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Use of an Impinging Stream Dryer for Agricultural Waste: Case Study with Soy Residue

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Abstract

Generally, agricultural wastes must be dried prior to being transported, processed or stored. These wastes are normally very high in surface moisture. A drying method that can rapidly remove this type of moisture is thus desired. Impinging stream dryer (ISD) is a unique class of dryers that has proved to be an excellent alternative to flash dryer for removing surface moisture of particulate materials due to collision of streams and of particles in the dryer. Although an impinging stream dryer prototype was built and tested [1] in the past, the dryer had many limitations and was tested only with a model material, not a real agricultural waste. The objective of this study was thus to modify the existing ISD to allow it to be used with a real agricultural waste, i.e., soy residue. In addition, the effects of various operating and geometric parameters, i.e., inlet air temperature, inlet air velocity, feed rate of drying particles and spacing between the two opposed inlets, on the overall performance of an ISD in terms of its volumetric water evaporation rate and volumetric heat transfer coefficient were investigated.

Keywords: Hot Air Drying / Soy Residue / Surface Water / Unhindered Drying Rate Period / Volumetric Heat Transfer Coefficient / Volumetric Water Evaporation Rate

1. Introduction

The principle of an impinging stream dryer is the flow of two or more streams of gas, at least one containing wet particles or liquid droplets, on the same axis but in the opposite directions. The two streams impinge at the midpoint of their flow paths in the area, which is called an impingement zone. A result of collision between the opposed streams leads to excellent conditions for intensifying heat, mass and momentum transfer. This is due to the high shear force and turbulence in the impingement zone. The particles also have more chances to exchange heat, mass and momentum with the streams as they penetrate through the impingement plane into the opposite streams and do so repeatedly until they are discharged from the system. The two above-mentioned properties of an impinging stream dryer make this type of dryer require less volume than other types of dryers for the same drying load.

The aims of this study were to modify the existing impinging stream dryer [1] to make it more suitable for use with real agricultural waste (soy residue) as well as to investigate the effects of various operating parameters on the overall performance of the modified impinging stream dryer using hot air as the drying medium.

2. Modification of impinging stream dryer

As mentioned earlier, the operational problems of the existing impinging stream dryer the existing impinging stream dryer when being used with real agricultural waste were the accumulation of the feed in the inlet pipes as well as the difficulty in controlling the feed rate of the waste into the system. These problems were mainly due to the inherent sticky characteristics of fresh soy residue (which was used as the tested agricultural waste); this problem also led to much error of the calculated performance of the dryer.

In this study, modifications of the existing impinging stream dryer were performed by enlarging the two inlet pipes and changing the residue feeding system. The inlet pipes were enlarged by increasing the diameter of the pipes from 0.025 m to 0.038 m in order to allow easier feeding of the soy residue.

The next step was the modification of the feeding system. In the case of the original screw feeder, accumulation of soy residue would occur at the head of the screw due to the inherent sticky characteristics of soy residue as noted earlier. A belt feeder was therefore adopted instead of the original screw feeder. The feeding system consists of a hopper with a belt conveyor attached beneath the hopper. The belt conveyor acted as a puller to pull out the residue from the hopper by its own friction. The feed rate was controlled by the speed of the belt conveyor and by the opening height of the sliding gate at the bottom of the hopper. Comparison of the original and modified feeding system is illustrated in Figure 1. After finishing the modification the belt feeder was tested with prepared soy residue at different set values. It was found that the variation of the soy residue feed rate was in the range of 2-3%.

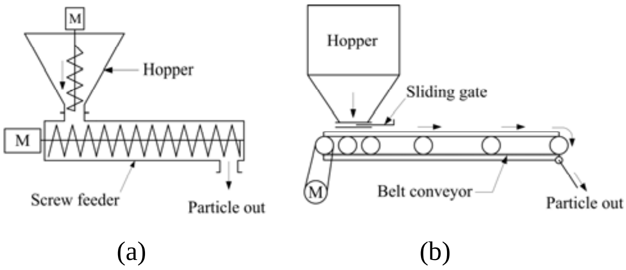

Figure 1. Material feeding systems (a) original version and (b) modified version.

3. Materials and Methods

3.1 Materials

Soy residue was used as the test material in this study. The initial moisture content of soy residue was about 84% (w.b.). After receiving soy residue from a soy milk factory, the fresh soy residue was mechanically dewatered by a hydraulic press in order to reduce some excess water from the residue. Removing excess water also helped to make the residue be able to flow more freely in the drying system as well. After dewatering the residue was sieved with the screen size of 2×2 mm. Then, it was kept in a tightly sealed plastic container at 4ºC for 24 hours until its moisture content was uniform throughout; the moisture content of the residue at this point was around 75% (w.b.).

3.2 Experimental Set-up

A schematic diagram of the impinging stream drying system is shown in Figure 2. The system consists of a drying chamber made of stainless steel type 304 with an inner diameter of 0.25 m and a volume of 0.014 m^3. The dryer is insulated with 2 inches fiber glass insulator. The inlet pipes of the drying chamber are 0.038 m in diameter. Adaptors are connected to the inlet pipes inside the drying chamber and they allow the adjustment of the impinging distances of either 0.05 or 0.13 m. A high pressure blower, which could deliver the maximum pressure of 4000 mmH_2O and air volumetric flow rate of 8.4 m^3/min at a fan speed of 1440 rpm, was used to generate the air stream, which was then forced to pass through a heater rated at 15 kW. The heater was controlled by a proportional-integral-differential (PID) controller with an accuracy of ±1°C. The temperatures at different positions were continuously recorded by a data logger. The inlet air dry-bulb and wet-bulb temperatures, T_{di} and T_{wi}, respectively, were measured at points A and C as shown in Figure 1 by type T thermocouples connected to the data logger. The wet-bulb and dry-bulb temperatures of the outlet air, T_{do} and T_{wo}, respectively, were measured and continuously recorded by a moisture sensor (Vaisala, model HM70, Finland) at point B. The heater was controlled by the temperature measured at points C and D. Air velocity was adjusted by two globe valves that are connected to the inlet pipes and a pitot tube (Testo, model 445, Germany) was used to measure the air velocity at points A and C with an accuracy of ± 0.2 m/s. The feed rate of soy residue was controlled by controlling the speed of a belt conveyor, which received the residue from a hopper situated just above the conveyor; the speed of the conveyor was controlled by regulating the power supply to a motor that drove the conveyor.

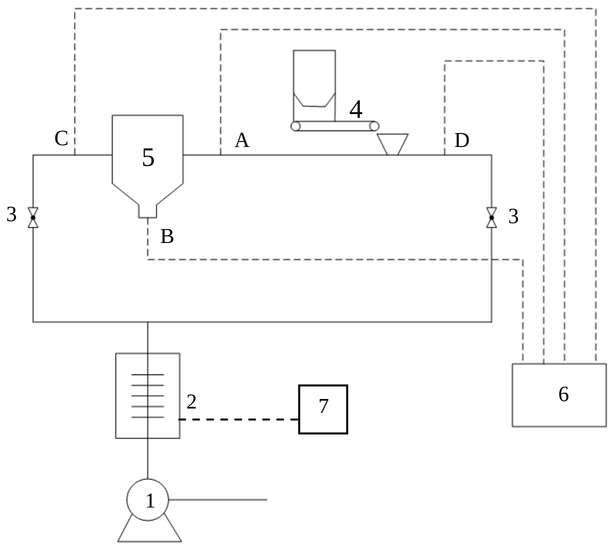

Figure 2. A schematic diagram of the impinging stream dryer and associated units.
1) High pressure roots blower; 2) Electric fins heater; 3) Globe valves; 4) Hopper and belt conveyor feeder; 5) Drying chamber; 6) Data logger; 7) PID controller

3.3 Experimental Procedures

First, the high pressure blower and the heater were switched on. After the temperature reached the setting value, feeding of soy residue into the system was started via the use of the belt conveyor feeder. The feed rate was controlled by adjusting the speed of the motor installed at the end of the belt conveyor. After feeding the residue into the system for approximately 7 minutes, which was more or less the time that the system needed to adjust itself to steady state, collection of the dried sample at the dryer outlet began. The steady state condition was considered by checking if the dry-bulb and wet-bulb temperatures at the inlet and outlet of the drying chamber were constant. The dried soy residue was collected at 7, 8 and 9 minutes. The collected sample was then dried in a hot air oven at 105ºC for 16 h [2] for determining its moisture content.

3.4 Calculation of Volumetric Water Evaporation Rate and Volumetric Heat Transfer Coefficient

The performance of the impinging stream dryer was evaluated in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient, which are defined by the following equations:

Volumetric water evaporation rate (N_v) [3]:

$$N_v = \frac{W_{dp}(X_i - X_o)}{V_r} \quad (1)$$

Volumetric heat transfer coefficient (h_v) [3,4]:

$$h_v = \frac{W_{dp}\lambda(X_i - X_o)}{V_r \Delta T_{lm}} \quad (2)$$

where ΔT_{lm} is the logarithmic mean temperature difference of the inlet and outlet air:

$$\Delta T_{lm} = \frac{(T_d - T_w)_o - (T_d - T_w)_i}{\ln \frac{(T_d - T_w)_o}{(T_d - T_w)_i}} \quad (3)$$

Subscripts *o* and *i* designate outlet and inlet of the dryer, respectively. X is moisture content of particles (d.b.), W_{dp} is mass flow rate of dry particles, V_r is the volume of the dryer, which also includes the right side of the inlet pipe where the dry-bulb and wet-bulb temperatures of the inlet air were measured.

The dry-bulb temperature at the inlet of the dryer, T_{di} was calculated from the average of the dry-bulb temperature measured at points A and C (see Figure 3.).

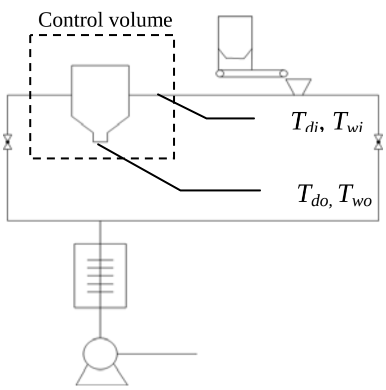

Figure 3. The temperature measurement points and control volume

3.5 Determination of System Steady State Condition

The dry-bulb and wet-bulb temperatures at the outlet and inlet of the drying chamber (see Figure 2) were measured in order to find the period before the system getting into steady state. Finally, it was found that at all drying conditions the dry-bulb and wet-bulb temperatures at the inlet and outlet decreased and approached constant values at not more than 7 minutes after feeding the particles. The first collection of the sample was then performed after operating the system for 7 minutes.

4. Results and Discussion

4.1 Effects of Operating Parameters on Volumetric Water Evaporation Rate

The impinging stream drying system was able to operate at the maximum temperature of 150ºC, air velocity of 20 m/s, impinging distance between 0.05-0.13 m and feed rate between 10-20 kg/h.

Figure 4 shows the plots of the volumetric water evaporation rate versus the inlet air temperature (130 and 150ºC) with the feed rate of particles (10 and 20 $kg_{dry\ solid}$/h) and impinging distance (5 and 13 cm) as parameters. It is seen that (see also Table 1) an increase in the inlet air temperature led to an increase in the amount of water removed. This is due to the larger difference between the air temperature and the particle surface temperature, which is the driving force for heat (and mass transfer), especially in the unhindered rate drying period.

The effect of particle flow rate on the volumetric water evaporation rate is depicted in Figure 4. An increase in the particle flow rate at each drying temperature led to an increase in the volumetric water evaporation rate. This is probably due to the fact that the capacity of the dryer exceeded the load required to evaporate water from the particles entering the system; the more particles entering the system, the higher volumetric water evaporation rate. This indicated that the choking point, as mentioned by Kitron et al. [5], was not yet reached and, in fact, higher particle flow rate could still be used.

The effect of the distance between the inlet pipes on the volumetric water evaporation rate is shown in Figure 4. In the case of the particle flow rate of 10 kg/h, the effect of impinging distance on the volumetric water evaporation rate was not significant. On the other hand, when the particle flow rate was adjusted to 20 kg/h, longer impinging distance led to higher rate of volumetric water evaporation rate. This is probably due to the larger effective volume for transport processes [6], which is not the actual volume of the drying chamber but is a certain volume located between the faces of the inlet pipes. The larger effective volume led to the longer residence time of the particles in the dryer, which means that particles could spend more time in the active drying zone.

Table 1. Statistical analysis of volumetric water evaporation rate and volumetric heat transfer coefficient

Run no.	Condition			Volumetric water evaporation rate	Volumetric heat transfer coefficient
	T (°C)	W_p ($kg_{dry\ solid}$/h)	L (cm)	(kg_{water}/m^3h)	(W/m^3K)
1	130	10	5	120.88±7.04^{ab}	2149.32±104.06^{ab}
2	130	10	13	112.14±6.80^{a}	1863.80±119.30^{a}
3	130	20	5	163.58±13.94^{d}	3461.44±296.35^{c}
4	130	20	13	217.21±10.71^{f}	4506.60±89.16^{d}
5	150	10	5	140.42±5.35^{c}	2252.60±54.63^{b}
6	150	10	13	134.42±10.11^{bc}	2026.83±153.07^{ab}
7	150	20	5	181.74±3.29^{e}	3400.67±32.27^{c}
8	150	20	13	233.62±10.74^{g}	4272.08±142.46^{d}

Different letters in the same column indicate that the values are significantly different ($p < 0.05$)

4.2 Effects of Operating Conditions on Volumetric Heat Transfer Coefficient

The effect of inlet air temperature on the volumetric heat transfer coefficient is shown in Figure 5 and Table 1. It can be seen that the volumetric heat transfer coefficient changed insignificantly with the inlet air temperature. This is because a larger difference between the air temperature and the particle surface temperature also led to larger logarithmic mean temperature difference (ΔT_{lm}). At the same time the moisture removal rate also increased. When combining these two effects together, according to equation (2), the effect of inlet air temperature on the volumetric heat transfer coefficient was negligible.

As is seen in Figure 5 and Table 1 the volumetric heat transfer coefficient increased with an increase in the particle flow rate at a fixed inlet air temperature. This confirmed that the capacity of the dryer exceeded the load required to evaporate water from the particles entering the system (as can be seen from the results of the volumetric water evaporation rate). In this case, the capacity of the dryer was high enough to remove all the surface water of particles, despite the increased moisture entering the system.

For the effect of the impinging distance on the volumetric heat transfer coefficient, this value depended on the feed rate of particles. At a particle flow rate of 10 kg/h, as shown in Figure 5, the effect of the impinging distance on the volumetric heat transfer coefficient was not insignificant. When the particle flow rate increased to 20 kg/h, longer impinging distance led to higher water evaporation rate this is due to the effect of lower loading ratio [7], which enhanced the effects of higher shear rate and turbulence intensity in the impingement zone. The higher accumulated energy within the particles at 150 °C might also help enhancing this effect and thus higher values of the volumetric heat transfer coefficient, however.

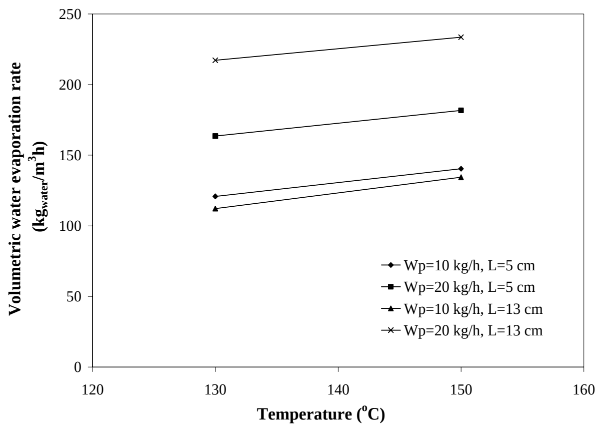

Figure 4. Effects of operating parameters on the volumetric water evaporation rate

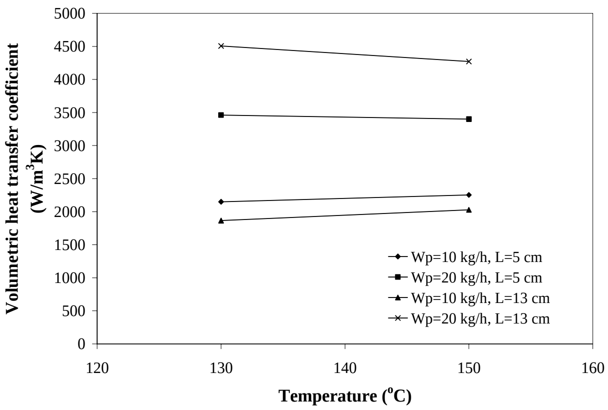

Figure 5. Effects of operating parameters on the volumetric heat transfer coefficient

5. Conclusion

In this work, the effects of the inlet air temperature, feed rate of drying particles and length between the two opposed inlet pipes of the drying chamber on the performance of the dryer in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient were investigated. At all drying conditions the volumetric water evaporation rate increased as the inlet air temperature increased; the effect of the inlet air temperature on the volumetric heat transfer coefficient was negligible, however. The volumetric water evaporation rate and the volumetric heat transfer coefficient were found to increase with the particle flow rate at each inlet air temperature. The effect of the impinging distance on the volumetric water evaporation rate and volumetric heat transfer coefficient depended on the values of the particle flow rate. The maximum volumetric water evaporation rate was found to be around 300 kg_{water}/m^3h while the volumetric heat transfer coefficient was about 5750 W/m^3K. The modified impinging stream dryer prototype could operate well under these conditions: maximum air velocity of 20 m/s, maximum inlet air temperature of 150^{o}C, and maximum particle flow rate of 20 kg/h, without the problem of clogging of the feeding particles.

Symbols

d = diameter of inlet pipe, m
h_v = volumetric heat transfer coefficient, W/m^3K
L = distance between faces of inlet pipes, m
N_v = volumetric water evaporation rate, kg_{water}/m^3h
T_{di} = dry-bulb temperature at the inlet of dryer, ^oC
T_{do} = dry-bulb temperature at the outlet of dryer, ^oC
T_{wi} = wet-bulb temperature at the inlet of dryer, ^oC
T_{wo} = wet-bulb temperature at the outlet of dryer, ^oC
V_r = volume of dryer including inlet pipe, 0.0177 m^3
W_{dp} = mass flow rate of dry particles, kg/h
W_p = mass flow rate of particles, kg/h
X_o = particle outlet moisture content, kg/kg (d.b.)
X_i = particle inlet moisture content, kg/kg (d.b.)
ΔT_{lm} = logarithmic mean temperature difference, K

Greek Symbol

λ = latent heat of vaporization, kJ/kg

Subscripts

w = wet-bulb temperature
d = dry-bulb temperature
i = inlet of the dryer
o = outlet of the dryer

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