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Paraboloid-Based Spouted Bed Drying of Paddy: Aerodynamics, Temperature Distribution, and Moisture Degradation

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Abstract: Aerodynamics, temperature variations in the annulus, and the moisture reduction of paddy in a paraboloid-based spouted bed (PBSB) dryer without draft tube and with solid and porous draft tubes were investigated. Draft tube caused a rapid decrease in the peak pressure drop and minimum spouting velocity when compared with PBSB without a draft tube. Pressure drops with draft tubes were 17 to 30% of the values for the PBSB without a draft tube. Temperature distribution along the bed height in the annular region during drying of paddy was also investigated. Heat-up in the spouted bed without draft tube was more rapid. The experiments were conducted for 70, 90, and 110 °C inlet air temperatures. The required length of drying time to dry the paddy with an initial moisture content of 0.35 db to a moisture content below 0.15 db could be reduced by 50–60% using a temperature of 110 °C instead of 70 °C. No constant rate period was observed. Drying took place in the falling rate period. Drying time decreased in the case of porous draft tube rather than the solid one. The highest drying rates were achieved by spouted bed without draft tube. Drying rates were in the range of 0.62–0.1, 0.51–0.06, and 0.37–0.06 (db.min^{-1}) for the spouted bed without draft tube, with porous, and solid draft tubes, respectively.

Keywords: spouted bed dryer; draft tube; drying kinetics; paddy

1. Introduction

Rice is an important crop because of the fact that it is a fundamental food for more than half of the world's population. The moisture content of rice after harvesting is usually higher than the safe level for storage. Therefore, drying becomes a crucial operation in order to preserve the quality of rice in storage [1]. Freshly harvested paddy has to be rapidly dried from moisture contents of 25–35% down to 18–20% (wet basis) for temporary storage. Further drying down to 12–14% is important for prolonged storage prior to milling [2].

Spouted bed technology in solid–gas systems [3] has proven to be an effective contacting way for gas and coarse solid particles, such as Geldart type D particles [4]. By far, drying of coarse and heat-sensitive granular materials has been the most well-known application of spouted beds. Agricultural products, wood chips, and various polymeric materials are some of these granular materials. In spouted beds, a high air temperature is permitted because of the agitation of solids, and so rapid drying occurs without the risk of thermal damage. A spouted bed is similar to a fluidized bed. However, in a spouted bed fluid moves through the spout region using a nozzle rather than a porous distributor as in the fluidized bed. The essential characteristics of spouted bed are comprised of the spout zone with solids moving upward by co-current gas flow and the downcomer zone with solids moving downward by counter-current gas flow [5]. A comparison between fluidized bed and spouted bed drying for seeds revealed that fluidized bed dryer had a faster drying rate, while a spouted bed dryer was better in terms of lower specific energy consumption [6]. In an operation like solids drying, use of porous draft tubes in a spouted bed helps in the lateral transport of hot air from spout to annulus region, thereby providing better contact between solid and fluid phases in the annular region as well [7].

Many modified spouted bed designs have been developed in the past few decades, such as the rotating jet spouted bed [8], pulsed spouted bed [9], industrial-scale prototype of continuous spouted bed dryer [10], pilot scale triangular spouted bed dryer [11], two-dimensional spouted bed batch dryer [12], paraboloid-based spouted bed dryer [13], slot-rectangular spouted bed [14], etc.

The experimental findings obtained for conventional cone-based spouted beds show that the individual particles in the annular part of the bed move vertically downward and radially inward, describing approximately parabolic trajectories. Spouted-bed bases with the same volume in different shapes—spherical, cone, and paraboloid—were used for the drying experiments to investigate the effect of the spouted-bed base shape on drying. A spherical-based spouted bed (SBSB), a cone-based spouted bed (CBSB), and a paraboloid-based spouted bed (PBSB) were compared for drying. It was seen that the geometrical shape of the contactor base influenced the drying time. The highest drying rate was achieved for drying in a paraboloid-based spouted bed [13].

In this study, drying of paddy was conducted in a paraboloid based spouted bed dryer (PBSB). The effects of the solid and porous draft tubes introduced into the PBSB on (a) thermal behavior of the annular region, (b) aerodynamics of the PBSB, and (c) moisture reduction of paddy, were investigated. The effect of the air inlet temperature in point of drying kinetics of paddy was also studied.

2. Experimental Set-Up and Procedure

The experimental set-up of PBSB dryer, developed by Evin et al. (2008), is shown in Figure 1. A screw air compressor (DVK-30, Turkey) is used to blow air to an air tank (103 L, 13 bar) that has a pressure gauge. Then air proceeds through an air filter, a pressure regulator, and two rotameters with a valve, respectively. An electric heater that is made of 5 fin strip heaters enclosed in an insulated sheet metal frame is used for heating air to the desired temperature. Each heater is 1 kW and can be controlled separately.

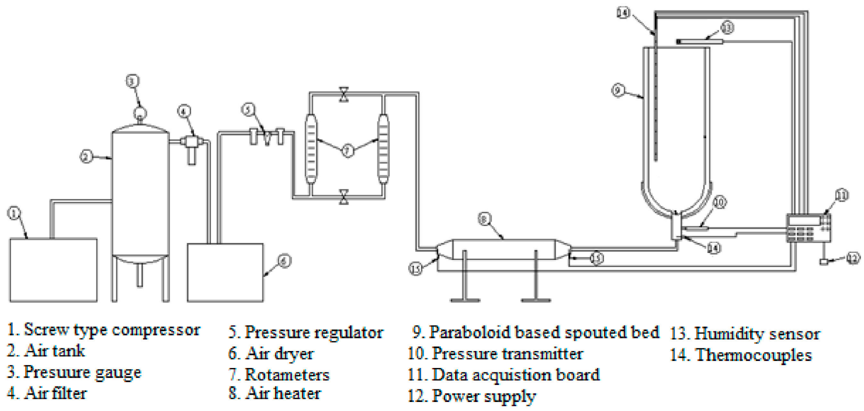


Figure 1. Schematic illustration of the experimental set-up.

The height of the paraboloid base was 131.3 mm. The diameters of the cylindrical column of the bed and the inlet nozzle of the spouted bed are 190 mm and 20 mm, respectively. Both the base and the column were insulated so as to avoid the heat loss.

Figure 2 shows the batch systems of PBSB without draft tube, with solid and porous draft tubes under steady state conditions. Porous and solid draft tubes were used in the experiments. The distance between the gas inlet nozzle and the bottom of the draft tube was held constant at 50 mm. This distance is called entrance zone. The draft tubes had a diameter of 50 mm and a length of 300 mm. The diameter of the holes of the porous draft tube was 1 mm.

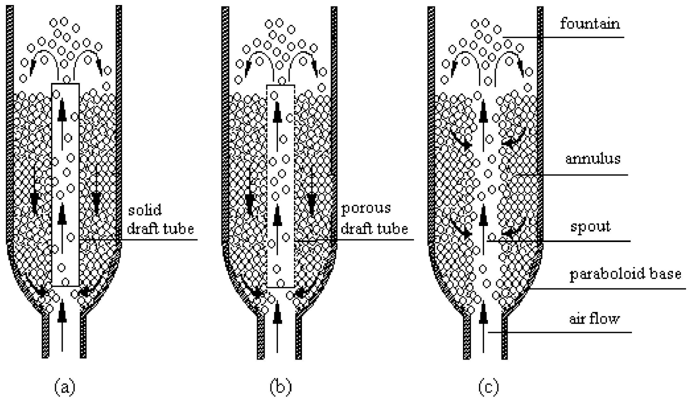


Figure 2. Schematics of the paraboloid-based spouted beds (PBSB) (**a**) with a solid draft tube, (**b**) with a porous draft tube, and (**c**) without a draft tube.

According to Geldart's classification (Geldart, 1986), the particles used in this work are group D particles, which are spoutable, large, and dense. Initial moisture content of paddy used for all the experiments is in the range of 0.31–0.35 kg water/kg dry matter (db). Before the drying experiments, a pressure transmitter (Omega PXM209, USA) was used at the inlet of the spouted bed to measure the total bed pressure drop ΔPs (13). Adequate flow rates for spouting of paddy for the beds without draft tube, with solid, and porous draft tubes were observed. Minimum spouting velocity for each condition was determined. Air flow rate and temperature were adjusted initially. The air flow rates were held constant at 58, 45, and 38 m^3/h without a draft tube, with a porous draft tube, and with a solid draft tube, respectively. Paddy was introduced into the PBSB after allowing the system to attain steady conditions. The weight of samples were measured by a digital balance (Sartorius GP5202, Göttingen, Germany) during the experimental runs. Two kilograms of solid were introduced into the dryer for each experiment. To measure the moisture content during the whole drying process, paddy samples were removed at 10 min intervals. For the determination of moisture content, an infrared moisture analyzer (Sartorius MA45, Göttingen, Germany) with a temperature range of 40–230 °C, adjustable in 1 °C increments and weighing readability of 1 mg, 0.001% moisture content, was used. This drying procedure was repeated for PBSB without a draft tube and with porous, and solid draft tubes at 70, 90, and 110 °C inlet air temperatures until the moisture content reduced approximately to 0.15 db. T type thermocouples (Omega TTSS, Norwalk, CT, USA) were used to measure the air temperature at the inlet of the spouted bed and also at the inlet and outlet of the heater. At the inlet of the spouted bed, air temperature was kept constant by means of a proportional–integral–derivative (P.I.D) controller (Hanyoung MX9, Incheon, Korea). Temperature along the bed axis (at H = 3–20 cm) in the annulus during drying of paddy was measured by a T type thermocouple (Omega TJ36, USA) with a 45 cm probe length fixed (at r = 4 cm) to an assembly mounted to the top of the cylindrical column. A data acquisition board (10) (Keithley 2700 data acquisition, Cleveland, OH, USA) was used to acquire the signals from the sensors.

3. Results and Discussion

Bed pressure drop is important to verify steady spouting. Figure 3 shows the variation of pressure drop with air velocity for PBSB with and without draft tubes. Flow characteristics for wet paddy in PBSB were recorded according to the slowly decreasing air flow. The pressure drop increased suddenly when a slight reduction of gas velocity caused the spout to collapse. This velocity is called minimum spouting velocity. Minimum spouting velocities for PBSB without a draft tube, with porous, and solid draft tubes are 0.48, 0.23, and 0.17 m/s, respectively. This figure also indicates the effect of the solid and porous draft tube on pressure drop. Peak pressure drop and minimum spouting velocity for PBSB with a draft tube decreased rapidly compared to PBSB without a draft tube. This means draft tube provides an important advantage in point of energy saving. While peak pressure drop for spouted bed (SB) without a draft tube was 4.57 kPa, it was 1.36 and 0.86 kPa for spouted beds with porous and solid draft tubes, respectively. Pressure drops with draft tubes were 17 to 30% of the values for the PBSB without a draft tube. Altzibar et al. (2008) obtained a similar result in their study with nonporous, porous, and open-sided draft tubes in order to ascertain the optimum configuration of this internal device [15].

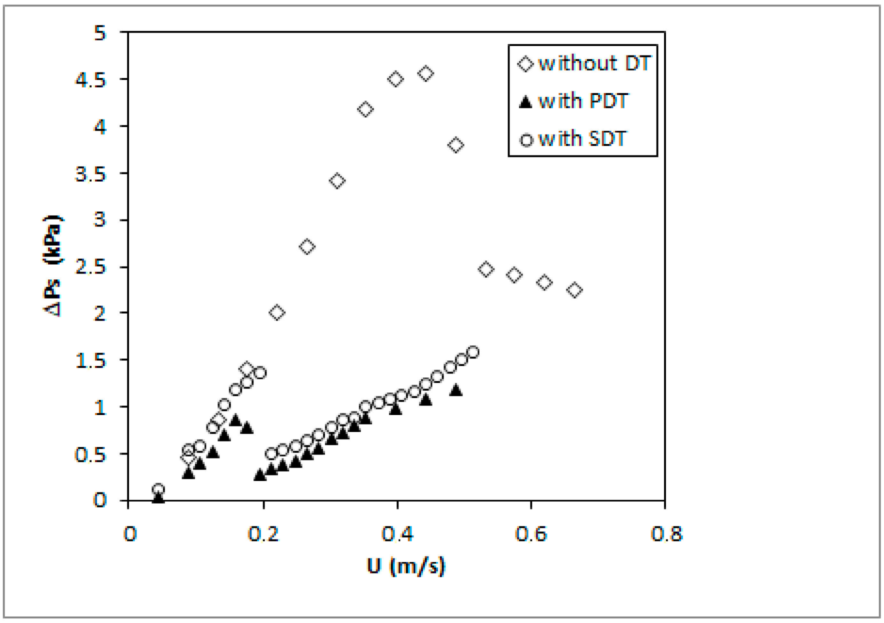
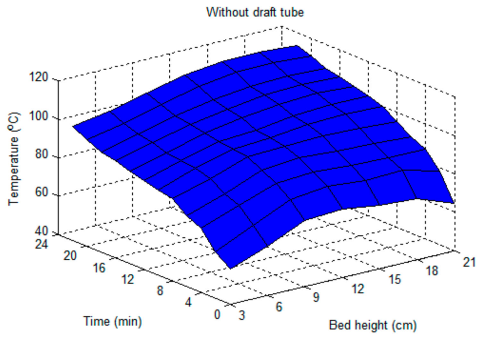
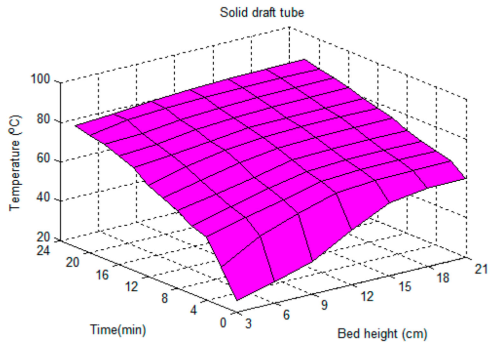


Figure 3. Bed pressure drop–air velocity curves for PBSB without and with solid and porous draft tubes.

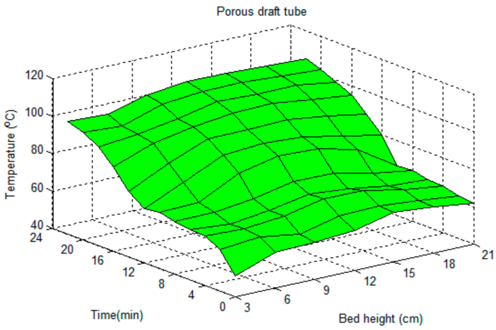
Temperature distribution along the bed height in the annular region (r = 0.004 m) during drying of paddy is shown in Figure 4 without draft tube and with solid and porous draft tubes. Temperatures at eight points along the height of the column were recorded during the whole drying process, which caused reduction in moisture content of paddy. According to the simulated results obtained in the literature, grain and air temperatures approached equilibrium within a few centimeters upstream from the inlet [10]. Therefore, temperature measurements should represent the grain temperature. As can be seen, paddy temperature decreased during the downstream movement in the annulus for all cases. A similar result was observed by [12]. Figures show that, heat-up in the spouted bed without draft tube was more rapid. This implies more efficient contacting in the spouted bed. The solid draft tube prevented radial gas percolation from the draft tube to the annulus. After twelve minutes of paddy drying, bed temperatures (at H = 14 cm, r = 4 cm) were 100, 83, and 70 °C for SB without draft tube, with porous and solid draft tubes, respectively. As can be seen, higher air temperatures can be achieved for PBSB without draft tube. However, the minimum spouting velocity is also higher in this case. Consequently, this will affect adversely the process efficiency. The curves show that air temperature increased with the drying time and also with the axial position in the annular region. However, especially at the progressive drying times, no pronounced difference in temperatures at different axial positions for the solid draft tube spouted bed was observed. This will adversely affect efficiency.



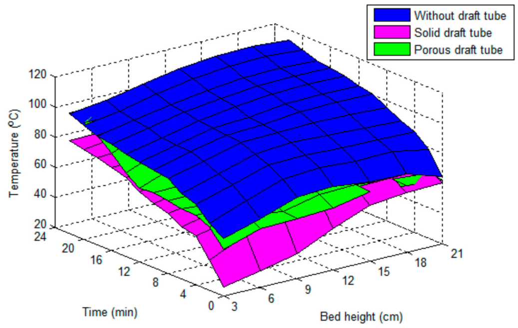
(**a**) without draft tube



(**b**) without draft tube



(**c**) with porous draft tube



(**d**) comparison

Figure 4. Temperature distributions along the bed axis during drying of paddy in PBSB (T_i = 110 °C; r = 0.04 m).

Drying curves for PBSB drying of paddy without draft tube, with porous and solid draft tubes are shown in Figures 5–7, respectively. The drying process is characterized by a progressive decrease in moisture content with time. The change in moisture content with time follows the exponential decay, implying that the internal resistance controls the moisture content. Air temperature is an important factor influencing the drying rate. Effect of air temperature in the range of 70–110 °C on SB drying of paddy is significant in these figures for all drying conditions. Drying time increased with the decreasing air temperature. A sharp decrease occurred in moisture content at 110 °C. While moisture content of paddy reduced to 11.13% db after 30 min of drying in PBSB without draft tube at 110 °C, it reduced to 16.5 and 19.6% db at 90 and 70 °C air inlet temperatures for the same drying time, respectively (Figure 5). The required length of drying time to dry the paddy to moisture content below 15% db could be reduced by 60% using a temperature of 110 °C instead of 70 °C for PBSB without a draft tube.

Figure 8 represents drying rate variation with moisture content of paddy during spouted bed drying. Especially in the spout region, the whole surface of paddy is in contact with the hot air, therefore surface moisture is evaporated rapidly due to the high heat and mass transfer coefficients. It is seen from the figure that no constant rate period was observed. The curve shows only the falling rate period. Solid and porous draft tubes located at the axis of the PBSB has a considerable effect on drying of paddy. The highest drying rates were achieved by spouted bed without draft tube. Drying rates were in the range of 0.62–0.1, 0.51–0.06, and 0.37–0.06 (db·min^{-1}) for spouted bed without draft tube, with porous draft tubes, and solid draft tubes, respectively. These results indicate that draft tube causes a decrease in drying rate. In the annulus region, the moisture and temperature gradients are being homogenized besides drying. This can be called as tempering. However, the draft tube prevents radial gas percolation from the spout region to the annulus. Therefore, the required contact between paddy and hot air cannot be provided. In that course, drying time increases as can be seen from the figure. Internal diffusion is essential in the falling period where time is required to transfer moisture through the grain. The annulus region absolutely acts as a tempering period allowing time for the internal moisture to migrate to the surface before paddy travels to the spout region again in a cyclic fashion. Porous draft tube caused a decrease compared to the solid one for PBSB. Similarly, Altzibar et al. (2008), showed that the drying time required when using porous draft tubes was much shorter than that needed when nonporous ones were used; the required drying time was around half or even less [15]. They stated that conventional nonporous draft tubes were also very stable but perform poorly due to gas by passing through the spout.

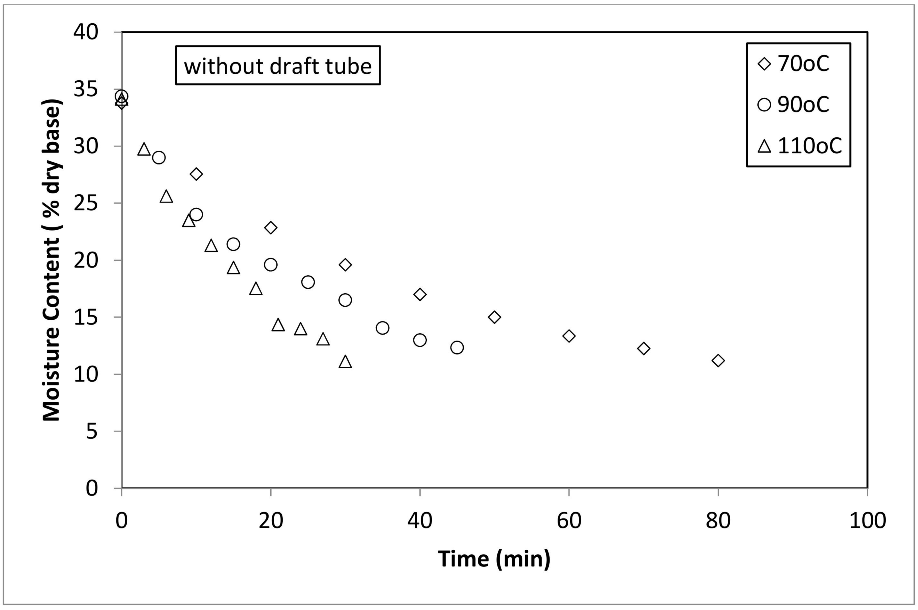


Figure 5. Moisture content variation during drying of paddy in PBSB without draft tube at different air temperatures.

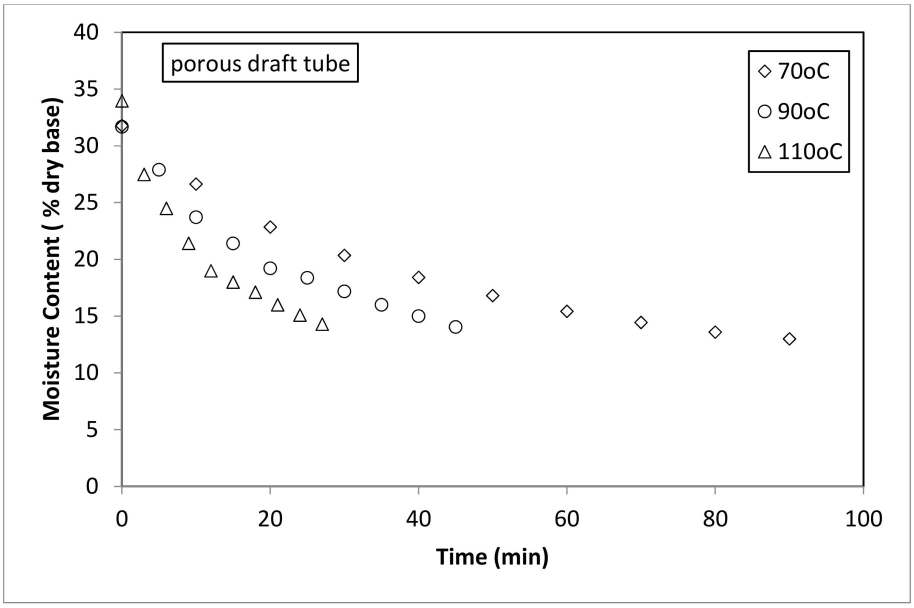


Figure 6. Moisture content variation during drying of paddy in PBSB with porous draft tube at different air temperatures.

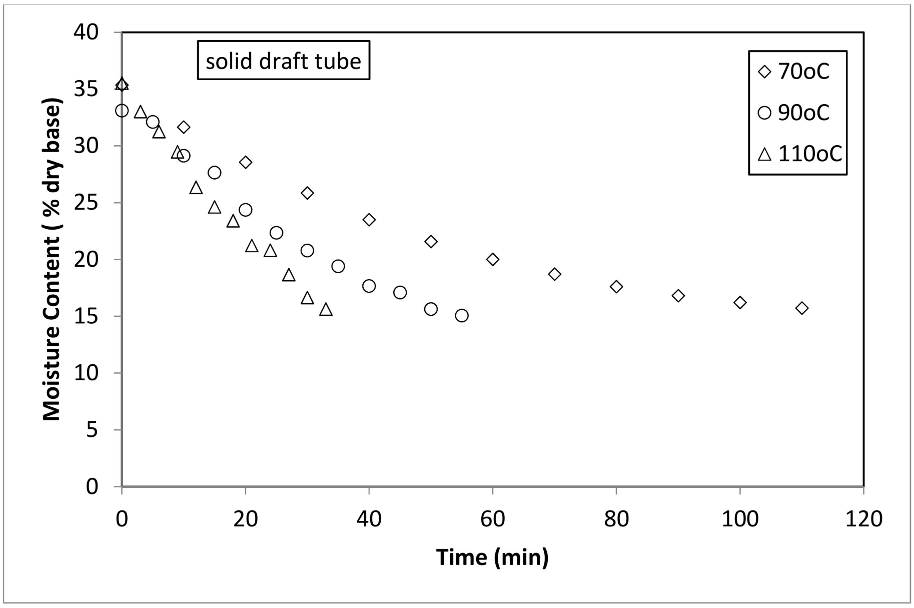


Figure 7. Moisture content variation during drying of paddy in PBSB with solid draft tube at different air temperatures.

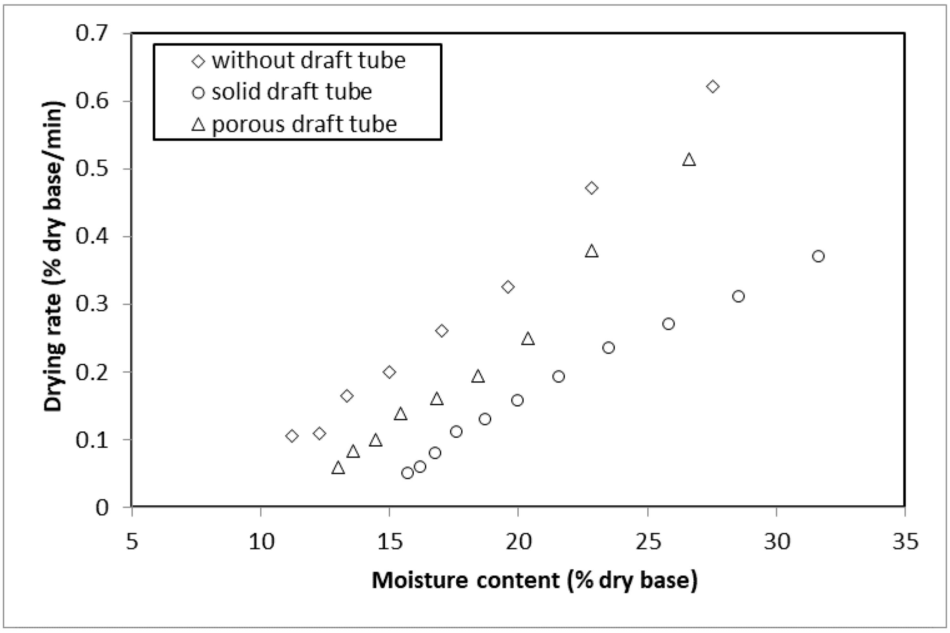


Figure 8. Drying rate versus moisture content during drying of paddy in PBSB without and with solid and porous draft tubes.

4. Conclusions

Draft tube provided an important advantage in point of energy saving. Pressure drops with porous and solid draft tubes were 17 to 30% of the values for the PBSB without a draft tube. Drying time increased with the decreasing air temperature. Heat-up in the PBSB without draft tube was more rapid. This implied more efficient contacting in the spouted bed. Air temperature increased with the drying time and also with the axial position in the annular region. Draft tube caused an increase in drying time. However, compared to the solid draft tube, drying time in the case of porous one is lower. Drying took place in the falling rate period. The highest drying rates were achieved by spouted bed without draft tube. Drying rates were in the range of 0.62–0.1, 0.51–0.06, and 0.37–0.06 (db·min^{-1}) for the spouted bed without draft tube, with porous, and solid draft tubes, respectively.

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Conflicts of Interest: The author declares no conflict of interest.

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