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Empirical Modelling of the Effect of Airflow on Oven Temperature Control in Cake Baking

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Abstract: *Understanding the dynamic behaviour of oven temperature is important to ensure proper temperature control during baking. This paper presents the development of an empirical model for the cake baking process with airflow. Increasing the airflow velocity to 100% and the baking temperature by 10°C reduced the temperature overshoot by 75%–86% at the oven centre. The resulting moisture contents of the cakes exhibited 8% differences or less. Empirical models were developed by applying step changes in the baking temperature and airflow velocity and can be represented by second-order-plus-time-delay (SOPTD). The response to changes in airflow was 61% faster compared to changes in baking temperature, which indicated that airflow is more significant in influencing convection heat transfer during baking.*

Keywords: Cake baking, airflow effect, empirical modelling, oven temperature control, temperature dynamic behaviour

1. INTRODUCTION

In food processing, baking is a common process that involves simultaneous complex physical, chemical and biochemical changes. This process requires an efficient operating chamber, commonly called an oven. The oven efficiency depends on heater size, oven size, insulation in the oven, ambient temperature, air circulation within the oven, air humidity, oven load and many other factors. Consequently, the final product can have inconsistent quality.[1,2]

Researchers have investigated methods to improve the product quality and make the process more efficient. These approaches include mathematical modelling, baking process design and optimisation of oven conditions.[3–5] Mathematical modelling is a practical tool that is useful for pre-design, optimisation and process control. By using the model, the interaction between the oven condition and the product can be measured easily, therefore minimising the work required in baking as well as reducing energy loss.[5]

Currently, extensive studies on modelling baking products such as cakes,[5–7] breads[8–9] and biscuits[10] can be found in the literature. However, the models presented focus only on such experimental conditions as the moisture, texture, volume and temperature of the product. The oven conditions during the baking process should be considered in the model to have a clear understanding for the purpose of control. These conditions include the actual oven temperature, airflow velocity and humidity. Among these factors, studies on the effect of airflow on temperature control during baking remain limited.

Therefore, the aim of this paper is to develop an empirical model for the baking process with airflow, controlled under a Proportional-Integral-Derivative (PID) controller. The effect of the process conditions on the final product is also highlighted.

2. EXPERIMENTAL

A standard cake batter recipe was used. The ingredients were mixed according to a standard creaming method using a hand mixer (Panasonic, MKGH1, Osaka). Batter with an initial weight range between 444 g and 448 g was produced per batch and then baked for 30 min. The oven was preheated to 160°C with airflow 15 min before the baking experiment to obtain a uniform baking condition.

The oven used was an electrical convection oven, 2.6 kW power, 66.2 l working volume, with overall outer dimensions of $60 \times 59.5 \times 56$ cm^3, from Gierre Ik-Interklimat S.P.A. (Milano). The case material and work chamber material were made of stainless steel. Figure 1 shows the experimental setup for the baking process using a modified convective oven. The temperature profiles of the oven were measured using 3 wire K-type thermocouples, identified as T1, T2 and T3, attached near the top surface, bottom surface and hot airflow exit from the fan, respectively. The control panel was placed externally for oven temperature control purposes. The top, bottom and circular heater can be individually controlled using a PID controller. The controller can also be set to manual mode, in which on-off control occurs.

The oven offers two baking modes, namely, forced convection and static air. In the forced convection condition, air is constantly re-circulated inside the oven by a fan installed on the back side of the oven. The fan is turned off in the static air condition. The velocity of airflow can be adjusted using a motor fan controller. The airflow values were 0 m s^{-1}, 0.98 m s^{-1}, 1.47 m s^{-1} and 1.88 m s^{-1}, corresponding to 0%, 50%, 75% and 100%, respectively.

The step test was conducted after the oven reached a nearly steady temperature. Changes made during the baking process with airflow mode included the temperature and airflow velocity settings. For the first process, a step test for a temperature setting of 130°C was performed. The input was changed by magnitude of +10°C. The step test for the second process was a reduction of 50% in airflow velocity, from 1.88 m s^{-1} to 0.98 m s^{-1}. The transfer functions of these processes were developed based on an empirical modelling method. The models were validated and justified.

Figure 1: Experimental configuration of the baking oven.

The final moisture content of the cake was compared for baking with the on-off controller and the PID controller. The moisture contents of the crust and crumb of the cakes were analysed separately by applying a standard method for the determination of total solids in biomass. A convection (drying) oven was used at 105°C ± 3°C for this purpose.

3. RESULTS AND DISCUSSION

3.1 The Effect of Airflow on Oven Temperature Profile

The presence of airflow in the oven during baking process increased the heat homogeneity in the oven chamber, as shown in Figure 2, which depicts the temperature profile in the oven chamber during baking with and without airflow.

The pattern of heating and cooling during the baking process obviously differed even when a similar controller type and settings were used.

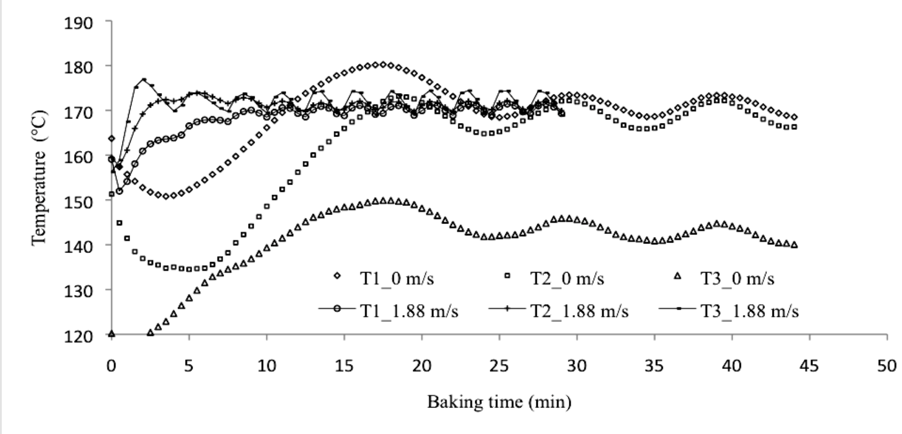

Figure 2: Comparison of baking process for the presence of airflow.

The presence of airflow caused the top, centre and bottom of the oven chamber to achieve a homogenous temperature as soon as the baking began. Meanwhile, without airflow, the centre oven temperature did not reach the desired temperature even by the end of the baking process. With airflow, the actual temperature oscillates in a smaller range with a lower steady state error. In contrast, the temperature profile for baking without airflow shows a greater amplitude of oscillation and a longer time to reach steady state.

The percentages of overshoot for baking temperature ranges from 160°C to 180°C are tabulated in Table 1. Baking with airflow greatly reduced the overshoot. In general, there was a reduction of approximately 75%–86% in temperature overshoot in the oven chamber upon changing from 0% to 100% airflow. For example, the temperature overshoot was reduced almost 85% at the top of the oven chamber by airflow at a baking temperature of 180°C.

Table 1: Comparison of the percentage of overshoot.

	160		170		180	
	Without airflow	With airflow	Without airflow	With airflow	Without airflow	With airflow
Top (T1)	29.63	4.54	26.86	5.10	23.79	3.52
Centre (T2)	17.19	2.44	17.16	4.06	12.98	3.17
Bottom (T3)	30.27	4.02	25.65	4.88	24.54	3.63

The centre location demonstrates the lowest overshoot for both baking conditions. The top and bottom of the oven have higher overshoot because of the effect of heating elements.[11] Another factor that might contribute to this occurrence is the circulation of hot air. The advantage of baking with airflow is that the temperature in the centre is maintained near the set point. Therefore, a product located at the centre of the oven probably receives more consistent heat.[12]

3.2 Empirical Modelling of the Baking Process using PID Control

The general transfer function is developed from the block diagram in Figure 3. The corresponding general closed loop transfer function for PID control is given below:

$$G_{CL}(S)=\frac{C(s)}{R(s)}=\frac{\frac{K}{\tau_I\tau_I\tau_2}(1+\tau_I s+\tau_I\tau_D s^2)}{s^3\frac{\tau_I+\tau_2+K\tau_D}{\tau_I\tau_2}s^2+\frac{1+K}{\tau_I\tau_2}s+\frac{K}{\tau_I\tau_I\tau_2}} \tag{1}$$

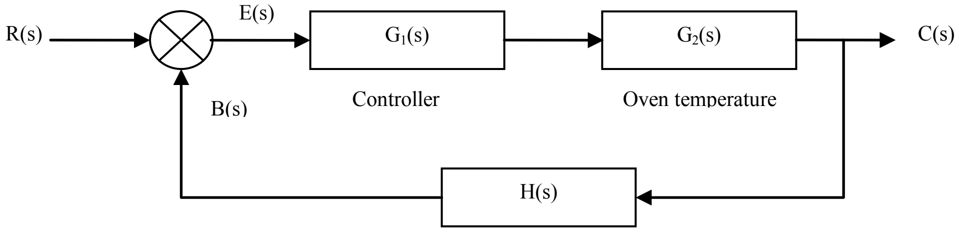

Figure 3: General block diagram for oven temperature control.

The closed loop response is obtained using the controller parameters. The corresponding parameters lead to the equation for G_1 below:

$$G_1(s)=Kc(1+\frac{1}{\tau_I}+\tau_D s) \tag{2}$$

$$G_1(s)=10(1+\frac{1}{233}+40s) \tag{3}$$

The empirical model is developed using experimental data from the closed loop system.[13] The closed loop identification is conducted under PID control. The measurements taken at the top, bottom and hot air exit are identified as T1, T2 and T3 respectively. The model is developed based on the closed loop step response data on the exit hot air temperature (T3).

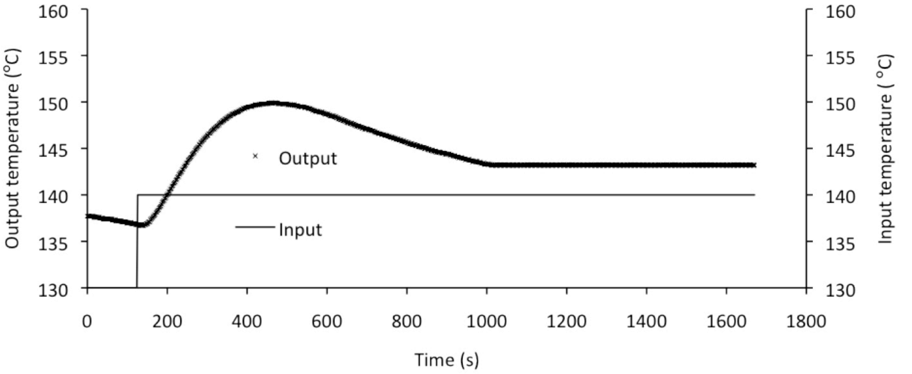

Figure 4: Transient response for hot air exit point, for a set point input of magnitude 10°C.

Figure 4 shows the hot air temperature profile in the oven operated under PID control. This figure represents the first process, that is, the step change in baking temperature from 130°C to 140°C. The response shows an under-damped transient behaviour. The approximate model is developed using a second order system plus time delay.[14] The backward calculation for temperature changes, as described in a research,[11] results in the following:

$$K = \frac{\Delta\ Output}{\Delta\ Input} = \frac{143.2 - 136.7}{140 - 130} = 0.65$$

$$OS = \frac{a\ (amplitude\ of\ oscillation)}{b\ (steady\ state\ value)} = \frac{6.7}{143.2} = 0.047$$

$$\zeta = \sqrt{\frac{(\ln OS)^2}{\pi^2 + (\ln OS)^2}} = 0.7$$

$$\tau = \frac{t_p\sqrt{1-\zeta^2}}{\pi} = \frac{456\sqrt{1-0.7^2}}{\pi} = 103.2$$

Thus, substituting the values for K, θ (estimation from graph), τ and ζ into Equation 4 gave the following:

$$G_P(s) = \frac{Ke^{-\theta s}}{\tau^2 s^2 + 2\zeta\tau s + 1} \tag{4}$$

$$G_{PI}(s) = \frac{0.65e^{-16s}}{103.5^2 s^2 + 2(0.7)(103.5)s + 1} \tag{5}$$

$$G_{PI}(s) = \frac{0.65e^{-16s}}{10712s^2 + 145s + 1} \tag{6}$$

The second process was conducted to examine changes in airflow velocity. The response for the reduction of 50% in airflow velocity, that is, from 1.88 m s^{-1} to 0.98 m s^{-1}, is shown in Figure 5. The reduction in airflow velocity decreased the actual oven temperature by at least 5%.

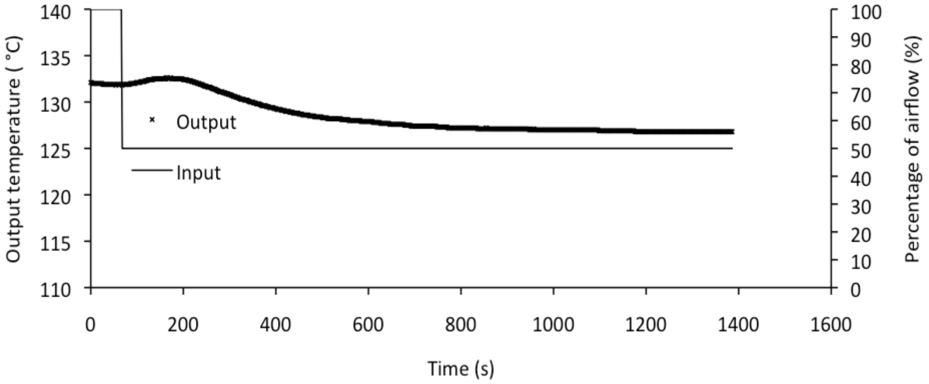

Figure 5: Transient response for hot air exit point, for airflow change of –50%.

The corresponding calculation for the parameter estimation and transfer function for this response is given below:

$$K = \frac{\Delta\ Output}{\Delta\ Input} = \frac{126.8 - 131.9}{0.98 - 1.88} = 5.67°C/(m/s)$$

$$OS = \frac{a\,(amplitude\ of\ oscillation)}{b\,(steady\ state\ value)} = \frac{5.7}{126.8} = 0.045$$

$$\zeta = \sqrt{\frac{(\ln OS)^2}{\pi^2 + (\ln OS)^2}} = 0.7$$

$$\tau = \frac{t_p\sqrt{1-\zeta^2}}{\pi} = \frac{175\sqrt{1-0.7^2}}{\pi} = 39.8$$

Thus,

$$G_{P2}(s) = \frac{5.67e^{-18s}}{39.8^2 s^2 + 2(0.7)(39.8)s + 1} \tag{7}$$

$$G_{P2}(s) = \frac{5.67e^{-18s}}{1587s^2 + 56s + 1} \tag{8}$$

It is interesting to note that the time constant for the change in airflow is faster than the set point changes. However, changing the airflow results in higher gain and increases the time delay by a few seconds. This significant result can be used to inform future work on the simulation and tuning of baking process.

Evaluation of the model is required to determine how well the model fits the experimental data used for parameter estimation. Future validation work will compare the developed model to the simulation model and previous research found in the literature.

3.3 Comparison of Product Quality for Different Control Strategies

The changes in baking temperature and airflow velocity influenced the oven temperature significantly. The resulting oven temperature profile affects the baking mechanism by increasing or reducing the internal heating rate of cakes. This occurrence can be explained briefly as the effect of changing the heat transfer process in the oven.

The implication of temperature variation in the oven can be seen in the percentage of moisture content because, as the oven temperature increases, heat transfer to the cake also increases. Thus, the internal cake heating rate will increase simultaneously with the vapour evaporation rate of the cake.

Table 2 compares moisture content for several processes during baking. The moisture content for baking with airflow results in less than 8% differences compared to the condition without airflow, provided the same controller setting is used. However, the crumb of cakes is less affected by the varying oven operating condition than the crust of cakes. This difference is one reason most of the bakery production cuts off the crust part of the cakes, that is, to remove the part with inconsistent quality. This activity is a significant waste.

Table 2: Moisture content of cakes for the various conditions.

Controller Setting	On-Off	PID	On-Off	PID	On-Off	PID	On-Off	PID
Temperature (°C)	170	170	170	170	180	180	180	180
Airflow (%)	0%	0%	100%	100%	0%	0%	100%	100%
Crust								
Top surface	14.47	17.85	13.15	16.52	11.91	15.12	12.06	16.12
Side	12.17	14.60	12.61	14.09	8.34	15.75	13.45	12.86
Bottom	25.20	23.08	24.91	22.61	26.03	22.05	23.88	23.66
Crumb								
Near glass side	28.68	29.84	30.33	31.59	28.58	30.25	29.60	31.38
Centre	29.63	29.89	30.33	31.45	29.65	30.23	30.19	32.02
Near stainless steel	28.42	29.40	28.89	30.86	28.61	29.98	29.16	30.12

4. CONCLUSION

Closed loop identification is studied using experimental data on the cake-baking process. Changing the temperature shows a slower response than changing the airflow velocity towards the oven temperature profile at the hot air exit point. The gain of the process with airflow shows higher value as well as a longer delay. Validation will be one part of the future work regarding this study. The different process conditions result in different final moisture contents of the cakes, especially in the crust. However, the percentage of moisture content only varies within a small range.

5. ACKNOWLEDGEMENT

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