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Kwanchai Choicharoen [a]; Sakamon Devahastin [b]; Somchart Soponronnarit [a]
[a] School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok, Thailand [b] Department of Food Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

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Performance and Energy Consumption of an Impinging Stream Dryer for High-Moisture Particulate Materials

Kwanchai Choicharoen,[1] Sakamon Devahastin,[2] and Somchart Soponronnarit[1]
[1]*School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangkok, Thailand*
[2]*Department of Food Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand*

Impinging stream dryers (ISDs) are a novel alternative to flash dryers for high-moisture particulate materials. However, studies on hydrodynamics and heat/mass transfer as well as drying characteristics of an ISD are still limited or incomplete. The effects of various geometric and operating parameters of an ISD on its performance, in particular, are not conclusive. In addition, ISD was tested mainly with model materials that do not represent the real challenge of higher-moisture materials, which tend to be sticky in nature. In this study, modifications were made to an existing coaxial two-impinging stream dryer of Sathapornprasath et al.[1] to make it more suitable for high-moisture particulate materials. This newly modified dryer was then evaluated for its performance in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient. Soy residue (okara), which is a by-product of a soymilk production process, was used as a test material. Particle mean residence time was also evaluated and the results were used to support and explain the performance data of the dryer. Finally, the specific energy consumption of the dryer was assessed at various geometric and operating conditions. The maximum volumetric water evaporation rate was found to be around 520 kg_{water}/m^3h and the maximum volumetric heat transfer coefficient was around 4,500 W/m^3K for the mean particle residence time of approximately 0.97–1.74 s. In terms of the specific energy consumption the lowest specific energy consumption was found to be around 5.6 MJ/kg_{water}.

Keywords Flash drying; Okara; Residence time; Soy residue; Specific energy consumption; Volumetric heat transfer coefficient; Volumetric water evaporation rate

INTRODUCTION

Impinging stream dryers (ISDs) are a novel alternative to flash dryers for high-moisture particulate materials. Due to an intensive collision of impinging (or opposed) streams, a region that offers intensive exchange of heat, mass, and momentum is created. Rapid removal of surface moisture from a wet material is therefore feasible. ISDs are also said to have advantages over other types of dryers in terms of its smaller footprint and high robustness due to lack of moving parts.[2–4] Despite its potential, studies on hydrodynamics and heat/mass transfer as well as drying characteristics of an ISD are still limited or incomplete. The effects of various geometric and operating parameters of an ISD on its performance are also not conclusive because different investigators have observed and reported different trends of the results.

Kitron and Tamir[5] studied the performance of a coaxial gas–solid two-impinging stream dryer in terms of its hydrodynamics, particle residence time distribution, and drying heat transfer behavior. It was found that the holdup of particles at a fixed air flow rate increased with an increase in the particle flow rate, whereas the heat transfer coefficient increased with an increase in the particle flow rate but was independent of the volume of the dryer as well as the volume of the inlet pipes. In fact, it was found that the effective volume for the transport processes was not the actual volume of the dryer but was a certain volume located between the faces of the inlet pipes within the drying chamber.

Hu and Liu[6] studied the flow and drying characteristics of vertical and semicyclic combined impinging stream dryers. It was found that both the inlet air temperature and initial moisture content of particles played important roles in water removal from the particles and the loading ratio (ratio between the particle mass flow rate and the air mass flow rate) significantly affected the particle residence time. A higher initial moisture content led to an increased amount of water that could be removed from the drying particles. The water removal rate decreased as the loading ratio increased. This is because an increase in the loading ratio led to a decrease in the particle residence time. However, when the loading ratio increased to a certain value, the particle residence time did not change further.

Huai et al.[7] studied the drying characteristics of a semicircular impinging stream dryer. The multiphase flow characteristics as well as the heat and mass transfer within the dryer were numerically investigated. The effects of various

Correspondence: Sakamon Devahastin, Department of Food Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha u-tid Road, Bangkok 10140, Thailand; E-mail: sakamon.dev@kmutt.ac.th

parameters—i.e., inlet air temperature, loading ratio, and initial moisture content of particles—on the performance of the dryer were investigated. It was found that a higher inlet air temperature could greatly enhance the drying rate. Water removal rate was found to increase with a decrease in the loading ratio and an increase in the particle initial moisture content. The numerically predicted results agreed well with the experimental results.

Sathapornprasath et al.[1] designed and fabricated a prototype of a coaxial two-impinging stream dryer and evaluated its performance using resin as a test material. It was found that an increase in the inlet air temperature led to an increase in the volumetric water evaporation rate at all drying conditions. The change of the volumetric heat transfer coefficient was, however, negligible with the change of the inlet air temperature. The volumetric water evaporation rate and the volumetric heat transfer coefficient increased with the inlet air velocity and particle flow rate at each inlet air temperature, whereas the effect of the impinging distance on the volumetric water evaporation rate and volumetric heat transfer coefficient depended on the values of the inlet air velocity and particle flow rate. The maximum volumetric water evaporation rate was found to be around 110 kg_{water}/m^3h, whereas the maximum volumetric heat transfer coefficient was around 880 W/m^3K. In this study, a great difficulty was noted in controlling the inlet air flow rate and particle flow rate. Although the prototype dryer could operate well with a model material (resin) that had an initial moisture content of even 81–85% (d.b.), it could still not be used with the real agricultural residue (soy residue) due to the difficulty in controlling its feed rate and due to clogging of the residue in the system.[8]

Jantaka[9] modified the impinging stream dryer of Sathapornprasath et al.[1] by increasing the diameter of the inlet pipes to allow easier flow of a drying material within the system. The screw-conveyor-based particle feeding system was also replaced by a belt-conveyor-based feeding system; the change has proved very effective because the problem of particle stickiness in the screw-conveyor-based system could be eliminated. After the modification, experiments were performed using soy residue as a test material. The system was found to be much easier to control. Regarding the performance test results it was found that an increase in the inlet air temperature led to an increase in the volumetric water evaporation rate, whereas the volumetric heat transfer coefficient did not change with the inlet air temperature. The effect of the impinging distance on the volumetric water evaporation rate and the volumetric heat transfer coefficient depended on the particle feed rate. The maximum volumetric water evaporation rate was found to be around 300 kg_{water}/m^3h, whereas the maximum volumetric heat transfer coefficient was around 5750 W/m^3K. The higher value compared with the results of Sathapornprasath et al.[1] was due to the ability to better control the feeding of the drying material, which led to significant enhancement of heat and mass transfer within the system. Another cause of the differences was the differences in the measuring positions of the inlet air temperature. In the case of Jantaka,[9] the wet-bulb and dry-bulb temperatures of the inlet air were, respectively, measured at points D and A as shown in Fig. 1. On the other hand, the wet-bulb and dry-bulb temperatures of the inlet air were measured at points B and A, respectively, in the case of Sathapornprasath et al.[1] The effects of the different positions of temperature measurement were thus significant. However, there still existed a difficulty in controlling the inlet air temperature. This is because there was only one heater used to supply heat to the drying air that entered the drying chamber on both sides.

The aim of the present study was to further modify the impinging stream dryer designs of Sathapornprasath et al.[1]

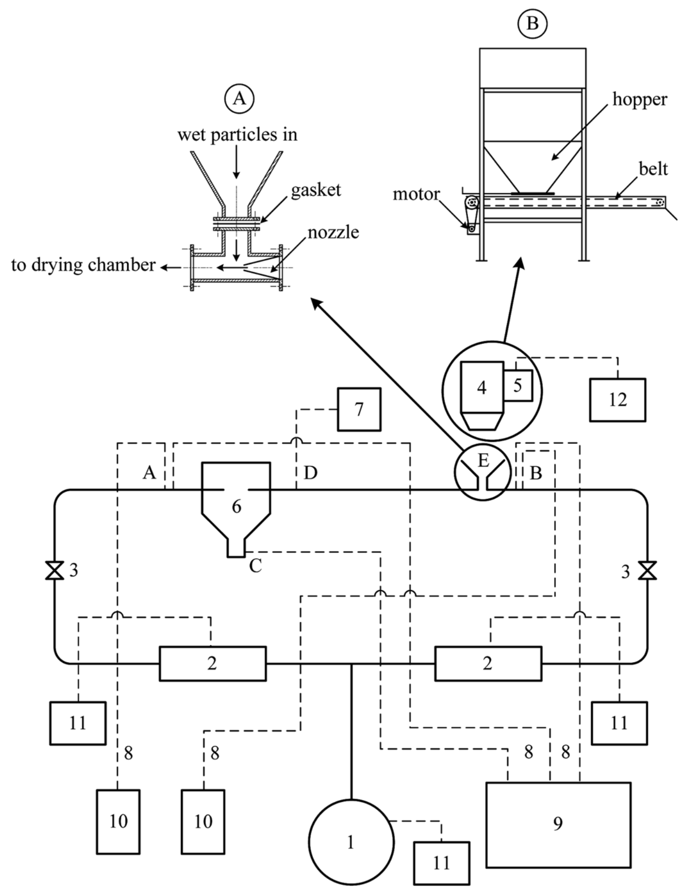

FIG. 1. A schematic diagram of the impinging stream dryer and associated units. (1) high-pressure blower; (2) electric heaters; (3) globe valves; (4) belt conveyor feeder; (5) DC motor; (6) drying chamber; (7) velocity measurement probe; (8) thermocouples; (9) temperature data logger; (10) PID controllers; (11) kilowatt-hour meters; (12) voltage regulator. A = detailed sketch of nozzle-type inlet; B = detailed sketch of belt conveyor feeder.

and Jantaka[9] by adding another electric heater and placing the two heaters symmetrically on either side of the drying chamber. The temperature-control system was also separated in order to be able to independently control the inlet air temperature of each inlet stream. In addition, the material inlet to the feeding pipe was modified; the originally used orifice-type inlet was changed to a nozzle-type inlet (see insert A in Fig. 1). Experiments were then performed to investigate the effects of various parameters of the new ISD—i.e., inlet air temperatures of 130, 150, and 170°C; impinging distances of 5, 9, and 13 cm; inlet air velocities of 20 and 27 m/s; and particle flow rates of 10 and 20 $kg_{drysolid}/h$—on the performance of the dryer in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient. Soy residue (okara) was used as a test material. The mean residence time of model particles (resin) at various combinations of geometric and operating conditions was investigated to confirm the effects of the various parameters on the performance data of the dryer. Finally, the specific energy consumption of the ISD was also evaluated.

EXPERIMENTAL SETUP, MATERIALS AND METHODS

Experimental Setup

A schematic diagram of a newly modified impinging stream dryer is shown in Fig. 1. The dryer consists of a stainless steel drying chamber of 0.25 m in diameter and has a volume of 0.018 m^3, insulated with 2-inch fiberglass. The inlet pipes of the drying chamber are 0.038 m in diameter. The impinging distance between the faces of the inlet pipes can be adjusted at three levels; i.e., 5, 9, and 13 cm. A high-pressure blower rated at 5.5 kW (Heywel, model RSS-80, Taiwan), which is able to generate a maximum pressure of 4000 mmH_2O and a volumetric flow rate of 8.4 m^3/min at a fan speed of 1440 rpm, was used to supply the air to the system. The air velocity was adjusted by two globe valves and measured by a Pitot tube (Testo, model 445, Lenzkirch, Germany) at points A and D (see Fig. 1) with an accuracy of ± 0.2 m/s. The particle flow rate was adjusted through the use of a voltage regulator, which was used to control the speed of an DC electric motor rated at 117 W, which in turn was used to drive the belt conveyor feeder (see insert B in Fig. 1). The inlet air temperature was controlled by two electric heaters, each rated at 6 kW, which were controlled by two proportional-integral-differential (PID) controllers (Omron, model E5CN-RMTC-500, Tokyo, Japan) with an accuracy of ± 1°C; the inlet air temperature was recorded continuously by K-type thermocouples connected to a data logger (Yokogawa, model $\mu R100$, Tokyo, Japan). The wet-bulb temperature of the inlet air to the dryer as well as the wet-bulb and dry-bulb temperatures of the outlet air from the dryer were measured and recorded by a moisture sensor (Vaisala, model HM70, Helsinki, Finland). The wet-bulb and dry-bulb temperatures of the inlet air to the dryer, T_{wi} and T_{di}, were measured at point B (see Fig. 1). The wet-bulb and dry-bulb temperatures of the outlet air from the dryer, T_{wo} and T_{do}, were measured at point C (see Fig. 1).

In this study, the energy consumption of the high-pressure blower and electric heaters was measured directly using a kilowatt-hour meter with an accuracy of ± 0.1 kWh.

Materials

Soy residue or okara, which is a by-product of the soymilk production process, was used as a test material. At its initial moisture content of around 82–85% (w.b.) or 4.5–5.6 kg/kg (d.b.) the residue appeared like clay because it contained an excessive amount of water. The soy residue was therefore mechanically dehydrated by a hydraulic press (Sakaya, model 4104, Bangkok, Thailand) to remove its excess moisture. The partially dehydrated residue was then sieved with a screen with openings of 2×2 mm. The moisture content of the residue after sieving was about 72–75% (w.b.) or 2.6–3.1 kg/kg (d.b.).

Instead of using the soy residue, the particle mean residence time was determined in this study using resin. The resin was used because it did not stick to the walls of the feed pipe or the drying chamber and hence would not cause large errors in the experimental results. The resin used in this study had a mean diameter of 0.5 mm and a bulk density of 1250 kg/m^3.

Methods

First, the impinging distance between the faces of the inlet pipes within the drying chamber was adjusted to a predetermined value. The high-pressure blower was then switched on. When the inlet air velocity reached the desired value the heaters were turned on. After the temperature in the system reached the desired value, feeding of soy residue into the system started. A steady-state condition was considered by checking whether the wet-bulb and dry-bulb temperatures at both the inlet and outlet of the drying chamber were constant. The dried soy residue was collected at the dryer outlet and was dried in a hot air oven at 105°C for 16 h to determine its moisture content.

Calculation of Volumetric Water Evaporation Rate and Volumetric Heat Transfer Coefficient

Generally, the performance of a dryer could be evaluated in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient, which are calculated as:[1,10]

- Volumetric water evaporation rate (N_v):

$$N_v = \frac{W_p(X_i - X_o)}{V_r} \tag{1}$$

- Volumetric heat transfer coefficient (h_v):

$$h_v = \frac{W_p(X_i - X_o)\lambda}{V_r \Delta T_{lm}} \tag{2}$$

where ΔT_{lm} is the logarithmic mean temperature difference, which is calculated as:

$$\Delta T_{lm} = \frac{(T_d - T_w)_o - (T_d - T_w)_i}{\ln[(T_d - T_w)_o/(T_d - T_w)_i]} \tag{3}$$

Subscripts i and o represent the inlet and outlet of the dryer, respectively. X is the moisture content of the particles (kg/kg, d.b.); W_p is the mass flow rate of the particles ($\text{kg}_{\text{drysolid}}$/h); V_r is the volume of the drying chamber (m^3), which also includes the particle feed pipe; and λ is the latent heat of vaporization (kJ/kg).

Determination of Particle Mean Residence Time

The mean residence time was calculated from the amount of the particle holdup within the system and the inlet mass flow rate of the particles:[11,12]

$$\tau = m_p/W_p \tag{4}$$

where τ is the mean residence time (s); m_p is the particle holdup (kg); and W_p is the mass flow rate of particles (kg/s). Because the determination of the particle mean residence time involved much error, the experiments were repeated at least 5–10 times.

Determination of Particle Holdup

The system was first allowed to reach steady-state at each condition. Then, feeding of the particles was stopped and the high-pressure blower was suddenly turned off. The resin was collected at the exit port of the dryer to obtain the holdup of the resin. The mass of the collected resin was then used for the calculation of the mean residence time.

Estimation of Specific Energy Consumption

The efficiency of energy utilization during drying was evaluated through the specific energy consumption, which is a measure of the energy required during the process to remove 1 kg of water from the product being dried. The specific energy consumption was calculated as:[13,14]

$$\text{SEC} = E/m_{\text{w}} \tag{5}$$

where SEC is the specific energy consumption of either the high-pressure blower or the electric heaters ($\text{MJ/kg}_{\text{water}}$); E is the measured electric energy consumption of either the high-pressure blower or the electric heaters (MJ); and m_w is the amount of water removed (kg), which is the difference between the initial and final masses of the drying particles. In the present situation, the total amount of water removed was calculated as:

$$m_{\text{w}} = \dot{m}_{\text{a}}\ \Delta w\ t \tag{6}$$

where $\dot{m}_{\text{a}}$ is the inlet air mass flow rate ($\text{kg}_{\text{dryair}}$/min); Δw is the difference between the absolute humidities of the inlet and outlet air ($\text{kg}_{\text{water}}/\text{kg}_{\text{dryair}}$), which was evaluated from the wet-bulb and dry-bulb temperatures of the inlet and outlet air; and t is the drying time (min).

Statistical Analysis

All experiments were performed in duplicate except when specified otherwise and the mean values with standard deviations were reported. The experimental data were analyzed using an analysis of variance (ANOVA). Duncan's multiple range tests were used to establish multiple comparisons of the mean values; mean values were considered at 95% confidence level. A statistical program SPSS® (version 13) was used to perform all statistical calculations (SPSS, Inc., Chicago, IL).

RESULTS AND DISCUSSION

After modifying the impinging stream dryer of Jantaka[9] it was found that the time to reach the steady-state of the system, both before and after feeding of soy residue, was much reduced. The time to reach the steady-state after starting up of the system (but with no feeding of the residue) was in the range of 10–15 min. After feeding of the residue steady-state was regained within about 4 min. However, after operating the dryer for some period of time, it was found that some soy residue deposited on the surface of the drying chamber and inlet pipes, which caused blockage of the system. This also led to a difficulty in controlling the feed rate of soy residue into the system. To eliminate this problem, the drying chamber and inlet pipes were cleaned with a spiral wire brush before starting of a new experiment.

Heat losses from the dryer were assumed to be negligible since both the drying chamber and inlet pipes were carefully insulated with 2-inch fiber glass. In addition, the temperature between the insulated surface and the ambient was observed to be quite low.

Effects of Various Parameters on Volumetric Water Evaporation Rate

Figure 2 depicts the relationship between the volumetric water evaporation rate and the inlet air temperature with the inlet air velocity (20 and 27 m/s), feed rate of particles (10 and 20 $\text{kg}_{\text{drysolid}}$/h), and impinging distance (5, 9, and 13 cm) as parameters. The moisture content of the soy residue at the dryer outlet was in the range of 64–70% (w.b.) or 1.9–2.8 kg/kg (d.b.). It is seen that an increase in the inlet air temperature led to an increase in the volumetric water evaporation rate in all cases (see also Table 1). This is due

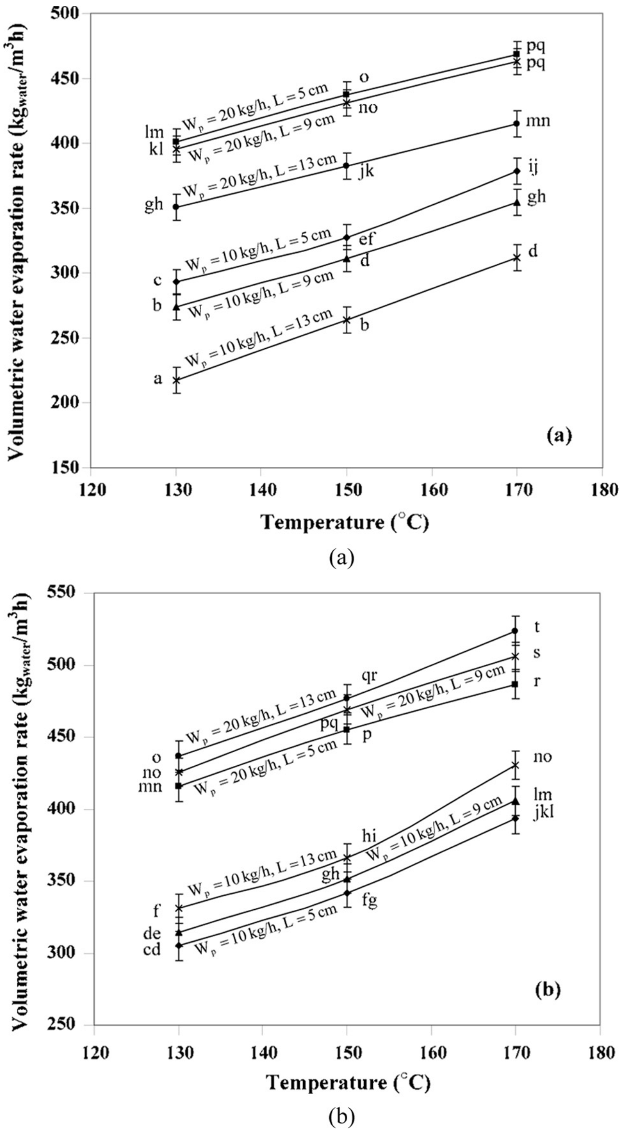

FIG. 2. Effects of operating parameters on the volumetric water evaporation rate at different inlet air velocities: (a) inlet air velocity = 20 m/s, (b) inlet air velocity = 27 m/s. Different letters above the curves indicate that the values are significantly different at 95% confidence level ($p < 0.05$).

to the fact that a higher inlet temperature caused a larger difference between the medium temperature and the particle surface (wet-bulb) temperature, which is the driving force for heat transfer, which is in turn related to mass transfer, especially to the evaporation of moisture from the particle surface during the unhindered rate period drying.[1,15]

The effect of inlet air velocity on the volumetric water evaporation rate is shown in Fig. 2 and Table 1. At a fixed particle flow rate and a fixed impinging distance, at each drying temperature an increase in the air velocity led to an increase in the volumetric water evaporation rate. This is because a higher air velocity led to a stronger collision between the opposed streams; the shear rate and turbulence intensity within the impingement zone were higher, leading to a thinner boundary layer around the particles, which caused less resistance to heat and mass transfer from the particles and hence higher rate of water removal from the particles.[1,15]

The effect of particle flow rate on the volumetric water evaporation rate is also shown in Fig. 2 and Table 1. It was observed that an increase in the particle flow rate led to enhanced volumetric water evaporation rate at a fixed inlet air velocity and a fixed drying air temperature. Although the humidity of air in the system increased with the particle flow rate, the capacity of the dryer was probably still higher than the load required to evaporate water from the particles entering the system. With more particles entering the system, the volumetric water evaporation rate was thus higher.[1,5,16]

The effect of the impinging distance on the volumetric water evaporation rate is again depicted in Fig. 2 and Table 1. When the particle flow rate was fixed at each drying temperature and the inlet air velocity was adjusted to 20 m/s (see Fig. 2a) it was noted that a shorter impinging distance resulted in a higher volumetric water evaporation rate. This is probably because an inlet air velocity of 20 m/s did not provide enough momentum to the particles to move into the opposed streams; therefore, the particles had shorter mean residence time (see Table 2). A shorter impinging distance, which implies a stronger collision between the opposed streams and hence higher shear rate and turbulence intensity within the impingement zone, therefore led to a higher volumetric water evaporation rate. In this case, high shear rate and turbulence intensity played a more major role than did the time the particles stayed in the system.

At a particle flow rate of 20 $kg_{drysolid}$/h and impinging distances of 5 and 9 cm, the effect of the impinging distance on the volumetric water evaporation rate was not significant. The loading ratio (ratio between the particle mass flow rate and the air mass flow rate) might be high and result in lower particle kinetic energy and lower efficiency of the particle flow. Only when the spacing between the two impinging faces increased to 13 cm did the effect of increasing distance started to show. On the other hand, when the particle flow rate was lowered to 10 $kg_{drysolid}$/h (decreasing loading ratio), the effect of the impinging distance became significant, even at lower values.

When the inlet air velocity was adjusted to 27 m/s (see Fig. 2b), the results showed that a longer impinging distance led to a higher volumetric water evaporation rate. This is because a higher inlet air velocity resulted in higher momentum of particles; the particles could thus flow into the opposed streams and undergo oscillatory motion within the impingement zone. As a result, the particles had longer mean residence time (see Table 2). The longer impinging distance allowed for a greater moving area and

TABLE 1
Volumetric water evaporation rate and volumetric heat transfer coefficient

Condition				Volumetric water evaporation rate	Volumetric heat transfer coefficient
T (°C)	L (cm)	W_p ($kg_{drysolid}/h$)	V (m/s)	(kg_{water}/m^3h)	(W/m^3K)
130	5	10	20	293 ± 2.0^{c}	2926 ± 3.8^{cd}
150	5	10	20	328 ± 4.4^{ef}	2905 ± 15.1^{cd}
170	5	10	20	379 ± 16.1^{ig}	2975 ± 91.2^{de}
130	9	10	20	274 ± 1.0^{b}	2794 ± 3.72^{b}
150	9	10	20	311 ± 4.0^{d}	2796 ± 4.6^{b}
170	9	10	20	354 ± 2.0^{gh}	2839 ± 8.8^{bc}
130	13	10	20	217 ± 2.0^{a}	2428 ± 41.5^{a}
150	13	10	20	264 ± 12.1^{b}	2434 ± 6.7^{a}
170	13	10	20	312 ± 2.0^{d}	2517 ± 18.2^{a}
130	5	20	20	401 ± 4.0^{lm}	4216 ± 1.6^{lm}
150	5	20	20	437 ± 0.4^{o}	4234 ± 2.9^{m}
170	5	20	20	468 ± 4.0^{pq}	4216 ± 73.6^{lm}
130	9	20	20	396 ± 4.0^{kl}	4129 ± 13.3^{kl}
150	9	20	20	431 ± 14.3^{no}	4169 ± 94.8^{l}
170	9	20	20	463 ± 4.0^{pq}	4177 ± 28.9^{lm}
130	13	20	20	351 ± 11.9^{gh}	3956 ± 41.4^{k}
150	13	20	20	382 ± 23.0^{jk}	3949 ± 18.1^{k}
170	13	20	20	415 ± 7.9^{mn}	3958 ± 8.1^{k}
130	5	10	27	305 ± 4.2^{cd}	3084 ± 64.7^{f}
150	5	10	27	342 ± 5.0^{fg}	3018 ± 29.6^{ef}
170	5	10	27	393 ± 2.6^{jkl}	3096 ± 39.7^{f}
130	9	10	27	315 ± 3.4^{de}	3231 ± 14.2^{g}
150	9	10	27	352 ± 4.6^{gh}	3217 ± 46.3^{g}
170	9	10	27	406 ± 6.4^{lm}	3265 ± 13.4^{gh}
130	13	10	27	331 ± 26.5^{d}	3349 ± 49.0^{hi}
150	13	10	27	366 ± 6.5^{hi}	3364 ± 54.3^{ij}
170	13	10	27	431 ± 3.7^{no}	3445 ± 42.7^{j}
130	5	20	27	415 ± 2.8^{mn}	4359 ± 39.5^{n}
150	5	20	27	455 ± 5.9^{p}	4350 ± 17.8^{n}
170	5	20	27	487 ± 5.2^{r}	4347 ± 39.1^{n}
130	9	20	27	426 ± 5.9^{no}	4457 ± 51.8^{o}
150	9	20	27	469 ± 3.6^{pq}	4504 ± 57.9^{op}
170	9	20	27	506 ± 3.6^{s}	4512 ± 26.1^{op}
130	13	20	27	437 ± 2.4^{o}	4593 ± 43.1^{p}
150	13	20	27	477 ± 7.5^{qr}	4576 ± 79.0^{p}
170	13	20	27	524 ± 5.9^{t}	4567 ± 20.4^{p}

Different letters in the same column indicate that the values are significantly different at 95% confidence level ($p < 0.05$).

a longer time that the particles were in the impinging zone. This in turn led to an increase in heat and mass transfer between the drying particles and the drying air.

The effect of the impinging distance on the volumetric water evaporation rate was compared with the results of Sathapornprasath et al.[1] At a particle flow rate of $20\,kg_{drysolid}/h$ and inlet air velocity 16 and 45 m/s the results were similar to those of Sathapornprasath et al.[1] On the other hand, at a particle flow rate of $10\,kg_{drysolid}/h$ at both inlet air velocities the results were quite different from those of Sathapornprasath et al.[1] The differences might be due to the modification of the feeding system, which improved the consistency and controllability of the particle flow rate and hence smaller errors

TABLE 2
Mean residence time of particles in the system

Condition			Mean residence time of particles (s)
V (m/s)	W_p ($kg_{drysolid}$/h)	L (cm)	
20	10	5	1.24 ± 0.2^{b}
20	10	9	1.09 ± 0.1^{ab}
20	10	13	0.97 ± 0.2^{a}
20	20	5	1.25 ± 0.1^{b}
20	20	9	1.17 ± 0.2^{b}
20	20	13	1.06 ± 0.1^{ab}
27	10	5	1.44 ± 0.2^{c}
27	10	9	1.57 ± 0.1^{cd}
27	10	13	1.68 ± 0.1^{d}
27	20	5	1.45 ± 0.1^{c}
27	20	9	1.59 ± 0.1^{cd}
27	20	13	1.74 ± 0.1^{d}

Different letters in the same column indicate that the values are significantly different at 95% confidence level ($p < 0.05$).

in the experimental results; hot air temperature was also better controlled. In addition, in this study, inlet air wet-bulb and dry-bulb temperatures were measured at point B as shown in Fig. 1, whereas Sathapornprasath et al.[1] measured inlet air dry-bulb temperature at point A and inlet air wet-bulb temperature at point B (see Fig. 1), which might not be an appropriate way to measure the temperature. The differences in the positions of the temperature measurement affected the value of the logarithmic mean temperature difference and hence the calculated performance results. The maximum volumetric water evaporation rate was found to be around 520 kg_{water}/m^3h.

Comparing with the values of 1.8 kg_{water}/m^3h and 77 kg_{water}/m^3h in the cases of a spray dryer that was used to dry coffee and of a spouted bed that was used to dry wheat grains,[16] respectively, it is seen that the ISD has a much higher water removal efficiency than some popular competing dryers.

Effects of Various Parameters on Volumetric Heat Transfer Coefficient

Figure 3 depicts the effect of the inlet air temperature on the volumetric heat transfer coefficient. The particle flow rate, impinging distance, and inlet air velocity were set as the parameters. It was found that the volumetric heat transfer coefficient changed insignificantly with the inlet air temperature (see also Table 1). Although a higher inlet air temperature led to a larger difference between the drying medium temperature and the particle surface temperature, the rate of water evaporation was also higher.

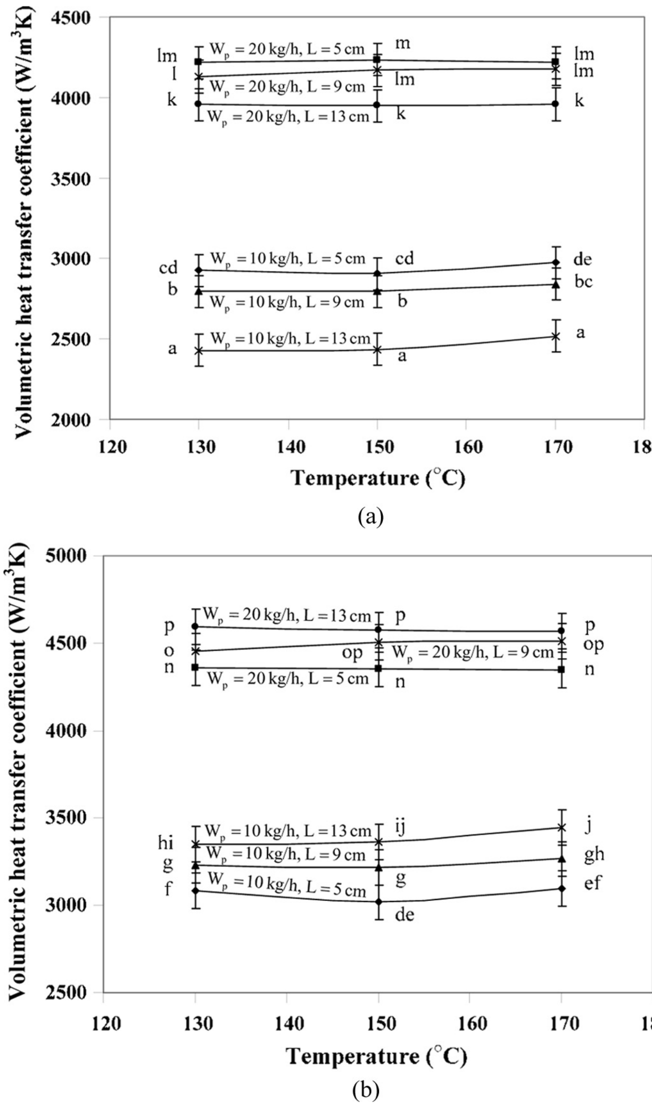

FIG. 3. Effects of operating parameters on the volumetric heat transfer coefficient at different inlet air velocities: (a) inlet air velocity = 20 m/s, (b) inlet air velocity = 27 m/s. Different letters above the curves indicate that the values are significantly different at 95% confidence level ($p < 0.05$).

Because the volumetric heat transfer coefficient was calculated from both the logarithmic mean temperature difference and the rate of water evaporation, the resulting coefficient did not increase with increased inlet air temperature.[1]

The effect of the inlet air velocity on the volumetric heat transfer coefficient is also depicted in Fig. 3 and Table 1. At a fixed particle flow rate and impinging distance, at each drying temperature the volumetric heat transfer coefficient increased with an increase in the inlet air velocity for the same reasons mentioned in the previous section.

The effect of the particle flow rate on the volumetric heat transfer coefficient is illustrated in Fig. 3 and

Table 1. The volumetric heat transfer coefficient increased with an increase in the particle flow rate at a fixed inlet air velocity at each drying temperature. The reasons for the observed phenomenon are again the same as those mentioned in the previous section.

The effect of the impinging distance on the volumetric heat transfer coefficient is also shown in Fig. 3 and Table 1. The data reveal that the volumetric heat transfer coefficient correlated well with the volumetric water evaporation rate. The maximum volumetric heat transfer coefficient was found to be around 4,500 W/m^3k.

Comparing with the values of 18 W/m^3k and 3,774 W/m^3k in the cases of a spray dryer that was used to dry coffee and of a spouted bed that was used to dry wheat grains,[16] respectively, it is again seen that the ISD is a very efficient dryer.

TABLE 3
Specific energy consumption at different drying conditions

Condition						
T (°C)	L (cm)	W_p ($kg_{drysolid}/h$)	V (m/s)	ΔT (°C)	SEC_{blower} (MJ/kg_{water})	SEC_{heater} (MJ/kg_{water})
130	5	10	20	65.1	6.5	2.8
150	5	10	20	69.7	5.9	2.5
170	5	10	20	74.7	5.5	2.4
130	9	10	20	64.9	6.7	2.9
150	9	10	20	69.8	6.0	2.6
170	9	10	20	74.8	5.6	2.4
130	13	10	20	64.9	6.8	2.9
150	13	10	20	69.1	6.3	2.7
170	13	10	20	74.9	6.0	2.6
130	5	20	20	64.8	6.0	2.6
150	5	20	20	69.8	5.6	2.4
170	5	20	20	75.0	5.1	2.2
130	9	20	20	64.5	6.0	2.6
150	9	20	20	69.6	5.6	2.4
170	9	20	20	74.6	5.3	2.3
130	13	20	20	64.8	6.4	2.7
150	13	20	20	69.8	5.9	2.5
170	13	20	20	74.5	5.6	2.4
130	5	10	27	64.4	5.1	2.2
150	5	10	27	69.4	4.6	2.0
170	5	10	27	74.7	4.3	1.8
130	9	10	27	64.7	5.0	2.2
150	9	10	27	69.3	4.4	1.9
170	9	10	27	74.7	4.2	1.8
130	13	10	27	64.7	4.8	2.1
150	13	10	27	69.5	4.3	1.8
170	13	10	27	74.2	4.0	1.7
130	5	20	27	64.4	5.0	2.1
150	5	20	27	69.6	4.4	1.9
170	5	20	27	74.4	4.2	1.8
130	9	20	27	64.3	4.8	2.1
150	9	20	27	69.2	4.3	1.9
170	9	20	27	74.6	3.9	1.7
130	13	20	27	64.1	4.6	2.0
150	13	20	27	69.7	4.2	1.8
170	13	20	27	74.3	3.9	1.7

Effects of Various Parameters on Particle Mean Residence Time

Table 2 shows the mean residence time of particles at different conditions. When the inlet air velocity was 20 m/s the mean residence time was in the range of 0.97–1.25 s and was not significantly different at different conditions. On the other hand, when the inlet air velocity was 27 m/s the mean residence time was in the range of 1.44–1.74 s but was not significantly different at different conditions. Higher inlet air velocity led to longer mean residence time because an increase in the air velocity resulted in enhanced momentum of the particles, so they could move into the opposed streams; the particles could thus spend a longer time in the impingement zone.

At a lower inlet air velocity a longer impinging distance led to a decrease in the mean residence time. This is probably because the lower inlet air velocity tested in this study was insufficient for increasing the momentum of the particles to retain a straight path and pass through the opposing streams. Consequently, the particles might escape from the impinging zone almost immediately after being released from the opening of the inlet jet. The longer impinging distance resulted in a sharper turn of the particles from the impingement zone to the bottom exit of the dryer and hence shorter mean residence time.

Specific Energy Consumption of the System

Table 3 lists the specific energy consumption of the high-pressure blower (SEC_{blower}) and electric heaters (SEC_{heater}) at various conditions. In the case of the specific energy consumption of the high-pressure blower (SEC_{blower}), a decrease in the SEC_{blower} was noted at a higher inlet air temperature. This is expected because an increase in the inlet air temperature led to a higher rate of water evaporation and hence a larger amount of water was removed (see Table 1). It is noted that the high-pressure blower consumed a constant power at different conditions, so an increase in the inlet air temperature led to a decrease in the SEC_{blower}. The data listed in Table 3 show that a decrease in the SEC_{blower} was noted at a higher particle flow rate at a fixed inlet air velocity. This is due to a higher concentration of the particles in the drying system, resulting in a higher water evaporation rate and a decrease in the SEC_{blower}. Finally, the effect of the inlet air velocity on the SEC_{blower} was investigated at a fixed particle flow rate and a fixed impinging distance. The SEC_{blower} at an inlet air velocity of 27 m/s was lower than the SEC_{blower} at an inlet air velocity of 20 m/s because a higher inlet air velocity caused a higher water evaporation rate; the energy consumption of the high-pressure blower was the same in both cases, however. On the other hand, the SEC_{blower} was not correlated with the impinging distance at a fixed inlet air velocity and a fixed particle flow rate at each drying temperature.

In the case of the specific energy consumption of the electric heaters (SEC_{heater}) it is seen that the SEC_{heater} was lower than the SEC_{blower} in all cases. This is because the high-pressure blower worked continuously, whereas the electric heaters worked only intermittently. The relative energy consumption of the high-pressure blower and electric heaters was about 70 and 30%, respectively. The lowest $SEC_{blower/heater}$ was around 5.6 MJ/kg_{water} at $T = 170°C$, $L = 13\,cm$, $W_p = 20\,kg_{dry\ solid}/h$, and $V = 27\,m/s$.

The specific energy consumption of the ISD and its auxilliary units was in the range of 5.6 to 9.7 MJ/kg_{water}, which falls in a typical range of the specific energy consumption of a spray dryer, which is in the range of 3–20 MJ/kg_{water}.[17]

CONCLUSION

The performance of a newly modified impinging stream dryer for high-moisture particulate materials, in terms of the volumetric water evaporation rate and the volumetric heat transfer coefficient, was evaluated; soy residue was used as a test material in this study. The effects of various parameters, namely, inlet air temperature, inlet air velocity, particle flow rate and impinging distance, were assessed. The particle mean residence time in the system was also evaluated to support the results of the effects of the various tested parameters on the performance of the dryer. It was found that an increase in the inlet air temperature, inlet air velocity, and particle flow rate led to an increase in the volumetric water evaporation rate. The effect of the impinging distance was dependent on the value of the inlet air velocity, however. For the effects of the various parameters on the volumetric heat transfer coefficient, it was found that the volumetric heat transfer coefficient varied insignificantly with the inlet air temperature. However, the volumetric heat transfer coefficient increased with an increase in the inlet air velocity, particle flow rate, and impinging distance. The mean residence time results could very well be used to explain the observed changes of the dryer performance. Finally, it was found that the specific energy consumption of the high-pressure blower (SEC_{blower}) and electric heaters (SEC_{heater}) decreased with an increase of all the tested parameters, except for the impinging distance. The lowest specific energy consumption of $SEC_{blower/heater}$ was around 5.6 MJ/kg_{water}. To explore the feasibility of further enhancing the performance of an ISD, superheated steam is now being tested as an alternative drying medium.

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