UNIVERSITI PUTRA MALAYSIA

EFFECTS OF VARIOUS CONDITIONS ON AND EMPIRICAL MODELING OF BAKING PROCESS IN CONVECTION OVEN

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Master of Science

October 2015

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Master of Science

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October 2015

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The presence of airflow during heating process is expected to increase the heat uniformity in a closed heating chamber. The circulation of hot air in convective oven has overcome the static and dominant radiant heat that occurs in conventional oven. The objectives of this study are to investigate the effect of airflow and setting temperature on oven and cake temperatures, and final cake qualities for convectional and modified oven, and to develop an empirical model, simulate and control the oven temperature during baking. Experimental studies were conducted in convective oven (0 m/s=0% for without airflow and 1.88 m/s=100% for with airflow condition) and in modified convective oven within different airflow velocity (0 m/s=0%, 0.95 m/s=50%, 1.43 m/s=75% and 1.88 m/s=100%), setting temperature (low=160°C, medium=170°C and high=180°C) and type of controller (On-off and Proportional-integral-derivative, PID). During baking, oven and cake temperatures were measured simultaneously whereas cake expansion, weight loss and air humidity were measured periodically. Measurement of final quality includes volume, moisture content, surface colour and texture. Step tests were conducted during baking by changing the setting temperature from 150°C to 190°C. MATLAB R2013a was used to identify the model that relates the oven temperature at hot air exit stream to the setting temperature. The process model is represented as First Order Plus Time Delay (FOPTD) model and the SIMULINK was used for model and tuning verification. Lambda method was used as the tuning method. The presence of airflow increased the heating rate by 3 times and maintained the oven temperature near to the setting temperature. With the presence of airflow in the convectional oven, the oscillation reduced from 12.98 - 30.27% to 3.17 - 4.02%. Significant reduction in heating time, overshoot and fluctuation were seen in the modified convective oven. The presence of airflow in the modified convective oven showed a significant effect during second stage of baking with 12%, increase of internal cake heating rate and the relative height increased up to 110% than its initial height. The increase of setting temperature and airflow velocity resulted in larger cake volume, moister crumb layer but drier top crust layer. The firmness was reduced but springiness increased. Cake baked with the presence of airflow are more porous in crumb texture, intense browning surface colour (ΔE = 32.28 - 36.79) and acceptable moisture content (25-28%). The developed closed-loop model had an excellent agreement with the experimental data (R^2>0.9) and the maximum errors was less than ±2%. The process model parameters are Kp=0.1, τp=10.91 s and τd=4.74 s. The new Modified Lambda method obtained satisfactory performance in terms of overshoot, response time and settling time. The simulation result showed the new controller setting (controller gain, K_C=11.70 and integral gain, K_I=0.092) gave good performance to the set point change. Uniform heat in the oven is needed to have better product qualities. The presence of airflow, sophisticated controller and appropriate tuning is useful to attain uniform heating.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

KESAN VARIASI KEADAAN KE ATAS PROSES PEMBAKARAN DALAM KETUHAR PEROLAKAN DAN PEMODELAN EMPIRIKAL

Oleh

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Kehadiran aliran udara semasa proses pembakaran dijangka akan meningkatkan keseragaman haba di setiap ruang ketuhar. Peredaran udara panas di dalam ketuhar perolakan telah mengatasi haba radiasi yang statik dan dominan yang sering berlaku di ketuhar konvensional. Objektif kajian ini adalah untuk menyiasat kesan aliran udara dan suhu tetap kepada suhu ketuhar dan kek, dan kualiti akhir kek bagi ketuhar perolakan dan terubahsuai dan untuk membina model empirikal, mensimulasi dan mengawal suhu ketuhar semasa proses pembakaran. Kajian dikendalikan dalam ketuhar perolakan (0 m/s=0% bagi ketiadaan aliran udara dan 1.88 m/s=100% bagi keadaan beraliran udara) dan dalam ketuhar perolakan terubahsuai yang diubah halaju aliran udara (0 m/s=0%, 0.95 m/s=50%, 1.43 m/s=75% dan 1.88 m/s=100%), suhu tetap (rendah=160°C, sederhana=170°C dan tinggi=180°C), dan jenis pengawal suhu (Buka-tutup dan Berkadar-kamiran-derivatif, PID). Semasa pembakaran, suhu ketuhar dan kek diukur serentak manakala pengembangan kek, kehilangan berat dan kelembapan udara diukur secara berkala. Selepas pembakaran, pengukuran kualiti dijalankan meliputi isipadu, kandungan kelembapan, warna permukaan dan tekstur akhir kek. Ujian berperingkat telah dijalankan semasa proses pembakaran dengan mengubah suhu tetap dari 150-190°C. MATLAB R2013a digunakan untuk mengenalpasti model yang mengaitkan suhu ketuhar di bahagian aliran udara panas kepada suhu yang disetkan. Model ini diwakilkan oleh Tertib Pertama Dengan Tunda Masa (FOPTD) dan SIMULINK digunakan untuk verifikasi model dan penalaan. Kaedah Lambda digunakan sebagai kaedah penalaan. Aliran udara boleh meningkatkan kadar pemanasan dalam ketuhar 3 kali ganda lebih cepat dan mengekalkan suhu ketuhar hampir dengan suhu yang disetkan. Dengan kehadiran aliran udara dalam ketuhar perolakan, lajakan berkurang dari 12.98 - 30.27% kepada 3.17 - 4.02%. Penurunan

selanjutnya dapat dilihat bagi masa pemanasan, lajakan dan fluktuasi suhu pada ketuhar perolakan terubahsuai. Kehadiran aliran udara dalam ketukar perolakan terubahsuai menunjukkan kesan ketara semasa peringkat kedua pembakaran kek di mana ia meningkatkan kadar pemanasan kek sebanyak 12% untuk setiap kenaikan 50% halaju aliran udara dan tinggi relatif kek naik sehingga 110% berbanding tinggi asalnya. Peningkatan suhu tetap ketuhar dan halaju aliran udara mengakibatkan isipadu kek bertambah besar, lembapan kek bertambah di bahagian tengah tetapi berkurang di kerak atas. Sifat tekstural berkurang kekukuhannya tetapi meningkat keanjalannya. Bagi kedua-dua ketuhar, kek yang dibakar dengan kehadiran aliran udara bertekstur lebih berongga pada bahagian dalam kek, berwarna lebih keemasan (ΔE = 32.28 - 36.79) dan kandungan lembapan yang boleh diterima (25-28%). Model gelung tertutup yang dibina mempunyai persetujuan yang baik dengan data eksperimen (R^2>0.9) dan kesalahan maksimum kurang dari ±2%. Parameter model proses ialah Kp=0.1, τp=10.91 saat and τd=4.74 saat. Kaedah baru Lambda Terubahsuai dapat memberi prestasi yang memuaskan dari segi lajakan, masa respons dan masa berhenti. Keputusan simulasi menunjukkan pengawal persekitaran yang baru (dapatan pengawal, K_C=11.70 dan dapatan kamiran, K_I=0.092) memberi prestasi baik kepada perubahan titik tetap. Keseragaman haba dalam ketuhar diperlukan untuk mendapatkan produk yang lebih berkualiti. Kehadiran aliran udara, pengawal yang canggih dan penalaan yang bersesuaian sangat berguna untuk mendapatkan haba yang seragam.

.

ACKNOWLEDGEMENTS

My deepest gratitude belongs to my loving parents, husband, family and friends for their endless love and continuous supports.

I would like to express my appreciation to the members of my supervisory committee, Associate Professor Dr. Farah Saleena Taip (chairman), Associate Professor Dr Norashikin Ab Aziz and Associate Professor Dr. Anvarjon Ahmedov for their guidance, constructive comments and encouragement throughout my study.

I would also like to express my sincere thankful to Tuan Haji Kamarulzaman Dahlan, Encik Sharul, Encik Raman and Encik Zahir from the department of Process and Food Engineering for providing me technical support and guidance.

I certify that a Thesis Examination Committee has met on 20 October 2015 to conduct the final examination of Nur Syafikah Bt Mohamad Shahapuzi on her thesis entitled "Effects of various conditions on and empirical modeling of baking process in convection oven" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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Signature: ____________________________
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LIST OF SYMBOLS

m	Manipulated input
d	Disturbances
d_m	Measured disturbances
d_u	Unmeasured disturbances
y_m	Measured output
y_u	Unmeasured output
y_{sp}	Set point
e	Error
$y_{sp}(s)$	Laplace transform of the set point
$e(s)$	Laplace transform of the error signal
$c(s)$	Laplace transform of the controller action
$d(s)$	Laplace transform of the disturbance
$m(s)$	Laplace transform of the manipulated variable / input
$y(s)$	Laplace transform of the controlled variable / output
$u(s)$	Laplace transform of the manipulated variable / input
$y_m(s)$	Laplace transform of the measured value of controlled variable
$g_c(s)$	Controller transfer function
$g_f(s)$	Final control element transfer function
$g_p(s)$	Process transfer function
$g_d(s)$	Disturbance transfer function
$g_m(s)$	Measuring element transfer function
$c(t)$	Control signal
$e(t)$	Error value
g_c	Controller algorithm
K	Gain
K_P	Process gain
K_I	Integral gain
K_D	Derivative gain
τ	Time constant
τ_p	Process time constant
τ_i	Integral time
τ_D	Derivative time
τ_{CL}	Closed loop time constant
τ_d	Time delay
τ_w	Natural frequency
λ	Lambda
ζ	Damping factor
Δy	The magnitude of output changes
Δu	The magnitude of input changes
D_e	Effective moisture diffusivity
θ	Time delay
R	The ratio of time delay to time constant
R	Correlation coefficient
R^2	The coefficient of determination
MC	Moisture content
T_{sp}	Setting temperature
T1	Top temperature
T2	Centre temperature

T3	Bottom temperature
T_{top}	Top temperature (after modification)
T_{bottom}	Bottom temperature (after modification)
T_{fan}	Hot air exit stream temperature (after modification)
T_{cake}	Internal cake temperature at the centre
$T_{surface}$	Surface cake temperature at the centre
T_r	Rise time
$T_{setting}$	Settling time
OS	Oscillation
RH	Air humidity sensor
p_1	Point 1, at the right side of baking pan
p_2	Point 2, between the centre and the right side
p_3	Point 3, at centre of cake
p_4	Point 4, between the centre and left side
p_5	Point 5 at the left side of baking pan
L*	Lightness value
a*	Redness value
b*	Yellowness value
p	Significant value

LIST OF ABBREVIATIONS

LPG	Liquefied petroleum gas
CFD	Computational fluid dynamics
PIV	Particle image velocimetry
1D	One dimensional
2D	Two dimensional
DS	Direct synthesis
PRC	Process reaction curve
Z-N	Ziegler-Nichols
FO	First order
FOPTD	First order plus time delay
SOPTD	Second order plus time delay
SISO	Single input-single output
P	Controller output
P	Proportional
PI	Proportional-integral
PID	Proportional-integral-derivative
IMC	Internal model control
RH	Relative humidity
U	Output
Y	Input
Ysp	Set point
L	Length
W	Width
H	Height
TPA	Texture profile analysis
PB	Proportional band

CHAPTER 1

INTRODUCTION

1.1 Cake Baking

Cake baking is a process that transform batter into a light, readily digestible and flavorful product under the influence of heat. This process involves a complex physical, chemical and biochemical changes in a cake batter. The aim of cake baking is to produce final cake quality that is moist and fine grained, with an even crumb, a tender texture, an optimum volume and a lightly browned delicate crust (Bennion and Bamford, 1997). A carefull selection of the ingredients, a proper mixing method and time, together with an optimum baking conditionsare needed to accomplish a highly cake quality.

Efficient baking process will increase the energy efficiency and better product quality (Fellows, 2000). Many research studies were conducted on baking process to improve the energy efficiency of the process as well as the food product quality (Savoye *et al.*, 1992; Sablani *et al.*, 1998; Lostie *et al.*, 2002; Baik and Marcotte, 2002; Sakin, 2005; Sakin *et al.*, 2007a,b). The efficiency of the oven is improved when the baking time, thermal input and energy consumption can be deducted without degradation of product quality (Purlis, 2012).

1.2 Baking Oven

Ovens are enclosed space in which food is heated, usually by hot air. Baking ovens are classified into direct or indirect heating types, operate in batches, continuous or semi-continuous operation.

Heat transfer in the oven rely on the heat supply, airflow pattern, humidity, oven load and baking time, as listed in Therdthai *et al.* (2004). In conventional baking process, heat is transmitted to the baking product mainly through three ways, which are radiation, convection and conduction. Radiation occur when the heated internal surface of the oven emanates radiant heat, which then being absorbed by the exposed surface of the products and thus rising the product temperature. Meanwhile, the natural convection air in the baking cavity promotes convective heat transfer. The heat is then transferred to the product by conduction when the hot air contacts their surfaces. A schematic diagram of heat transfer is represented in Verboven *et al.* (2000b) as shown in **Figure 1.1**.

The diffusion of heat will be more efficient and rapid as the air movement is increased (Chang, 2006).This initiated the use of fan and blowers in the convection oven in order to increase the efficiency of convection heat transfer during baking process. Optimum baking condition with reduced heat supply can be realized by increasing the airflow volume (Therdthai *et al.*, 2004). However, the study of the influence of airflow towards heating process is difficult since the airflow can be laminar, turbulent or mixed, that will have an effect on convection process (See Section 2.2.2). Since fan is used to enhance the efficiency of convection heat transfer in the convection oven, the manipulation of airflow velocity or airflow circulation could be an alternative to increase the heat transmission during the baking process.

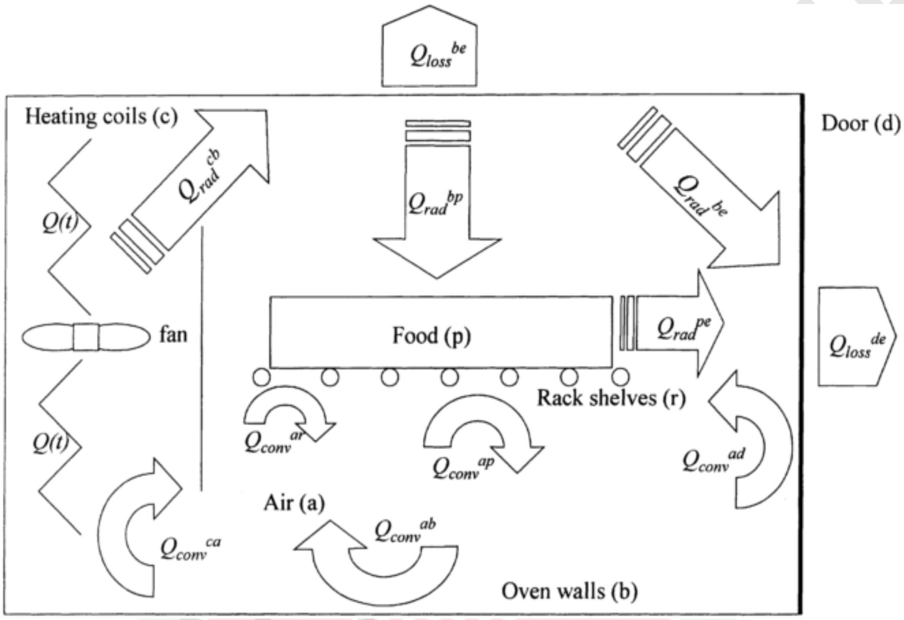

Figure 1.1. Schematic Representation of Heat Exchanges in a Forced Convection Oven using Dry Air
(Source: Verboven *et al.***,** 2000b)

1.3 Problem Statements

As the normal practices in baking process, too hot an oven will cause high crust colour, small volume, peaked tops, close or irregular crumb, and probably all the faults due to under baking. Since product appearance and sensorial attributes give a high impact in consumer evaluation, a proper method for monitoring the baking process and controlling the oven is necessary.

Among the factors that contribute to the effectiveness of the oven are the control of heat supply, steaming condition and proper heat distribution. In baking process, temperature control of baking oven is the most crucial part in the system. The inability to properly control and maintain the temperature will cause detrimental effect on the product quality. The failure in temperature control might also cause insufficient or excessive oven heat. It will result in higher bake-out losses or darker top crust and under-baked side walls. A clear relationship between operating temperature and product quality is needed for easily monitoring and controlling the baking process.

Airflow rate influence the homogeneity of temperature in the oven chamber, hence affecting the product quality. An increase in airflow rate improve the product appearance such as more golden colour and increased product volume, but decreased water content of the batter. There are studies on the effect of airflow on oven temperature profile but, on large scale industrial ovens(Khatir *et al.*, 2015, 2013, 2012; Navaneethakrishnan*et al.*, 2010; Williamson & Wilson, 2009; Mistry *et al.*, 2006; Therdthai *et al.*, 2004; Verboven*et al.*, 2000a, 2000b;). A study in convective oven should also be conducted since its application was increased over the years. Using a high airflow velocity as an alternative method to increase the temperature homogeneity in the oven chamber is still new for convective oven. Therefore, it is worthwhile to conduct this research study so that it can contribute to the body of knowledge of bakery oven operation and control process.

Savoye *et al.*, (1992) built a baking process model where the air velocity parameter was adjusted during simulation. They found that the air circulation in the oven cavity influenced the heating process. The variation of temperature and water content during the heating process was predicted with high accuracy by the model developed by Purlis and Salvadori (2009). A study conducted by Allais *et al.* (2007) concluded that airflow rate is a key variable influencing most of the product properties. Careful selection of the flow model, together with the implementation of realistic boundary conditions will give an accurate temperature prediction throughout the oven (Khatir *et al.*, 2011).

1.4 Objectives

The objectives of this study are:

1. To study the effect of airflow and setting temperature onthe temperature profile of oven chamber, cakes internal temperature, volume expansion and final product qualities for convective and modified convective oven.
2. To develop an empirical model , simulate and control the oven temperature during cake baking process.

1.5 Scope of Work

The purpose of this study is to investigate the effect of different baking condition to the product quality and perform a suitable control action to improve heat transfer in the oven. Convective oven batch type is used as the working oven while butter cake is chosen as the baked product.

During cake baking process, airflow velocity and setting temperature is varied in the range of 0 - 1.88 m/s and 160 - 180°C respectively to examine the effect of convective heat transfer. The temperature of the oven at top, bottom and hot air exit stream and the temperature of the cake at top surface and core centre are measured online to observe the heat transfer from the oven to the product. The height of cake is measured from side to centre point during baking to represent the effect of oven condition towards cake volume expansion. The final quality of cakes baked at different oven condition is evaluated in terms of its moisture content, surface colour and textural properties.

An empirical model is developed that relates the setting temperature to the oven temperature during baking. System Identification toolbox in MATLAB R2013a was utilized to develop the closed loop model. FOPTD model was identified as the suitable process model because it offers a convenient way to quantify key aspect of control objective to process variable relationship for use in controller design and tuning. SIMULINK was used for verification process of the model. A modified lambda method is selected as a tuning method to estimate the tuning parameters for PI controller system in the baking process.

Overall, the study is conducted to enhance the equipment and energy efficiency, product quality and equipment safety. The ranges of parameters used were selected based on the range suggested by previous researchers. No process optimization involved. Airflow velocity is measured offline due to the limitation of airflow meter that have maximum operating temperature of 80°C. The step tests are conducted in closed loop system due to oven safety.

1.6 Contribution of Thesis

This thesis starts with Chapter 1, which consist of an introduction in cake baking and baking oven, problem statement, objectives and scope of the study. In Chapter 2, detail reviews of literature were presented. The raw materials, equipments and methods used in performing this study were explained in Chapter 3.

Two working chapters were performed in this present thesis. The first working chapter (Chapter 4) comprises the preliminary and experimental studies. A preliminary study was conducted to get appropriate cake recipe, preparation method and baking conditions. The experimental works is to study the effect of airflow and setting temperature to the temperature profile of the oven chamber and internal temperature of cakes. The qualities of cakes due to the variation in baking modes was evaluated in terms of moisture content, volume, texture and surface colour of the cake.

The second working chapter (Chapter 5) consists of the development of empirical models for cake baking with the presence of airflow. The validation of the models also included in this chapter. The tuning and simulation work were performed to identify the tuning parameters. Chapter 6 concluded the findings and recommendation for future work.

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