Abstract: This study examines the performance of three heat pump dryers: the original reference design, a modified drying chamber, and an external desiccant wheel design. Unlike most existing studies that normally adopt organic products as the drying materials, in this study we used moist sodium polyacrylate (Orbeez) as the drying material for consistent characterization of the heat pump performance. R-134a was adopted as the refrigerant for the heat pump system. The experiments were performed subject to different weights of Orbeez (drying material) at a constant volumetric flow rate of 100 m$^3$/h. During experimentation, different parameters like the coefficient of performance ($\text{COP}_{\text{HP}}$), drying rate, heat transfer rate by the condenser, moisture extraction rate, and specific moisture extraction rate were calculated. The average $\text{COP}_{\text{HP}}$, mass transfer rate, heat transfer rate, MER, and SMER of the system were calculated as 3.9, 0.30 kg/s, 0.56 kW, 0.495 kg/h, and 1.614 kg/kWh, respectively. The maximum COP for the refrigeration system was achieved at lower test loads with the desiccant wheel. The moisture extraction rate for a lower test loading was higher than that for a higher test load due to the higher penetration of drying air at the lower test load, although the maximum test load showed the maximum relative humidity at the dryer outlet. The desiccant wheel showed good performance in terms of moisture extraction rate and $\text{COP}_{\text{HP}}$, but it showed poor performance in terms of the specific moisture extraction rate due to the high power consumption (around 2.6 kW) of the desiccant dehumidifier. The moisture extraction rate (MER) for all designs increased to a maximum value, followed by consistent decline. However, the maximum MER for the desiccant design exceeded those for the other designs.

Keywords: Orbeez; heat pump dryer; desiccant wheel; coefficient of performance

1. Introduction

Drying is widely used in polymer, food, pharmaceutical, mineral, and other industrial processes. However, current commercially available dryers mainly adopt hot air to complete the drying process, and most of the traditional hot air dryers use direct electric heating to raise the inlet air temperature to evaporate the moisture contents of the dry matter. The drying process is strongly associated with ambient conditions in terms of humidity. This is an especially essential consideration in tropical or subtropical countries where the humidity is comparatively high. For example, the average relative humidity in Taiwan is greater than 70% throughout the year, thereby imposing difficulties in drying systems and consuming more energy in the heating process.

An alternative drying process is via heat pump, which transports heat energy from a low temperature source to a high temperature source with supplied work. It can offer much larger thermal energy at the expense of much lower input work. Heat pumps have potential applications in heating, ventilation, and air conditioning, water heating, district heating,
and industrial heating, and heat pump dryers (HPDs) are energy efficient when compared to conventional heater dryers. Conventional dryers possess numerous limitations, such as non-homogeneous product quality caused by under/over-drying due to inadequate or long-time exposure of the product. Besides this, the lower contact efficiency between the product being dried and the drying medium is also a big issue. Furthermore, over-drying may result in surface hardening of the drying product. The aforementioned problems cause very poor drying and increase operational costs, which is especially likely with traditional drying. Hence, many efforts have been made in the literature to resolve these limitations of conventional drying methods. These efforts include improving the product quality and overcoming the operational problems. Most of the conventional drying methods (either by convection or direct heating) employ fossil fuels as the power source and are thereby accompanied by greenhouse gas emissions and pollution, which are a prime concern. Biomass and renewable energy may be incorporated to tackle this problem, but again, concerns regarding better preservation and drying product quality may prevail. This is because the quality and the cost of the drying product are directly influenced by the drying method and the operational conditions. Another important point to be considered is reliable and consistent product quality when using the same drying method.

In tackling the aforementioned problems, the HPD system has been proven a good solution. The HPD system has several advantages. Firstly, it can be used for effective heat recovery. Secondly, it offers a wide range of operational conditions (humidity, air temperature) that help to achieve better quality. Thirdly, the drying process can be performed at relatively low temperature to preserve the quality of the drying product. This is because the HPD systems employ dehumidified and low-temperature air as the drying medium. A short summary of experimental investigations on HPD systems for the drying of different products can be found in Table 1. From Table 1, an HPD is applicable for the drying of various products, including vegetables, fruits, etc., and studies evaluated the HPD system in terms of different performance metrics of the drying process, such as weight reduction, moisture extraction rate, specific moisture extraction rate, coefficient of performance, and heat transfer rate for different time durations. However, the foregoing studies mainly focused on different organic products, which are normally quite sensitive to drying conditions. Hence, one of the main objectives of this study is to adopt a non-organic drying material for examination to characterize the more general performance of a heat pump dryer. Moreover, limited investigations can be found in the literature regarding the development and assessment of new HPD system designs. Especially for humid environments, some systems should be integrated with an HPD to pre-condition (pre-dehumidify and pre-heat) the air before it enters the dryer. Thus, the present study examines the applicability of adding a desiccant rotary wheel along with the HPD.

In order to increase the drying efficiency of the traditional heat pump dryer and pre-condition the humid air before it enters the dryer, in this study, we developed an adsorption dehumidification device at the entrance of the traditional heat pump dryer, namely, a desiccant rotary wheel, to reduce the inlet humidity and use the energy released by the adsorption process to increase the inlet temperature. Subsequently, the applicability of this design is elaborated in detail. Experiments were performed to evaluate the drying performance on Orbeez material (sodium polyacrylate) over a period of eight hours. Moreover, experiments were conducted with a modified drying chamber to achieve better drying by improving the air distribution and reducing the air resistance. For each case, various performance parameters such as the weight reduction, moisture extraction rate, specific moisture extraction rate, coefficient of performance, and heat transfer rate were calculated for a constant flow rate.
Table 1. A summary of experimental investigations on HPD systems for drying.

| Dried Product Ref. | Product Initial Mass (kg) | Moisture Content Initial | Moisture Content Final | Wc (kW) (QEV (kW) | DT (°C) | RH (%) | MER kgw/h (MC%/h) | Drying Time (hr or min) | SMER (kgw/kW.h) (COP) |
|--------------------|--------------------------|--------------------------|------------------------|-------------------|---------|--------|-------------------|------------------------|------------------------|
| Vegetable seeds [1] | 0.2                      | 30 (N/S)                 | No                     | 6 (N/S)           | No      | 30     | 55                | No                     | 30                     | 3.1–4.48              |
| Paddy [2]          | 1200                     | 30–35 (w.b.)             | 13 (w.b.)              | 4.2               | No      | 42, 26 | 26, 14            | 8–15.9                 | 15–16 h               | 2.0                   |
| Potato slices [3]  | No                       | 4 kgw/kg                 | 0.5–1 kgw/kg           | (2–3.52)          | No      | 40     | 25, 30            | (32–44)                | 40                     | ~240 min              |
| Mushroom [4]       | 1                        | 203 (d.b.)               | 12 (d.b.)              | No                | 40.6    | 28.4   | 16.2              | DED                    | No                    | 30 to 81 h (total)     |
| Cranberry and potato [5] | No               | 84 (w.b.)                | 15 (w.b.)              | No                | −13 to  −13 to | 85 to 15 | 26, 14            | 8–15.9                 | 2 h                   | ~2.73                   |
| Chopped alfalfa [6] | 3.6                      | 70 (w.b.)                | 10 (w.b.)              | 0.424             | 30–40   | No     | 0.288             | 4 (batch)              | 2 h                   | ~2.73                   |
| Tomato [7]         | No                       | 23 (d.b.)                | 0.1 (d.b.)             | 2.2–2.6           | 40, 45, 50 | 10 to 15 | DED              | ~1000 min              | (2.56–2.68)           |
| Specialty crops [8] | 11.6–20.7                | 62.7–89.6 (w.b.)         | 5.1–10.8 (w.b.)       | No                | 30 & 35 | No     | DED              | 3.3–120 h              | 0.06–0.61              |
| Jew’s mallow, spearmint, and parsley [9] | 2.5–7.5                | 81–83 (w.b.)             | 6 (w.b.)              | No                | 40, 45, 50 | No     | DED              | 4.75 to 6.35 h         | DED                   |
| Ginger [10]        | 0.1                      | No                       | No                     | No                | 45      | 10     | DED              | 8 h                    | No                    |
| Ginger [11]        | 0.2                      | 800 to 900 (d.b.)        | 12 (d.b.)              | No                | 40      | 50, 60 | DED              | 120 to 200 min         | No                    |
| Shredded radish [12] | 200                     | 95                       | 16                     | 15 (CD)           | 40      | 30     | No               | 6.3                    | 25 h                  | 1.5 (3–4)              |
| Green sweet peppers [13] | 0.025                 | 1453 (d.b.)              | −10.7 (d.b.)           | No                | 35      | 27     | DED              | 16, 25 & 36 h          | 0.55 to 1.1            |
| Olive leaves [14]  | No                       | 69.55 (N/S)              | 5.17 (N/S)             | No                | 45–55   | No     | No               | 270 to 390 min         | No                    |
| Grain [15]         | ~1000                    | 21.3                     | 12.5                   | 14.6              | −69     | No     | 103.6             | ~1 h                   | −4.28                 |
| Saffron [16]       | 0.5                      | 80 (w.b.)                | 10 (w.b.)              | DED               | 40, 60  | No     | No               | ~0.5 h                 | 0.5–1.1                |
| Ivy gourd leaves [17] | 0.035                  | 17 (d.b.)                | 4 (d.b.)               | 0.25              | 20, 35, 50 | 35, 60 | No               | DED                    | 1 to 2 h              | (1.2)                 |

2. Equipment and Methods

In the current study, we develop a heat pump dryer (HPD) to assess the performance of a closed-loop heat pump dryer system. In total, three designs were made and tested, including an original reference design, a modified drying chamber with better airflow distribution and less flow resistance, and a desiccant wheel on top of the modified design. Moreover, the assessment was extended to examine various parameters in a transient state. In the current study, the refrigerant used for the HPD was R-134a. A single external blower was used to circulate the air in a closed loop for eight hours. The experiments were performed on different weights of Orbeez (drying material) at a constant volumetric flow rate of 100 m³/h (0.5 m/s velocity). During experimentation, different parameters like the COPHP, drying rate, heat transfer rate by the condenser, moisture extraction rate, and specific moisture extraction rate were calculated.

Figure 1 illustrates the schematic of the heat pump dryer. The experimental setup was developed in order to validate or verify the system performance of the HPD. In addition to the four basic components of refrigeration—compressors, condensers, expansion valves, and evaporators—the system included an adsorption wheel (Dehutech, DA/DT-450, Täby, Sweden, Total Power Connection 3.5 kW) acting as an external dehumidifier, heat exchangers, electronic scales, and a drying chamber. Drying air is heated by the condenser of the HPD, and the low-relative-humidity air flows into the drying chamber via centrifugal fan. Subsequently, the hot and dry air absorbs moisture from the wet material, yielding highly humid air at the outlet of the dryer chamber. Afterwards, the humid air enters the evaporator to remove its moisture content. Temperature and humidity sensors were installed at the inlet and exit of the test box, and the measurement temperature and humidity value were transmitted to the data extractor via a signal transmitter, with a temperature range of −100 °C to 200 °C, an accuracy of 0.1 °C, a humidity range of 0% to 100%, and an accuracy of 0.8%.
Figure 1. Heat pump dryer with an external dehumidification system.

Then, a flowmeter (SCHMIDT Technology SS30.302, Georgen, Germany) with a measuring range from 1.5 to 417 m$^3$/h of 20 °C and 1013.25 hPa, accuracy: ±3% of m.v. +0.3% of full scale, was employed to measure the changes in air speed in the circulated airflow and the static pressure of the airstream lifted by the blower; then a desiccant wheel was installed to further lower the humidity of the airstream, and the low-humidity air enters the condenser to lower the relative humidity to complete the air cycle. The voltages and currents of the compressor and blower were measured using a power meter (Arch Meter Corporation PA310, measurement range from 0 to 200A, accuracy 0.5%.

2.1. Drying Material

Orbeez or sodium polyacrylate (or Acrylic Polymer Salt sodium) was used as a drying material as it can absorb 200~300 times its mass in water. Sodium polyacrylate is used in many products, such as items for baby and feminine use, surgical sponges, fuel, cables, etc. Dry and wet Orbeez are shown below in Figure 2. The diameter of the Orbeez increased from 2.75 mm to 15.5 mm after absorbing water, and its porosity was 47.64% at the beginning of the test.

Figure 2. Dry and wet Orbeez (as a drying material).

2.2. Design of the Drying Chambers

In the current research work, the drying chamber was modified to improve the system efficiency and drying rate for the material subject to different test loads under a constant flow rate.

Figure 3 shows the original drying chamber where the drying air enters through the small blower from the corner side. There are only few holes in the second bucket for passing airflow to facilitate drying. For more efficient drying, a new drying chamber was developed to enhance the drying rate, to decrease air resistance, to consume less auxiliary power, and to increase the effective surface area for higher heat and mass transfer between the hot air and wet product. A schematic of the modified design is shown in Figure 4.
2.2. Design of the Drying Chambers

In the current research work, the drying chamber was modified to improve the system efficiency and drying rate for the material subject to different test loads under a constant flow rate.

Figure 3 shows the original drying chamber where the drying air enters through the small blower from the corner side. There are only few holes in the second bucket for passing airflow to facilitate drying. For more efficient drying, a new drying chamber was developed to enhance the drying rate, to decrease air resistance, to consume less auxiliary power, and to increase the effective surface area for higher heat and mass transfer between the hot air and wet product. A schematic of the modified design is shown in Figure 4.

Figure 3. Heat pump drying chamber.

Figure 4. Schematic of the modified drying chamber.

2.3. Data Analysis

2.3.1. Coefficient of Performance

The coefficient of performance (COP) of an HP is used in a drying process to calculate the energy consumption of the system. The heat energy supplied in the condenser was evaluated using Equation (1). The analysis was divided into two parts: heat transfer and operating cost.

\[
\text{COP} = \frac{\dot{Q}_{cd}}{\dot{W}_{comp}} \tag{1}
\]

\[
\dot{Q}_{cd} = \dot{m}_{ia} C_{p,air} (T_{co} - T_{ci}) \tag{2}
\]

\[
\dot{m}_{ia} = \rho_{ia} \dot{V}_i \tag{3}
\]

Here,

- \(\dot{Q}_{cd}\) = heat transfer rate by condenser (kW);
- \(\dot{m}_{ia}\) = mass flow rate of dry air (kg/s);
- \(C_{p,air}\) = specific heat of dry air (kJ/kg K);
- \(T_{co}\) = condenser outlet temperature (°C);
- \(T_{ci}\) = condenser inlet temperature (°C);
- \(\rho_{ia}\) = density of air (kg/m³);
- \(\dot{V}_i\) = volumetric flow rate (m³/h).
2.3.2. Moisture Content (Wet Basis %)

The moisture content (MC) for moist Orbeez can be calculated on a wet basis (\(w.b\)) as

\[
MC_{w.b} \, (\%) = \frac{W_w}{W_p} \times 100
\]  

(4)

where
\[W_w = \text{weight of water in material};\]
\[W_p = \text{total weight of material}.\]

The moisture ratio was determined by the following equation

\[
M = \frac{M - M_e}{M_o - M_e}
\]  

(5)

The drying rate (\(DR\)) was calculated from the change in moisture content for sodium polyacrylate that occurred in each consecutive time interval by using the equation

\[
DR = \frac{(M_{t+dt} - M_t)}{dt}
\]  

(6)

where
\[DR = \text{drying rate (kg_{water}/kg_{dry solid}).}\]

The relative humidity was measured at four points during heat pump drying: two at the dryer inlet and two at the evaporator outlet and condenser inlet. The amount of water removed per hour is called the moisture extraction rate or water removal rate (\(MER\)). The \(MER\) represents the effectiveness of a dryer in terms of water removal. It can be calculated from the humidity ratios by using the temperature and relative humidity at the dryer inlet and outlet:

\[
MER = \dot{m}_{da}(\omega_{\text{d out}} - \omega_{\text{d in}})
\]  

(7)

where
\[MER = \text{moisture extraction rate (kg/h)};\]
\[\dot{m}_{da} = \text{mass flow rate of dry air (kg/s)};\]
\[\omega_{\text{d out}} = \text{Humidity ratio at dryer outlet (kg_{DA}/kg_{DA})};\]
\[\omega_{\text{d in}} = \text{Humidity ratio at dryer inlet (kg_{DA}/kg_{DA})}.\]

The term \(SMER\) is related to the power consumption and is determined using the following equation:

\[
SMER = \frac{\dot{m}_{da}(\omega_{\text{d out}} - \omega_{\text{d in}})}{W_{\text{comp}} + W_{\text{blower}}}
\]  

(8)

where
\[SMER = \text{moisture extraction rate (kg/kWh)};\]
\[\omega_{\text{d out}} = \text{humidity ratio at outlet (kg_{DA}/kg_{DA})};\]
\[\omega_{\text{d in}} = \text{humidity ratio at inlet (kg_{DA}/kg_{DA})};\]
\[\dot{m}_{da} = \text{mass flow rate (kg/s)};\]
\[W_{\text{comp}} = \text{compressor output power (kWh)};\]
\[W_{\text{blower}} = \text{blower output power (kWh)}.\]

The experiment would have been affected by the environment or the accuracy of the parameters, so the uncertainty of the mean values of measured and calculated parameters was calculated and presented in Table 2.
### Table 2. Uncertainty of mean values of measured and calculated parameters.

| Parameter                                         | Symbol | Unit       | ± Value  |
|---------------------------------------------------|--------|------------|----------|
| Blower power consumption                          | $W_b$  | kW         | ±0.3     |
| Compressor power consumption                      | $W_c$  | kW         | ±0.056   |
| Heat transfer rate at condenser                    | $Q_{cd}$ | kW         | ±0.736   |
| Moisture extraction rate                           | MER    | kg/hr      | ±0.45    |
| Specific moisture extraction rate                  | SMER   | kg/kWh     | ±0.336   |
| Air mass flow rate                                 | $n$    | kg/s       |          |
| Coefficient of performance of heat pump            | COP    | -          | ±0.458   |
| Moisture content                                  | MC     | g water/g wet material | ±0.024   |

### 3. Results and Discussion

Figure 5 illustrates the drying cycle in a psychrometric chart for the airstream for a typical heat pump dryer and the heat pump dryer with an integrated desiccant wheel. In Figure 5, the drying air across the desiccant wheel is denoted 5→1, and state 1→2 represents sensible heating at the condenser while the humidity ratio is constant. The state 2→3 is for the airstream in the drying chamber to facilitate the drying process. State 3→4→5 represents the sensible cooling and dehumidification of the humid air at the evaporator.

![Psychrometric representation of drying air paths of both systems.](image)

In this section, we discussed various aspects such as the variation in the drying air temperature, variation in the relative humidity at the dryer inlet, comparative RH% at the dryer outlet, moisture content (% wet basis), weight reduction, moisture extraction rate, specific moisture extraction rate, heat transfer rate, and coefficient of performance for different HPD system designs including the original design, a modified drying chamber, and an HPD with a desiccant dehumidifier with 4 kg or 7 kg of drying material.

#### 3.1. Variation in the Drying Air Temperature at the Inlet of the Drying Chamber

Figure 6 shows the variation in the drying air temperature with time for different designs with variable test loads. The results are provided only for the maximum and minimum test loads under transient conditions and a constant volumetric flowrate of 100 m$^3$/h. During the operation, the temperature gradually increased and later showed asymptotic behavior to reach a nearly steady state for all three designs (original, modified, and with a desiccant wheel (DW)) subject to 4 kg or 7 kg of drying material. For the original design, a steady-state temperature of 50 °C for both 4 kg and 7 kg was observed with an average relative humidity of 25% at the dryer inlet.
Variation in the relative humidity at the dryer inlet for all three cases.

Figure 6. Variation in the drying air temperature at the dryer inlet.

Also, Figure 6 shows that the temperature increment for a test load of 4 kg with a modified drying chamber reached steady state earlier than the original design. This is because the air resistance was decreased and a better airflow distribution into the drying chamber prevailed. For the case with a desiccant wheel, slightly higher RH% was observed (1–2%), the average temperature across the condenser was 51–54 °C, and the time to reach steady state was even shorter. The temperature profile at the dryer inlet for the 4 kg test load with the desiccant wheel was slightly higher than those for the other cases. This is somewhat expected due to the generated adsorption heat accompanying the desiccant.

Figure 7 indicates the relative humidity at the inlet of the drying chamber for different designs with different test loads. Upon operation, the relative humidity decreased appreciably initially and approached a rather low RH accordingly. Figure 7 indicates that the respective initial values of the relative humidity of the drying air at the inlet of the drying chamber were about 57.1%, 80%, and 60% for the three designs. However, the final RHs of the original and modified designs for 4 kg and 7 kg test loads reached average steady relative humidity levels of 24% and 27%, respectively. On the other hand, upon introducing the desiccant wheel dehumidifier, the average relative humidity was observed to plunge further to only around 1–2%. The relative humidity at the drying chamber inlet was maintained below 2.5% with the desiccant wheel dehumidifier during the eight hours experimentation.

Figure 7. Variation in the relative humidity at the dryer inlet for all three cases.
3.2. Comparison of the RH at the Dryer Outlet

Figure 8 indicates the relative humidity levels at the dryer outlet for variable test loads on three different designs. The drying rates shown in the figure can be categorized into transient, constant, and falling rates. At the beginning, the original and modified designs show the maximum RH at the outlet of the drying chamber. For the test load of 7 kg, the air resistance of the bucket was much higher for the original design as compared to the others, and the material possessed a large water content, thereby resulting in a rather low dehumidifying process and a high relative humidity, accordingly. With the introduction of the modified drying chamber, a better heat and mass transfer process occurred; consequently, the RH at the outlet dropped consistently from the initial peak toward a lower value in a steady manner. This was further made clear with the introduction of the DW dehumidifier, where an even lower RH prevailed for the much lower inlet RH at the inlet of the drying chamber, as depicted in Figure 7.

![Figure 8. Variation in the relative humidity at the dryer outlet.](image)

3.3. Moisture Content (% Wet Basis)

Figures 9 and 10 illustrate the effect of test loads (4 kg and 7 kg with initial moisture contents (wet basis) of 98% and 99%, respectively) on the drying process of the heat pump dryer subject to an air velocity of 0.5 m/s under transient conditions. Before the experiment, the dry weight of the material was calculated, and it was then immersed in water for three hours. The comparison here is based on the dry weight and wet weight. In the graph, the moisture content of the Orbeez is given as a function of time. After drying, the moisture content or water content was reduced. For 4 kg loading, the modified drying chamber showed better drying performance compared to the original design and the design with a desiccant dehumidifier.

This is because the modified drying chamber experiences much lower air resistance, and the drying rate is therefore relatively effective. The graph also illustrates that the moisture decreased from 99% to 97% for the original design, from 99% to 87% for the modified drying chamber, and from 99% to 94% for the DW design. The lowest moisture reduction was observed in the original design.
for three hours. The comparison here is based on the dry weight and wet weight. In the graph, the moisture content of the Orbeez is given as a function of time. After drying, the moisture content or water content was reduced. For 4 kg loading, the modified drying chamber showed better drying performance compared to the original design and the design with a desiccant dehumidifier.

**Figure 9.** Variation in the moisture content at the minimum test load.

![Graph showing moisture content variation](image)

**Figure 10.** Variation in the moisture content at the maximum test load.

This is because the modified drying chamber experiences much lower air resistance, and the drying rate is therefore relatively effective. The graph also illustrates that the moisture decreased from 99% to 97% for the original design, from 99% to 87% for the modified drying chamber, and from 99% to 94% for the DW design. The lowest moisture reduction was observed in the original design.

3.4. Weight Reduction

As the drying continued, the weight of the Orbeez material was gradually reduced due to the evaporation or loss of moisture from the surface of the material. Initially sensible heat was transferred to the material’s surface and caused the moisture to evaporate quickly. The weight reductions of the moisturized Orbeez were observed to be (for a starting weight of 4 kg) 1.6 kg, 0.5 kg, and 1 kg in different cases in eight-hours experiments with an average mass flowrate of 0.031 kg/s and drying air temperature in the range of 48 °C to 54 °C (see Figure 11).
3.4. Weight Reduction

As the drying continued, the weight of the Orbeez material was gradually reduced due to the evaporation or loss of moisture from the surface of the material. Initially, sensible heat was transferred to the material's surface and caused the moisture to evaporate quickly. The weight reductions of the moisturized Orbeez were observed to be (for a starting weight of 4 kg) 1.6 kg, 0.5 kg, and 1 kg in different cases in eight-hours experiments with an average mass flowrate of 0.031 kg/s and drying air temperature in the range of 48°C to 54°C (see Figure 11).

Figure 11. Weight reduction for the minimum test load.

Note that the flow resistance for the dry air was much higher in the original design because of the irregular drying path. However, during the 7 kg test load, the results with the modified drying chamber were superior to those with the other designs, as shown in Figure 12. The results with the DW dehumidifier also showed the influence on the drying rate because the desiccant wheel reduces the relative humidity of the air cycle at the inlet of the drying chamber.

3.5. Moisture Extraction Rate

The HPD, along with the drying chamber, was designed to decrease the air resistance and auxiliary power and to check the performance and effect of an external dehumidifier with variable test loads. The heat pump dryer performance can be evaluated with respect to the capacity of water removal and energy effectiveness. The moisture extraction rate indicates the amount of water removed per hour. Figure 13 indicates the results for an eight-hours drying process. Initially, for all three cases, the specific moisture extraction rate...
increased toward a plateau value, followed by a steady decline. As seen from Figure 13, the maximum MER values for 4 kg were observed as 0.68 kg/h, 0.82 kg/h, and 1.0 kg/h for the original design, modified drying chamber, and design with the DW dehumidifier, respectively, during the eight-hours experiment. Note that the desiccant wheel design offered the highest initial peak plateau, followed by the modified design and, finally, the original design. As depicted in Figure 7, the relative humidity for the DW design was the lowest among the three designs, resulting in the highest initial MER when compared to the other designs. As time proceeded, the Orbeez close to the edge of the drying chamber shrunk more pronouncedly due to the high mass transfer rate and returned to a much smaller size, like that of the original dry Orbeez, as shown in Figure 14. As a consequence, the very dry and small Orbeez particles packed together more closely. This eventually led to a further mass transfer barrier for the dry air to penetrate into the center to facilitate effective drying. For this reason, the MER of the DW design fell behind that of the modified design after 200 min, while it was about the same as that of the original design after 400 min.

![Figure 13](image1.png)  
**Figure 13.** Moisture extraction rate versus drying time for the minimum test load.

![Figure 14](image2.png)  
**Figure 14.** Images of the drying Orbeez in the drying chamber. The left-hand image shows the original chamber, and the right-hand image shows the modified chamber with better air distribution.
3.6. Specific Moisture Extraction Rate (SMER)

In the drying process, the specific moisture extraction rate represents the efficiency of energy or effectiveness of energy used in the drying process. The term SMER is related to the cost and the output of the drying system, which indicates the heat energy absorbed and the evaporation of water from the wet Orbeez. Figure 15 shows the SMERs for all three cases with a test load of 4 kg. As observed from the graph, the SMER with a desiccant wheel was rather low due to the appreciable power consumption requirements to regenerate the desiccant wheel. Initially, the SMER gradually increased for all three cases due to significant mass transfer from the material’s surface; it then reached a maximum value and declined thereafter.

![Figure 15. Specific moisture extraction rate versus drying time.](image)

For a larger test load of 7 kg, Figure 16 also indicates that the specific moisture rate initially increased for all cases and later reduced gradually with drying time. The modified chamber showed the maximum performance with an average SMER of around 2.6 kg/kWh because of lower drying air resistance with 27% relative humidity and 52 °C drying air temperature at the dryer inlet. Also, it was found that the SMERs for all cases at the 7 kg test load were higher than those at the 4 kg test load. This is somehow expected because more water is evaporated from larger contact surfaces. The SMER of the DW dehumidifier was minimal because of the high power draw associated with regeneration of the desiccant wheel (about 2.6 kW).

3.7. Variation in the COP and Heat Transfer Rate at the Condenser

By using the heat transfer rate and compressor power, the COP$_{HP}$ of the heat pump can be obtained.

Again, two test loads of 4 kg and 7 kg were used to check the performance of the modified drying chamber. The average temperature ranged from 33 °C to 34 °C and the relative humidity was around 62–66% at the inlet of the condenser; heat transfer rates of 0.55 kW and 0.60 kW, respectively, were observed for 4 kg and 7 kg loads in Figures 17 and 18, whereas the average COP$_{HP}$ values of the heat pump cycle were calculated as 3.1 and 3.5, respectively, under the volumetric flow rate of 100 m$^3$/h. Note that higher COP and capacity prevailed for the larger test loading of 7 kg due to the greater heat transfer rate.
Figure 16. Specific moisture extraction rate versus drying time.

Figure 17. Variation in COP_{HP} and the sensible heat transfer rate at the condenser for the old design.

Figure 18. Variation in COP_{HP} and the sensible heat transfer rate at the condenser for the modified drying chamber.
4. Conclusions

In the current study, we developed a heat pump dryer (HPD) to assess the performance of a closed-loop heat pump dryer system, and a modified drying chamber was designed to offer a lower airflow resistance to facilitate effective drying. On top of the modified design, a desiccant wheel was installed to further lower the humidity of the drying air, and further examination regarding its applicability was conducted. Unlike most of the existing studies, which normally adopt organic products as the drying materials, in this study we used moist sodium polyacrylate (Orbeez) as the drying material for consistent characterization of the heat pump performance. R-134a was adopted as the refrigerant for the heat pump system. The experiments were performed subject to different weights of Orbeez (drying material) at a constant volumetric flow rate of 100 m³/h. The test loads of 4 kg to 7 kg of Orbeez were tested in the drying chamber. Based on the foregoing discussion, the following conclusions are drawn:

1. The average COP_{HP}, mass transfer rate, heat transfer rate, MER, and SMER of the system were calculated as 3.9, 0.30 kg/s, 0.56 kW, 0.495 kg/h, and 1.614 kg/kWh.
2. The moisture extraction rate for the lower test load was higher than that for the higher test load due to the higher penetration of drying air at the lower test load, although the maximum test load showed the maximum relative humidity at the dryer outlet.
3. The maximum MERs for 4 kg were observed as 0.68 kg/h, 0.82 kg/h, and 1.0 kg/h for the old design, modified drying chamber, and design with the external dehumidifier, respectively, during eight-hours experiments. The addition of the desiccant wheel showed good performance in terms of the moisture extraction rate and coefficient of performance, while it showed poor performance in terms of the specific moisture extraction rate due to the required high-power regeneration (around 2.6 kW) of the desiccant dehumidifier.
4. The moisture extraction rate (MER) for all designs increased to a maximum value, followed by a consistent decline. The maximum MER for the desiccant design exceeded those for the other designs. However, the MER for the desiccant dehumidifier design decreased faster and may become lower than those of the other designs as time proceeds further due to the close packing of dry Orbeez at the edge of the drying material.
5. In the future, further validation and more elaboration on reductions in the heat and mass transfer processes of the drying materials should be carried out, and the blockage phenomenon of the drying materials at the outer edge should be quantitatively studied. More effective drying chamber designs should be studied through numerical examinations (CFD) and verified through experiments.

Author Contributions: Conceptualization, K.-S.Y. and K.H.; methodology, K.H. and U.S.; writing—original draft preparation, K.-S.Y. and K.H.; writing—review and editing, C.-C.W.; supervision, S.-K.W. and C.-C.W.; project administration, C.-C.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Bureau of Energy of the Ministry of Economic Affairs under the contracts of 110-E0209 and by the Ministry of Science Technology of Taiwan under grant numbers: MOST 109-2628-E-167-001-MY3 and MOST 108-2221-E-009-037-MY3.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request due to restrictions.

Acknowledgments: The authors gratefully acknowledge the financial support from the Bureau of Energy of the Ministry of Economic Affairs under the contracts of 110-E0209 and by the Ministry of Science Technology of Taiwan under grant numbers: MOST 109-2628-E-167-001-MY3 and MOST 108-2221-E-009-037-MY3.

Conflicts of Interest: The authors declare no conflict of interest.
Nomenclature

- **RH**: relative humidity (%)
- **SMER**: specific moisture extraction rate (kg/kWh)
- **$Q_{cd}$**: heat transfer rate by condenser (kW)
- **$m_{ia}$**: mass flow rate of dry air (kg/s)
- **$C_{pair}$**: specific heat of dry air (kJ/kg K)
- **$T_{co}$**: condenser outlet temperature (°C)
- **$T_{ci}$**: condenser inlet temperature (°C)
- **$\rho_{ia}$**: density of air (kg/m$^3$)
- **$V_i$**: volumetric flow rate (m$^3$/h)
- **$W_w$**: weight of water in material
- **$W_p$**: total weight of material
- **DR**: drying rate (kg$_{\text{water}}$/kg$_{\text{dry solid}}$)
- **MER**: moisture extraction rate (kg/h)
- **$m_{da}$**: mass flow rate of dry air (kg/s)
- **$\omega_{\text{dout}}$**: humidity ratio at dryer outlet (kg/kg$_{\text{DA}}$)
- **$\omega_{\text{din}}$**: humidity ratio at dryer inlet (kg/kg$_{\text{DA}}$)
- **$\omega_{\text{dout}}$**: humidity ratio at outlet (kg/kg$_{\text{DA}}$)
- **$\omega_{\text{din}}$**: humidity ratio at inlet (kg/kg$_{\text{DA}}$)
- **$W_{\text{comp}}$**: compressor output power (kWh)
- **$W_{\text{blower}}$**: blower output power (kW)
- **$T$**: temperature of refrigerant (K)
- **$T_R$**: regeneration temperature (K)
- **$t$**: temperature of air (K)
- **$T_{\text{wb}}$**: wet-bulb temperature (K)
- **$V$**: volume (m$^3$)
- **$Q_{\text{cv}}$**: volumetric air flow rate (m$^3$/s)
- **$v_a$**: specific volume of air (m$^3$/kg dry air)
- **$v_{r1}$**: specific volume of refrigerant vapor at suction (m$^3$/kg)
- **$v_W$**: specific molar volume (m$^3$/mol)
- **$\omega$**: humidity ratio of air (kg water/kg dry air)
- **$\Delta T$**: temperature drop (K)
- **$\Delta T_c$**: cold air temperature reduction (K)
- **$\eta_{\text{is}}$**: isentropic efficiency (%)
- **COP**: coefficient of performance
- **COP$_{\text{HP}}$**: COP of the heat pump
- **$c_p$**: specific heat at constant pressure (kJ/kg K)
- **$c_{pa}$**: specific heat of dry air (kJ/kg K)
- **$c_{pam}$**: specific heat of moist air (kJ/kg K)
- **$c_{of}$**: specific heat of condensate refrigerant film (kJ/kg K)
- **DBT**: dry bulb temperature (°C)
- **DPT**: dew point temperature (°C)
- **DW**: desiccant wheel
- **$P_{\text{comp}}$**: compressor power requirement (kW)
- **$P_{\text{fan}}$**: fan power requirement (kW)
- **$h$**: specific enthalpy of refrigerant (kJ/kg)
- **$h_a$**: specific enthalpy of air (kJ/kg K)
- **$h_{fg}$**: specific latent heat of vaporization of refrigerant (kJ/kg)
- **$h_{fg}$**: specific latent heat of vaporization of water at reference temperature of 0°C (kJ/kg)
- **$h_{g}$**: specific enthalpy per unit mass of saturated vapors (kJ/kg)
- **HP**: heat pump
- **HPD**: heat pump dryer
- **HPDW**: heat pump desiccant wheel
- **$h_o$**: specific enthalpy of water vapors (kJ/kg)
CD  thermal capacity of the heat pump’s condenser
DED  deductible value based on data provided (drying curves, etc.)
No  no Information or data not provided
N/S  not specified
QEV  evaporator thermal capacity (kW)

References
1. Li, M.; Ma, Y.; Gong, W.; Su, W. Analysis of CO$_2$ Transcritical Cycle Heat Pump Dryers. *Dry. Technol.* 2009, 27, 548–554. [CrossRef]
2. Zhang, J.; Wu, Y. Experimental Study on Drying High Moisture Content Paddy by Super-Transducting Heat Pump Dryer. In Proceedings of the 5th Asia-Pacific Drying Conference, Hong Kong, China, 13–15 August 2007; pp. 385–390. [CrossRef]
3. Ho, J.C.; Chou, S.K.; Mujumdar, A.S.; Hawlader, M.N.A.; Chua, K.J. An optimisation framework for drying of heat-sensitive products. *Appl. Therm. Eng.* 2001, 21, 1779–1798. [CrossRef]
4. Chin, S.K.; Law, C.L. Product Quality and Drying Characteristics of Intermittent Heat Pump Drying of Ganoderma tsugaeMurrill. *Dry. Technol.* 2010, 28, 1457–1465. [CrossRef]
5. Alves-Filho, O. Combined innovative heat pump drying technologies and new cold extrusion techniques for production of instant foods. *Dry. Technol.* 2002, 20, 1541–1557. [CrossRef]
6. Adapa, P.K.; Schoenau, G.J.; Sokhansanj, S. Performance study of a heat pump dryer system for specialty crops—Part 2: Model verification. *Int. J. Energy Res.* 2002, 26, 1021–1033. [CrossRef]
7. Queiroz, R.; Gabas, A.L.; Telis, V.R.N. Drying Kinetics of Tomato by Using Electric Resistance and Heat Pump Dryers. *Dry. Technol.* 2004, 22, 1603–1620. [CrossRef]
8. Adapa, P.K.; Schoenau, G.J. Re-circulating heat pump assisted continuous bed drying and energy analysis. *Int. J. Energy Res.* 2005, 29, 961–972. [CrossRef]
9. Fatouh, M.; Metwally, M.N.; Helali, A.B.; Shedid, M.H. Herbs drying using a heat pump dryer. *Energy Convers. Manag.* 2006, 47, 2629–2643. [CrossRef]
10. Hawlader, M.N.A.; Perera, C.O.; Tian, M. Comparison of the Retention of 6-Gingerol in Drying of Ginger Under Modified Atmosphere Heat Pump Drying and other Drying Methods. *Dry. Technol.* 2006, 24, 51–56. [CrossRef]
11. Phoungchandang, S.; Nongsang, S.; Sanchai, P. The Development of Ginger Drying Using Tray Drying, Heat Pump–Dehumidified Drying, and Mixed-Mode Solar Drying. *Dry. Technol.* 2009, 27, 1123–1131. [CrossRef]
12. Lee, K.H.; Kim, O.J. Experimental Study on the Energy Efficiency and Drying Performance of the Batch-Type Heat Pump Dryer. In Proceedings of the 5th Asia-Pacific Drying Conference, Hong Kong, China, 13–15 August 2007; pp. 428–433. [CrossRef]
13. Pal, U.S.; Khan, M.K.; Mohanty, S.N. Heat Pump Drying of Green Sweet Pepper. *Dry. Technol.* 2008, 26, 1584–1590. [CrossRef]
14. Erbay, Z.; Icier, F. Optimization of Drying of Olive Leaves in a Pilot-Scale Heat Pump Dryer. *Dry. Technol.* 2009, 27, 416–427. [CrossRef]
15. Xiang, F.; Wang, L.; Yue, X.-F. Exergy Analysis and Experimental Study of a Vehicle-Mounted Heat Pump–Assisted Fluidization Drying System Driven by a Diesel Generator. *Dry. Technol.* 2011, 29, 1313–1324. [CrossRef]
16. Mortezapour, H.; Ghobadian, B.; Minaei, S.; Khoshtaghaza, M.H. Saffron Drying with a Heat Pump–Assisted Hybrid Photovoltaic–Thermal Solar Dryer. *Dry. Technol.* 2012, 30, 560–566. [CrossRef]
17. Potisate, Y.; Phoungchandang, S. Chlorophyll Retention and Drying Characteristics of Ivy Gourd Leaf (*Coccinia grandis* Voigt) Using Tray and Heat Pump–Assisted Dehumidified Air Drying. *Dry. Technol.* 2010, 28, 786–797. [CrossRef]