product quality. Compared to conventional oven (static air condition), convective oven offers special features with the installation of fan inside the oven chamber, it may perhaps give an advantage of uniform heat distribution. Consequently the absorption of heat by the product might be affected and thus become critical for final product quality. For instance, lower oven temperature results on lesser heat absorption by the product thus slower the baking mechanism therefore affects the commercial value of the product such as volume, moisture content and surface color [3].

Experimental studies have been conducted by many research teams to distinguish the relationship between operating temperature to several parameters such as product surface temperature, internal product temperature, volume expansion and moisture content in biscuits [4-6], cakes [7-10] and bread [11-13]. However, only few study stress on comparing the product qualities by manipulating oven operation mode with and without airflow. The comparison is important to indentify the major differences or similarities on product as the baking mode is switch.

A study have been conducted to characterize the cake baking condition in two tunnel type multi-zone industrial ovens: gas fired band oven and electrical powered mold oven [14]. Different temperature was applied at different chamber along the tunnel oven throughout baking process, results on shorter baking time. Another study restricted the heat supplied only over the upper face of the batter sample under static air condition thus longer baking process up to 3-10 times [8]. Hence the present study is carried out under standard cake baking temperature and baking time using experimental convective oven where the baking mode can be switch to with and without airflow condition.

The objective of the present study is to compare the baking condition, baking mechanism and quality of final product for the baking operation with and without airflow. Butter cake was baked in an electrical convective oven under two distinct operations: with and without airflow at temperatures varying from 160°C to 180°C. The following batter parameters were recorded during a run: oven internal temperatures, cake internal temperature and cake dynamic height.

MATERIALS AND METHODS

Cake batter was prepared using standard creaming method using hand mixer (Panasonic, MKGH1, Osaka). Major ingredients are listed in Table 1. Room temperature butter was beaten at medium-to-high speed for 1.5 minutes. Sugar was added gradually and was beaten at low-to-medium speed for 30 seconds. The mixture was scrapped before beating continued at medium-to-high speed for 3 minutes. Vanilla essence was added to the mixture, beaten at medium speed for 30 seconds. Eggs was added one at a time and was beaten at slow-to-medium speed for 30 seconds on each addition, and then the mixture was beaten until the batter smooth, approximately 1.5 minutes. One third of flour portion was added and beaten slowly before half of milk was poured. The same step was repeated until last portion of flour was added. 30 seconds mixing time required for each flour addition. Finally all the left over flour at mixing bowl was scrapped down and well mixed into the batter.

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

An aluminium baking pan with dimension 15 cm x 15 cm x 7.5 cm (L x W x H) wide was modified to have transparent glass at front side. The batter (ranged from 444 g to 448 g) was poured into the baking pan, and was tapped three times before the top surface was smoothed with an offset spatula. The initial height of cake batter has a range from 28 mm to 30 mm.

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 conditions (with airflow) and static air conditions (without airflow). The oven was preheated 15 minutes before the baking experiment to obtain uniform baking condition. For heating with airflow condition, the air was circulated by a fan installed on the back side of the oven at average speed (0.97 m/s measured at the center of the oven chamber by Thermal anemometer (Testo 425, USA).

An overall schematic diagram of the experimental apparatus is presented in Fig. 1. Three wire K-type thermocouples, identified as T1, T2 and T3 are attached to the specific points in the oven chamber to measure the internal oven temperatures. A wire K-type thermocouple was inserted into cake baking pan through a small hole at right side of baking pan, measured as T4. All thermocouples are connected to data logger (Monarch Instrument, Monarch 309, USA) for temperature display and recording.

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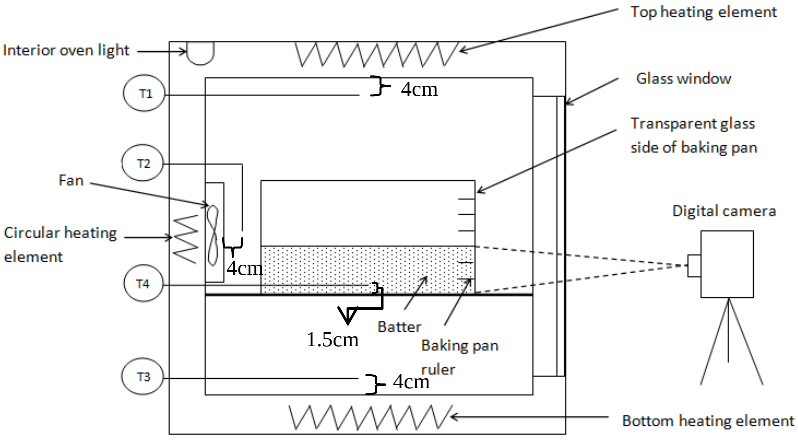


Fig. 1: Experimental baking apparatus.

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 oven glass window. Lighting was also provided by the ambient lighting within the oven. Height of the cake was measured at every 1 cm interval from the left side until the center point as shown in Fig. 2 from the digital image after the calibration of the images using the stainless steel ruler marking at the right side of baking pan. The crust and crumb thickness were also measured for every baked cakes. The data of three replicates are recorded for each experiment.

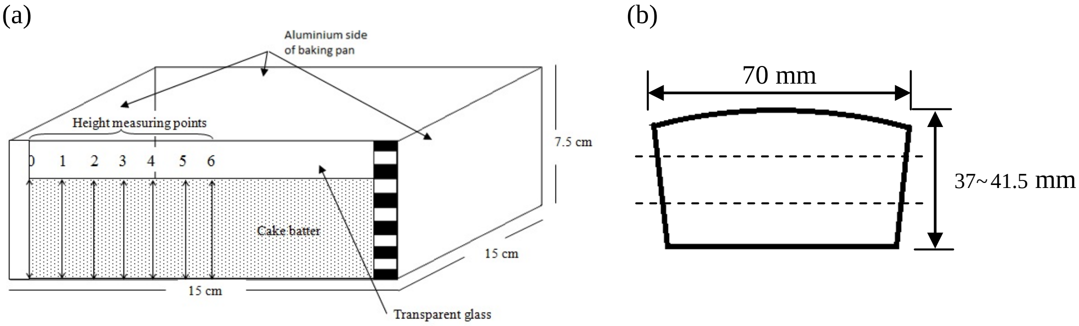


Fig. 2: Experimental cake baking pan (a). Sectioning of cake samples for analysis of moisture (b).

Initial and final moisture content 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 start key was pressed to heat it. Meanwhile, the fresh baked cake was allowed to cool at room temperature for 15 minutes prior sampling process. Then cake was cut into half and 2 mm sample was sliced from the center part of the first half. The sample was then divided into three portion; top crust, crumb center and bottom crust and placed in air tight container, subsequently the moisture content were measured separately.

RESULTS AND DISCUSSIONS

Effect of airflow on oven temperature

Fig. 3 shows the temperature profiles in the oven chamber during cake baking process for with and without airflow. The oven temperatures were measured at three points; top, center and bottom of oven chamber, identified as T1, T2 and T3 respectively. Baking without airflow shown distinct temperature difference between T1, T2 and T3 where T1 always higher than T3, followed by T2 with average standard deviation for the first 20 minutes is 9.3°C and then reduced to 3.3°C in 10 minutes later.

With the presence of airflow in the oven chamber during baking, all three measured locations shown relatively similar temperature and heating pattern with average standard deviation 1.54°C between one to another. However, the bottom surface of oven chamber exhibits slightly higher temperature than center and top surface location. The circulation of hot air in the oven chamber might influence this trend. The hot air is expelled at the fan's circumference, passing over a circular heating element before travelling behind the panel to reenter the oven chamber via vents along the edges of the rear panel. Higher velocity of hot air at bottom chamber was indentified thus give slightly higher temperature than other location.

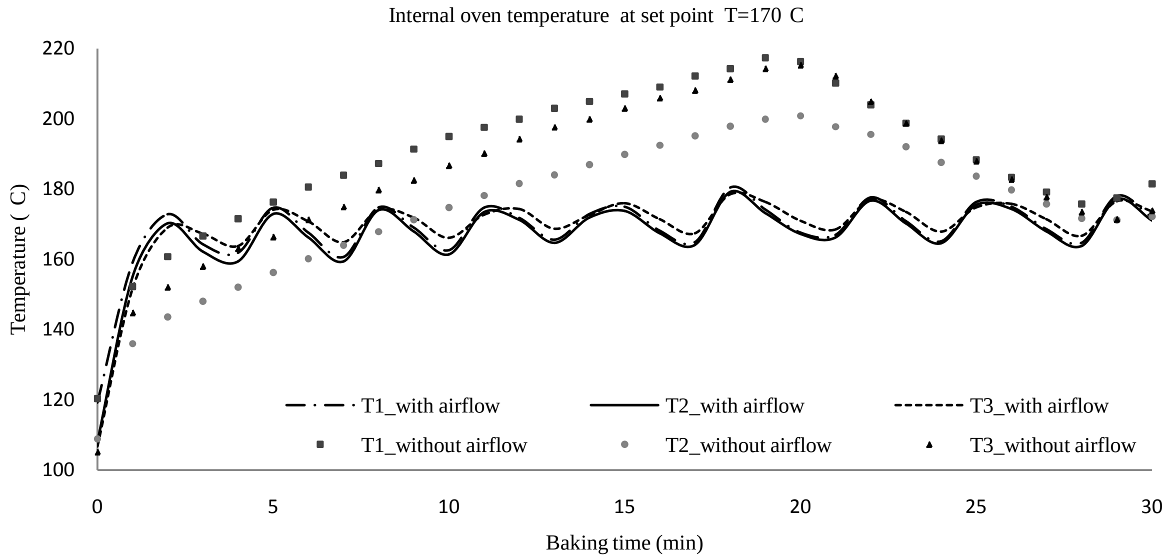


Fig. 3: Internal temperature profiles during cake baking in convection oven for two different modes, with and without airflow (T1, close to top oven surface, T2, center location close to fan, T3, close to bottom oven surface).

In terms of temperature pattern, heating with airflow demonstrates uniform and steady heating and oven operating temperature is always closer to the set point temperature. A schematic diagram is given in Fig. 4 to show the recirculation flow in and out of the oven chamber. Initially top and bottom heating elements heated up the air in the oven chamber. Then the heated air is sucked in by the fan that installed at the center, back side of the oven thus increase the air velocity. This high air velocity is then passing through a circular heating element that located behind the panel before flowing back to the oven chamber through the edges of rear panel. This on-going process increased the convection heat therefore improved the heat transfer to the cake during baking process. The airflow assists in temperature control and distributes heat evenly to the oven chamber.

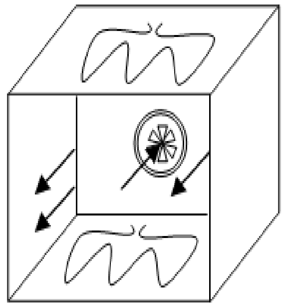


Fig. 4: Illustration of convection oven showing flow in and out of the oven chamber

On the other heating mode, the air temperature profiles in the oven chamber during heating without airflow shows a continuous temperature increment to 216°C even when the set point temperature of 170°C. Then the temperature starts to decline steeply from minutes 20 to reach 171°C at minutes 29 and possibly the temperature went up again if the baking process continued. Both locations close to heating element (T1 and T3) always retain a higher temperature than center location of oven chamber. This phenomenon might be due to the absence of air circulation inside the oven chamber. Top and bottom heating elements need to heat up the air progressively in order to raise the temperature of oven chamber. Since there is no airflow, radiation becomes predominant heat transfer hence results on lower air temperature at center location of oven chamber. This surface temperature profile was similar to that found in [3] for continuous industrial bread baking oven.

Effect of baking temperature on internal cake temperature

The internal cake temperature for three different baking temperatures is illustrated in Fig. 5. There were three distinct stages during cake baking, namely initial heat penetration, heating up period and crust and crumb formation. Initial heat penetration stage occurs in the first 4-6 min of baking, there was relatively little temperature gradient. This was followed by a heating up period where cake temperature increase rapidly until minutes 18-22. The internal cake temperature reached a pseudo-plateau during crust and crumb formation at 99.5°C, 99.6°C and 99.9°C after 27, 25 and 22 minutes for baking at 160°C, 170°C and 180°C respectively.

By varying the baking temperature, not much different exists in internal cake temperature for initial and final stages. This is closely related to the heat penetration mechanism and maximum heat occupancy in cake. Meanwhile heating up period apparently to be the critical stages since increasing the baking temperature demonstrates sharper slope. The temperature increment during heating up period responsible for the several reactions occurs during baking such as caramelization, Maillard reaction, starch gelatinization, protein denaturation, water movement, cell structure formation and enzyme activities [15]. This finding confirms that by increasing the baking temperature, the rate of internal cake temperature also increases correspondingly with the same curve shape and tendencies as reported in [8].

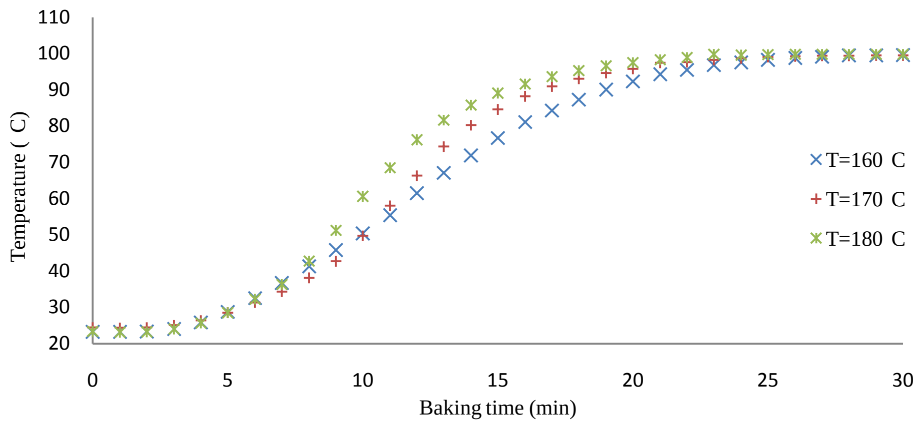


Fig. 5: Internal cake temperature for the increasing of baking temperature under with airflow heating condition

Effect of airflow on internal cake temperature

Different baking mode influenced the rate of heat transfer to the product at certain baking stages. Fig. 6 shows a distinct three stages of internal temperature of cake baked with and without airflow conditions. Initially for both heating conditions, heat penetrated slowly to the cake batter. Second stage starts as cake internal temperature increase repeatedly. Baking condition without airflow shows slow but steady heating rate throughout second stage. The heating rate is linear until it reaches a steady state. In contrast, with airflow heating condition indicates higher internal cake temperature and faster temperature increasing rate by referring on the steep slope. Furthermore the cake reached temperature plateau more than 60% earlier for cake baking under heating with airflow.

Large temperature differences between both heating conditions might preferably due to the amount of heat received on the cake surface. Steady and uniform heat distribution during heating with airflow resulted in progressive heat transfer via convection and radiation process. Therefore baking condition with airflow offers better heat distribution thus enhance heat transfer to the product and increase heating rate, possibly less time required to finish baking.

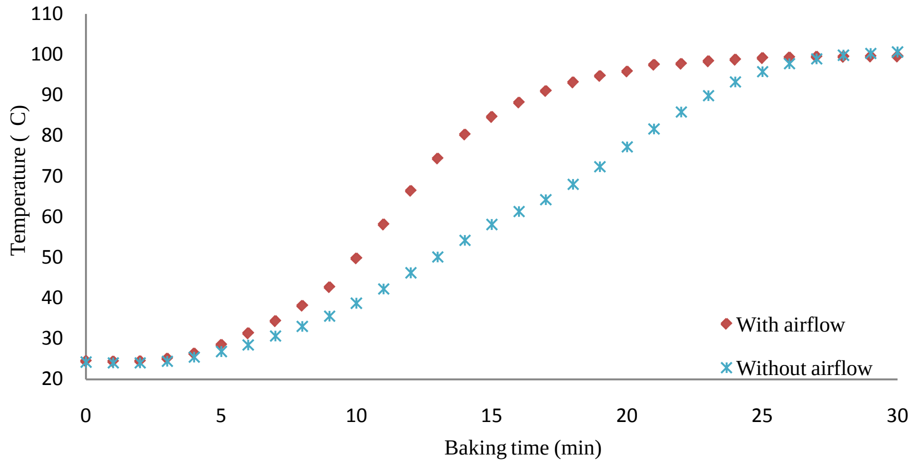
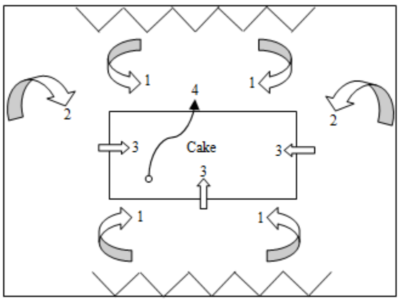


Fig. 6: Internal temperature of cake baking at medium temperature (T=170°C) in different baking mode

There are three different ways for heat transmission to the baking product, namely radiation, convection and conduction as illustrated in Fig 7. Radiant heat emanates from the heated internal surface of the oven. This heat is absorbed by the exposed surface of the product, thus increasing internal product temperature. Meanwhile the existing of air flow in the oven chamber helps in heat distribution through convection process to the entire of oven. Then this heat is transferred to the product by conduction as the hot air contacts their surface. Finally the interior product will receive heat that is transmitted through the bottom and sidewall of the product from radiant heat and conduction heat [15]. The more rapid the air movement, the more rapid and efficient will be the diffusion of heat as confirmed in Fig. 6.



[1] Convection heat, [2] Radiation heat, [3] Conduction heat, [4] Diffusion of water

Fig. 7: Illustration of heat and mass transfer in baking oven.

Cake expansion

The photos of typical cake expansion that occurred during baking at 170°C heating with airflow are showed in Fig. 8. The first 3 minutes is the early stages of baking where heat penetrating into cake batter which does not cause considerable expansion. The batter expanded repeatedly approximately from minutes 3 to minutes 21 as a result from the expansion of bubbles from the increase in vapor pressures of water and air in the bubbles. This heating up period mechanism has been explained clearly in [8]. The appearance of the superficial dry crust illustrated by the brown surface color gave an indication to the end of expansion period. The cake remained steady for awhile and then followed by a slight shrinkage.

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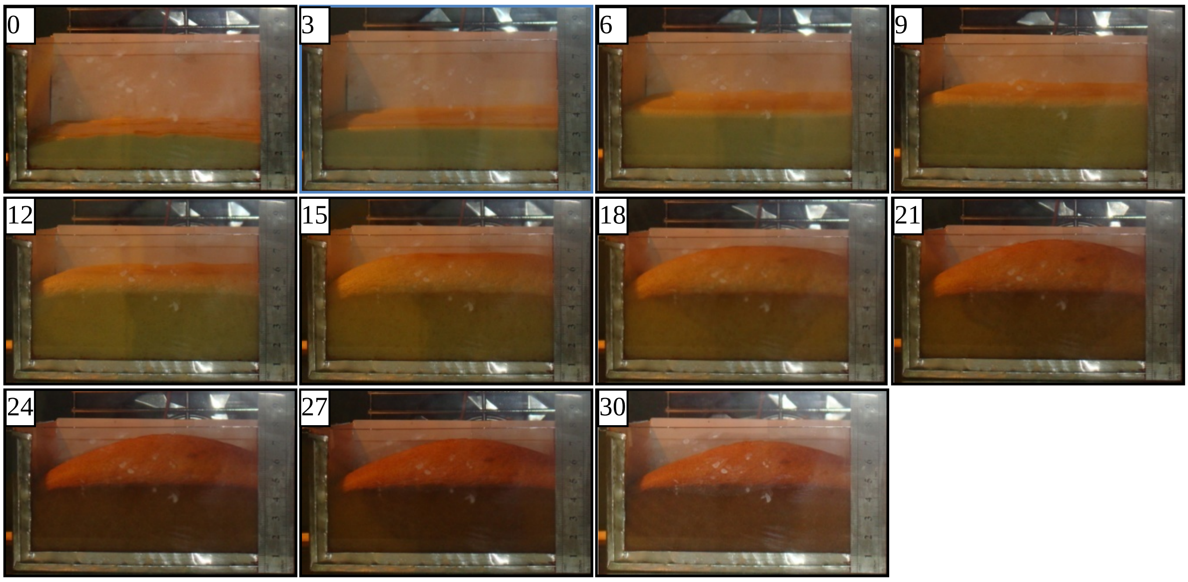

Fig. 8: Successive images taken during batter expansion. The numbers on each image represent the time (min) of baking at which the image was taken.

The profile of cake height changes during baking was plotted in Fig. 9 based on the center point of the cake height. Cake baked at 180°C showed highest percentage of height changes and attained its maximum volume at minutes 20, remained steady for several minutes before started to shrink at minutes 25. Even though baking temperature of 160°C showed the lowest percentage yet produced highest cake height at the end of baking. The height of cake for baking temperature of 170°C lies between the other two temperatures.

However still Fig. 9 alone cannot tell us which baking temperature is the best to get the highest cake volume since the cake will undergo a series of cake shrinkage just after been taken out from the oven. In this experiment, the higher the temperature, the lower percentage of cake shrinkage, average values are 22.7%, 21.9% and 15.9% of baking temperature 160°C, 170°C and 180°C respectively.

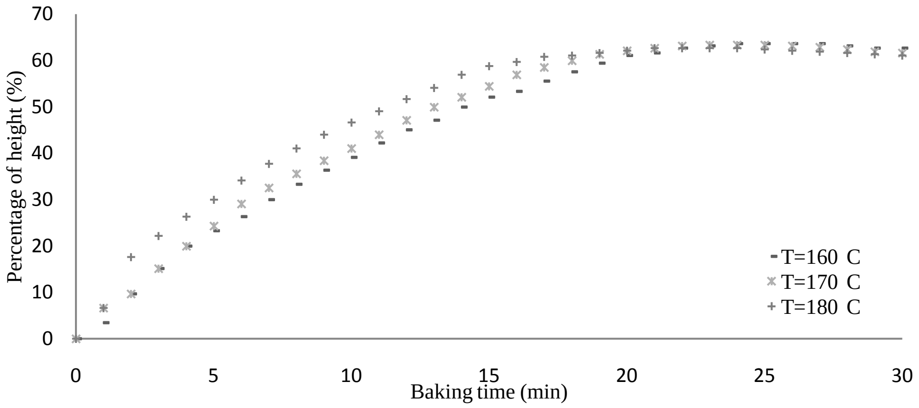

Fig. 9: The profile of cake height changes for low (160°C), medium (170°C) and high (180°C) baking temperature baking with airflow heating condition.

Baking temperature might affect the percentage of height changes of cake under some magnitude but still demonstrates similar curve shape [16]. The higher the baking temperature, the higher cake rises during baking process [17]. Besides the effect of fan towards the airflow inside the oven chamber give a significant difference of height changes of cake. Fig. 10 showed an obvious difference of the height percentage between minutes 3 to 20 for the cake baking with and without airflow heating mode. Higher percentage of height changes can be seen on heating with airflow mode. However starting from minutes 21 both modes accomplished quite similar cake height until baking ends.

There was qualitatively similar sample volume changes were measured by [6] in biscuits, [8] in sponge cake, [10] in ring cake and [11] in the case of bread baking. However volume expansion in biscuit began slower (batter temperature ranged from 45°C to 50°C) as compared to cake batter where cake expansion image was shown in Fig. 8.

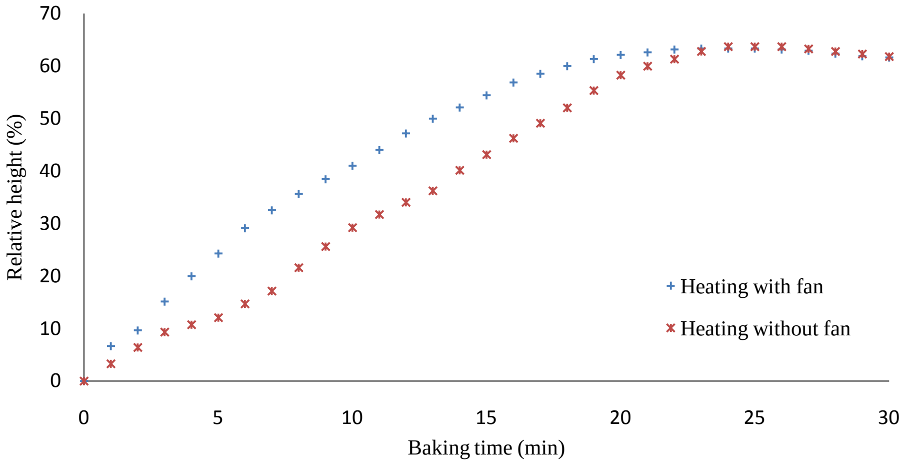

Fig. 10: The profile of cake height changes for different baking mode at medium baking temperature (T=170°C)

Moisture content of cakes

Water movement is one of the reactions that take place during cake baking process in which moisture in the batter moves to its surrounding and then evaporates. Water movement also participates in the heat transfer and diffusion. However, cake will become dry and large crust portion if too much water evaporates thus lessen the taste and cake quality.

The initial moisture content of batter is 34.06± 0.12% (wet basis). Table 2 shows the percentage of moisture content of cake after baking ends with the range 25.27% to 33% in this experiment. Generally for all baking temperatures, the moisture content was lowest for surface portion (part 1), highest for middle portion (part 2) and intermediate moisture content value for the bottom portion (part 3). This was comparable to [14] for thick cake layer baked in tunnel type industrial oven. They suggested that temperature distribution in the product (generally, surface>bottom>center) could affect moisture movement.

By comparing the moisture content in the cake which undergone different baking mode, cakes baked in the condition with airflow showed a bit lower percentage of moisture content. This might be due to the thermal gradient in the cake internal temperature for both baking mode as shown in Fig. 10 earlier. The higher thermal gradient might enhance the migration of moisture from hotter to colder part.

Table 2: Percentage of moisture content in wet basis of cake after baking

Portion[a]	Baking mode without airflow			Baking mode with airflow		
	160°C	170°C	180°C	160°C	170°C	180°C
1	25.49±1.56	27.19±0.93	27.27±3.21	26.12±0.85	25.27±0.45	25.27±0.01
2	32.08±2.18	33±0.44	32.38±0.32	31.92±0.54	32.33±0.94	32.1±0.38
3	29.06±0.95	29.45±0.73	27.97±0.19	29.05±0.01	27.69±0.12	27.14±0.02

[a] Correspond to the portions indicated in Fig. 2b

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. 11 below. Besides, the cake baked from heating with the present of airflow result on higher weight loss compared to without airflow heating condition. This might be due to the enhanced airflow velocity by the fan to distribute heat throughout the oven chamber thus increase heat penetration to the batter. Therefore the drying rate might increase to certain level.

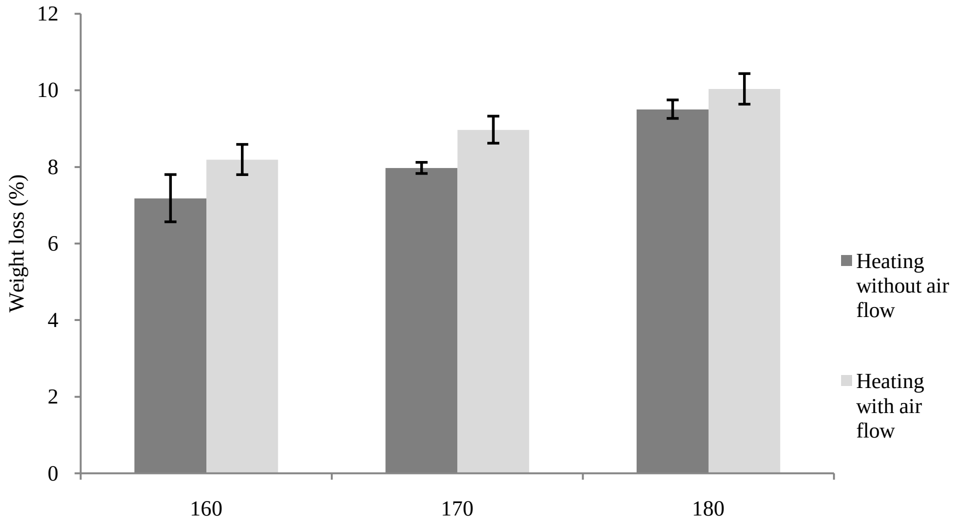

Fig. 11: The percentage of weight loss with an error bar for low (160°), medium (170°C) and high temperature (180°) under different heating mode

Cake properties and qualities

The texture of cake might depends on several factors such as ingredients, batter mixing process, baking temperature, time, air velocity and types of oven. In the present study, there was a focus on the varying baking temperature and airflow. The surface color becomes darker and cake crust becomes thicker as baking temperature increases. The cake volume rises was higher for the increase of baking temperature, contrarily to baking without airflow condition, as similar trends were found by [8].

The present of airflow during baking results on uniform but darker surface color of cake. However, if fan is off (static air condition), there were some dark spot on the cake surface which give an interpretation that the heat is not well distributed throughout the oven chamber.

After cooling to room temperature for 15 minutes, the cakes have undergone a slight shrinkage. Cakes that baked from heating with airflow mode shrank lesser (about 11-17%) rather than heating without airflow mode that shrank from 12.5 to 21%, where higher the baking temperature will lesser the shrinkage.

Even so, the final height of cake baked under airflow baking condition just a bit lower. This might complied with the result in Fig. 9 where the percentage of height changes for cakes heated with airflow mode decreased in 8 minutes before baking ends.

The weakness appearance of cakes that baked under static air condition is the pale surface color with some dark spot, cracked surface and compact texture. Too hot of oven temperature as shown in Fig. 3 might contribute to this undesirable outcome.

CONCLUSION

The presence of airflow during baking process obviously affected the oven temperature in which the temperature profile become steady and heat is uniformly distributed to the entire oven chamber. This thermal phenomena makes a large different in terms of heat distribution to the product. Better heat distribution could increase the heat received to the product, thus thermal gradient inside the product also increase to a certain rate and finally can initiate several reaction in the cake batter to start earlier and faster during baking. The final product also have a quite different quality based on the reaction occurs during baking, for example cake baked with airflow shows higher in volume expansion, structure properties, brownish surface color and lower percentage of moisture content.

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