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Vibration Effect on Particle Bed Aerodynamic Behavior and Thermal Performance of Black Tea in Fluidized Bed Dryers

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ABSTRACT

Black tea sample was dried by a vibro-fluidized bed dryer to find its aerodynamic behavior and thermal performance during drying. The drying experiments were conducted at three different inlet air temperatures of 100, 115 and 130°C and fluidization condition at five vibration intensity levels of 0 (no vibration), 0.063, 0.189, 0.395 and 1.184. The results showed that bed channeling and defluidization problems were decreased in vibration condition. The vibration system decreased the requirement of minimum fluidization velocity of tea particles and this velocity reduced by increasing the vibration intensity. In the experiments, the maximum evaporation rate (13×10^{-3} kg_v m^{-2} s^{-1}) was at the vibration intensity of 1.184 and inlet air temperature of 130°C. Also the minimum specific energy consumption (4953.785 kJ kg_v^{-1}) was observed at 1.184 vibration intensity and 100°C inlet air temperature condition. Based on lower minimum fluidization velocity and specific energy consumption, the vibration intensity of 1.184 and inlet air temperature of 100°C were recommended for drying black tea particles.

Keywords: Evaporation rate, Minimum fluidization, Specific energy consumption, Vibration intensity.

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INTRODUCTION

In commercial drying of agricultural products heated air is used. Mechanical systems, especially those using hot air for rapid drying of natural materials high in moisture content are becoming increasingly popular. One new efficient drying technique is the fluidized bed drying system [1]. Fluidization is a process by which solid particles act as a fluid and thoroughly contact with a gas [2]. Fluidized bed dryer with vibration system was reported as a method for improving fluidization quality of moist and sticky materials [3]. Also, the bed uniformity was reported as a result of using vibration in fluid beds, because of preventing bubbles in the bed [4]. Moreover, vibration helps to overcome interparticle forces [5].

Mori *et al.* (1990) reported that C-group particles cannot be fluidized properly without vibration, even with gas velocities up to 4.5 cm s^{-1} [6]. They improved fluidization of these particles along with vibration so that particles with sizes of 1 and 0.4 μm completely fluidized with vibration system at gas velocities of 1.8 and 4.5 cm s^{-1}, respectively. Moreno *et al.* (2000) studied drying behavior of sawdust particles in an experimental batch vibro-fluidized bed dryer [7]. They found that by using vibration in the fluidized dryer, air velocity for drying of sawdust reduced significantly. Also, by this method, drying of sawdust particles with moisture contents greater than 2 kg kg^{-1} dry basis (66.7% wb) was possible without defluidization.

Temple and Van Boxtel (1999) found that higher air velocities were required for drying tea by industrial fluidized bed dryer at

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higher moisture content [8]. They determined the fluidization characteristics of black tea particles for dryer design, operation and control. A sequence reading of air velocity and pressure drop across the bed and bedplate was recorded until the tea particles started to move. In this research, minimum fluidization velocity of tea samples with the average geometric mean diameter of 0.84 mm and moisture content of 8 to 10% (wb) for four types of bedplate was found to be between 0.35 and 1.2 m s^{-1}.

Fluidized bed dryer is a new drying method with some advantages. They are reported as suitable mixing and easy transportation of particles and uniform and intensive rate of heat and mass transfer between gas and particles [9]. In spite of these advantages, bed channeling and defluidization are the problems of using this method, especially for the materials with high moisture content. Fluidized bed dryer method can be used to improve the drying process of tea particles. Because of its high moisture content, vibration system can be recommended to increase tea fluidization characteristics. The objectives of this research were to study the aerodynamic behaviors and drying thermal performance of tea particles by the vibro-fluidized bed dryer.

MATERIALS AND METHODS

The experiments were conducted using a laboratory vibro-fluidized bed dryer (Figure 1) which was designed and fabricated by Sadeghi *et al.* [10]. To vibrate the bedplate, a mechanical system was used to change the amplitude and frequency. It had an automatic control system to regulate inlet air flow and temperature. During drying experiments, the inlet and outlet air temperature and relative humidity and bed particle temperature were measured and recorded. For fluidization and drying process, inlet air was provided by a centrifugal air blower. The blower's rotational speed was changed by a frequency inverter (7300- L2.2, Topvert, Taiwan) to supply different air velocities.

To study aerodynamic behaviors of tea particles, the fluidization experiments were

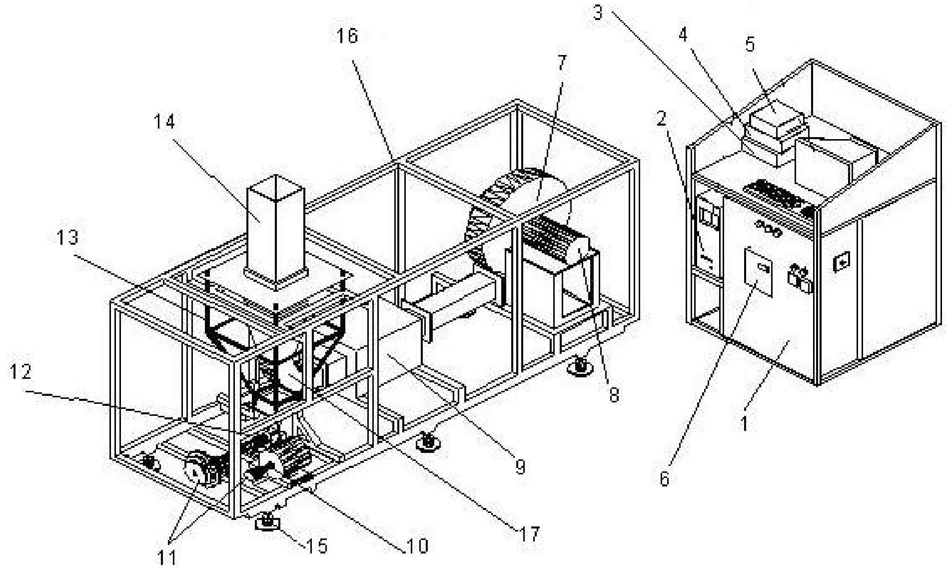

Figure 1. Schematic of experimental vibro-fluidized bed dryer: (1) Electrical unit; (2) Computer; (3) Power supply; (4) Main circuit and sensors amplifier circuit; (5) Relays circuit; (6) Inverter; (7) Blower; (8) Blower motor; (9) Electrical heater; (10) Vibration motor; (11) Pulleys; (12) Slider crank; (13) Vibratory arms; (14) Fluidization chamber; (15) Dampers; (16) Frame, (17) Elbow.

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carried out and fluidization characteristic curves were obtained at different conditions. In this curve, pressure drop across the bed with respect to the air velocity was drawn. Pressure drop was measured by a differential manometer (505-P1, Testo, Germany) with the accuracy of ±1 mm H_2O. A vane anemometer (A-M-4202, Lutron, Taiwan) with the accuracy of ± 0.1 m s^{-1} was used to measure the air velocity.

The fluidization experiments were conducted in two cases: conventional and vibrated beds. In the case of using vibration, the amplitudes of 1 and 3 mm and frequencies of 4 and 10 Hz were used. In vibrated beds the dimensionless ratio of Λ which is the ratio of vibrational acceleration to gravitational acceleration (Equation (1)) was used to indicate the intensity of vibration [7]:

$$\Lambda = A\omega^2/g = A(2\pi f)^2/g \quad (1)$$

Where, A is the amplitude (m), f is the frequency (Hz) and ω is the angular velocity (rad s^{-1}). Based on the selected amplitudes and frequencies for the vibrated bed, the vibration intensities of 0 (no vibration), 0.063, 0.189, 0.395 and 1.184 were selected for the experiments.

For drying experiments, the tea samples were taken from shoots of tea bushes of Colon 100 by harvesting two leaves and the apical bud from Lahijan orchards (Guilan province, Iran). The Orthodox method was used to process the tea samples. After withering, rolling and fermentation processes, the samples were dried under different treatments by the dryer. The drying experiments were conducted in full fluidization. In other words, the air velocity was more than the minimum fluidization velocity so that complete mixing existed in the bed particles. Table 1 shows the characteristics and operational conditions of the experiments. All experiments were carried out in three replicates. Before starting the experiments, the drying chamber was filled up to 0.08 m with a dummy sample. Then after connecting the computer

Table 1. Particles characteristics and operational conditions used in drying experiments

Ambient temperature (°C)	30±2
Ambient humidity (%)	34±2
Particles type	Orthodox tea
Bed height (m)	0.08
Inlet air temperature (°C)	100, 115 and 130
Initial moisture content (% wb)	60
Final moisture content (% wb)	Approximately 3
Vibration intensity	0.063, 0.189, 0.395 and 1.184

Table 2. Effect of vibration intensity and inlet air temperature on thermal performance of tea drying.

Temperature (°C)	Λ^a	Drying time (s)	Air velocity (m s^{-1})	Final MC^b (% w.b.)	POR^c 10^{-3}(kg_d m^{-2} s^{-1})	ER^d 10^{-3}(kg_v m^{-2} s^{-1})	SEC^e (kJ kg_v^{-1})
100	0.063	2940	0.75	3.5	3.880	5.408	11106.490
	0.189	2250	0.73	3.4	5.087	7.688	8184.634
	0.395	2150	0.70	3.6	5.305	7.413	7581.998
	1.184	1585	0.62	3.4	7.221	10.031	4953.785
115	0.063	2070	0.72	3.3	5.510	7.680	9140.216
	0.189	2112	0.71	3.4	5.419	7.491	9267.924
	0.395	1663	0.70	3.5	6.906	9.537	7163.457
	1.184	1440	0.61	3.3	7.948	11.013	5434.243
130	0.063	1653	0.71	3.1	6.877	9.642	8454.101
	0.189	1587	0.69	3.0	7.187	10.018	8041.590
	0.395	1410	0.65	3.3	8.062	11.303	7033.959
	1.184	1226	0.60	3.1	9.272	13.000	5310.682

[a] Vibration intensity; [b] Moisture content; [c] The product output rate; [d] The evaporation rate, [e] The specific energy consumption..

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and settings the temperature, the heater elements were turned on to supply the required temperature. The dryer remained on for about 20 minutes to balance heat and then the experiment was started. The ending of the drying process was distinguished by the exhaust air relative humidity. When the exhaust air relative humidity reached 15%, the operation finished. Under this condition the tea particles' moisture content was about 3% wb, which is suitable for storage and transferring [8]. Table 2 shows the final moisture content of the dried samples.

From drying curves, the drying periods were determined at different conditions. Then the product output rate (POR) in $kg_d\ m^{-2}.s^{-1}$, the evaporation rate (ER) in $kg_v\ m^{-2}.s^{-1}$ and the specific energy consumption (SEC) in $kJ\ kg_v^{-1}$ were calculated to evaluate the thermal performance of drying operation. The *POR* and *ER* were calculated by dividing dried product mass and evaporated moisture mass by drying chamber area and drying time, respectively, and the *SEC* was calculated as follow [11]:

$$SEC = \frac{t \times Q \times (C_{Pa} + C_{Pv} \times H_a)(T_{in} - T_{am})}{V_h \times M_v} \qquad (2)$$

Where, t is the drying time (s), Q is the air flow rate ($m^3\ s^{-1}$), C_{Pa} and C_{Pv} are the specific heat capacity ($kJ\ kg^{-1}.°C^{-1}$) of dry air and vapor at drying conditions, respectively, H_a is the absolute humidity of the air ($kg_{vapor}\ kg_{dry\ air}^{-1}$), T_{in} and T_{am} are the inlet air and ambient temperatures (°C), respectively, V_h is the specific volume of the air ($m^3\ kg_{dry\ air}^{-1}$) and M_v is the evaporated moisture mass (kg).

RESULTS AND DISCUSSION

Bed Aerodynamic Behavior

Figure 2 shows bed material pressure drop (ΔP) *versus* air velocity (u_g) for the conventional bed (Λ=0) at two conditions of increasing u_g up to fluidization status and then decreasing u_g down to zero. By increasing the u_g, the amount of ΔP increased linearly up to 335 Pa, which was the minimum fluidization point, and then decreased drastically. One of the important points in Figure 2 is the hysteresis phenomenon which is the discrepancy between pressure drops at the two conditions. This is explained by the fact that the bed porosity differs in increasing and then decreasing the air velocity. For beds with a good quality of fluidization, the pressure drop does not change or its reduction is small after the minimum fluidization point [2]. Meanwhile, in

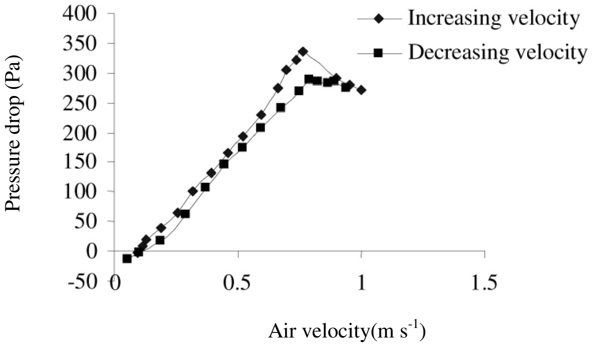


Figure 2. Bed pressure drop across tea particles for the conventional bed (Λ= 0).

Figure 2 a major decrease in pressure drop was observed because of bed channeling.

In the vibrated bed, the fluidization characteristics curves were obtained for different vibration intensities (0.063, 0.189, 0.395 and 1.184). (Figures 3a and b) show typical curves for Λ= 0.063 and Λ= 1.184, respectively. By increasing the u_g, the ΔP increased linearly up to the minimum fluidization point and then remained almost constant. This trend of varying ΔP with respect to u_g shows better fluidization quality in the vibrated bed in comparison with the conventional bed, which caused no defluidization and channeling in the bed. Also, there is no hysteresis phenomenon in the vibrated bed. At low air flow rate (Figure 3a) there is a little discrepancy between pressure drops at two conditions of varying u_g. This result shows a more stable status in the case of using vibration at velocities higher than 0.4 m s^{-1}, because of higher uniformity in bed porosity variation.

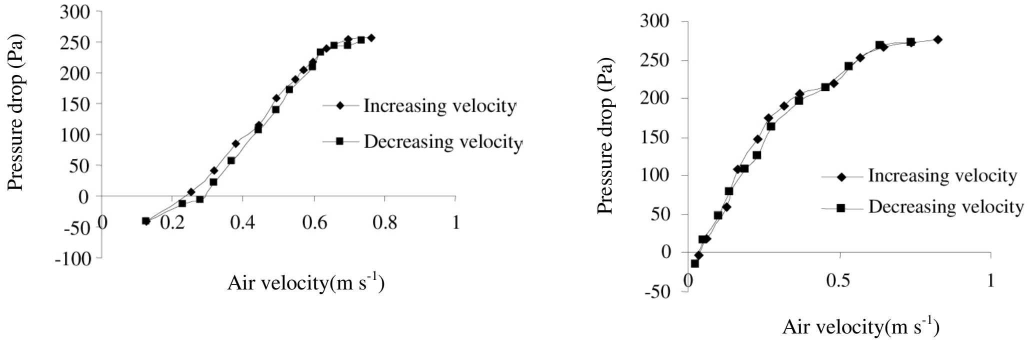
The convexity of fluidization curve was increased by increasing vibration intensity (Figure 3b). At A= 3 mm (vibration intensities of 0.189 and 1.184), the characteristic curve consists of two plateau parts also observed in other studies [12]. These two parts are called lower plateau and upper plateau. Therefore, it can be concluded that the vibration parameters and specially the vibration amplitude affect the fluidization characteristic curve.

Figures 2 to 3 also show that vibration helps transition from the fixed bed to the fluidized bed. For the conventional bed (Figure 2), the minimum fluidization velocity is 0.76 m s^{-1}. The velocity for vibration intensities of 0.063 and 0.395 (A= 1 mm) are 0.64 and 0.57 m s^{-1}, respectively (the onset of the plateau part of the curve). For vibration intensities of 0.189 and 1.184 (A= 3 mm), the minimum fluidization velocities are 0.54 and 0.5 m s^{-1}, respectively (the onset of the upper plateau part of the curve). This shows that the vibration parameters and specially the vibration amplitude affect the minimum fluidization velocity. Other studies also confirm these results [7, 12]. For comparison, variations of bed pressure drop across tea particles with air velocity (only increasing) are shown in Figure 4 for all vibration intensities.

In the vibrated bed, due to the periodic compression and expansion of the bed, a negative pressure drop was observed for low velocities, which is called the pumping effect. This negative pressure drop depends on the vibration amplitude and frequency [12].

Thermal Performance

Table 2 shows the effect of vibration intensity and inlet air temperature on



(a)

(b)

Figure 3. Bed pressure drop across tea particles for the vibrated bed (a): (Λ= 0.063) and (b): (Λ= 1.184)

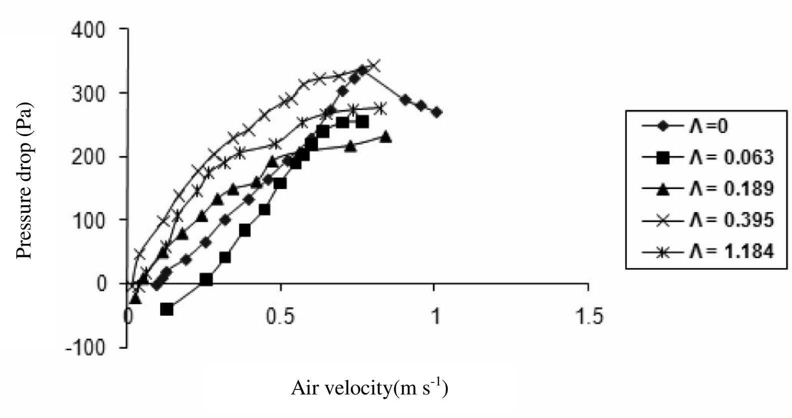


Figure 4. Bed pressure drop across tea particles while increasing air velocity for various vibration intensities.

thermal performance variables. The values of the air velocity used for drying of the black tea when the vibration was used are also given. At all temperatures, the *POR* and the *ER* increased and the *SEC* decreased by increasing Λ. In fact, when Λ increased, the particles' contact area increased which in turn improved the rate of heat and mass transfer from air to the particles through increasing convective heat and mass transfer coefficients. Also, the results indicate that at constant Λ, the *POR*, the *ER* and *SEC* improved by increasing T_{in}. In this regard, there is only an exception for the *SEC* at the vibration intensity of 1.184 and temperature of 100°C, which is the least specific energy consumption in all the experiments. Although at the temperature of 130°C and Λ= 1.184 the drying time reduced in comparison with the temperature of 100°C and Λ= 1.184, increasing temperature itself had more influence than shorter drying time. To the contrary of this exception, in other cases the effect of drying time on *SEC* improvement has been more than T_{in} effect.

Conclusions

The vibration system can be used to overcome problems such as bed channeling and defluidization during fluidization of tea particles.

The vibration system decreased the requirement of minimum fluidization velocity of tea particles and this velocity reduced by increasing the vibration intensity.

The hysteresis phenomenon was not observed in fluidization characteristic of the vibro-fluidized bed dryer.

Based on lower minimum fluidization velocity and specific energy consumption, the vibration intensity of 1.184 and inlet air temperature of 100°C were recommended for drying black tea particles.

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بررسی تاثیر ارتعاش در رفتار آیرودینامیکی بستر ذرات و عملکرد گرمایی چای سیاه در خشک‌کن بستر سیال

م. صادقی و م. ه. خوش تقاضا

چکیده

در این تحقیق، رفتار آیرودینامیک بستر ذرات چای سیاه و عملکرد حرارتی خشک‌کردن این ذرات در یک خشک‌کن بستر شناور ارتعاشی آزمایشگاهی مورد بررسی قرار گرفت. آزمایش‌های خشک‌کردن در سه سطح دمای هوای ورودی ۱۰۰، ۱۱۵ و ۱۳۰°C و شرایط شناورسازی در پنج سطح شدت ارتعاش صفر (بدون ارتعاش)، ۰/۰۶۳، ۰/۱۸۹، ۰/۳۹۵ و ۱/۱۸۴ صورت پذیرفت. نتایج نشان داد که اعمال ارتعاش مشکلات کانالیزه شدن بستر و خارج شدن آن از حالت شناوری را کاهش داد. سیستم ارتعاش، سرعت حداقل سیال‌سازی مورد نیاز ذرات چای را کاهش داده و این سرعت با افزایش شدت ارتعاش کاهش می‌یابد. بیشترین مقدار نرخ تبخیر (۱۳×۱۰$^{-۳}$ $\mathrm{kg_V/m^۲.s}$) مربوط به وضعیت بستر شناور ارتعاشی با شدت ارتعاش ۱/۱۸۴ و دمای هوای ورودی ۱۳۰°C بود. همچنین کمترین مقدار مصرف ویژهٔ انرژی (۴۹۵۳/۷۸۵ $\mathrm{kJ/kg_V}$) مربوط به وضعیت بستر شناور ارتعاشی با شدت ارتعاش ۱/۱۸۴ و دمای هوای ورودی ۱۰۰°C به‌دست آمد. بنابراین می‌توان نتیجه گرفت که عملکرد حرارتی خشک‌کردن چای با افزایش شدت ارتعاش و دمای هوای ورودی خشک کن، بهبود می‌یابد. بر اساس کمترین

سرعت حداقل سیال‌سازی و مقدار مصرف ویژهٔ انرژی، شدت ارتعاش ۱/۱۸۴ و دمای هوای ورودی ۱۰۰°C برای خشک کردن ذرات چای سیاه توصیه می‌شوند.

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