Recent advances in fluidized bed drying

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Abstract. Fluidized bed drying are very well known to yield high heat and mass transfer and hence adopted to many industrial drying processes particularly agricultural products. In this paper, recent advances in fluidized bed drying were reviewed and focus is given to the drying related to the usage of Computational Fluid Dynamics (CFD). It can be seen that usage of modern computational tools such as CFD helps to optimize the fluidized bed dryer design and operation for lower energy consumption and thus better thermal efficiency. Among agricultural products that were reviewed in this paper were oil palm frond, wheat grains, olive pomace, coconut, pepper corn and millet.

1. Introduction
Fluidized bed dryer (FBD) has been used widely for drying various products due to its many advantages, including high drying rate due to an excellent gas-solid contact, high thermal efficiency, relatively low cost of operation etc [1]. In fluidized bed drying, hot air is forced through a distributor into 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. This condition is called fluidization which is a physical process that transforms solid particles into a fluidized state through suspension in a liquid or gas [2, 3]. 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 [4]. When fluidization occurs, the solid particles have 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 [5]. Before drying process was conducted in fluidized bed system, it is importance to understand the system characteristics and bed behaviour during fluidization. Among that aspects identified are regimes of operation, minimum fluidization velocity (U_{mf}), particle entrainment velocity, bed voidage (\varepsilon), bed pressure drop (\Delta P_b), superficial velocity (V_s) and minimum fluidization velocity (U_{mf}). Pressure fluctuations in the fluidized bed column to characterize the bed behaviour were measured at a certain location in the axial direction in the bed above the distributor [6-11].

2. Drying of agro products in FBD
As reported by many researchers, fluidized bed technology has been successfully used in drying of wet solid particles as shown in Table 1. Table 2 summarizes the FBD performances studies.
| Particles          | Aim                                                                 | Findings                                                                                                                                                       |
|-------------------|----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oil palm frond    | Investigation of drying kinetics in agitated fluidized bed dryer.     | - Agitation in fluidized bed allowed fluidization of the fibrous material and hence homogeneous mixing in the bed was achieved.                               |
|                   |                                                                      | - Drying rate increased with the increase in drying temperature and superficial air velocity, however, decreased with an increase in bed load.                   |
|                   |                                                                      | - Drying rate was greatly affected by drying temperature, followed by air velocity, bed load and lastly agitation speed.                                  |
|                   |                                                                      | - Proposed drying rate model provided the best fit model among all of the models.                                                                            |
| Wheat grains      | Present drying kinetics of wheat grain and the effects of the swirling flow field on the drying performance.          | - Moisture removal rate, the specific moisture removal rate and the dryer efficiency effected by air mass flow rate, drying temperature and flow field characteristics |
|                   |                                                                      | - Drying rate in swirling flow fields are higher than in non-swirling flow fields.                                                                          |
| Olive pomace      | Investigate the effect of drying air temperature and bed height on the drying kinetics of olive pomace in a fluidized bed dryer, and to fit the experimental data to known mathematical models. | - Drying process of olive pomace occurred in falling rate period.                                                                                           |
|                   |                                                                      | - Effective diffusivity values were calculated between 0.68 and 2.15 x 10^{-7} m²/s, increasing with increase of temperature or bed height of the sample.       |
|                   |                                                                      | - Higher activation energy values resulted by higher bed height of the sample.                                                                               |
| Coconut           | Effects study on drying kinetics with different operating parameters such as inlet air velocity and drying or air temperature and quality of coconut colour and surface oil content. | - Drying rate become higher since higher drying temperature or higher inlet air velocity was used.                                                           |
|                   |                                                                      | - Less drying temperature remove a lot of surface oil content, while higher inlet air velocity led to higher quantity of surface oil content.               |
|                   |                                                                      | - Colour of coconut was affected by air temperature.                                                                                                         |
| Pepper corn       | Comparison on drying kinetics between typical distributor plate and helical distributor plate in fluidized bed.      | - Different velocities leads to no significant effect on drying rate for typical distributor plate but provides a substantial influence for helical distributor plate. |
|                   |                                                                      | - Swirling drying bed reduce drying time than the typical fluidized-bed                                                                                      |
| Millet            | Study on drying kinetics of millet in a batch fluidized bed.        | - Drying rate and effective diffusivity were found to increase with increase in drying temperature and air velocity while decrease with increase in solids holdup. |
|                   |                                                                      | - Effective diffusivity of millet is found to be lower than that of ragi (food grain) and corn.                                                              |
| Particles                           | Aim                                                                 | Results/Outcome                                                                                                                                                                                                 |
|------------------------------------|----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Spherical PVC particles [6]        | Study on hydrodynamic characteristics in the swirling regime of operation. | - Three or four regime of operation observed depend on bed weight.  
- Pressure drop in swirling regime increase with increase in air flow rate.  
- Low distributor pressure drop recorded in swirling fluidized bed. |
| Jowar seed, ragi seed, wheat [18]  | Understanding the hydrodynamics behaviour of swirled fluidized bed.   | - Minimum swirl velocity increase with higher bed height, bigger column diameter, smaller fluid inlet size and less fluid inlets.  
- Minimum swirl velocity also affected by particle properties.  
- No bubble formation, gas channeling, solids segregation and slugging of bed. |
| PVC material [19]                 | Heat transfer study in swirling fluidized bed dryer.                 | - There are a few regime of operation; incipient mode, partial swirling, stable swirling and two-layer fluidization.  
- Heat transfer coefficient, \( h \), dissipates with higher bed height.  
- Higher heat transfer coefficient resulted with smaller particles than bigger particles.  
- Cylinder shaped center-body having higher heat transfer coefficient than cone shaped center-body. |
| Granular material [20]            | Study the variation in diffusion coefficient with different sizes of solid holdup. | - Higher bed temperature indirectly increases the rate of diffusion of moisture, thus increasing the drying rate.  
- Higher effective diffusivity coefficient resulted from smaller bed loading.  
- Fick’s diffusion equation only applied to individual particle with assumption that all the materials are exposed to uniform drying process conditions. |
| Paddy [21]                       | Investigates the drying characteristics of a fluidized bed dryer by inclining the bed, subsequent using spiral inside the drying chamber. | - Energy consumptions for inclined bed were lower compared to vertical bed dryer.  
- Blower energy consumption and heat input decreased with inclination of bed and the use of spiral.  
- The results indicate the highest drying efficiency and minimum energy consumption for the inclined bubbling fluidized bed dryer with spirals. |
| Wheat [22]                        | Study on drying kinetics of millet in a batch fluidized bed.         | - Energy efficiency and exergy efficiency was found to be decrease as the bed hold up decreased.  
- No significant difference in drying time for different initial moisture ratio.  
- Energy and exergy efficiency increase with decreasing air velocity or increasing drying temperature. |
3. Assisted fluidized bed dryer
Reports by [23, 24] presented potato slices and macaroni beads dried using microwave assisted FBD. FBD were placed in microwave oven by cutting circular holes with diameter of 10 mm at top and base of the microwave oven. The microwave+FBD then covered with a removable rectangular container which made of perforated stainless-steel sheets to ensure that no microwaves escaped into the surroundings. The other parts of the system were the same as those in the FBD [23]. The microwave oven assisted FBD significantly reduced drying time of the particles [24].

Paddy was dried in multi-stage dryer consist of FBD, far-infrared (FIR) irradiation and ambient air ventilation. The experimental results showed that FIR assisted FBD reduced moisture content of paddy about 2% d.b. difference rather than FBD drying process [25]. A spouted bed dryer was assisted by solar collector [26]. This type of combination consists of solar collector which covered with glass sheet, blower and spouting column to dry peas. Moisture removal in this dryer was increased compare to the sun drying method. Another hybrid FBD were reviewed by [27] whereby the FBD dryer was immersed in a heater, heat pump assisted FBD dryer and ultrasonic transducer assisted FBD dryer.

4. Computational fluid dynamics (CFD) study in FBD
CFD was used as numerical tool to get better understanding of airflow distribution through stainless steel woven wire mesh distributor as reported by [28]. In the report, CFD validation and experimental results were in good agreement in velocity and pressure drop characteristics. Other than that, a uniform airflow contacting upon the distributor, modelling of the distributor was better performed using the 2-D porous jump boundary condition. However, when dealing with unequal airflow conditions contacting upon the distributor, the distributor should be modelled using the full 3-D porous media model. CFD modelling also reveals that non-homogenous airflow through the distributor cause by tangential air inlet.

CFD simulation carried out to compare with experimental hydrodynamics study of coarse and fine particles. Bed height and pressure drop characteristics of both coarse and fine particle were compared to the CFD simulation show less than 7% and 14% deviations respectively. For CFD simulation, a few assumptions such as isothermal non-reactive, no lift force, no mass transfer between gas and solid phase, constant pressure gradient and constant density of each phase were considered [29].

A multifluid Eulerian model and kinetic theory of granular flow for solid particles was applied to simulate the gas–solid flow in Fluent 6.0. Momentum exchange coefficients were calculated using drag functions from literature while, solid-phase kinetic energy fluctuation was characterized by varying the restitution coefficient values from 0.9 to 0.99. 2D computational modelling well predicted with experimental bed hydrodynamics such as pressure drops at different superficial velocities and minimum fluidization velocity, \( U_{mf} \) [30].

Hydrodynamic and thermal behaviour are studied to verify particles temperature distribution in pseudo-2D fluidized bed. Experimental results were validated with computational fluid dynamics and discrete element model (CFD-DEM) concerning heat transfer in the fluidized bed with heat production in the particle phase [31].

Eulerian–Granular multiphase model were used in CFD to predict gas-solid flow of fluidization in circulating fluidized bed. Prediction on main features of the complex gas–solids flow, coexistence of up-flow in the lower regions and downward flow in the upper regions at the wall for high gas velocity and solid mass flux were found. [32].

5. Conclusion
In conclusion, vast study of agro product drying in FBD has been proposed in the literature. These FBDs are unique in design and usually product specific. Among studied parameters were hydrodynamics, energy and exergy consumption apart from proposal of various mathematical models to predict drying characteristics. The design and operation of FBD were also studied by researchers using CFD for optimization of the system.
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