DRYING KINETICS OF PEPPER IN SWIRLING FLUIDIZED BED DRYER

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SPECIAL GRATITUDE TO;

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Zainab Bte Abd Aziz, Azeian Binti Abdullah, Khabib Ali Bin Nazrul Syaif

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ABSTRACT

Malaysia is one of the pepper producing nation with exports reaching more than 90,000 tonnes between 2010 until 2016. Pepper requires drying before and traditionally sun drying is the favourite technique due to low-cost feature. However, the recent climate change has affected the sun drying which is heavily dependent on weather conditions. This study proposes the swirling fluidized bed dryer (SFBD) as an alternative technique for pepper drying. A lab scale SFBD was used to investigate the bed's hydrodynamics and drying characteristic. Batch experiments were carried out for three bed loadings of 1.0 kg, 1.4 kg & 1.8 kg at a five drying temperature of 50 °C, 60°C, 70°C, 80°C and 90°C. From the hydrodynamics study, the SFBD exhibited excellent particle mixing with relatively low bed pressure drop. Four regimes of operation were discovered namely the packed regime, minimum fluidization, minimum swirling and swirling regime. As for the drying studies, lower bed loadings and higher drying temperatures result in higher moisture removal rate. The drying curves plotted indicate that the constant rate drying period was insignificant and thus drying of pepper in SFBD can be assumed to be in falling-rate period for all bed loadings and drying temperatures. A total of six thin-layer models were chosen from the literature to model the drying kinetics of pepper and it was found that Logarithmic model provided the best fit for the present drying condition with coefficient of determination, R^2 = 0.9990807, root mean square error, RMSE = 0.0105431, residuals = 0.116631 and reduce chi-square, χ^2 = 0.00111156. In conclusion, SFBD was found to be a suitable and efficient method in drying of pepper and may be used for continuous drying processes.

ABSTRAK

Malaysia merupakan salah satu pengeluar lada hitam dengan kuantiti eksport sehingga lebih 90,000 tan di tahun 2010 sehingga 2016. Lada hitam perlu dikeringkan sebelum dipasarkan dan kaedah pengeringan yang digunakan secara tradisinya adalah pengeringan di bawah cahaya matahari.Walaubagaimanapun, perubahan iklim yang berlaku telah menjejaskan kaedah pengeringan ini kerana kebergantungan kepada cuaca. Kajian ini mencadangkan kaedah lapisan terbendalir berpusar, (LTB) sebagaimana yang diketahui mempunyai keupayaan pencampuran tinggi dan interaksi lada-gas (udara) lebih baik untuk memendekkan masa pengeringan produk. Sebuah sistem LTB berskala makmal dibina untuk menjalankan kajian ini. Beberapa eksperimen telah dijalankan untuk mengkaji sifat hidrodinamik diikuti dengan kajian pengeringan untuk beban iaitu 1.0 kg, 1.4 kg dan 1.8 kg pada suhu 50 °C, 60 °C, 70 °C, 80 °C dan 90 °C. LTB menunjukkan potensi yang sangat baik berbanding kaedah konvensional yang mana memerlukan masa pengeringan hanya 3 jam. Didapati, semakin banyak beban pengeringan atau semakin rendah suhu pengeringan, semakin lambat pengeringan lada hitam berlaku. Empat hinga lima rejim operasi yang berbeza didapati ketika proses pengeringan di dalam LTB dan keadaan operasi ini menunjukkan fleksibiliti operasi pengeringan berlaku. Jumlah jatuhan tekanan adalah agak rendah ketika pengeringan. Selain itu juga, model lapisan nipis untuk keadaan kadar jatuhan menunjukkan model lapisan nipis Logarithmic model adalah yang sesuai dengan ujikaji yang dilaksanakan dengan pekali penentuan, $R^2 = 0.9990807$, root mean square error, RMSE = 0.0105431, Residuals = 0.116631 dan reduce chi-square, $\chi^2 = 0.00111156$. Kesimpulan yang dapat dibuat LTB adalah kaedah yang cekap dan berdaya maju bagi menjalankan pengeringan.

CONTENT

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

LIST OF FIGURE

LIST OF TABLE

LIST OF SYMBOLS AND ABBREVIATIONS

MR	moisture ratio
SFBD	swirling fluidized bed dryer
RMSE	Root Mean Square Error
D_{eff}	effective diffusivity
d_m	average diameter
dM/dt	drying rate
M_e	equilibrium moisture content
R^2	coefficient of determination
Re_p	particles Reynolds number
U_{mf}	minimum fluidization velocity
U_{ms}	minimum swirling velocity
V_s	superficial velocity
ΔP_b	bed pressure drop
ΔP_d	distributor pressure drop
χ^2	reduced chi-square
ε	bed voidage
T	Temperature

CHAPTER 1

INTRODUCTION

1.0 Introduction

Piper nigrum Linn belongs to the family Piperaceae and its dried unripe fruit is used commonly as “black pepper.” This perennial shrub is indigenous to the Western coasts of India and tropical parts of Asia [1]. Black pepper – the dried unripe fruit of Piper nigrum is used as a condiment in various cuisines worldwide and is a part and parcel of every kitchen. In 2013, the global production of black pepper was reported to be nearly 355,000 tones [2]. Due to its widespread consumption, biochemical and pharmacologic properties of black pepper have been investigated extensively.

Drying (or dehydration) is one of the important unit operations in food manufacturing, mainly aimed at the preservation of foods by reducing the amount of moisture in the food matrix to levels that will slow down/inhibit microbial and enzymatic activities and the associated product quality deterioration [3]. It involves the removal of water from a wet feedstock by inducing phase changes of water from solid or liquid into a vapor phase via the application of heat (except in the case of osmotic dehydration during which the water is removed without a change in phase by the diffusion of liquid water from solid foods to an osmotic solution through an osmotic pressure difference). Drying is an energy-intensive process, which usually leads to pronounced alterations in product quality attributes due to the exposure to long drying times at high temperatures. The process of drying food materials is extremely complex, involving coupled transient mechanisms of heat, mass, and momentum transfer processes accompanied by physical, chemical, and phase change transformations. In food drying, a major challenge is to remove water from the material in a most efficient way, with better product quality, minimal impact on the environment, and at the lowest capital and operating costs of the process [4, 5].

The problems of drying are diverse. Various food materials with diverse physical/chemical properties need to be dried at different scales of production and with very different product quality specifications [6]. With the growing consumer demand for better quality products and the need for eco-friendly and sustainable processes to maintain competitiveness with minimal impact on the environment, researchers will continue to seek innovations in the drying process. This will further drive efforts in improving the performance of the existing drying technologies and the development of new drying concepts.

1.1 Problem statement

Pepper is one of the largest consumed spice in the world with increasing demand every year due to the population growth as well as the growth in food industry. Nevertheless, the production technique of pepper remained traditional and has not shown much significant change over the decade. This is mainly to avoid the increase in production cost of pepper. However, the recent climate change due to global warming has affected pepper production particularly drying where most pepper producing nations depend heavily on sun drying. Drying is the key process in pepper production. At present, pepper was sun-dried, and takes 4 to 5 days to dry. During rainy season, pepper drying may take more than 1 week. As a result, pepper drying is still low in productivity and inefficient. As such, this study proposes an innovative method in pepper drying by using the swirling fluidized bed dryer (SFBD). In contrast to the conventional fluidized bed dryers, the SFBD provides lateral momentum inside the dryer to simultaneously suspend the pepper as well as swirl them, in order to enhance the contact between drying air and pepper. Thus, the study focuses on the hydrodynamics of pepper in SFB and pepper's drying kinetics for different bed loadings and drying temperatures. Thin-layer mathematical modelling to predict to drying behavior was also attempted to predict pepper's drying kinetics.

1.2 Objectives

The objectives of this study are:

1.2.1. To determine the hydrodynamics at pepper in SFBD.

1.2.2. To determine the drying kinetics of pepper in a SFBD at varying bed height and bed temperature.

1.2.3. To select the best thin-layer mathematical model for predicting drying kinetics of pepper in SFBD; and

1.2.4. To estimate the effective diffusivity and activation energy.

1.3 Scope of study

The scope of study includes the following:

1.3.1. batch drying experiments of 1.0 kg, 1.4kg and 1.8 kg.

1.32. drying temperatures of 50℃, 60℃, 70℃, 80℃, and 90℃.

1.3.3. thin-layer modelling for falling-rate drying period using Henderson and Pabis model, Logarithmic model, Modified Henderson and Pabis model, Newton or Lawis model, Verma et al. model and Two term model followed by statistical analyses.

1.4 Significance of the study

The findings of this study will enable the understanding on the fundamental aspects of pepper drying in the swirling fluidized bed dryer, particularly the effect of bed loading and drying temperature on the drying rate. Apart from that, establishment of suitable thin-layer model to describe the drying behavior will enable the prediction of drying kinetics apart from providing basic information required for scaling-up for industrial used.

1.5 Thesis Organization

The thesis is divided into five chapters. In chapter two, understand and identify on the related studies to this thesis and summarized. In the third chapter, experimental set up was elaborated in details while chapter four present and analyses all the findings from experimental work and modelling. The thesis is concluded in chapter five with recommendation for future studies.

CHAPTER 2

LITERATURE REVIEW

2.0 Chapter Overview

This chapter gives an insight on the fundamental aspects of drying and also reviews previous studies related to the present study. The important aspects of fluidization were also highlighted in the light of proposed drying technique i.e swirling fluidized bed dryer (SFBD). Utilization of thin-layer models in predicting drying kinetics was also discussed.

2.1 Drying

Drying commonly described as process removing substances (moisture) thermally, to yield a dried product. Moisture held in loose chemical combination, forms as a liquid solution within a solid or even converges in the microstructure of the solid, which exerts a vapour pressure less than that of pure liquid is called bound moisture. Two processes will occur when a wet solid is exposed to thermal drying. The first is energy transfer from the environment to evaporate the surface moisture. The second is internal moisture transfer to the surface of the solid and it is subsequent evaporation [7].

2.2 Drying Kinetics

Drying kinetics play a significant role in determining drying method as well as selecting dryers. Drying kinetics allow the understanding of many important parameters in drying such as location of the moisture (whether near surface or distributed in the material), nature of moisture (free or strongly bound to solid), mechanisms of moisture transfer (rate-limiting step), physical size of product, and conditions of drying medium (e.g., temperature, humidity, flow rate of hot air for a convective dryer). Hence establishing the drying kinetics is imperative before the drying process begins [8-9].

The drying kinetics can be represented a set of drying curves as depicted in Figure 2.1. Figure 2.1 presents the typical drying characteristics which represented by several variables namely the drying rate, drying temperature and mass against time. It also represents the typical curves during drying such as the moisture change, drying rate, and exhaust temperature of drying medium, product temperature as well as the relative direction of flow of the drying medium

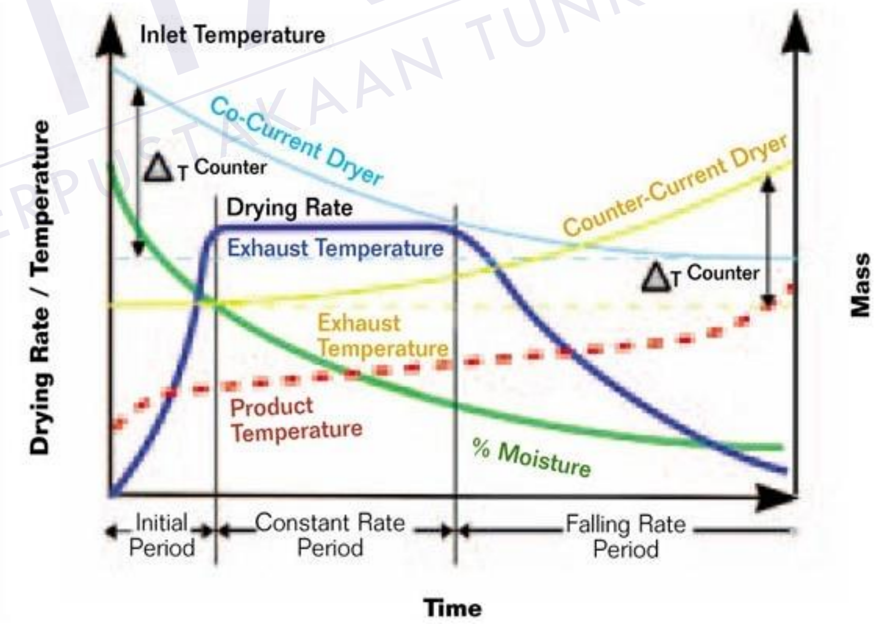

Figure 2.1: Typical drying curves representing drying kinetics [10].

2.3 Moisture Content

Moisture content can be describe as the amount of moisture present in product or sample divided by the mass of the product or sample without the moisture. The value will be read in percentage. The main purpose to calculate the moisture content is to find the suitable temperature to dry the product or sample. When the mass is decrease it means that the moisture content become low. Moisture content can be calculated by the following equation:

$$X_{db} = \frac{W_t - W_d}{W_d} \quad . (2.1)$$

Where X_{db} is the moisture content fraction in dry base, Wt is the sample weight at specific time and W_d is dried sample weight [11].

2.4 Fluidization

Fluidization refers to the contact between a bed of solids in a stream of flowing fluid. As a result, the solid particles are transformed into a fluid-like behavior that can be used for different purposes [12]. The particles are fully supported in bed when the drag forces are happen by the gas flow through the bed resulting equal to the weight of the particles and the bed is said to be fluidized [13].

When gas flow through the bed is increases, cause bubbles to form in the bed, much as in a fluid, and early researchers noted that this resembled a fluid and called this a fluidized state. When fluidized happen, fluidized mass (called a fluidized bed) has many properties of a liquid that is the fluidized particles seek their own level and assume the shape of the containing vessel. Large, heavy objects sink when added to the bed, and light particles float [14].

Increasing the gas velocity will eventually result in a state in which the drag induced by the upward flowing gas will balance out with the weight of the particles.

This fluidization state is commonly referred to as incipient or minimum fluidization; the point at which the particles are just fluidized [15]. The gas velocity associated with minimum fluidization is referred to as the minimum fluidization velocity.

Increasing the gas velocity beyond that of minimum fluidization will result in excess gas being introduced into the fluidized bed. The excess gas will coalesce to form bubbles causing greater instability in the bed. This regime, as its name implies, is known as the bubbling regime and these regimes demonstrates more aggressive particle movement within the bed itself as particles are carried up through the bed in the wake created by the passing bubble.

Larges bubbles will arise when operating at higher gas velocity. If a situation occurs where a bed is sufficiently deep as compared to its width, there is a potential for bubbles to become so large that they spread across the entire bed cross-section. This is referred to as a slugging regime. Slugging regimes exist depend on the characteristics of the fluidized particles. Eventually, a maximum stable bubble size is reached in the bubbling fluidization regime and bubble splitting will begin to replace bubble coalescence as the primary mechanism of bubble interaction in the bed.

The point at which bubble splitting dominates bubble coalescence is marked as the transition to the turbulent fluidization regime. In the turbulent fluidization regime, bubble splitting results in irregular shaped voids which appear as streaks or channels within the fluidized bed [16].

After turbulent fluidization, entrainment regimes will arise when gas velocity increase. This occurs because the terminal velocity of the fluidized particles is exceeded by the velocity of the fluidization gas, hence entraining the particles in the gas flow stream.

Two important fluidization regimes are associated with this type of behavior that is fast fluidization and pneumatic conveying or pneumatic transport. As mentioned, these types of regimes occur at very high fluidization velocities and therefore are employed in operations where solids flow-through is desirable (e.g., circulating fluidized beds).

2.5 Fluidized Bed Drying

Fluidized bed technology has been used in industrial dryers for the drying of wet solid particles for many years. Fluidized bed dryers have successfully been used for drying of products such as coal, maize, paddy, coconut, biosynthesis products, chilies, nylon, baker's yeast, black tea and bleaching agents (sodium per borate).

It is due to the evolving designs of fluidized bed for fluidization of coarse material which are rather difficult to fluidize [17]. A fluid bed is formed when a bed of particles is transformed into a fluid-like state by forcing a gas through the bed.

Typically, pressurized gas enters the fluidized bed vessel through the distributor plate and the fluid flows upward in the bed, subsequently make the solid particles to be suspended. This process can be made to take place at high temperatures.

At a certain gas velocity (called the minimum fluidization velocity) the weight of the particles is balanced by the frictional force between a particle and the air, so the vertical component of the compressive force between adjacent particles disappears, and the pressure drop through any section of the bed approximates the weight of air and particles in that section.

In this case, the bed is referred to as bed at minimum fluidization. With an increase in airflow rates beyond minimum fluidization, the particles behave like a fluid and in many cases the bed behaves like a boiling liquid [18].

2.6 Swirling Fluidized Bed Dryer

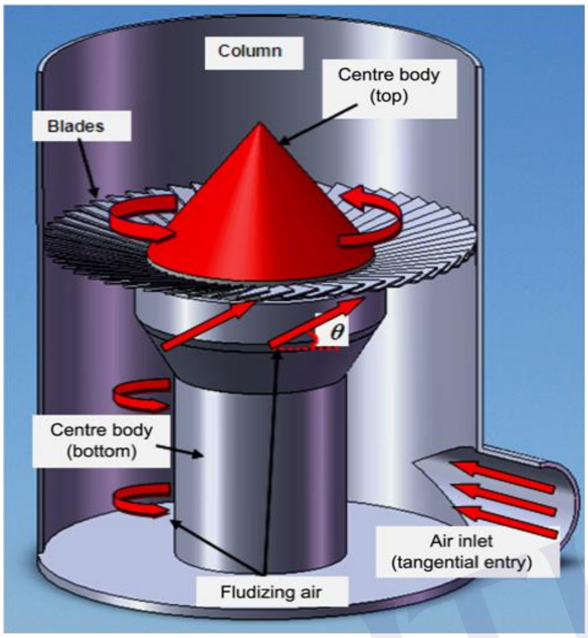

Figure 2.2: Basic configuration of a SFBD [19]

The swirling fluidized bed studied in the present work is similar to add spacing a gas turbine system in air crafts. It features an annular bed and inclined injection of gas through the distributor blades, resulting in a swirling motion of solid particles in a confined circular path. Figure 2.2 are illustrated as a basic of SFBD. When a jet of gas enters the bed at an angle θ to the horizontal, the vertical component of the velocity, υ sin θ, causes fluidization, and the tangential component, υ cos θ, is responsible for the swirl motion of the bed material.

As the gas penetrates deeper into the bed, its horizontal momentum is attenuated, and it finally dies out at a certain height above the distributor, if the bed is sufficiently deep. If the bed is shallow enough, the velocity of the gas leaving the bed will still have two components. In this case, the bed will be a single swirling mass. Use of a lower angle of injection ensures vigorous mixing of solids and hence, high transport coefficients. The gas velocity can be increased to high values with little carry-over of particles because the vertical component of the velocity is only a fraction of the jet velocity [20].

2.7 Mathematical Modelling of Drying Curves

Moisture ratio (MR) or can be defining as dimensionless of moisture content can be calculated by this equation:

$$\mathrm{MR} = \frac{M(\mathrm{t}) - M_{\mathrm{eq}}}{M_0 - M_{\mathrm{eq}}} \tag{2.2}$$

Where M_0, M(t) and M_{eq} are initial, at any moment (t), and equilibrium moisture content, respectively. Extremely small compared with M_0 and M(t), M_{eq} included in the MR definition may be left especially for drying at high temperature, where M_{eq} values normally approach zero [21]. Table 2.1 lists several mathematical models that usually used to characterize the drying kinetics of food products:

Table 2.1: Common thin-layer drying models in the literature [22]

No	**Model names**	**Model**
1	Newton or Lewis	MR = exp($-kt$)
2	Page	MR = exp($-kt^n$)
3	Henderson and Pabis	MR =a exp($-kt$)
4	Logarithmic	MR =a exp($-kt$)+b
5	Two term	MR =a exp($-k_0t$) + b exp($-k_1t$)
6	Midilli	MR =a exp($-kt_n$) + bt
7	Verma et al.	MR =a exp($-kt$) +(1- a) exp($-gt$)
8	Modified Henderson and Pabis	MR =a exp($-kt$) + b exp($-gt$) + c exp($-ht$)

The list adapted to experimental drying data at different temperatures for chopped coconut. To determine each constant, non-linear regression was utilized for

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