Drying in a desiccant wheel dehumidification system-assisted hot air dryer: desiccant wheel effectiveness and carrot drying

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Abstract. A desiccant wheel dehumidification system was used in this study to reduce humidity of the air supplied to a hot air dryer. Desiccant wheel effectiveness was determined based on the ideal adiabatic dehumidification process. Best results of adiabatic dehumidification effectiveness and adiabatic enthalpy effectiveness in the range of 0.89 to 0.99 were achieved. Specific adsorption of silica gel in the desiccant wheel was rotational speed dependent. The desiccant wheel system could reduce the relative humidity from 70 to 44%. Drying of cylindrical carrot in the desiccant wheel dehumidification system-assisted hot air dryer was also conducted in this study. The drying temperatures were varied from 80 to 120°C. The desiccant material regeneration process reused exhaust drying air for heat exchanging with the regenerating air, higher drying temperature caused higher moisture evaporated from the desiccant material. Comparing between dehumidified hot air drying and conventional hot air drying, greater drying rates of dehumidified hot air drying were achieved at the drying temperatures of 100 and 120°C.

1. Introduction

In hot air drying, two parameters of air conditions, i.e. air temperature and air flowrate, have been proved in many literatures to have substantial effects on the drying process. However, the study of an effect of air humidity, which is one of the important air parameters, on the drying process is still very rare. The process of drying can be accomplished only when moisture from the material is evaporated to the surrounding air. In this regard, drying air is the moisture receiver, and it can receive extrinsic moisture more effectively if its intrinsic moisture is lower.

Hot air drying assisted by an air dehumidification system can be one of the promising hybrid drying methods. In general, desiccant wheel dehumidifiers are used for air dehumidification in air cooling systems. Desiccant or moisture adsorbent in the wheel can remove water from the air and result in humidity reduction. Advantages of using the air dehumidification system can include both enhancement of drying characteristics and improvement of quality of the dried product. Low air moisture can promote water removal from the material to the drying air and hence reduce the drying time [1]. Hot air drying under dehumidified air also leads to uniform moisture removal from the material and increased product quality. Naidu et al. [2] found that hot air drying of dill green at the low air relative humidity of 28-30% produced the dried product with higher antioxidant activity as compared to normal hot air drying at the relative humidity of 58-63%.
In this study, the hot air dryer assisted by the desiccant wheel dehumidification system was used. The dryer was also considered as the energy conservation system as the exhaust air from the drying chamber was used to regenerate the desiccant material in the wheel. Therefore, the objectives of this study were (1) to evaluate the effectiveness of the desiccant wheel and (2) to conduct drying experiments in the desiccant wheel dehumidification system-assisted hot air dryer, test the energy conservation system for regeneration of the desiccant material and determine drying characteristics of carrot in the dryer.

2. Materials and methods

2.1. The desiccant wheel dehumidification system-assisted hot air dryer

A schematic view of the hot air dryer assembled by the desiccant wheel dehumidification system is shown in figure 1.

The rotary desiccant wheel was made of stainless steel and had a diameter of 70 cm and a thickness of 1 cm. It was filled with 3 kg of silica gel as a desiccant material. Half of the wheel was for moisture adsorption and the other half was for desiccant regeneration. During the operation process, continuous rotation of the wheel caused the moisture adsorption and desiccant regeneration to occur simultaneously.

The drying chamber was cylindrical with an inner diameter of 20 cm and a length of 30 cm. Two 1-HP blowers (MA40B, EuroVent Co., Ltd., Thailand) were used to supply the drying air and the desiccant regenerating air (shown as Blower 1 and 2). The electrical heater of 3.74 kW (Technology instruments Co., Ltd., Thailand) were used to generate hot air fed to the drying chamber. The drying tray (10 × 20 cm²) was fixed with an electrical balance to measure the moisture loss of the material during the drying process.

The air-to-air heat exchanger was used to exchange the heat from the exhaust air of the drying chamber to the inlet ambient air for regeneration of the desiccant material. The heat exchanging area was 50 m².

Figure 1. A schematic view of the desiccant wheel dehumidification system-assisted hot air dryer.
2.2. The moisture dehumidification and desiccant regeneration processes in the dryer

There are two process lines shown in figure 1, i.e. the air dehumidification process, line \( A \) and the desiccant regeneration process, line \( B \). In the dehumidification process, the ambient air was passed through the desiccant wheel from \( A1 \) to \( A2 \). The dehumidified air was then used for drying and exited the drying chamber as a hot humid exhaust air. The exhaust air was fed to the heat exchanger at \( A3 \), transferred its heat to the air from the desiccant regeneration line, and went out at \( A4 \). In the regeneration process, inlet ambient air was started from \( B1 \), received the heat from the exhaust drying air in the heat exchanger, \( B2 \), and passed through the desiccant wheel for regenerating the desiccant material inside, \( B3 \).

2.3. Evaluation of the effectiveness of the desiccant wheel

Dehumidification of air is the adiabatic process that is no net heat loss or heat gain in the process (See the adiabatic path in figure 2). However, in the real situation, enthalpy between inlet and outlet air may be different depending on wheel operating conditions, regeneration air and inlet air conditions, and desiccant material [3]. With respect to the ideal adiabatic dehumidification process, the effectiveness of the desiccant wheel could be expressed in terms of the adiabatic dehumidification effectiveness (\( \varepsilon_{Deh} \), equation (1)) and the adiabatic enthalpy effectiveness (\( \varepsilon_{Ent} \), equation (2)) [3].

\[
\varepsilon_{Deh} = \frac{\omega_{A2} - \omega_{A1}}{\omega_{A1} - \omega_{A2,adiabatic}}
\]

\[
\varepsilon_{Ent} = 1 - \frac{(h_{A2} - h_{A1})}{h_{A1}}
\]

where \( A1 \) is the ambient inlet air and \( A2 \) is the dehumidified air.

The effectiveness of the desiccant wheel was evaluated at varied rotational speeds of the wheel of 0.5, 1.0, and 1.5 rpm. The air flow rate was 0.08 m\(^3\)/s. The specific moisture adsorption of silica gel in the wheel was also determined as the rate of water absorbed by 100 g of the desiccant material.

2.4. Drying experiments in the desiccant wheel dehumidification system-assisted hot air dryer

The material used for drying was cylindrical carrots having a diameter of 1 cm and a height of 1 cm. A single layer of carrots was prepared on the drying tray for drying. The studied drying temperatures were 80, 100, and 120˚C. The air flow rate was fixed at 0.08 m\(^3\)/s.

The energy conservation system for regeneration of the desiccant wheel was run when the exhaust humid drying air \( A3 \) transferred its heat to the ambient inlet air \( B1 \) in the heat exchanger, and then the hot air \( B2 \) regenerated the desiccant material by evaporating its moisture content and exited the desiccant wheel as \( B3 \). In this process, the amount of air humidity increased at \( B3 \) was suppositionally equal to the amount of moisture evaporated from the silica gel. To evaluate the performance of the energy conservation system for regenerating silica gel in the desiccant wheel, the humidity difference between \( B2 \) and \( B3 \) was determined. The performance was determined both in no load condition and during the carrot drying. The air flow rate used in the process line \( B \) was 0.04 m\(^3\)/s.
During the process of carrot drying, the moisture content (g water/g dry matter), moisture ratio (MR, unitless), and drying rate (DR, g water/g dry matter·min) were determined over times (equations (3)-(5)). The final moisture content of dried carrot needed was 0.15 g water/g dry matter.

\[
\text{Moisture content} = \frac{\text{Weight of water}}{\text{Weight of dry matter}} \quad (3)
\]

\[
\text{MR} = \frac{M_t - M_e}{M_1 - M_e} \quad (4)
\]

\[
\text{DR} = \frac{M_t - M_t + \Delta t}{\Delta t} \quad (5)
\]

where \(M_i, M_t, M_e,\) and \(M_t + \Delta t\) are initial, specific time, equilibrium, and \(t+\Delta t\) moisture content (dry basis), respectively; and \(t\) is drying time (min). The equilibrium moisture content was zero for high temperature drying.

Drying of carrot in the dryer without the desiccant wheel dehumidification system was also conducted to compare the drying characteristics of carrot undergoing normal hot air drying and dehumidified hot air drying.

2.5. Statistical analysis
Experiments were repeated three times. Mean and standard deviation were shown in the results. The independent samples T test and one-way ANOVA with Duncan’s Multiple Range Test were used for analysis of the mean differences among two and three treatments at the confident interval of 95%, respectively.

3. Results and discussions

3.1. Effectiveness of the desiccant wheel
The adiabatic dehumidification effectiveness and adiabatic enthalpy effectiveness of the desiccant wheel at rotational speeds of 0.5-1.5 rpm are present in Table 1. The effectiveness values were in the good range of 0.89-0.99. Although no significant difference was observed \((P>0.05)\), it is interesting that increasing the rotational speed resulted in increased effectiveness. The result of specific adsorption of silica gel in the desiccant wheel also shows the same trend, i.e. the highest rotational speed significantly gave the highest specific moisture adsorption of the silica gel \((P \leq 0.05)\). Therefore, the rotational speed of 1.5 rpm was selected for further study.

During the air dehumidification process, relative humidity and temperature of the dehumidified air \(A_2\) were monitored (figure 3). The results show that relative humidity of the air was reduced continuously throughout the total process time of 30 min. The dramatic decrease in the relative humidity was observed in the first five min. The initial relative humidity of almost 70\% could be reduced to about 44\%, which indicated the successful operation of the desiccant wheel for air dehumidification in the system. The system could keep the relative humidity constant at 44\% from the process time of 15 min onwards. The dehumidified air could be held throughout the drying process as well.

Table 1. Adiabatic dehumidification effectiveness, adiabatic enthalpy effectiveness, and specific adsorption of desiccant material at different rotational speeds of the desiccant wheel.

| Rotational speed (rpm) | \(\varepsilon_{\text{Deh}}\) | \(\varepsilon_{\text{Ent}}\) | Specific adsorption of desiccant material (g water/g dry air·100 g desiccant·min) |
|------------------------|------------------------|------------------------|--------------------------------------------------------------------|
| 0.5                    | 0.91±0.02ns            | 0.97±0.04ns            | 10.6±0.5b                                                          |
| 1.0                    | 0.89±0.05ns            | 0.98±0.07ns            | 11.0±0.4b                                                          |
| 1.5                    | 0.93±0.02ns            | 0.99±0.04ns            | 14.5±0.5a                                                          |
3.2. Performance of the energy conservation system for regeneration of the desiccant wheel

In table 2, it is obvious that higher drying temperature resulted in the significantly greater difference in humidity ratios between B2 and B3, representing the greater amount of moisture evaporated from the desiccant material to the air (P≤0.05). This could be due to higher drying temperature yielded higher temperature of exhaust drying air A3 and contributed to the higher amount of heat to be transferred to the ambient air for regeneration B1; hence, the greater amount of moisture was evaporated from the desiccant material.

Comparing at the same drying temperature, the significant difference in humidity ratios during the imitated drying process (no load in the drying chamber) was bigger than the difference obtained during carrot drying. As no drying occurred during the imitated drying, the exhaust drying air A3 had almost the same temperature as the drying temperature set in this study. Therefore, the higher amount of heat could be transferred to the ambient air for regeneration B1.

Table 2. Differences in humidity ratios between hot air for regeneration B2 and outlet air after regeneration B3.

| T (˚C) | ω_{B3}-ω_{B2}, no load (g water/g dry air) | ω_{B3}-ω_{B2}, carrot drying (g water/g dry air) |
|-------|--------------------------------------------|-----------------------------------------------|
| 80    | 0.81±0.05^C,a                              | 0.41±0.06^C,b                                 |
| 100   | 1.25±0.03^B,a                              | 1.12±0.05^B,b                                 |
| 120   | 3.04±0.08^A,a                              | 2.14±0.07^A,b                                 |

In the same column, means with the same capital letters were not significantly different (P>0.05).
In the same row, means with the same small letters were not significantly different (P>0.05).

3.3. Drying characteristics of carrot in the desiccant wheel dehumidification system-assisted hot air dryer

Drying curves of dehumidified hot air drying of cylindrical carrots are shown in figure 4. The drying times required to meet the desirable moisture content of dried carrot of 0.15 g water/g dry matter were 240, 195, and 150 min for the drying temperatures of 80, 100, and 120˚C, respectively.
To compare the drying characteristics of carrot drying with and without the desiccant wheel dehumidification system, drying rate curves of conventional and dehumidified hot air drying of cylindrical carrots are presented in figure 5. It is clear in figures 5(b) and (c) that the drying rates obtained by dehumidified hot air drying were higher than the rates obtained by conventional hot air drying. However, in figure 5(a), most of the drying rates obtained by conventional hot air drying was higher than the rates obtained by dehumidified hot air drying. In relation to the result in table 2, the lowest amount of moisture from the desiccant wheel was evaporated to the air, indicating low performance in regeneration of the desiccant wheel. This may lead to less effect of dehumidification on hot air drying at the lowest temperature of 80˚C.

![Figure 5](image-url)
4. Conclusions
The desiccant wheel dehumidification system was successfully used to dehumidify the air subsequently supplied to the hot air dryer. Adiabatic dehumidification effectiveness and adiabatic enthalpy effectiveness of the desiccant wheel were in the ranges of 0.89 to 0.93 and 0.97 to 0.99, respectively. Specific adsorption of the desiccant material was in the range of 10.6 to 14.5 g water/g dry air·100 g desiccant·min depending on the rotational speed of the desiccant wheel. The relative humidity was reduced from 70 to 44% during the dehumidification process for 30 min. During the regeneration process using the exhaust drying air for heat exchanging with the air for regenerating the desiccant material, the air humidity ratios were increased by 0.81 to 3.04 g water/g dry air in the no load case and 0.41 to 2.14 g water/g dry air in the carrot drying case with increasing drying temperatures. At the lowest drying temperature of 80°C, the convective hot air drying gave higher drying rates than the dehumidified hot air drying. Greater drying rates of dehumidified hot air drying were obtained at higher drying temperatures of 100 and 120°C.

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