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STIRRER SPEED CONTROL OF A FLUIDIZED BED DRYER FOR BIOMASS PARTICLES USING PWM TECHNIQUE

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Abstract

This study an experimental work was carried out to investigate the effects of speed control of a stirrer motor on the drying quality of biomass particles (i.e. wet wheat particles). Pulse width modulation (PWM) control technique was employed at fluidized bed to find out the required drying time at different static bed heights. To meet these objectives, a stirred fluidized bed dryer (SFBD) was used while a conventional fluidized bed was utilized for comparison purposes. The experiments were conducted at the same operational conditions as in the real working environment where the inlet air temperature is 37°C, inlet air velocity is1.45 cm/s, diameter of wheat particle is 2mm, and its moisture content of particles is 12% for each value of static bed heights, which were 9,12, and 15 cm, respectively. SFBD has two levels straight paddle stirrer with two blades on each level. The ratio of stirrer diameter to the diameter of the fluidized column is 0.95. The controller of stirring speed was build based on the relative humidity inside the bed. The voltage and speed of the stirrer motor were represented at different duty cycle. The results showed that the enhancement in the total drying time was increased from 17.87% to 27.39% as the static bed height increases from 9 cm to 15 cm.
Keywords: Fluidized bed dryer, stirrer, PWM, biomass.

Introduction

In many engineering applications, the control at drying process is one of the most effective techniques in maximizing or minimizing the desired objective functions with prevailing constraints Dufour, (2006), and N. Malekjani *et al*. (2011).

In an early study, a model for fluidized-bed tea drying was utilized by Temple *et al*. (2000) for the development of a control strategy instead of manual control of the drying operation that limited because of the time taken to reach stability. The fluidization requirements and the drying kinetics for this model were established in experimental studies. The model was simulated in MATLAB. A monitor and control processing in a control strategy in data logging was developed by SLOGGER which consists of microprocessor-based satellite units connected into a network by RS485 serial communication wiring. Other found that to improve fluidization for solid materials that have cohesive characteristics which has some restrictions in the conventional fluidized bed.

So, agitation is required. Ambrosio and Taranto (2002) used a mechanical anchor shaped stirring paddle on the drying of fine crystalline organic acid particles, which have diameter 80 mm and density 1.443 g/cm^3. The influences of initial moisture content and temperature of the drying gas at the entrance of the bed were evaluated by the drying kinetics curves. The result showed that the dried particles produced had better fluidity, which could facilitate the continuity of industrial processing, handling, transport and storage.

In a continuous paddy drying process, the paddy moister content varies all times. So, the required drying process to paddy is to maximize the drying capacity of paddy dryer at minimum loss in head yield and minimum energy consumption without affecting the rice quality. Atthajariyakul and Leephakpreeda, (2006) proposed a systematic determination of optimal condition for fluidized bed paddy drying and adaptive fuzzy logic control in order to guarantee good quality and consume energy efficiently. The drying air temperature and the percent of recycle air were considered as controlled variables in the drying process. The results showed the effectiveness of the proposed methodology on the rice quality and energy consumption.

Later, Liang and Langrish, (2010) investigated controlling the temperature and the humidity in a stirrer fluidized bed, in order to crystallize skim milk powder from spray drying without caking the powders. The results depicted that the samples from the fluidized bed did not adsorb as much water as the original samples, suggesting that the samples from the fluidized bed were more stable than the original samples.

On the other hand, Bait *et al*. (2011) considered three types of agitator, a straight-blade, pitch-blade, and helical ribbon–type agitator to study the effect of the agitator type on the mixing characteristics and drying kinetics of micrometer-sized, cohesive particles at low air velocity. The study was carried out at different parameters, such as inlet air velocity, temperature, agitation speed and feed loading. The controller and indicator of agitation speed and temperature were installed on the control panel attached to the agitated fluidized bed dryer. The results showed the paving way for a more efficient spiral agitator of the helical ribbon type.

Due to make a combination between two dynamic models (linear–nonlinear) of dryer plant to solve the drying rate equation, to improve the dryer control of the rotary dryer plant process, Areed *et al*. (2012) utilized three different modern adaptive control techniques, (Direct PID controller, Fuzzy logic controller, and Neuro-Fuzzy controller). The results revealed that the Neuro-Fuzzy control is better and more versatile compared with the other controller techniques.

To maintain the quality of husk rice grains that have diameter 0.03 m, moisture 16 % and density solid 700 kg/m^3, the temperature must remain in a specific domain, i.e. control of the moisture content and temperature of husk rice grains on the fluidized bed are required. Thus, the mathematical model of the fluidize bed dryer was used by *et al*. Razzaghi, (2016) to shape the control algorithm. Three control methods were applied, including High-passed filter, Low-passed filter and Linear Quadratic Regulator controllers. Linear Quadratic Regulator was found more flexible in the control gain design and able to control the process in about 50 minutes.

To reduce a fluidized bed drying time and at the same time improve the homogeneity of the moisture of the wet and adhesive particles (with an initial diameter of about 580 mm) Hoffman *et al*. (2017) evaluated the positive effect of parameters, such as stirrer design, speed and size on the total drying time to find its optimum. It was found that the total drying time to reach the required moisture content of material was a 63% shorter drying time than for the curve with no stirrer.

Theoretical performance of energy-saving processes of biomass was represented by Junpeng Yi *et al*. (2019) to reduce the energy consumption of drying system, multistage drying, self-heat recuperation and process integration were introduced in the bioenergy plant. The purpose of this work is to reduce the total drying time during the drying process of the wet grain wheat particles in a SFBD using PWM control technique. Furthermore, to allow the online measurement and consequently controlling the moisture content in a SFBD, a single-input single-output feedback control system was designed. The drying experiments were conducted at various static bed heights.

Materials and Methods

Materials

The experiments were executed using adhesive biomass particles of grain wheat that have initial diameter of 2 mm, moisture 12 % and density 800 kg/m3 .

Fluidized bed drying unit

Schematic diagram of the test rig includes fluidized bed drying with controlling system consisting of air compressor was used to supply the air to the rig working section during the experiments. The outlet air flow from the compressor is controlled by using an adjustable one way valve fitted at the compressor drum outlet. The compressor delivers the air to the settling chamber (pressure tank), for damping the pressure fluctuations of delivery flow and to supply air at constant pressure. The air volumetric flow rate to the test rig was measured by orifice (designed to B.S.1042) with 9 mm diameter. U-tube manometer was used to measure the pressure drop across the orifice. The compressed air was fed to the fluidized bed through calming section at conical angle 75° with horizontal. The fluidized bed dryer was a cylindrical column shape made of glass enables to be monitored with an internal diameter of (4.6 cm) and 116 cm height. At the top of fluidized bed dryer, a top mounted D.C. gear motor of 300 Watt capacity was used to couple the stirrer type coaxial straight blade. A schematic drawing of the stirrer is shown in figure (1), and the schematic diagram of the test rig in figure (2). The ratio of its diameter to the diameter of the fluidized bed dryer is (0.95), Nielsen (1974).

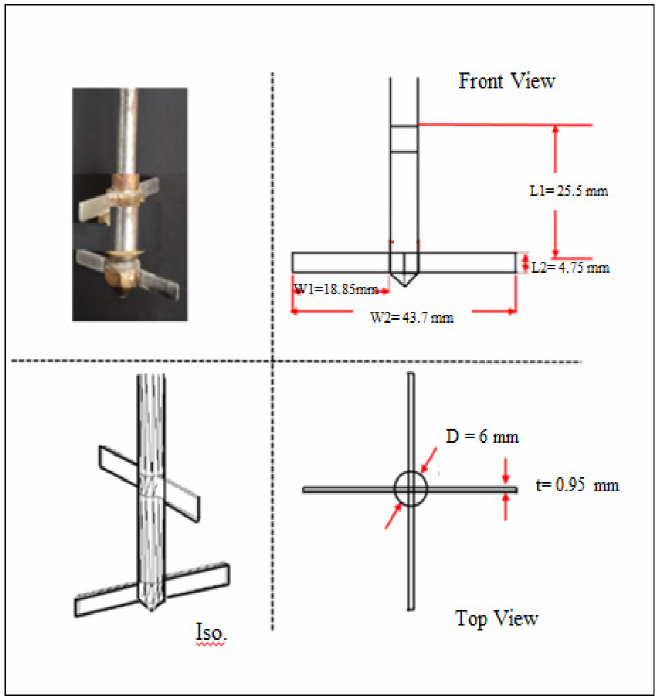


Fig. 1 : Dimension of stirrer (Units in mm)

The output unit is controlled automatically by changing the voltage using control system. At the bottom of the fluidized bed dryer, a distributor plate having (37) holes each with a diameter of 1mm, forming a total open area of 1.74% of fluidized bed. Over the distributor, a screen for a uniform distribution of air was used. To measure the pressure drop through the fluidized bed, two pressure taps were provided using analog reader sensor type (6CE6D/201518Y) for range 1 bar with accuracy of (0.26%). One of the pressure tap was located at the upstream of distributor, while the other was at a location of 77.5 cm downstream of distributor. Two digital signal sensors module (DHT11-AM2303 with accuracy ±0.1) were used for measuring the relative Humidity (RH) and temperature of the air at inlet and outlet of fluidized bed. The outlet sensor was positioned at a constant height of the fluidized bed (85 cm) above the distributor. Experiments were carried out for weighting the biomass particles ranging from (100, 150, and 200 g) with bed height (H) (9, 12, and 15 cm) and inlet air velocity of (1.45 cm/s) The initial moisture content of the sample was 10%, and the speed of the stirrer could be varied from (0-70 r.p.m).

Control System

The most desirable control of the output variables in stirred fluidized bed dryer is the product moisture content. Often, the moister content of the dried product can be inferred from the temperature and humidity of the exhaust air. So, DHT sensors were used to sense the relative humidity of the air at the inside and outside of the fluidize column. The difference between the relative humidity of air inside the fluidize column, ΔRHPV, represents the process variable, PV, that is important to maintain under the control of signal input and signal output of the present automatic feedback control, as shown in Figure (3). The desired value of the ΔRHPV is ΔRHSP (difference of relative humidity at set point), which was adjusted at 2%, and the difference between the relative humidity of ΔRHPV and ΔRHSP is represented by the error (e) magnitude. The controller of moisture content is integrated with the speed of stirring. The speed of stirrer is read by Hall sensor that is mounted on a D.C. motor, which actuated the stirrer. The motor is derived by D.C volt, which is supplied by two steps, as shown in figure (4). The first step is transforming the power supply from 220V A.C. to 110V A.C. by using transformer then converting the A.C. voltage into D.C. voltage by a full-wave bridge rectifier, and capacitor, which is used for reducing the ripple or voltage variations on the D.C. voltage. The second step is converting the D.C voltage from the rectifier to the armature windings of the motor through the switching element (MOSFET), diode (D1) and some filters (inductor and capacitor C1), the specification can be seen in table (1). In the present work, a field effect transistor (MOSFET) type N-channel was used in the designing a switch-mode power supply (SMPS), its location between motor and power supply voltage. The MOSFET was operated by control signal that supplied from the output digital pin (~9) of microcontroller Arduino (Mega), which is operated based on a frequency of 500 Hz and a voltage of 5V. This signal was treated by PWM, that was controlled by varying the duty cycle of the pulses. D.C. motor was controlled by programing Arduino that used to set the duty- cycle of a PWM pulse train suitable for the output desired speed. In the present work, a square wave duty cycle with PWM was used. The duty cycle is represented as follows:

$$Dutycycle\_(out\ level)= ON/(ON+OFF)*100\% \quad \ldots(1)$$

$$P\ (Watt)= V * I \quad \ldots(2)$$

Where,

P : Electrical Power Supply (Watt).

V : output voltage (Volt).

I : output current (Amper).

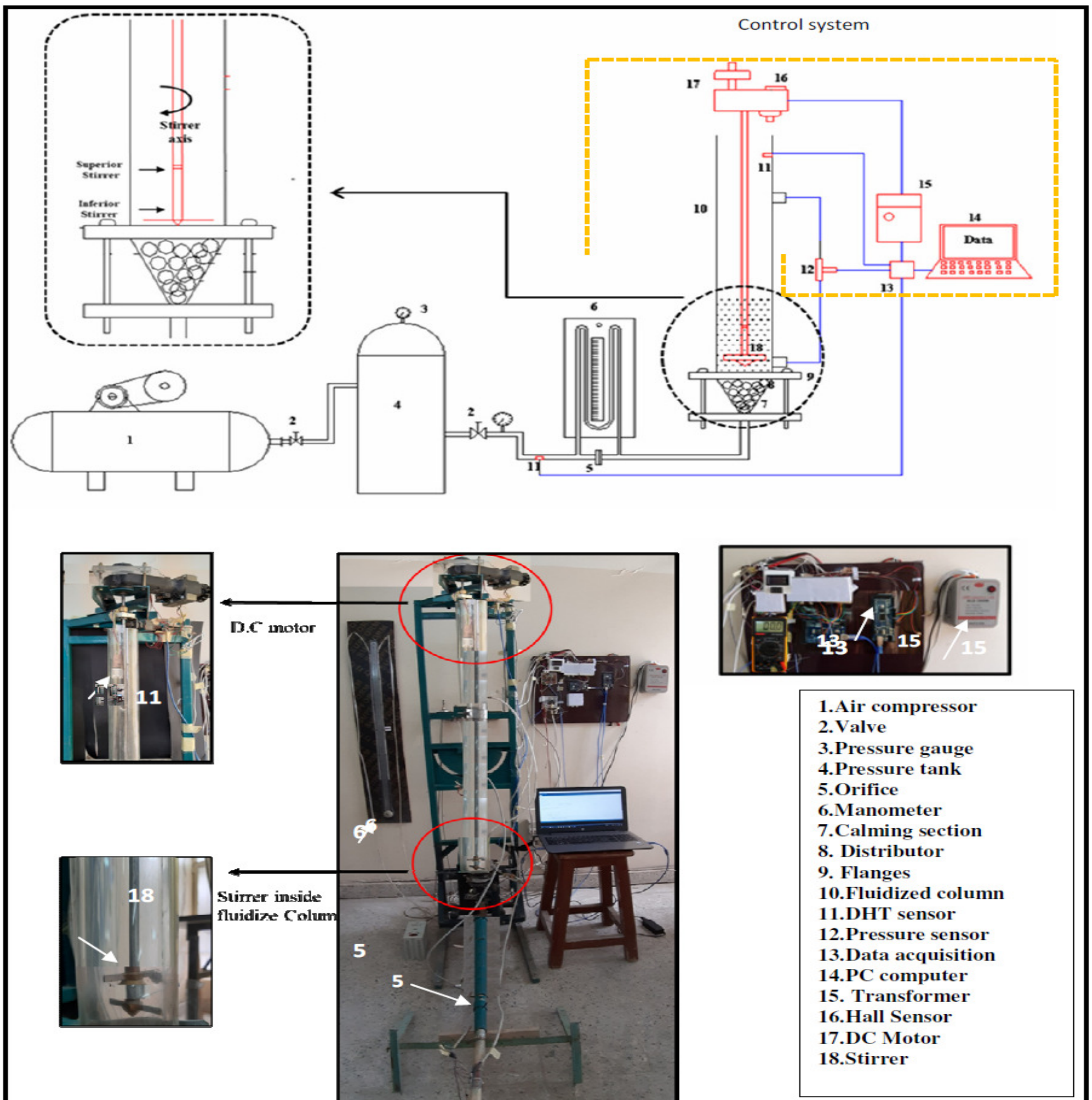


Fig. 2 : The schematic diagram and test rig of the stirred fluidized bed dryer

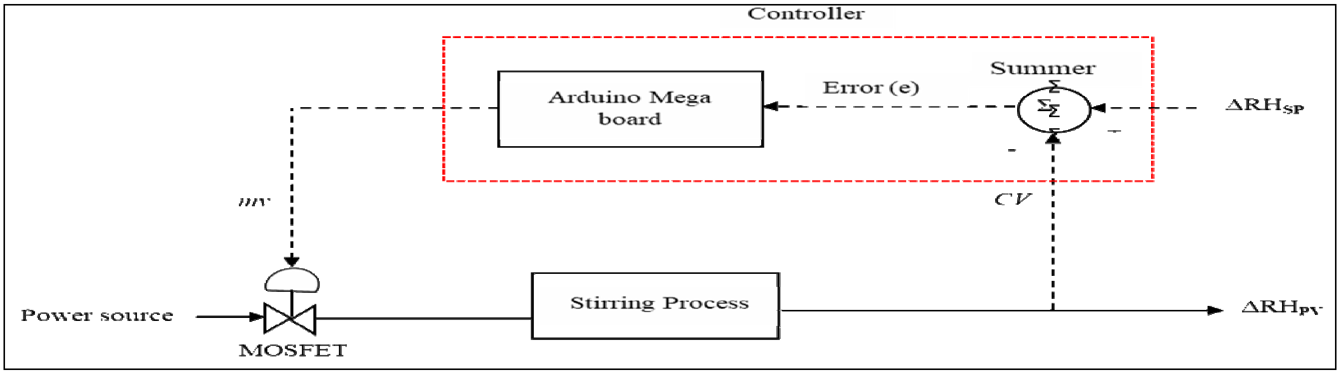


Fig. 3 : Feedback control loop schematic for the stirred fluidized bed dryer

Table 1 : Specification of the circuit

Type	Rate	Unit
Capacitor (Cr)	25	μF
MOSFET	Gate-source voltage =±30 Drain-source voltage=500 Min. gate-source voltage=2	V
Resistor	10	KΩ
Diode (D1)	Amper=1	A
	Voltage=700	V
Capacitor (C1)	10	μF

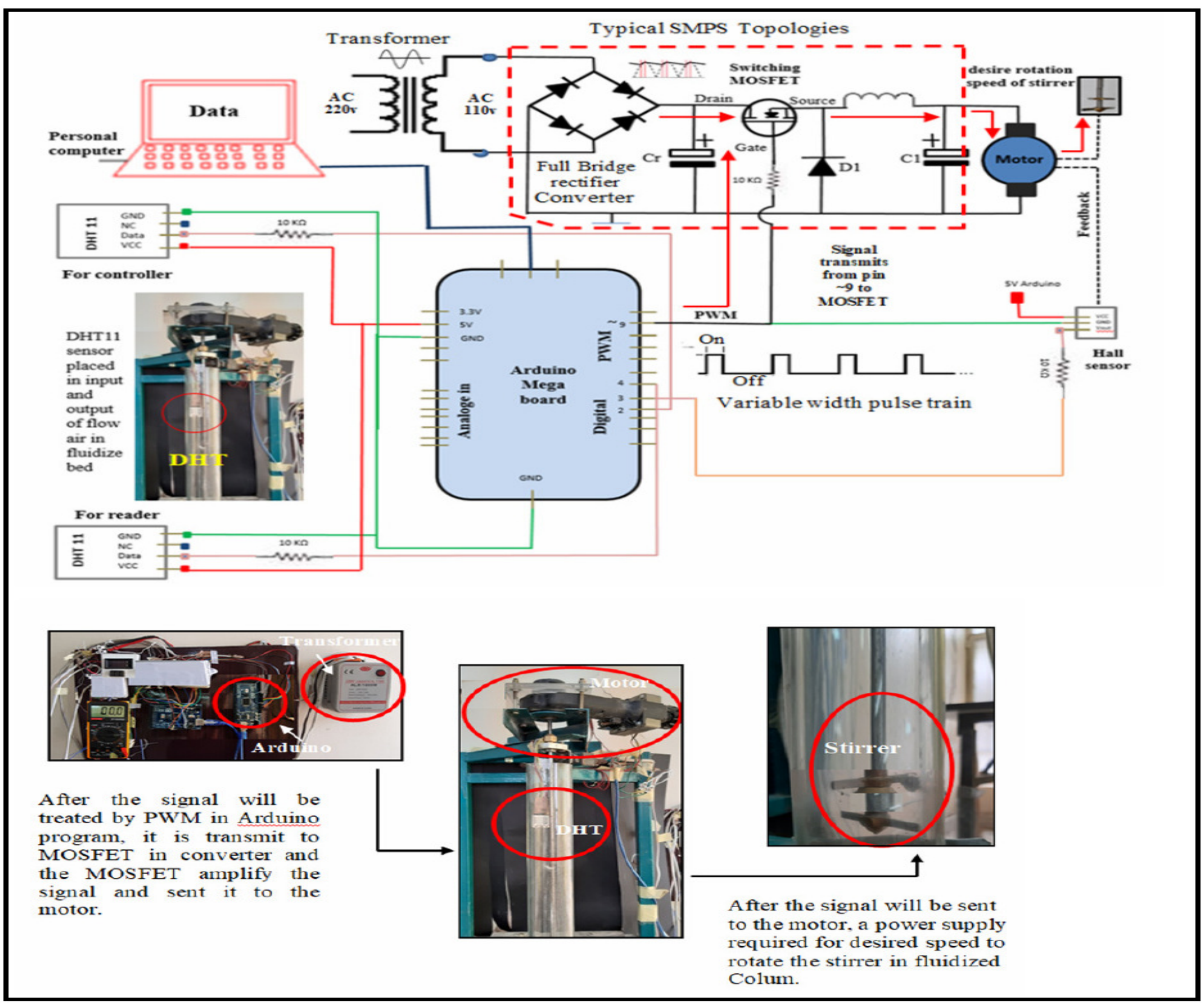


Fig. 4 : Controller Circuit Diagram for Stirred Fluidized Bed Dryer

Results and Discussion

The principle of the drying process is similar for each type of fluidized bed dryer, that is a conventional, and stirred. So, it will be mentioned once at section conventional fluidized bed dryer.

Conventional Fluidized Bed of Dryer

The drying process of the wet biomass for conventional fluidized bed dryer at a range of the bed height (9, 12, and 15) cm , as shown in figure (5. A upto 7. A) that have been done at constant parameters as 37°C temperature of air with velocity of 1.45 cm/s, a particle with diameter 2 mm and initial moisture content for biomass particle is 12%. In general, in each run test for changing value of static bed height, it is noted in figures that a value of moisture at point O is a lowest value then increased gradually to a point A, this most likely caused by placing a fresh wet particles into the fluidized bed dryer, hence the incoming dry air leads to evaporated the surface moisture on the wet particles and saturate a humidity sensor. This period is called sensor response and its increased with increasing static bed height. In the period A to D, the drying process can be divided into three parts: The first part is warmed –up period (A-B), as seen in figures (5 A) (6 A) (7 A), during this period, material start to heat from initial temperature to wet bulb temperature, i.e. the heat from the air is consumed to evaporate moisture from the surface of material, so the concentration of water decreases. While second one is the constant rate period (B-C), during this period the temperature of the air remains constant at wet bulb temperature of the air, i.e. the added heat is consumed by evaporation of the free water to the layer that is adjacent to the surface of biomass. Then, the critical moisture content (C), it is a transmission point between the constant rate period and the third period (falling rate period C-D), at point (C) the surface of material dries up and the drying rate start to decrease. Then, the temperature of the air is rising during falling period. If the drying continued for long enough of time the value approaches the equilibrium moister content (D) and which is impossible to dry material more than under actual condition. The Figures shows, also the effect of the bed height ,where decreases bed height decreases the time required to attain the equilibrium point. Thus, as the bed height decreases, the drying operation accelerates due to decreases in weight solid, and the drying time become shorter. As well, critical moisture content decreases while increased constant rate drying period with decreases in the bed height but it has no effect on the equilibrium moisture content. Tables (2 and 3) show moisture content of air and constant rate period during drying process.

Stirred Fluidized Bed Dryer

The effect of stirred on drying process of biomass for three different static bed heights (9, 12, and 15) cm can be shown in figures (5 B upto 7 B). The inlet air temperature, inlet air velocity, stirred speed, diameter of particle, and moisture content of particles were kept constant at 37°C, 1.45 cm, 70 rpm, 2 mm and 12 % . It has been observed in the figures that as static bed height is increased, the time period of response sensor is increased slightly for example: from 0 to 26 sec. for static bed height 9 cm and from 0 to 44 sec. for static bed height 15 cm. However, a compare of these curves with the curves of conventional during this period, it is observed that there is a positive effect of the stirrer on the adhesive layer where is significant reduction in the time to be 80 % for bed height 9 cm and 91 % for bed height 15 cm. In the period of drying process (i.e. A to D), as seen in figures, the drying time was found to increase from (2051) sec. to (2824) sec. as bed height is increased from 9 cm to 15 cm respectively. This may be explained by noting that higher height the larger mass loading of solid inventory, the larger the total moisture present in the fluidized bed. Because the air flow rate remained the same for all three bed height, the drying time was expected to increase with an increase in bed height. As compared this period with conventional it was found that the drying time is reduced from (17.87) % for bed height 9 cm to (27.39) % for bed height 15 cm. This is due to the existence of the stirrer that has move wet particles adhering in the fluidized bed, therefore the adhesive layer of particles are disturbed, causing more uniform flow of drying air through the layer. The result is a substantial reduction in drying time.

Effect of the Duty Cycle

To represent the PWM duty cycle of motor in FBD, figures (8 upto 10) show the varying in speed at duty cycles 9, 12 and 15 cm. Arduino (Mega) microcontroller and a A.C converter are employed in the D.C motor speed controller system circuit. Arduino microcontroller provides flexibility to the circuit by incorporating two switches on-off in order to increase and to decrease the duty cycle rate. The characteristics and performance of the motor speed controller system using microcontroller Arduino (Mega) was examined at duty cycle rate for 50%. It is obvious that the speed is zero during the period (O-A) of the duty-cycle because electric voltage supplied is not enough to rotate the motor. This is represented the time period of response DHT sensor to sense the relative humidity of the air at inside of the fluidized column, as shown in figures (5 to 7). At 50% duty cycle as seen in figures, the speed of the stirrer is increased during the period (A-B), which represent warm- up period. At this period there is rapidly response of Arduino (Mega) microcontroller to process relative humidity that resulting increased stirrer speed from 0 rpm to speed 60 rpm and the convertor output voltage is also increased nearly 24 V. The stirrer is operated at its desired speed 70 rpm during constant rate period (B-C). It is noted in this figure, that there is fluctuating in stirrer speed with a percentage 1.4% of desired stirrer speed. However as the surface of material dries up (i.e., point (C)) and the drying rate start to decrease, the stirrer speed and converter output voltage decreasing as the duty cycle decreases to 14%, (i.e., point(D)) during this period (C-D), falling period, the value of moisture content approaches the equilibrium moister content (D) and which is impossible to dry material more than under actual condition. So, the stirrer is stopped when the value for the difference relative humidity (between inlet and outlet) approaches the desired value 2%, which is represented error (e) magnitude.

Table 2 : Effect of static bed height on moisture content for conventional and stirred fluidized.

Bed height (cm)	Initial moisture content at point (A) m_i (g_{water}/kg_{air})	Critical moisture content at point (C) m_c (g_{water}/kg_{air})	Equilibrium moisture content at point (D) m_e (g_{water}/kg_{air})	Time at Point (B-C) (sec.)	Constant rate period $\frac{(m_iA - m_cc)}{t_{B-C}}$ (g_{water}/kg_{air} .sec)
9	12.9	6.3	0.77	520-1150	10.4761*10^ -3
12	15.9	8.7	0.78	990-1750	9.4736*10^ -3
15	17.9	9.3	0.79	1160-2100	9.1489*10^ -3

Table 3 : Effect of static bed height for stirred fluidized on the moisture content

Bed height (cm)	Initial moisture content at point (A) m_i (g_{water}/kg_{air})	Critical moisture content at point (C) m_c (g_{water}/kg_{air})	Equilibrium moisture content at point (D) m_e (g_{water}/kg_{air})	Time at Point (B-C) (sec.)	Constant rate period $\frac{(m_iA - m_cc)}{t_{B-C}}$ (g_{water}/kg_{air} .sec)
9	12	7.1	0.71	250-850	8.1666*10^ -3
12	15	9.1	0.73	360-1020	8.9393*10^ -3
15	17	10.3	0.75	450-1290	7.9761*10^ -3

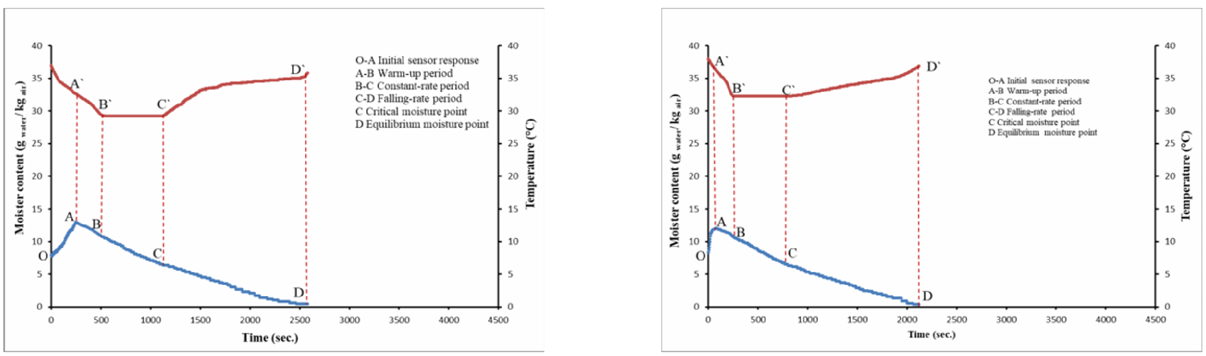
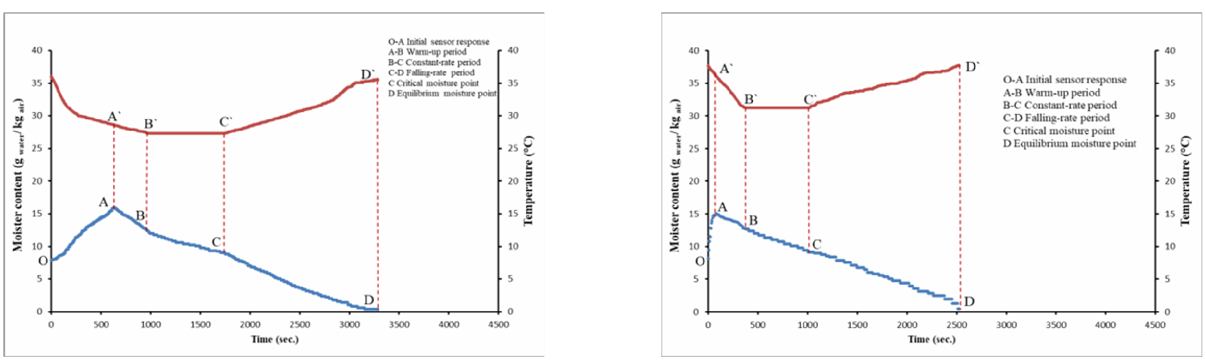
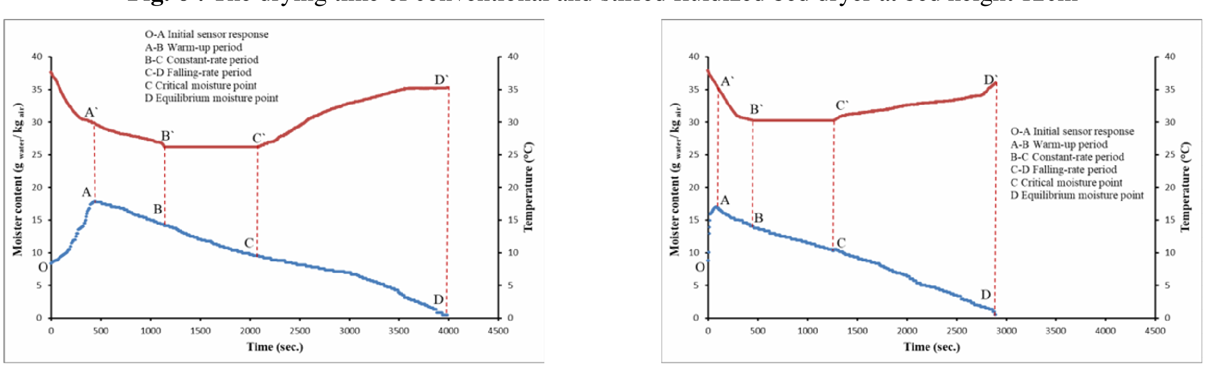


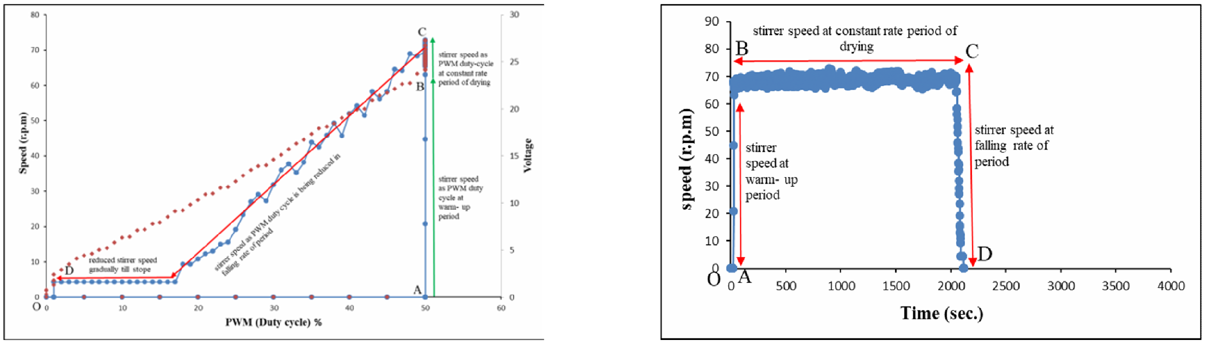
Fig. A : Conventional Fluidized Bed Dryer **Fig. B :** Stirred Fluidized Bed Dryer
Fig. 5: The drying time of conventional and stirred fluidized bed dryer at bed height 9cm



A. Conventional Fluidized Bed Dryer B. Stirred Fluidized Bed Dryer
Fig. 6 : The drying time of conventional and stirred fluidized bed dryer at bed height 12cm

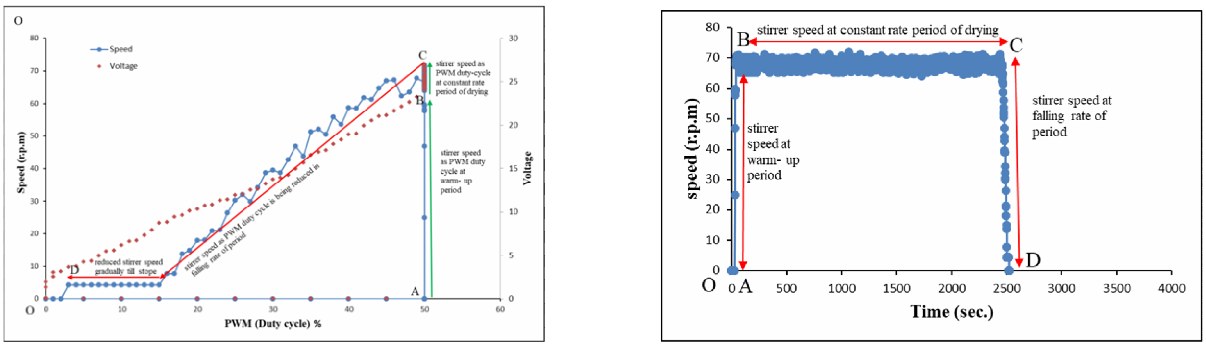


A. Conventional Fluidized Bed Dryer **B.** Stirred Fluidized Bed Dryer
Fig. 7: The drying time of conventional and stirred fluidized bed dryer at bed height 15cm



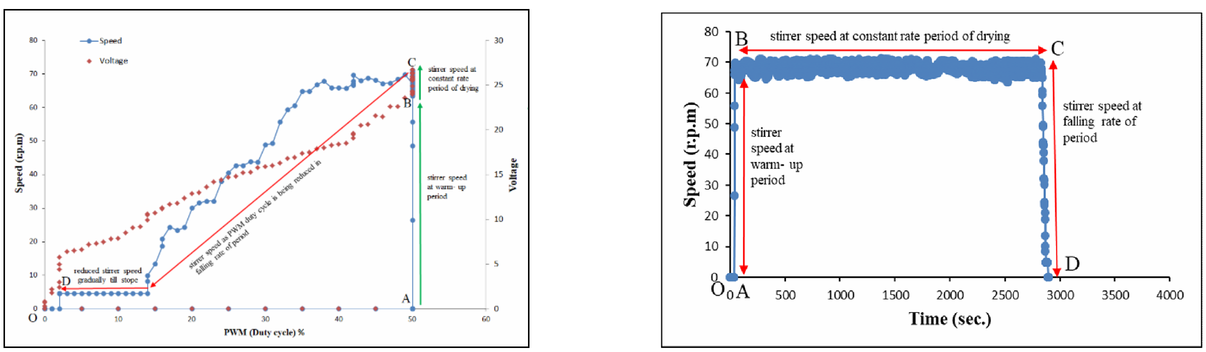
A. Stirrer speed and voltage at different duty cycle **B.** Variation stirrer speed with time

Fig. 8 : Motor speed performance during drying process at bed height 9cm.



A. Stirrer speed and voltage at different duty cycle **B.** variation stirrer speed with time

Fig. 9 : Motor speed performance during drying process at bed height 12 cm.



A. Stirrer speed and voltage at different duty cycle **B.** variation stirrer speed with time

Fig. 10 : Motor speed performance during drying process at bed height 15 cm.

Conclusion

The obtained results of this study showed that:

1. The stirred motor speed controller system inside FBD using PWM technique was efficiently represented. The relationship between the duty cycle and the converter output voltage has been investigated for controlling the speed of the DC motor to rotate the stirrer flexibly in accordance with the response of the DHT sensor.
2. A positive effect for the stirrer on the time period (O-A) of moisture response sensor for biomass was got, where a significant reduction in the drying time was obtained to be 17.8% for bed height 9 cm and 27.3% for bed height 15 cm as compared to the conventional fluidized bed.
3. Increasing the bed height from 9 cm to 15 cm has no effect on the equilibrium moisture content in both drying techniques (either stirred fluidized bed or conventional fluidized bed).
4. Reduction in the total drying time for the stirred fluidized bed by 12.3% for the bed height 9 cm and 24.3% for the bed height 15 cm as compared with the conventional fluidized bed.
5. Constant rate period was decreased with increasing the bed height. Also, it generally decreases with increasing the initial moisture concentration. However, this period for stirred fluidized bed in this study is shorter than the period in the conventional fluidized bed.

References

Ambrosio, M.C.B. and Toranto, O.P. (2002). The drying of solids in a modified fluidized bed, Brazilian Journal of Chemical Engineering, 355-358.

Areed, F.F.G.; El-Kasassy, M.S. and Mahmoud, Kh. A. (2012). Design of Neuro-Fuzzy Controller for a Rotary Dryer, International Journal of Computer Applications, 0975– 8887.

Atthajariyakul, S. and Leephakpreeda, T. (2006). Fluidized bed paddy drying in optimal conditions via adaptive fuzzy logic control, Journal of Food Engineering, Elsevier, 104–114.

Bait, R.G.; Pawar, S.B.; Banerjee, A.N.; Mujumdar, A.S. and Thorat, B.N. (2011). Mechanically agitated fluidized bed drying of cohesive particles at low air velocity, Drying Technology, 808-818.

Dufour, P. (2006). Control engineering in drying technology: Review and trends. Drying Technology, 24: 889–904.

Hoffman, P.; Penicka, M. and Fort, I. (2017). Effect of fluidized bed stirring on drying process of adhesive particles, Chem, Biochem Eng., 1-10.

Junpeng, Yi.; Xin, Li.; Jian, He. *and* Xu Duan (2019). Drying efficiency and product quality of biomass drying: a review, Journal Drying Technology/ Taylor & Francis Group.

Liang, Z. and Langrish, T. (2010). Control of crystallization and caking of skim milk powder in fluidized beds, A preliminary study, Dairy Journal, 345-353.

Malekjani, N.; Jafari, S.M.; Mirzaee, H. and Rahmati, M.H. (2011). "Design and Application of a Novel Dehumidifying System for a Fluidized Bed Dryer for the Drying of Canola Seeds", International Journal on Advanced Science, Engineering and Information Technology, 1(1): 47-49.

Nielsen, R.H. (1974). Particle mixing and circulation in gas fluidized beds of flour and starch, Retrospective Thesis and Dissertations, 6357.

Razzaghi, E.; Zarafshan, P. and Akandi, S.R.K. (2016). Dynamics Modeling and control of a fluidized bed dryer, International Conference on Control , Instrumentation, and Automation (ICCIA), 27-28 January 2016 , Qazvin Islamic Azad University, Qazvin, Iran.

Temple, S.J.; Tambala, S.T. and Van Boxtel, A.J.B. (1999). Monitoring and control of fluid – bed drying of tea, Control Engineering Practice 8(2000): 165-173.