A review of the impinging stream dryer

Kittichote Supakumnerd[1], Kitti Sathapornprasath[2]
Department of Mechanical Engineering, Faculty of Engineering, Srinakharinwirot University
Ongkarak, Nakhon-Nayok, 26120, Thailand
Corresponding author's telephone: +662 367 8417 ; E-mail: kittichote_dip@yahoo.com

ABSTRACT

The demoisturizing or drying process is an essential technique to prolong the life of agricultural product. Typically the impinging steam dryer (ISD), one of hot-air drying process, is suitable to dry particulate materials that contain very high moisture. This dryer allows high speed steam carrying the grains to impinge against each other at the middle point of two opposite steams. The particles can be theoretically accelerated to a velocity near the speed of gas. The impingement between solid-in-gas steams causes an impingement zone that has high turbulence with high concentration of particles so this two-phase turbulence area provides excellent heat and mass transfer. The literatures related to this research show that various parameters including distance between the tube and the drying chamber, inlet air temperature, loading ratio, material moving time through the system have affected the performance of an impinging stream dryer. The performance of an impinging stream dryer can also be evaluated in terms of the volumetric water evaporation rate, volumetric heat transfer coefficient and specific energy consumption. However, researches of impinging stream dryer are considered as a new technology in Thailand. Hence, it is necessary to study on the effects of various parameters on the performance of an impinging stream dryer in order to be really applied to the Thai industries.

Keyword: impinging stream dryer; volumetric water evaporation rate; volumetric heat transfer coefficient

1. Introduction

Generally the basic procedures of drying process for the agricultural products include rotary dryer, spray dryer as well as fluidized bed dryer. However, there are limitations of using these dryers for high-moisture agricultural products**.** For example, it may cause agglomeration of the particles during the drying process that results in irregular temperature distribution on the particles or high energy required for drying (low performance of dryer). Theoretical thermal efficiency of hot-air drying process used for de-moisturizing very wet particulate materials can be increased by various methods such as reducing the particle size for enhancement of heat exchange between the particles and hot air, increasing the duration of the heat transfer in the dryer and reducing the resistance to mass and heat transfer at the surface of the grains. From all above applications on the improvement of thermal efficiency in hot-air dryers, an impinging stream dryer can achieve all of those phenomena.

2. Basic principles of impinging stream dryer

The basic concept of impinging stream drying process is to allow two oppositely directed high-velocity solid-in-gas streams to strike against each other at the middle point of the two streams [1]. Then, the particles are carried by the air flow into the system. The particles can theoretically be accelerated to a velocity near that of gas. The impingement between the two-phase streams causes an impingement zone of high turbulence with the highest concentration of particles which provides excellent conditions for heat and mass transfer. In a case that the densities of the two phases are quite more different such as the case of a solid-in-gas suspension, particles will penetrate from one stream into the opposing one due to their inertia. The particles will then decelerate since the friction force of the opposing stream until the velocity of particles is zero. After that, the particles will be accelerated again by the opposite direction towards the impinging plane and will be penetrated back into the original stream. After several repetitions of penetration into and from the opposing streams, the particles will finally lose their momentum and will be carried out from the impingement zone by the lateral gas flow.

An oscillatory motion of the particles into and from the opposing streams leads to an increase of residence time of the particles in the impinging zone. This implies that the time for heat and mass transfer can continue longer. As mentioned above, it implies that the effectiveness in thermal drying of impinging stream dryer is more than other types of dryers. This means that the impinging stream dryer is smaller and takes less residence time for drying (resulting in a higher rate of drying) than other drying machine at the same loading ratio. Therefore, it could be said that it is interesting to apply the impinging stream dryer especially for high moisture particles.

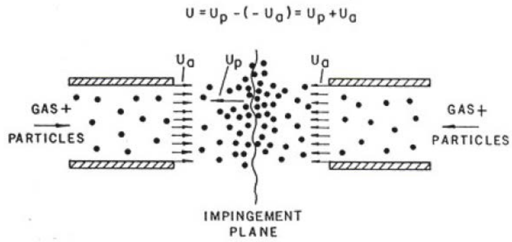

Figure 1 Basic principle of impinging streams [1]

3. The effect of variable parameters on performance of the impinging stream dryer

Generally, the performance of the impinging stream dryer can be evaluated in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient determined by the following equations

The volumetric water evaporation rate (N_v) [1]

$$N_v = \frac{W_p(x_i - x_o)}{V_r} \qquad (1)$$

Volumetric heat transfer coefficient (h_v) [1]

$$h_v = \frac{W_p(x_i - x_o)\lambda}{V_r \Delta T_{lm}} \qquad (2)$$

Where N_v is the volumetric water evaporation rate (kg_{water}/m^3h) ; h_v is the volumetric heat transfer coefficient (W/m^3K) ; X_i is the inlet moisture content of the particles ($kg_{water}/kg_{dry\ solid}$) ; X_o is the outlet moisture content of the particles ($kg_{water}/kg_{dry\ solid}$); W_p is the mass flow rate of the particles (kg/s) ; V_r is the volume of the drying chamber (m^3), which includes the particle feed pipe; λ is the latent heat of vaporization (kJ/kg) ; ΔT_{lm} is the logarithmic mean temperature difference (^oC), which is calculated in the case of hot air drying as following:

$$\Delta T_{lm} = \frac{(T_{db.} - T_{wb.})_o - (T_{db.} - T_{wb.})_i}{\ln \frac{(T_{db.} - T_{wb.})_o}{(T_{db.} - T_{wb.})_i}} \qquad (3)$$

Where $T_{db.}$ is the dry-bulb temperature of air (^{o}C); $T_{wb.}$ is the wet-bulb temperature of air (^{o}C), which subscripts 'I' and 'o' are represented as the inlet and outlet of the dryer, respectively.

Table 1 Volumetric water evaporation rate and volumetric heat transfer coefficient of different dryers [1]

Dryer type	Material processed	Volumetric water evaporation rate (kg_{water}/m^3h)	volumetric heat transfer coefficient (W/m^3K)
Spray dryer	Coffee	1.8	18
Spouted bed	Wheat grains	77	3,774
Spouted bed	Polymer	2.7-162	151.4-3,390
ISD	Millet seeds	720-5,400	138-133,114

The performance of an impinging stream dryer depends on the effect of various parameters including the distance between a tube and a drying chamber, inlet air temperature, loading ratio and material moving time through the system. Thus, the study on the effect of different variables is important for developing the impinging stream dryer to increase thermal efficiency. There are several studies relate to the impinging stream dryer.

3.1 The studies on performance of the impinging stream dryer.

According to Kitron et al. [2], the drying and mixing of solids and particle residence time distribution in four-impinging stream and multistage two-impinging stream dryers have been studied. A comparison of performance between the dryers and other devices could be shown by calculating the volumetric heat transfer coefficient (h_v) of each system. A certain trend observed was that h_v increased with an increase in the particle mass flow rate. The best condition for drying with an impinging stream dryer may be obtained by increasing the particle load up to a value where choking is expected or an excessive pumping energy is required. Additionally, Kitron and Tamir 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.[3] It was found that the hold-up of particles at a fixed air flow rate enhanced with the increase in the particle flow rate while the heat transfer coefficient augmented with the increase in the particle flow rate. However, it was independent of the volume of the dryer as well as the volume of the inlet pipes. In fact, it was discovered that the effective volume for the transporting processes was not the actual volume of the dryer but it was a certain volume located between the faces of the inlet pipes within the drying chamber.

3.2 Experimental conditions affecting the performance of impinging stream dryer.

Modifying the operating conditions on the performance of the impinging stream dryer was experimented. Sathapornprasath et al. studied the effects of different operating conditions on the overall performance of an impinging stream dryer by calculating the rate of water evaporation from a single particle during drying in the unhindered drying rate period.[4] In the case of hot air drying, it was found that an increase in the inlet air velocity and inlet air temperature led to an increase in the water evaporation rate, while the inlet air relative humidity had an adverse effect on the water evaporation rate. In the case of superheated steam drying, it was shown that the inlet steam velocity and inlet steam temperature led to an increase in the water evaporation rate, while the steam pressure had a negative effect on the water evaporation rate. Furthermore, an inversion temperature of the impinging stream dryer was calculated and reported to be around 212 °C at the evaporation rate of 60 kg/m^2h.

Moreover, Sathapornprasath et al. designed and fabricated a prototype of a coaxial two impinging stream dryer and evaluated its performance using a resin as a test material. [5] 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, while 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, while the maximum volumetric heat transfer coefficient was around 880 W/m^3K. In this study, 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 because of a difficulty in controlling its feed rate and clogging of the residue in the system.

From [6], Jantaka modified the ISD of Sathapornprasath et al.[5] by increasing the diameter of the inlet pipes in order that a drying material would flow easier within the system.

The screw-conveyor based particle feeding system was also replaced by a belt-conveyor based feeding system; the change has proved as a problem of particle stickiness in the originally used screw-conveyor based system could be effectively eliminated. After the modification, the experiments were performed using soy residue (okara) as a test material. The system was found to be much easier to control. With regard to the performance test results, an increase in the inlet air temperature led to an increase in the volumetric water evaporation rate, while 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 a particle feed rate. The maximum volumetric water evaporation rate was found to be around 300 kg_{water}/m^3h, while the maximum volumetric heat transfer coefficient was around 5,750 W/m^3K. The higher values when comparing with the results of Sathapornprasath et al.[5] was owing to the ability to better control the feeding of the drying material, which led to significant increase of heat and mass transfer within the system. The distinctions in the measuring positions of the inlet air temperature are also one of the reasons of differences. Studied by Jantaka [6], the wet-bulb and dry-bulb temperatures of the inlet air were, respectively, measured at points A and D as shown in Figure 2. Conversely, 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.[5] Hence, the effects of the different positions of temperature measurement were important. In spite of the improvement, some difficulties in controlling the inlet air temperature still exist since there was only one heater used to supply heat to the drying air that entered the drying chamber on both sides.

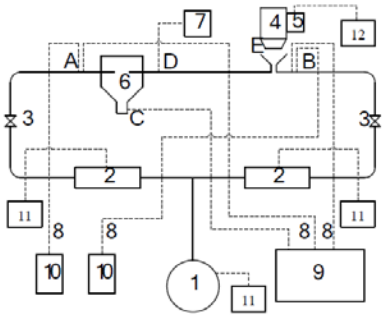

Figure 2: A schematic diagram of a hot air impinging stream dryer and associated units. [7]

From figure 2, the diagram present the detail of impinging stream dryer with (1) High-pressure blowers (2) Electric heaters (3) Globe valves (4) Belt feeders (5) DC Motor (6) Drying chamber (7) Velocity measurement probe (8) Thermocouples (9) Data Logger (10) Temperature Controller (11) Kilowatt-hour meter (12) Voltage regulator

4. Particle Mean Residence Time

The mean residence time was calculated from the amount of the particle hold-up within the system and the inlet mass flow rate of the particles [2,8].

$$\tau = \frac{M_p}{W_p} \qquad (4)$$

where

τ is the mean residence time (s)

M_p is the particle hold-up (kg)

W_p is the particle flow rate (kg/s)

Xiao and Eckehard [8] said that the mean residence time (MRT) is important for drying process. Since that time, the particles are exchanged heat and mass transfer with intermediate drying. The particles staying longer in system will have heat and mass transfer more than the particle stored in the system for shorter time.

5. Specific Energy Consumption

Tamir et al. tested the performance of a two tangentially fed impinging stream dryer operated in the unhindered drying rate period and compared the results with those of other commonly used dryers. It was found that the performance of an impinging stream dryer was higher than that of conventional dryers such as spray dryer, spouted bed dryer and fluidized bed dryer [9].

The efficiency of energy consumption of the drying process was estimated through the specific energy consumption (SEC), which is a measure of the energy required during a process to remove 1 kg of water from a product being dried. The SEC was calculated as following equation (Nimmol et al., 2007; Nimmol and Devahastin, 2010; Wachiraphansakul and Devahastin, 2007) [10,11].

$$SEC = \frac{E}{M_W} \qquad (5)$$

Where SEC is the specific energy consumption of either the high-pressure blower or the electric heaters (MJ/kg_{water}); E is the measured electric energy consumption of either the high-pressure blower or electric heaters (MJ); and M_w is the amount of water removed from the flying particles (kg), which was the difference between the initial and the final masses of the drying particles and was calculated in the case of hot air drying as following:

$$M_w = W_p(x_i - x_e)t \qquad (6)$$

Where

W_p is the mass flow rate of the particles (kg $_{dry\ solid}$/min)

X_i is the moisture of the material at the entrance. (kg/kg, d.b.)

X_e is the moisture of the material at the exit . (kg/kg, d.b.)

t is the drying time (min).

6. The application of impinging stream dryer in Thailand.

Although an impinging stream dryer has several advantages in terms of thermal efficiency and uncomplicated process, it is known as a new technology in Thailand because it has not been widely used. The first impinging stream dryer in Thailand was developed by Sathapornprasath [12] but it was not enough potential for the adoption of drying particulate materials with high moisture content because the problem is found at the feeding of particulate materials in to the system and the clogging in the pipes.

The results of drying paddy using the impinging stream dryer only [13] or using the impinging stream dryer with the pneumatic conveying dryer [14] demonstrated that the moisture content of paddy could be reduced considerably when it was compared to the duration of paddy being in the drying. Additionally, the breaking of paddy at the outlet of impinging stream dryer did not appear (Based on visual observation). While the performance in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient of an impinging stream dryer is high, energy efficiency of the dryer in terms of specific energy consumption (SEC) is higher than other paddy dryers as well.

Besides, Choicharoen et al. [15] developed the impinging stream dryer in order to reduce the moisture content of okara, the agricultural waste with high adhesion. The drying results showed that if okara was prepared to be in a particle form (aggregate) with appropriate procedures before feeding into the impinging stream dryer, the impinging stream dryer could reduce the moisture content of the okara. Nevertheless, this level of moisture content is not low enough to suitable for storage. Then, the okara obtained from this drying process can be reduced moisture content by other drying methods.

7. Summary and recommendations

The impinging stream dryer is suitable for reducing moisture on the surface of material, especially particulate materials such as grains and crops. The mechanism of the imping stream dryer spends less time and significantly reduces the moisture content for drying. As a result, the drying rate is very high. In addition, the energy efficiency is higher than other dryers. The imping stream dryer is also smaller than others at the same burden.

To optimize the imping stream dryer, the reuse of air flow (hot air circulation) or devices for improving its performance should be provided. Also, to understand the optimal conditions for drying various types of materials with the impinging stream dryer, many factors influence the performance in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient of the dryer such as drying temperature, material feed rate, number of input materials into the system and the amount of air flow should be studied. Not only the energy efficiency of the impinging stream dryer, but also the physical quality of the dried material should be examined.

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