SPONGE MEDIA DRYING USING A SWIRLING FLUIDIZED BED DRYER

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SPECIAL GRATITUDE TO;

THE MOST BELOVED PARENTS,
Zakaria Bin Daud and Hamidah Binti Deraman
For their support in whole of my life

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Only Allah S.W.T can repay your kindly and hopes Allah S.W.T blesses our life.
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Surface preparation today has seen the introduction of sponge media as an alternative product against the traditionally used abrasive materials. Being soft and elastic, the sponge media reduces air borne emission significantly during surface preparation with capability to be re-used. However the environmental conditions limit the sponge media usage whereby wet surroundings prohibit the re-use of the sponge without being dried properly. This study proposes the swirling fluidized bed dryer as a novel drying technique for sponge media. Batch experiments were conducted to study the bed’s hydrodynamics followed by drying studies for three bed loadings of 0.5 kg, 0.75 kg and 1.0 kg at three drying temperatures of 80°C, 90°C and 100°C. It was found that, minimum fluidization velocities for the wet sponge particles were found to be 1.342, 1.361 and 1.382 m/s with minimum swirling velocities of 1.400, 1.469 and 1.526 m/s. Drying times were recorded between 6 to 16 minutes depending on bed loading and drying temperature. Smaller bed weights exhibits faster drying with constant-rate drying period while higher drying temperature and larger bed load resulted in falling-rate drying period. Thin layer modelling for the falling-rate region indicates that Verma et. al model provides the best fit for the present experimental data with coefficient of determination, $R^2 = 0.98773$, root mean square error, $RMSE = 0.05048$, residuals = 0.3442 and reduced chi-square, $\chi^2 = 0.00254$. The effective diffusivity, $D_{eff}$, for 0.5 kg bed load was found to be $3.454 \times 10^{-9}$ m$^2$/s and $1.751 \times 10^{-9}$ m$^2$/s for 0.75 kg bed load. In conclusion, SFBD was found to be a viable and efficient method in drying of sponge media for various industrial applications particularly surface preparation.
ABSTRAK

Penyediaan permukaan pada hari ini telah memperkenalkan media span sebagai produk alternatif berbanding kaedah tradisional yang menggunakan bahan pelelas. Bersifat lembut dan kenyal, media span mengurangkan pelepasan bahan berbahaya dengan ketara semasa penyediaan permukaan dan boleh diguna semula beberapa kali. Walau bagaimanapun keadaan persekitaran menghadkan penggunaan media span di mana persekitaran yang basah menghalang penggunaan semula span tanpa dikeringkan dengan baik. Kajian ini mencadangkan penger ring lapisan terbendalir berpusur sebagai teknik penger ring baru untuk media span. Beberapa eksperimen telah dijalankan untuk mengkaji sifat hidrodinamik diikuti dengan kajian penger ring untuk tiga berat iaitu 0.5 kg, 0.75 kg dan 1.0 kg pada tiga suhu penger ring 80°C, 90°C dan 100°C. Didapati bahawa, halaju minima terbendalir bagi span basah adalah 1.342, 1.361 dan 1.382 m/s dan halaju minima berpusur adalah 1.400, 1.469 dan 1.526 m/s. Masa penger ring yang direkodkan adalah di antara 6 hingga 16 minit bergantung kepada berat media dan suhu penger ring. Berat media yang lebih rendah menunjukkan penger ring lebih cepat dengan keadaan penger ring kadar-tetap manakala suhu penger ring yang lebih tinggi dan berat media yang besar menuruti keadaan penger ring kadar-kejatuhan. Permodelan matematik bagi keadaan penger ring kadar-kejatuhan mendapati bahawa model Verma et. al menunjukkan penyesuaian lengkung terbaik untuk data eksperimen dengan pekali penentuan, \( R^2 = 0.98773 \), ralat punca min kuasa dua, \( \text{RMSE} = 0.05048 \), residual = 0.3442 dan pengurangan chi-kuasa dua, \( \chi^2 = 0.00254 \). Keberkesanan resapan, \( D_{eff} \), untuk berat 0.5 kg adalah \( 3.454 \times 10^{-9} \) \( \text{m}^2/\text{s} \) dan \( 1.751 \times 10^{-9} \) \( \text{m}^2/\text{s} \) untuk berat 0.75 kg. Kesimpulannya, kaedah penger ring lapisan terbendalir berpusur didapati amat sesuai bagi penger ring media span.
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LIST OF SYMBOLS AND ABBREVIATIONS

MR moisture ratio
SFBD swirling fluidized bed dryer
RMSE Root Mean Square Error
$D_{\text{eff}}$ effective diffusivity
$d_m$ average diameter
$dM/dt$ drying rate
$M_e$ equilibrium moisture content
$R^2$ coefficient of determination
$R_{\text{p}}$ particles Reynolds number
$U_{\text{mf}}$ minimum fluidization velocity
$U_{\text{ms}}$ minimum swirling velocity
$V_s$ superficial velocity
$\Delta P_b$ bed pressure drop
$\Delta P_d$ distributor pressure drop
$\chi^2$ reduced chi-square
$\varepsilon$ bed voidage
CHAPTER 1

INTRODUCTION

1.0 Background

Industrial surface preparation for corrosion protection is vital in many heavy industries such as marine engineering, automotive engineering, oil and gas, power plants and many more. With the evolving nature of engineering and advent of high-tech machineries and equipments, the industrial surface preparation process has also undergone much sophistication. One such sophistication is the utilization of sponge media as blasting material, replacing the traditional abrasive material used in the process.

This revolutionary concept of industrial surface preparation provide distinct advantages such as low dust/airborne particle produced during the process hence requiring minimal containment, flexibility of preparation, recyclability, safer working area and wider range of operation. These sponge media are open-celled and some are water based polyurethane impregnated with abrasive material. As a result, it provides inherent cost and time saving benefits. The physical characteristic of sponge media allows its particles to flatten upon impact and absorbs the energy before leaving the surface. As such, the media constricts pulling and encapsulating what would normally have become airborne contaminants [1].

The concept of sponge media blasting is shown in Figure 1.1. First, high pressure air from compressor is directed into the blasting nozzle containing sponge media. When this blasting nozzle is directed towards the surface to be prepared, the sponge media is released at high velocity. As a result, the chunks of sponge media hit the surface, and transfer the impact energy. In a matter of few micro-seconds, the
sponge media flattens and suppresses the surface to scrap the unwanted surface before falling on the ground with the debris [1].

![Figure 1.1: The sponge media blasting concept [1]](image)

However, using this sponge media in wet and humid and surrounding imposes additional challenge in the surface preparation process. Just like a domestic sponge, these sponge particles readily absorb moisture and under wet surroundings, it can’t be re-used without drying it first. Therefore, large inventory of these sponge media is usually required when surface preparation takes places in rainy seasons as the present drying method of wet sponge media is very inefficient.

Recently, swirling fluidized beds are reported to exhibit excellent solid-air contact and making them ideal for processes involving heat and mass transfer such as drying. Unlike the existing fluidized bed systems, the swirling fluidized bed (SFB) provides swirling motion inside the bed apart from fluidization [2]. In the SFB system the fluidizing medium enters the bed at an inclination to the horizontal directed by a suitable design of a distributor [3]. Figure 1.2 shows the schematics of the SFB system.

![Figure 1.2: shows the schematic of the SFB system](image)
1.1 Problem Statement

Sponge media blasting process requires the use clean and dry media for surface preparation. During rainy season, all the scattered sponge media used in the process (during blasting) are soaked in rain water. This becomes a problem to the blasting process since the sponge media are recycled to reduce the material inventory during blasting. Another arising problem is during retrieval of the media after blasting it contains foreign particles besides debris. Drawback of conventional drying method is not suitable for the high volume sponge media demand during blasting and to use new or unused sponge media is not favourable since it incurs additional cost, transportation time and storage space. Fluidized bed dryers are known to yield very high rate of heat and mass transfer and widely used for various drying processes. Among the promising variant of fluidized bed is the swirling fluidized bed dryer (SFBD). As reported in the literature [4, 5, 6], SFBD is capable in providing vertical and horizontal momentum inside the bed which allows vigorous mixing and high degree of solid-gas contact which is ideal for drying. Thus, it is proposed here drying of wet sponge media using the SFBD. Experimental investigation and thin layer modelling were carried out in the SFBD to evaluate the drying kinetics of sponge the media.

1.2 Objective

The objectives of this study are:

(a) to examine the basic hydrodynamic characteristics of sponge media in a swirling fluidized bed

(b) to investigate the drying characteristics of sponge media using a swirling fluidized bed dryer

(c) to model the sponge media drying process using thin layer models available in the literature
1.3 Scope of Study

To achieve the objectives above, the following scopes were outlined:

a) Industrial sponge media was provided by Deleum Primera Sdn. Bhd with average diameter, $d_{m}$, of 4.514 mm

b) Basic hydrodynamics study of both dry and water laden sponge media including minimum fluidization velocities, minimum swirling velocities, distributor and bed pressure drop and regimes of operation

c) Batch drying experiments with bed loads of 0.5 kg, 0.75 kg and 1.0 kg with drying temperature of 80°C, 90°C and 100°C, in accordance to the requirement of industry

d) The drying characteristics include moisture content against drying time, moisture ratio against drying time, drying rate against moisture ratio and calculation of effective diffusivity

e) Thin layer modelling for falling-rate drying period using Henderson and Pabis model, Logarithmic model, Modified Henderson and Pabis model, Newton model or Lawis model and Verma et al. model

1.4 Significance of Study

The findings from this study enable the determination of viability and performance of sponge media drying in a SFBD system. It will also facilitate the up-scaling and development of an actual SFBD system for industrial use. This will encourage the utilization of environment-friendly technologies in the surface preparation industry since this method solves one of the drawbacks in using sponge media mainly to save drying time process. On top of that, productivity in the industry will be increased with better safety aspects during operation.
1.5 Thesis Organization

The first chapter gives an introduction to the present study by highlighting the fundamental aspects of sponge media drying, objective and scope of this study. In the second chapter, a review on related studies to this thesis is summarized. In the third chapter, experimental set-up was elaborated in detail while chapter four present and analyzes 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 Energy Consumption in Drying

In various industries, a large part from the total energy use is spent in drying. Production of wood products for instance, has the highest energy consumption with 70% of total energy spent, followed by textile fabrics with 50%, pulp production with 33%, paper with 27% and food and pharmaceutical was around 15% as shown in Figure 2.1. Energy spent for drying varies between countries and ranges between 15-20% of the total energy consumption in industry [7, 8, 9].
Figure 2.1: Percentage of energy used for drying for different industries [9]

The energy efficiency in the drying process was affected by various factors, for instance the evaporation rate, steam consumption and energy uptake by other processing units. Energy efficiency is defined as the ratio between the total energy required for evaporating water from the product and the total amount of energy spent to the system [7].

Considering the given energy efficiency values it is a challenge to work on the development of innovative dryers with a high drying rate, high energy efficiency, low investment and operational costs, and feasible for low and medium drying temperatures [10]. Many improvements from innovation and research in drying technology took place since decades ago but breakthrough solutions with respect to the energy efficiency were limited. Innovation in drying technology tends to reach a saturation level as reported [11] and a further significant reduction in energy consumption seems difficult to achieve.

2.2 Fundamentals of Drying

Drying is a process of removing or separating moisture from wet a material thermally. Although the driving force for drying is moisture difference, drying often
carried out using hot air supply as heating medium to enhance the moisture transfer rate from the wet material. Drying may also be viewed as either a preservation technique or as a manufacturing step and in many cases performs both functions simultaneously [12, 13]. Drying process of wet particles consist two processes which occur simultaneously [14]:

a. Energy transfer (mostly as heat) from the surrounding environment to evaporate the surface moisture.

b. Internal moisture transfer to the surface of the solid and its subsequent evaporation due to previous process.

Energy transfer as heat from the surrounding environment to the wet particles or solids can exist as a subsequence of convection, conduction, or radiation and in some case as a combination of these effects. Generally, heat is transported to the wet solid surface and then to the internal solid body. In the initial stage of drying, moisture evaporate as vapour from the material surface, depending on the temperature, humidity and velocity of the air, exposed surface area, and pressure. Then, the movement of moisture internally within the solid is a function of the physical nature of the solid, the temperature, and its moisture content. In a drying operation, any one of these processes may be the limiting factor governing the rate of drying, although they both proceed simultaneously throughout the drying cycle. Method of moisture transfer can be occurring in any following mass transfer condition as below:

i. Liquid diffusion, if the wet solid is at a temperature below the boiling point of the liquid,

ii. Vapour diffusion, if the liquid vaporizes within material,

iii. Knudsen diffusion, if drying takes place at very low temperatures and pressures, e.g., in freeze drying,

iv. Surface diffusion (possible although not proven),

v. Hydrostatic pressure differences, when internal vaporization rates exceed the rate of vapour transport through the solid to the surroundings,

vi. Combinations of the above mechanisms.
Since the physical structure of the drying solid was subject to change during drying, the mechanisms of moisture transfer may also change with elapsed time of drying.

2.2.1 Process 1: External Conditions

The external condition variables are temperature, humidity, velocity and direction of air, the physical form of the solid, the desirability of agitation, and the method of supporting the solid during the drying operation.

External drying conditions are especially important during the beginning of drying process when unbound surface moisture is removed. Surface evaporation is controlled by the diffusion of vapour from the surface of the solid to the surrounding atmosphere through a thin film of air in contact with the surface. Since drying involves the inter-phase transfer of mass when a gas is brought in contact with a liquid in which it is essentially insoluble, it is necessary to be familiar with the equilibrium characteristics of the wet solid. Also, since the mass transfer is usually accompanied by the simultaneous transfer of heat, due consideration must be given to the enthalpy characteristics [12, 14].

2.2.2 Process 2: Internal Conditions

When heat is transferred to a wet solid, a temperature gradient develops within the solid while moisture evaporation occurs from the surface. This produces a movement of moisture from the inside of solid to the surface, which occurs through one or more mechanisms, namely, diffusion, capillary flow, internal pressures set up by shrinkage during drying, and in the case of indirect (conduction) dryers, through a continuous and progressive occurring vaporization and re-condensation of moisture to the exposed surface. An appreciation of this internal movement of moisture is important when it is the controlling factor, as it occurs after the critical moisture content, in a
drying operation carried to low final moisture contents. Variables such as air velocity and temperature, which normally enhance the rate of surface evaporation, are of decreasing importance except to promote the heat transfer rates. Longer residence times and higher temperatures where permissible become necessary. The temperature gradient occurring in the solid will also create a vapour–pressure gradient, which will in turn result in moisture vapour diffusion to the surface; this will occur simultaneously with liquid moisture movement [12, 14].

2.3 Drying Techniques

A large number research and innovation on the types of dryers and drying methods were reported in the literature. Most of them were application specific and usually cost and efficiency are the main criteria in the dryer selection. Drying methods may range from conventional sun drying to various industrial drying types as follows.

2.3.1 Solar Drying

Solar drying is the simplest and cheapest drying technique but also associated with low efficiency. This is due to the dependence on many parameters such as humidity, air flow in the surrounding, daily temperature, the shape and size distribution of the wet solids and many more. Sun drying also difficult to control and hence result in necessity of larger area, longer drying time and the final product may be contaminated from dust and insects and suffer from enzyme and microbial activity.
2.3.2 Hot Air Drying

When hot air is in contact with the wet material to aid heat and mass transfer; convection is mainly involved. Two important aspects of mass transfer are the transfer of water to the surface of the material that is dried and the removal of water vapour from the surface. The hot air dryers generally used for the drying of piece-form fruits and vegetables are cabinet, kiln, tunnel, belt-trough, bin, pneumatic and conveyor dryers. Energy source to heat the air would be electricity or renewable energy resources such as solar and geothermal energy.

2.3.2.1 Cabinet Dryer

A cabinet dryer can be a small batch tray dryer. Heat from the drying medium to the product is transferred by convection. The convection current passes over the product, not through the product. It is suitable for drying of fruits, vegetables, and meat and its product. The main feature of a cabinet dryer is its small size and versatility. The main problem with cabinet dryer is difficulty in even distribution of heated air over or through the drying material.

2.3.2.2 Pneumatic Conveyor Dryers

Pneumatic conveyor dryers are generally used for the drying of powders or granulated materials and are extensively used in the making of potato granules. The feed material is introduced into a fast moving stream of heated air and conveyed through ducting of sufficient length to bring about desired drying. The dried product is separated from the exhaust air by a cyclone or filter.
2.3.3 Microwave Drying

High-frequency electromagnetic waves were used in microwave drying. The transfer of these waves to the particle is similar to the transfer of radiant heat. The advantages of using microwave energy are penetrating quality, which effects a uniform heating of materials upon which radiation impinges; selective absorption of the radiation by liquid water; and capacity for easy control so that heating may be rapid if desired.

2.3.4 Spray Drying

The spray drying method is most important for drying liquid food products and has received much experiment study. Spray drying is the transformation of a feed from a liquid state into a dried form by spraying into a hot, dry medium. In general it involves atomization of the liquid into a spray and contact between the spray and the drying medium, followed by separation of dried powder from the drying medium.

2.3.5 Freeze-Drying

Freeze-drying, which involves a two-stage process of first freezing of water of the food materials followed by the application of heat to the product so that ice can be directly sublimed to vapour, is already a commercially established process. The advantages of freeze-drying are: minimized shrinkage, minimal movement of soluble solid, the porous structure of the product facilitates rapid dehydration and retention of volatile flavor compounds are high.
2.3.6 Fluidized Bed Dryer

In fluidized bed drying, hot air is forced through a bed at a sufficiently high velocity to overcome the gravitational forces on the products. When the air velocity is greater than the gravitational force and the bed resistance, the products will suspend.

2.4 Drying Mechanism

Moisture in solid may be either unbound or bound. Evaporation and vaporization methods were used to remove unbound moisture. Evaporation occurs when the vapour pressure of the moisture on the solid surface is equal to atmospheric pressure by raising the temperature of the moisture to the boiling point. The boiling point where evaporation occurs is the temperature which could be lowered by lowering the pressure; if the dried material is sensitive to heat. Further in vaporization, convection forces the drying which warm air were transfer into the solid body. While the temperature of warm air decreases, the specific humidity increases because of moisture content of the solid. Drying behaviour of solids can be described by measuring the function of moisture content loss versus drying time. Continuous weighing, humidity difference and intermittent weighing are the used methods [15].

In air drying processes, two drying periods generally occur as an initial constant-rate period and falling rate period. Constant rate drying occurs with evaporation of pure water. Moisture movement is controlled by internal resistances in the falling rate period. Moisture content as a function of drying time is shown in Figure 2.2.
The initial moisture content is shown at point A. In the beginning the solid is usually at a colder temperature than its ultimate temperature. Otherwise, if the solid is quite hot to start with, the rate may start at point A. Segment AB represents the initial unsteady-state, warming-up period. This initial unsteady-state adjustment period is usually quite short and it is often ignored in the analysis of times of drying [16]. Point BC is the constant rate period. The same points are marked in Figure 2.3, where the drying rate is plotted against the moisture contents [17].

During the constant rate period, the solid surface is initially very wet and a continuous film of water exists on the solid surface. Drying at this period is influenced by air temperature significantly but less effect of air velocity. The rate of evaporation under the given air conditions is independent of the solid and essentially the same as the rate from a free liquid surface [16, 18]. The transition moisture
content at which the departure from constant rate drying is first noticed is termed as the critical moisture content and indicated by point C at Figure 2.2 and Figure 2.3.

At this point there is insufficient water on the surface to maintain a continuous film of water. In food systems, where liquid movement is likely to be controlled by capillary and gravity forces, a measurable constant rate period is found to exist. With structured foods, liquid movement is by diffusion, and therefore the water that is evaporated from the surface is not immediately replenished by movement of liquid from the interior of the food. Such foods are likely to dry without exhibiting any constant rate period. Hot air drying of apples, tapioca, sugar beet root and avocado are such foods without exhibiting any constant rate period [17, 19, 20].

Between point C and D (Figure 2.2 and Figure 2.3) is termed the first falling rate period. During this period the rate of liquid movement to the surface is less than the rate of evaporation from the surface, and the surface becomes continually depleted in liquid water. The entire surface is no longer wetted, and the wetted area continually decrease in the first falling rate period until the surface is completely dry at point D. Beyond point D, the path for transport of both the heat and mass becomes longer and more tortuous as the moisture content continues to decrease. This period is called the second falling rate period. Finally, the vapor pressure of the solid becomes equal to the partial vapour pressure of the drying air and no longer further drying takes place. The limiting moisture content at this stage to which a material can be dried under a given drying condition is referred to as the equilibrium moisture content ($M_e$) [17].

### 2.5 Fluidization

Fluidization occurs when there is interaction between a bed of solids and flow of fluid which transforming the solid particles into a fluid-like behavior [21]. The particles are fluidized in bed when the drag force created by the gas flow through the bed is equal to the weight of the particles [22]. When gas flow through the bed
increases, bubbles were formed in the bed. Early researchers noted that this resembled a fluid like behavior and called this condition as fluidized state. When fluidization occurs, fluidized mass (now called a fluidized bed) has many properties of a liquid. One noticeable property is the fluidized particles seek to level and assume the shape of the containing vessel. Large, heavy objects sink when added to the bed, and light particles float [23]. In its simplest terms, fluidization is a physical process that transforms solid particles into a fluidized state through suspension in a liquid or gas [24].

2.5.1 Fluidization Regimes

Regimes are referred as distinct fluidization state depends on the gas flow rate velocity. The differences between the classical fluidization regimes as outlined are summarized and illustrated schematically in Figure 2.4. Fixed state or packed bed condition is happen at very low gas velocities and momentum carried by the gas is too low to fluidize the particles as the gas simply move through the voids between the stationary particles. 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 [21, 25].
The gas velocity associated with minimum fluidization is referred to as the minimum fluidization velocity, $U_{mf}$. When the gas introduced into the fluidized bed at higher velocity than $U_{mf}$, the excess gas will coalesce to form bubbles with greater instability in the bed which known as bubbling regime and at this point, the bubbling regimes demonstrates more aggressive particle movement within the bed itself as particles are suspended through the bed due to the passing bubble. Larger bubbles will arise when operating at higher gas velocity. Slugging regime occurs when there is a potential for bubbles to expand the gap between the particles and spread across the entire bed cross-section. The slugging regimes exist depends on the characteristics of the fluidized particles.

As a maximum stable bubble size is reached in the bubbling fluidization regime and bubble splitting will begin to break 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 [27, 28].

After turbulent fluidization, entrainment regimes appeared when the velocity of the fluidization gas increase which higher than terminal velocity of the fluidized particles, 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 [28].

### 2.6 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 been successfully been used for drying of products such as coal, maize, paddy, coconut, biosynthesis products, chillies, nylon, baker’s yeast, black tea and bleaching agents (sodium perborate). It is due to the evolving designs of fluidized bed, for fluidization of coarse material, which are rather difficult to fluidize [29].

The mode of operation of a fluidized bed could either be batch or continuous. The batch dryer finds application for small-scale production, while the continuous systems are used for large-scale production [29]. Batch operation is preferred for small scale production and for heat sensitive materials. Fluidized bed dryers are widely used in a number of industry sectors to dry finely divided 50–5000 μm particulate materials. Compared with other drying techniques, fluidized bed drying offers many advantages [30]. The process conditions are easily selected in batch drying and the product is of uniform quality due to homogeneity of the bed at any instant during its operation. In continuous fluidized drying, product from the dryer under steady-state operation corresponds in its properties to the material within the dryer due to high degree of solids mixing. To overcome the drawback, internal baffles are often provided in industrial fluidized dryers [31].

### 2.7 Swirling Fluidized Bed Dryer (SFBD)

Advantage of using the SFBD with annular blade distributor is having low pressure drop imposed by the distributor for fluidization [4]. This significantly reduces total
energy consumption by the system. Bed behaviour or operation regimes depend on the gas flow rate. As the flow rate increases, the bed behaviour are as follow [6]:

a) Bubbling: At this condition particle having little explosion at some region.

b) Wave motion with dune formation: A localized swirl motion is initiated at any random location in the bed. Swirling at certain area of the bed, while the remaining area is static. Then the swirling motion moves to the static area, leaving the previous area statically.

c) Two-layer fluidization: This is observed only in bed height more than 45 mm. When the minimum two-layer velocity is reached, bottom layer is continuously swirling and top layer is vigorously bubbling are visible.

d) Stable swirling: On further increasing the air velocity, one can observe that the dune formation is attenuated, the swirling region gets wider, and finally, the dune disappears to present a fully swirling bed.

2.8 Hydrodynamics in Fluidized Bed Systems

Hydrodynamics of fluidized bed systems is importance to understand the system characteristics and bed behavior during fluidization before any industrial application is operated. Among the hydrodynamic aspects observed are on regimes of operation, minimum fluidization velocity ($U_{mf}$) particle entrainment velocity, bed voidage ($\varepsilon$) and bed pressure drop ($\Delta P_b$) [32]. Apart from that, the bed pressure drop $\Delta P_b$ against superficial velocity ($V_s$) used to investigate the bed development and regimes of operation due to the increasing fluidizing air flow rate. Pressure fluctuations in the fluidized bed column to characterize the bed behavior were measured at a certain location in the axial direction in the bed above the distributor. The pressure fluctuations frequency inside the bed were perceived as good since they represent random and frequent bubbles which uphold a higher degree of solid-fluid contact [33, 34].
2.8.1 Hydrodynamics of Swirling Fluidized Beds

Hydrodynamics characteristic of the swirling fluidized bed are differ than non-swirling beds. Research on distributor pressure drop, $\Delta P_d$, bed pressure drop, $\Delta P_b$, the minimum fluidization velocity, $U_{mf}$, the minimum swirling velocity $U_{ms}$, and fluidization regime characterization are done to study high degree of mixing between particles, solid-gas contact and fluidization regimes [4, 35, 36]. A study on superficial velocity, $V_s$, in fluidization shows that $V_s$ depends on hydrostatic pressure gradient, changes in surrounding temperature and changes in molar flow rates due to chemical reaction [37].

Observation on flow operation regimes and prediction on the minimum fluidization velocity, $U_{mf}$, and particle trajectory through a modified Torbed® reactor were done by [5]. The bed pressure drop, $\Delta P_b$, increasing due with increasing superficial velocity, $V_s$, in swirling mode due to the centrifugal bed weight were reported for particles diameter size above 600 μm [6]. Another hydrodynamics characteristic were studied through mathematical model which were used to validate experimental data to study slip velocity which can used to measure solid-gas contact.

Minimum velocity of full fluidization ($U_{mff}$) and minimum velocity of swirl-fluidization ($U_{msf}$) apart from the $U_{mf}$ based on the flow regimes operation changes with respect to the increasing gas flow rate were used on a conical bed integrated with annular-blade distributor. The authors plotted a nomograph of $\Delta P/\Delta P_{mf}$ against $U/U_{mf}$ for estimation of bed pressure drop at certain superficial velocity and also report a sudden decrease in bed pressure drop beyond $U_{mf}$ [38, 39].

An investigation by using particles diameters above 600 μm in a bed with multiple tangential inlets were done to get better understanding of minimum superficial velocity or minimum swirl velocity for swirling. As reported, minimum superficial velocity or minimum swirl velocity is necessary to trigger swirling motion. The authors also proposed empirical modelling to predict this minimum swirl velocity and marked the existence of swirlable bed height depending on the air velocity [40].
2.9 Thin Layer Drying Models

There are large number of thin layer models available in the literature, which were used to investigate further the drying kinetics of wet solids particularly for agricultural products. Thin layer modelling is a drying process analysis in a single layer of particles. Empirical models are important to describe thin layer water removal and also heat diffusion during water removal. Expression involving drying rate as a function of time and drying time as a function of moisture content are required to apply these empirical models [41]. Among well-known thin layer models available from the literature were tabulated in Table 2.1. Empirical modelling is used for experimental data prediction and usually compared with actual experimental data. The purpose of using non linear regression is to interpret the value of coefficient of determination \(R^2\), Root Mean Square Error (RMSE), reduced chi-square (\(\chi^2\)) and residuals.

Table 2.1: Thin layer drying models [42]

<table>
<thead>
<tr>
<th>No</th>
<th>Model names</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Newton or Lawis</td>
<td>(MR = \exp(-kt)) (2.2)</td>
</tr>
<tr>
<td>2</td>
<td>Page</td>
<td>(MR = \exp(-k t^n)) (2.3)</td>
</tr>
<tr>
<td>3</td>
<td>Henderson and Pabis</td>
<td>(MR = a \exp(-kt)) (2.4)</td>
</tr>
<tr>
<td>4</td>
<td>Logarithmic</td>
<td>(MR = a \exp(-kt)+b) (2.5)</td>
</tr>
<tr>
<td>5</td>
<td>Two term</td>
<td>(MR = a \exp(-k_d t)+b \exp(-k_i t)) (2.6)</td>
</tr>
<tr>
<td>6</td>
<td>Midilli</td>
<td>(MR = a \exp(-k t_a)+bt) (2.7)</td>
</tr>
<tr>
<td>7</td>
<td>Verma et al.</td>
<td>(MR = a \exp(-kt)+(1-a) \exp(-gt)) (2.8)</td>
</tr>
<tr>
<td>8</td>
<td>Modified Henderson and Pabis</td>
<td>(MR = a \exp(-kt)+b \exp(-gt)+c \exp(-ht)) (2.9)</td>
</tr>
</tbody>
</table>

Non-linear regression was utilized for the tested model to determine each constant. The effectiveness of model fit was evaluated via the statistical criteria such as coefficient of determination \(R^2\), root mean square error (RMSE), reduced chi-square (\(\chi^2\)) and residuals. The most precise mathematical model is chosen within the
highest $R^2$ and the lowest RMSE, $\chi^2$ and residuals [43, 44, 45, 46]. These parameters may be expressed as:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{N-p}$$  \hspace{1cm} (2.10)

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}$$  \hspace{1cm} (2.11)

$$\text{Residuals} = \sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})$$  \hspace{1cm} (2.12)

Where $MR_{exp,i}$ and $MR_{pre,i}$ are the $i$ experimental and predicted moisture ratios, respectively. The number of observations is $N$, and the number of constants is $p$.

Many researchers have shown interest in thin layer modelling in their studies. Various drying methods and temperatures on different particles were studied, hence, provided different best model. Table 2.2 presents the previous studies and model proposed as the best model.

Table 2.2: Thin layer modelling for various products

<table>
<thead>
<tr>
<th>No</th>
<th>Author</th>
<th>Year</th>
<th>Particle</th>
<th>Drying Temperature (°C)</th>
<th>Model Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Doymaz [44]</td>
<td>2006</td>
<td>Mint leaves</td>
<td>35, 45, 55, 60</td>
<td>Logarithmic</td>
</tr>
<tr>
<td>2</td>
<td>Sacilik et. al. [47]</td>
<td>2006</td>
<td>Organic apple slices</td>
<td>40, 50, 60</td>
<td>Logarithmic</td>
</tr>
<tr>
<td>3</td>
<td>Akpınar et. al. [48]</td>
<td>2008</td>
<td>Green pepper</td>
<td>- Solar heat</td>
<td>- Logarithmic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Sun heat</td>
<td>- Midilli et. al.</td>
</tr>
<tr>
<td>4</td>
<td>Aghbashlo et. al. [49]</td>
<td>2009</td>
<td>Potato slices</td>
<td>50, 60, 70</td>
<td>Page model</td>
</tr>
<tr>
<td>5</td>
<td>Madhiyanon et. al. [42]</td>
<td>2009</td>
<td>Chopped coconut</td>
<td>60, 70, 80, 90, 100, 110, 120</td>
<td>Modified Henderson and Pabis</td>
</tr>
<tr>
<td>6</td>
<td>Han et. al. [50]</td>
<td>2011</td>
<td>Rapeseed</td>
<td>40, 50, 60</td>
<td>Page model</td>
</tr>
<tr>
<td>7</td>
<td>Shi et. al. [51]</td>
<td>2013</td>
<td>Yacon slices</td>
<td>5, 15, 25, 35, 45</td>
<td>Midilli et al.</td>
</tr>
<tr>
<td>8</td>
<td>Abidin et. al. [43]</td>
<td>2014</td>
<td>Grated coconut</td>
<td>50, 60, 70, 80</td>
<td>Logarithmic</td>
</tr>
</tbody>
</table>
2.10 Summary of Literature Review

From the literature it was found that no attempt to dry sponge media using fluidized bed dryer system. Such information was not available from the industry nor published hitherto, to the author’s knowledge. Therefore the present study proposes the usage of SFBD in drying of sponge media, followed by study on hydrodynamics and drying kinetics. Finally, selected thin-layer models will be applied from the literature review.
CHAPTER 3

METHODOLOGY

3.0 Chapter Overview

This chapter describes the methods used in the present study. The details of experiments and modelling efforts were elaborated. Thin-layer modelling and curve fitting using LAB Fit software was also addressed, together with statistical analysis.
REFERENCES


