TEMPERATURE RESPONSE AND DRYING CHARACTERISTICS OF PALM KERNEL CAKE (PKC) IN A RADIAL PACKED BED (RPB)

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THIS THESIS IS SUBMITTED TO FULFILL THE REQUIREMENTS FOR THE DEGREE OF MASTER

SCHOOL OF ENGINEERING AND INFORMATION TECHNOLOGY
UNIVERSITI MALAYSIA SABAH
2013

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL: TEMPERATURE RESPONSE ANSD DRYING CHARACTERISTICS OF PALM KERNEL CAKE (PKC) IN A RADIAL PACKED BED

IJAZAH: MASTER DEGREE OF ENGINEERING (CHEMICAL)

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DECLARATION

This MSc thesis is an original research work. Wherever others researcher contributions are involved in the literature, proper references are quote for clarity and acknowledgement.

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DEGREE	:	**MASTER DEGREE OF ENGINEERING (CHEMICAL)**
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ACKNOWLEDGEMENT

First and foremost, I thank to the teaching of triple gems, the wisdom and the strength to make me to have the courage to accept and confront all the circumstances that encountered.

I extend my hearfelt and sincere gratitude to the list of the people below:

Dr. Sivakumar Kumaresan (supervisor) and Associate Professor Dr. Chris. Chu Chi Ming (Co-supervisor) for their kind supervision, guidance, encouragement, financial support and assistance in many ways throughout this study. Their enduring diligence and patience within these few years are highly appreciated. With a systematic and comprehensive learning process, I had the precious opportunity to gain useful training and knowledge as well as leadership, organizing and problem solving skills.

Dr. Jidon Janaun (PKC Project Leader and Supervisor in SKTM) for providing the research opportunity. Mr. Saw and all the undergraduates' students whom involved in the PKC project for their contribution in one way or another ways. Mr. Yoong for his technical assistance in the fabrication of reactor. Mr. Liau for his explanation and technical advices on statistic. Dr. Tham and Mr. Kenneth Teo for their encouragement and moral support. Md. Mizanur Rahman for his assistance in many areas. All the laboratory assistants of School of Engineering and Information Technology (SKTM), every staff members and all colleagues at UMS for their kind assistance and help.

Aunty Leag for providing a shelter to rest and let me to be concentrated to finish up my thesis writing as well as love, support, motivation and encouragement. Those friends, brothers and sisters in dhamma that I couldn't name it one by one for their prayers and encouragements.

Last, my beloved grandma, parent, brothers, other family members and friends for their love, unlimited support and patience.

This research work was supported by the Ministry of Higher Education through E-science grant (SCF0021 for 2009 to 2010) and MINI BUDGET 2009 (one semester for session 2009/2010).

PHANG HOOI KIM
7 September 2012

ABSTRACT

Temperature Response and Drying Characteristics of Palm Kernel Cake (PKC) in a Radial Packed Bed (RPB)

A batch type radial packed bed (RPB) was designed and fabricated for a palm kernel cake transport phenomena study. The RPB system consists of aeration control, heating control and data acquisition. A preliminary study of transport phenomena of non-fermented PKC for heat transfer and moisture mass transfer was conducted in the RPB. The heat and mass transfer (HMT) as a function of air temperature, initial moisture content and bed height was conducted at various particle mean sizes (0.80, 1.50, 2.68 mm) and various initial moisture content (25, 50, 75, 100% dry basis) with forced aeration. The steady state temperature of PKC was not affected by particle size, initial moisture content and bed height. The steady state value of moisture content was affected by particle size, initial moisture content and bed height. A longer duration was required for PKC to achieve the same final temperature increased with initial moisture content at fixed particle size, air flow rate and operating air temperature. Consequently, 1.50 mm PKC particle mean size and 50% dry basis initial moisture content were fixed in main HMT study. A factorial design of experiments was adopted to investigate the effect of air temperature (35, 45, 55 and 65 °C), aeration rate (65.33, 75.33, and 92.33 LPM), and bed height (8.50, 13.25, 18.00, 22.75 and 27.50 cm) on the HMT study. The bed shrinkage and changes in physical properties of PKC in HMT were assumed negligible. The HMT study of PKC in RPB air-water was modelled mathematically. For the transient heat transfer model, a first order process model was fitted to the inner temperature and outer temperature data with good agreement. The coefficients of determination (R^2) were above 0.87. The moisture content data were compared and fitted to the different semi-empirical models such as Lewis, Henderson and Pabis, Logarithmic, Page and modified Page based on the ratio of the difference between the initial and final moisture content and the equilibrium moisture content. All the models fitted the drying data satisfactorily although they have slightly different value of R^2. The Henderson and Pabis model which is simple and linearisable was chosen to model all the drying data. The temperature dependency of drying rate constant and effective diffusivity was described with the Arrhenius equation. The R^2 for drying rate constant was as high as 0.9903 but the R^2 for effective diffusivity was as high as 0.9732. Both semi empirical model, first order process model for heat transfer and Henderson and Pabis model for mass transfer adequately described the transport phenomena of PKC for the air temperature range of 35 to 65°C and air flow rate range of 65.33 to 92.33 LPM in air-water system of RPB.

ABSTRAK

Sebuah bioreaktor radial packed bed (RPB) berjenis kumpulan telah direka and difabrikasi untuk isirong kelapa sawit (PKC) dalam kajian fenomena pengakutan. Sistem RPB terdiri daripada kawalan pengudaraan, kawalan pemanasan dan pengumpulan data. Satu kajian awal fenomena pengangkutan PKC yang bukan fermentasi telah dijalankan kepada pemindahan haba dan jisim dalam RPB. Pemindahan haba dan jisim (HMT) sebagai fungsi suhu udara, kandungan lembapan awal dan ketinggian bioreaktor telah dijalankan dengan pelbagai min saiz zarah (0.80, 1.50, 2.68 mm) dan kandungan lembapan awal (25, 50, 75, 100% berasaskan berat kering) dengan pengudaraan paksa. Saiz zarah, nilai kandungan lembapan awal dan ketinggian bioreaktor tidak memberi kesan ke atas suhu mantap PKC. Saiz zarah, kandungan lembapan awal dan ketinggian bioreaktor mempunyai kesan ke atas nilai akhir kandungan lembapan. PKC memerlukan tempoh yang lebih lama untuk mencapai suhu mantap yang sama bagi kandungan lembapan permulaan yang lebih tinggi bagi saiz zarah, kadar aliran udara dan suhu udara yang sama. Akibatnya, 1.50 mm min saiz zarah PKC 50% berasaskan berat kering kandungan lembapan awal telah ditetapkan dalam kajian utama HMT. Rekabentuk ujikaji faktorial telah dipilih untuk mengkaji kesan suhu udara (35, 45, 55 dan 65 °C) and kadar pengudaraan (65.33, 75.33, dan 92.33 LPM) dan ketinggian di RPB (8.50, 13.25, 18.00, 22.75 and 27.50 cm) ke atas kajian HMT. Pengecutan katil dan perubahan dalam sifat-sifat fizikal PKC dalam kajian HMT telah diabaikan. Kajian HMT PKC dalam RPB udara-air telah dimodelkan secara matematik. Untuk model pemindahan haba tidak mantap, model proses peringkat pertama dipadankan kepada data suhu dalam dan suhu luar dengan bagus. Pekali penentuan (R^2) mempunyai nilai lebih 0.87. Data kandungan lembapan telah dibandingkan dan dipadankan kepada model semi-empirikal yang berbeza seperti Lewis, Henderson and Pabis, Logaritmic, Page and Modified page berdasarkan nisbah perbezaan antara kandungan lembapan awal dan akhir dan kandungan lembapan keseimbangan. Semua model dipadankan kepada data pengeringan memuaskan walaupun mempunyai nilai yang sedikit berbeza bagi R^2. Henderson dan Pabis model yang mudah and linearisable telah dipilih untuk memodelkan semua data pengeringan. Pemalar kadar pengeringan dan kemeresapan berkesan bergantung kepada suhu telah diterangkan dengan persamaan Arrhenius. R^2 untuk pemalar kadar pengeringan adalah setinggi 0.9903 dan R^2 untuk kemeresapan berkesan adalah setinggi 0.9732. Kedua-dua model semi-empirikal, model proses peringkat pertama untuk pemindahan haba dan model Henderson and Pabis untuk pemindahan jisim dapat menyifatkan fenomena pengangkutan PKC untuk julat suhu udara 35 ke 65 °C dan julat kadar pengaliran udara 65.33 ke 92.33 LPM dalam sistem udara-air RPB.

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ABBREVIATIONS

d.b.	Dry weight basis
DR	Drying rate
FOP	First order process
FOP+DT	First order process and time delay
HMT	Heat and mass transfer
MC	Moisture content
MR	Moisture ratio
PKC	Palm kernel cake
RMSE	Root mean square error
RPB	Radial packed bed
SmF	Submerged fermentation
SSE	Sum of square error
SSF	Solid state fermentation
SSR	Sum of squared residues
SST	Sum of squared total
USS	Unsteady state
w.b.	Weight basis
PSD	Particle size distribution

SYMBOLS

%	percentage
±	Plus minus
°C	Degree celcius
A	constant
cm	Centimeter (s)
c_s	Specific heat of solid
c_w	Specific heat of water
D_{eff}	Effective diffusivity
D_v	Vapour diffusion coefficient
E_{a}	Activation energy
g	gram
h	Hour (s)
H	Bed height (cm)
H	Lantent heat of vaporation
h_s	Surface heat transfer
J_x	Diffusion flux
k	Drying rate constant
kJ/mol	Kilo Joule per mole
$K_{\text{L}}a$	Oxygen mass transfer coefficient
K_T	Overall heat conduction coefficient or thermal conductivity
L	Characteristic dimension alont the flow path
Le_m	Lewis number
LPM	Liter per minute
m/s	Meter per second
m^2/s	Meter squared per second
min	minutes
mm	milimeter
Q	Volumetric air flow rate
q_v	Desorption heat or absorption of water
R	Universal gas constant

r	Radius of sphere
R^2	Coefficient of determination
s	seconds
t	time
T	temperature
$T(t)$	Response of system
T_∞	Final temperature
T_{in}	Inner temperature of PKC
T_{out}	Outer temperature of PKC
T_r	Intermediate reference temperature
X_0	Initial moisture content
X_c	Critical moisture content
X_{eq}	Equilibrium moisture content
X_s	Mass of solids
X_t	Moisture content at time t
X_v	Vapour concentration in the pores
X_w	Mass of water
β	constant
γ	constant
θ	Time delay
λ	Lantent heat
ρ_s	Solid skeleton density
τ	Time constant
φ	Void fraction of body

CHAPTER 1

INTRODUCTION

1.1 Research Background

In Malaysia, animal feeds in particular the poultry industries are dependent on imported feedstuffs used to improve feed efficiency and chicken growth. The demand for feedstuffs is markedly increasing due to population growth. More than 1.5 metric tonnes of maize was imported from different countries to meet local poultry feed demand annually since 1999 (Loh, 2002) and has achieved 2.4 million tonnes in 2005. In 2008, RM35 billion was spent to import food and feed to fulfill the market demand (Malaysian Biotechnology Information Centre, 2011) while 1.2 million tonnes of agricultural waste is disposed into landfills annually (Agamuthu, 2009). On the other hand, Malaysia exported 2.33 million tonnes of palm kernel cake (PKC) to the international market especially the European Union which absorbs more than 50% of Malaysian PKC annually in 2011(Malaysian Palm Oil Board, 2011). Most PKC which was traded commercially at the international market was utilized as a formulation for cattle feed since 1996 (Hishamuddin, 2001). As cattle feed and poultry feed share certain similarities in term of protein source and mineral contents, the abundance of PKC makes it as a potential source of poultry industry.

PKC has been successfully utilized as animals food as well as implemented as a substrate in solid state fermentation (SSF) for enzyme and animal feed production. The advantages of utilizing PKC includes contains no toxins, aflatoxin free, and palatable (Tang, 2001; Sundu *et al.,* 2006). Raw PKC has been implemented as a feed source for cattle and buffaloes (Wan Zahari and Alimon, 2004), and as ingredients in feed formulation for poultry (Onwudike, 1986; Sundu *et al.,* 2006), rabbits (Carrión *et al.,* 2011), pigs (Agunbiade *et al.,* 1999; Rhule, 1996), and fishes (Ng, 2004; Ng, 2003; Ng *et al.*, 2002).

PKC has also been applied as a carbon source for bioconversion to poultry (Sharon, 2008; Graminha *et al.,* 2007; Saw *et al.,* 2005), aquaculture (Hem, *et al.,* 2008) and as a carbon source for enzyme production such as β-mannanase (Peyman *et al.*, 2010; Abd-Aziz *et al.*, 2008), lipase (Gutarra *et al.,* 2005; How and Ibrahim, 2004), tannase (Sabu *et al.*, 2006; Sabu, *et al,* 2005), xylanase (Pang *et al*, 2005), phytase (Ramachandran *et al.*, 2005) and alpha amylase (Ramachandran *et al.*, 2004). Kolade *et al.* (2006) developed a composting process which converts PKC into compost utilizing goat manure and poultry droppings as nitrogen supplements. Moreover, PKC has been employed as a potential substitute for commercial biomass briquettes production (Nasrin *et al.*, 2008). Consequently, the major applications of PKC are enzymes and animal feed production through bioconversion.

To respond to the increasing trend of feedstuff demands in the domestic market and prospects for future feedstuff production, an alternative strategy is needed to enhance the protein content of agriculture residues such as PKC. SSF can be a strategic direction to provide a source of protein to animal feed industry (Villas-Bôas *et al.,* 2002) through environmental friendly and sustainable utilization of agriculture residues (HÖlker & Lenz, 2005). SSF is a fermentation process conducted under absence or near absence of free water where the substrate possessing enough moisture for metabolism and growth of microorganism (Pandey, 2003). The reduced water level is a favoured by cleaner industrial practice due to low levels of waste water and less processing energy. The SSF of agriculture residues is economically feasible (Sandhya *et al.,* 2005; Castilho *et al.,* 2000) and it also solves the problem of waste disposal (Xia and Cen, 1999).

1.2 Problem Statement

A bioreactor is the heart of a fermentation process where the substrate is converted to produce desired product under proper manipulated variables and process variables. There are many types of SSF bioreactor design that have been developed but the major issue is accumulation of metabolic heat and distribution of heterogeneous particles in a complex gas-liquid-solid multiphase bioreactor system (Lonsane *et al.,* 1992).

Aeration and mixing are the strategies that common in practice to enhance the heat and mass transfer within the bioreactor (Mitchell *et al.,* 2000). Although air is blown through the bed of bioreactors, the sufficiency of oxygen in proportion to the biomass is still a concern (Raghavarao *et al.,* 2003; Thibault *et al.,* 2000; Gowthaman *et al.,* 1995). The mechanism of substrate mixing may affect the growth of fungi. The mixing cause shear stress in the case where the hyphae may be severely damaged and thus the overall products formation was decreased (Stuart *et al.,* 1998). Thus, types of bioreactor has been designed and developed with respect to their processes and applications.

In laboratory scale, the SSF process is mainly conducted in flasks. Tray bioreactors, drum bioreactors, packed bed bioreactors and fluidized bed bioreactors are normally used to perform larger scale product formation (Mitchell *et al.,* 2010; Ronbinson and Nigam, 2003; Mitchell *et al.,* 2000). Each of the design tries to provide favourable conditions for SSF. Tray type bioreactor consists of flat trays. The substrate is spread onto each tray to form a thin layer. The critical depth of tray bioreactor was 2.4 cm in order to avoid occurrence of low oxygen concentration at the base level of substrate during SSF (Raghavarao *et al.,* 2003). Thus, the numerous of trays and large volume are required in the large scale production. A packed bed bioreactor bioreactor is composed of a plastic column, packed with solid substrates. The air is blown forcefully continuously through the perforated bed (Khanahmadi *et al.,* 2006; Ashley *et al.,* 1999; Mitchell *et al.,* 1999). The disadvantages of packed bed bioreactor are poor heat removal and non-uniform growth of microorganism (Doelle *et al.,* 1992). The circulation of air in a packed bed can be improved by blowing air, but high energy consumption is required. In rotating drum bioreactors, the bed is continuously or intermittently mixed with a fixed frequency and the air is circulated gently around the bed. The main drawback is that the rotating drum bioreactor can only be filled up to 30% capacity to ensure the mixing is sufficient for aeration (Couto & Sanroman, 2006; Mitchell *et al.,* 2006a). In fluidized bed bioreactors, the bed is forcefully blown by air. Although the mixing, aeration, heat and mass transfer is increased, the damage to the inoculum and the heat buildup through shear forces could affects the final yield of product in a fluidized bed bioreactor (Foong *et al.,* 2009).

Consequently, SSF has not found large scale production because of the limited number of bioreactors design that are suitable for SSF process.

1.3 Rational of the Study

A simple and practical design of a laboratory scale radial packed bed reactor with an air-water system was used for non-fermented PKC heat and mass transfer study. The influence of air temperature and volumetric air flow rate on the drying characteristic of non-fermented PKC in RPB was carried out in batch operation. The batch operation should be studied prior to the semi batch or continuous operation before fermentation process.

SSF of PKC is a complex process that involves heat and mass transfer between the microorganisms and substrates. The metabolic heat that accumulated during SSF as well as the aeration rate dried up the moisture content of PKC. The substrates are degraded by microorganism during SSF process but the sizes of microbes are relatively small in comparison with PKC solid particles. If the SSF process happens at the same temperature and moisture content, the particle size, drying rate, moisture diffusivity and bulk density of PKC should be the same. Although the study does not include SSF, should the experimental conditions coincide with SSF conditions, the physical properties can match between the SSF and non SSF system for SSF interpretation.

1.4 Research Theme

This research is to explore the transport phenomena of PKC in a modified packed bed which is named as radial packed bed (RPB).

1.5 Research Objectives and Scope

The objectives of this study are shown as below:

1. To investigate the influence of particle size and initial moisture content on the drying characteristic of PKC.
2. To study the effects of the hot air inlet temperature and air flow rate on the transport phenomena of PKC.
3. To mathematically model the transport phenomena of PKC.
4. To evaluate the performance of equipment and design.

The scope of this study is listed below:

1. PKC supplied by IOI Edible Oils Sdn. Bhd. is used.
2. Only a particle mean size and single initial moisture content is used for the experimental study and process model.
3. The experiment is limited to five levels of the RPB for which experimental data are available i.e. 8.50, 13.25, 18.00, 22.75 and 27.50 cm.
4. The process in the RPB is carried out without fermentation.

1.6 Significance of Research

This study models the transport phenomena of non-fermented PKC in a static batch type RPB with forced aeration. The heat and mass transfer model of air-water system in RPB filled with PKC provides useful information to predict the performance of bioreactor under the operating air temperature and aeration rate. Then, the amount of water can be predicted to maintain desired moisture content of PKC to prevent overheating during SSF process based on the drying characteristic and drying model.

Chapter 3 reviews the mathematical modelling of heat and mass transfer and the goodness of fit statistics for models.

Chapter 4 describes the methodology consists of physical characterization of PKC, the calibration of radial packed bed system, drying experiments, experimental design, preliminary studies and modelling methods.

Chapter 5 reports the results and discussion on the findings of particle characterization, the radial packed bed system and the modelling of heat and mass transfer of air-water system in a radial packed bed filled with PKC particles.

Chapter 6 summarizes the overall findings of the thesis and recommends some future works.