Applied Thermal Engineering 30 (2010) 2204–2212

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

# Evaluation of performance and energy consumption of an impinging stream dryer for paddy

Chatchai Nimmol [a,*], Sakamon Devahastin [b]

[a] Department of Materials Handling Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, 1518 Pibulsongkram Road, Bangsue, Bangkok 10800, Thailand

[b] Department of Food Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha u-tid Road, Tungkru, Bangkok 10140, Thailand

ARTICLE INFO

*Article history:*
Received 1 April 2010
Accepted 28 May 2010
Available online 4 June 2010

*Keywords:*
Double-point particle feeding
Drying rate
Mean residence time
Paddy
Single-point particle feeding
Specific energy consumption
Surface moisture
Volumetric heat transfer coefficient
Volumetric water evaporation rate

ABSTRACT

Impinging stream dryer has proven to be an excellent alternative means for removing surface moisture of particulate materials. In this study, a coaxial two-impinging stream dryer prototype for paddy, whose surface moisture needs to be removed prior to subsequent processing, was developed and tested. The effects of various operating and geometric parameters, i.e., inlet air temperature, impinging distance, particle flow rate and particle feeding characteristics (single-point feeding vs. double-point feeding), on the overall performance (in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient) and energy consumption of the dryer were then studied. It was found that the developed impinging stream dryer could reduce the moisture content of paddy by 3.4–7.7% (d.b.) within a very short period of time. The maximum value of the volumetric water evaporation rate was found to be about 198 $kg_{water}/m^3$ h, while the maximum value of the volumetric heat transfer coefficient was about 7013 $W/m^3$ K. The mean residence time of the particles (paddy) in the system was in the range of 1.81–2.42 s, leading to average drying rate in the range of 1.52–3.83 (% d.b.) $s^{-1}$, which is about 250 and 40 times higher than spouted-bed and fluidized-bed dryers, respectively. The lowest total specific energy consumption of the process was 5.1 $MJ/kg_{water}$ when using double-point particle feeding at an inlet air temperature of 110 °C, an impinging distance of 5 cm and particle flow rate of 150 $kg_{dry\ solid}/h$.


## 1. Introduction

Paddy is one of the world's most important food crops and Thailand is among the largest exporters of rice in today international market. Before being processed, freshly-harvested paddy with high moisture content needs to be dried in order to avoid quality deterioration by microorganisms and respiration. Nowadays, typical methods that have been used to dry paddy in Thailand and other countries include high-temperature fluidized-bed dryers [1,2], spouted-bed dryers [3,4] and pneumatic dryers [5]. Because freshly-harvested paddy is a high surface moisture particulate material, an impinging stream dryer (ISD), which belongs to a unique class of dryers that has proven to be an excellent high-energy efficiency alternative to flash dryer for removing surface moisture of particulate materials [6,7], is one possible means for drying paddy, especially during the first drying stage where mostly surface moisture is to be removed.

The principle of an impinging stream dryer is the flow of two or more streams of gas, at least one containing wet particles, on the same axis but in the opposite directions. The two streams then impinge at the midpoint of their flow paths in an area called an impingement zone [8]. 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 use of impinging stream dryer for drying of particulate materials has been proposed and tested with various degrees of success by numerous researchers [9–13]. A review of the characteristics of various impinging stream dryers for particulate and pasty materials is available in Kudra and Mujumdar [14].

Recently, Sathapornprasath et al. [15] developed a prototype of a coaxial two-impinging stream dryer and evaluated its performance using resin as a test material. It was found that 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 volumetric heat transfer coefficient were found to increase with the inlet air velocity and particle flow rate at each inlet air temperature. The

* Corresponding author. Tel.: +66 2 913 2500; fax: +66 2 587 4336.
*E-mail address:* ccnimmol@gmail.com (C. Nimmol).

1359-4311/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2010.05.034

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 $kg_{water}/m^3$ h, while the maximum volumetric heat transfer coefficient was around 880 $W/m^3$ K. Although the prototype dryer could operate well with a model material (resin) having an initial moisture content in the range of 81–85% (d.b.), it could not be used with a real agricultural product (especially waste, which has high moisture content) as the dryer had severe problems in terms of the ability to control feeding of sticky materials as well as clogging within the inlet pipes.

To eliminate the above-mentioned shortcomings, Choicharoen et al. [16] modified the original impinging stream dryer of Sathapornprasath et al. [15] by increasing the diameter of the inlet pipes to allow easier flow of a drying material within the system. The screw-conveyor type particle feeding system was also replaced by a belt-conveyor type feeding system. The temperature controlling system was also modified by placing two heaters symmetrically on either side of the drying chamber in order to be able to independently control the inlet air temperature of each inlet stream. After the modification experiments were performed to evaluate the performance and energy consumption of the modified dryer using soy residue (okara) as a test material. 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. However, the effect of the impinging distance was dependent on the value of the inlet air velocity. It was also found that the volumetric heat transfer coefficient was insignificantly affected by 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. In terms of the specific energy consumption of the drying process, it was observed that the specific energy consumption of the high-pressure blower and electric heaters decreased with an increase of all the tested parameters, except for the impinging distance. The lowest specific energy consumption was found to be around 5.6 $MJ/kg_{water}$.

Although there have already been works on drying of various types of particulate materials in impinging stream dryers of different designs, information on the performance of an impinging stream dryer when being applied to freshly-harvested paddy, which needs to be dried in very large tonnage every day around the world, is still not available. The objective of the present study was to investigate the possibility of reducing the high initial moisture content of paddy by using an impinging stream dryer as a first-stage dryer. A coaxial two-impinging stream dryer prototype for paddy was developed and the effects of various operating and geometric parameters, i.e., inlet air temperatures of 110, 130 and 150 °C; particle flow rates of 130 and 150 $kg_{dry\ solid}/h$; impinging distances or spacings between the two opposed inlets of 5, 10 and 15 cm; and particle feeding characteristics viz. single-point feeding vs. double-point feeding; on the overall performance (in terms of the volumetric water evaporation rate and volumetric heat transfer coefficient) and energy consumption of the dryer were then investigated. In addition, the mean residence time of paddy at several combinations of geometric and operating conditions was investigated and used to clarify the experimental results.

## 2. Materials and methods

### 2.1. Experimental set-up

A schematic diagram of the coaxial two-impinging stream dryer is shown in Fig. 1. The dryer consists of a drying chamber made of stainless steel with the inner diameter of 0.39 m and having a volume of 0.046 $m^3$. Both inlet pipes of the drying chamber are 0.05 m in diameter. The drying chamber and the inlet pipes are insulated with fiberglass insulator in order to minimize the influence of heat losses on the dryer's performance calculation. Adaptors are attached to both inlet pipes inside the drying chamber to allow adjustment of the impinging distance. Two high-pressure blowers, each rated at 5 kW (Crelec, model HB-629, Shanghai, China), which could deliver a maximum pressure of 280 mbar at an air flow rate of 5.2 $m^3$/min, were used to supply the air to the system. The inlet air temperature was controlled by two electric heaters, each rated at 20 kW, which were controlled by two independently operated proportional-integral-differential (PID) controllers (DHC, model DHC1 T-D, Wenzhou, China) with an accuracy of ±1 °C. The inlet air temperature was recorded continuously by type K thermocouples connected to a data logger (Hioki, model 842-51, Tokyo, Japan). The wet-bulb temperature of the inlet air as well as the wet-bulb and dry-bulb temperatures of the outlet air were also monitored and recorded by a moisture sensor (Vaisala, model HM70, Helsinki, Finland). The wet-bulb and dry-bulb temperatures of the inlet air, $T_{wi}$ and $T_{di}$, were measured at points A and B (see Figs. 1 and 2). The wet-bulb and dry-bulb temperatures of the outlet air, $T_{wo}$ and $T_{do}$, were measured at point C. Air velocity in both inlet pipes was adjusted by means of globe valves and measured at points D and E by a pitot tubes, which were connected to a multifunction measuring device (Testo, model 445, Lenzkirch, Germany) with an accuracy of ±0.2 m/s. The paddy feed flow rate was controlled by adjusting the speed of a belt feeder, which received the paddy from the hopper located above the belt feeder. The speed of the belt feeder was adjusted by varying the revolution speed of a DC powered motor installed at the end of the belt feeder. Cyclone was used to separate dried paddy from the moist air. It should be noted that the cyclone was removed during the

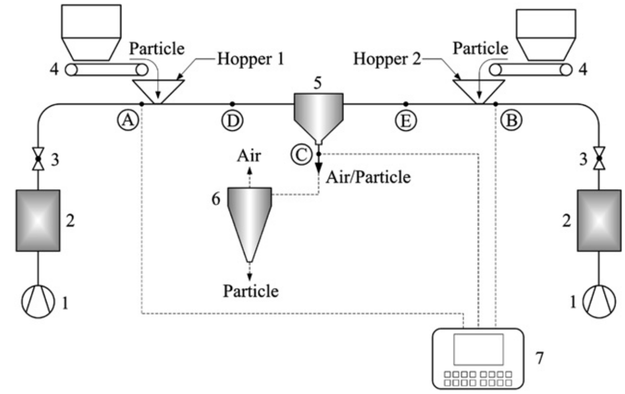


**Fig. 1.** A schematic diagram of the impinging stream dryer and associated units. 1) High-pressure blowers; 2) Electric heaters with PID controller; 3) Globe valves; 4) Belt feeders; 5) Drying chamber; 6) Cyclone; 7) Temperature data logger and humidity sensor.

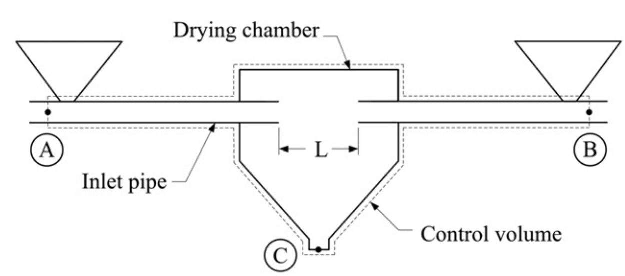


**Fig. 2.** Control volume for calculation of volumetric water evaporation rate and volumetric heat transfer coefficient.