Experimental Investigation of Thermal Conductivity and Specific Heat of the Calcium Phosphate Ore for a Drying Application

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This paper discusses an experimental investigation to determine regression models for thermal properties of phosphate particles and to analyze the performances of the phosphate flash dryer. For this purpose, the specific heat capacity and thermal conductivity of phosphate particles were experimentally determined by the modulated differential scanning calorimetry (MDSC) and the modified transient plane source method (MTPS), respectively. Multiple regression models were developed to correlate the specific heat and thermal conductivity to moisture content, particle size, and temperature. Experimental results showed that the measured thermal conductivity and dry specific heat were found in the range of 0.07–0.61 W/m K and 510–630 J/kg K, respectively. Furthermore, the specific heat increased almost linearly with temperature but decreased with particle size, while the thermal conductivity increased with moisture content and temperature but decreased with particle size. These correlations were integrated to the phosphate flash dryer mathematical model and used to analyze the thermal behavior of phosphate drying. Simulation results were compared to experimental data obtained on a bench-scale dryer, where the model exhibits an average error of 2% and 4% for moisture content and air temperature estimation, showing good fitting for practical data.

1. Introduction

The knowledge of the thermal properties is an essential tool used for many purposes, among which the analysis of heat transfers in complex systems, the choice of adequate insulating materials for energy-saving buildings and construction [1, 2], or the determination of the required energy to design equipment for the food industry [3].

Natural phosphates (NP) are the main source for phosphorus, an essential nutrient for plants and animals. They are used in various sectors, from the chemical industry to fertilization along with biomedical [4]. The availability of these natural resources should ensure food security for developing countries and fulfill the global need for phosphate and its derivatives. Mined phosphates are found either as “mono-dicalcium phosphate,” intended mainly for pet food manufacturing to enable animal growth, or “tricalcium phosphate,” having the chemical formula Ca$_3$(PO$_4$)$_2$.

Phosphate mining goes through beneficiation operations to enhance product quality before being dried to meet export requirements in terms of moisture content. Such drying is performed using large rotary or flash dryers. To improve the energy efficiency and develop the operating and control strategy, users of flash dryers seek to evaluate process performances while targeting optimal operating conditions. For this purpose, several tools exist among which is the mathematical modeling that is considered as an effective tool for R&D costs and time savings. The model describes the transfer phenomenon occurring during drying, and its formulation requires the knowledge of the properties of the drying medium and particles to be dried. Up to now, the information regarding the thermophysical properties of PHOSPHATE PARTICLES.
phosphate particles is scarce, thus the necessity for their investigation to analyze the performances of the flash dryer [5].

The determination of these thermal properties is generally carried out by means of two approaches: experimental measurement and/or modeling method [6]. The modeling approach requires a prior knowledge of the properties of the solid. This modeling approach is however not appropriate with the lack of information concerning the phosphate properties at the dry phase, such as the porosity and the geometry of the pore structure. Hence, the statistical modeling using the experimental approach is adopted.

Thermal conductivity is defined as the ratio of heat flux through a material to a temperature gradient (equation (1)). It describes the ability of the material to conduct heat. Two methods are used to experimentally establish the thermal conductivity: the steady-state technique and the transient method. The first is based on Fourier’s first law, where a one-directional heat flux is applied through the sample. The drawback of this method is the long time required to reach equilibrium as the thermal conductivity is calculated for a constant gradient temperature. Among the steady-state techniques, there are the guarded hot plate and guarded heat flux methods. The second property of concern is the specific heat capacity, defined as the amount of heat required to increase the temperature of one gram of the material of a unit of temperature (equation (2)). The experimental determination of the specific heat can be achieved by two methods: direct and indirect. Direct methods involve the measurement and/or modeling method [6]. The modeling approach requires knowledge of the specific heat of the material and can be less precise in their estimation. Among these methods are the flash method [19, 20] and technical MTPS [21, 22].

$$dQ = m \cdot C_p \cdot dT.$$  

Direct methods rely on the use of calorimeters, such as adiabatic calorimeters [23], reaction calorimeters, or differential scanning calorimeters (DSC). The last technique is commonly used for the accuracy and ease of handling of the apparatus [24] while requiring only a small amount of the sample (few milligrams are enough). Several studies have used this technique to characterize the specific heat of various products, including foods [25-28], energy storage materials [29, 30], minerals [31], phase change material (PCM) [32], bentonite [33, 34], and quartz sand [35].

In this sense, Krupka et al. [31] measured the specific heat of different minerals (corundum, periclase, anorthite, muscovite, etc.), using the DSC technique in the temperature range 100–800°K. They observed a linearly increasing trend of the specific heat with temperature for all materials. The same trend was observed by Baumann and Zunft [35] when measuring the specific heat of quartz sand and sintered bauxite in the temperature range of 50–600°C. Toman and Černý [36] investigated the effect of the moisture content on the specific heat of high-performance concrete, ranging from dry matter to fully saturated, using a nonadiabatic calorimeter. They observed an increasing tendency of the specific heat with the moisture content.

This study targets the experimental investigation of the phosphate particles’ thermal properties and performance analysis of phosphate particles’ flash drying. In this regard, the thermal conductivity and specific heat capacity of phosphate particles are experimentally determined with moisture content, temperature, and particle size variation using the central composite design approach. The property experimental data are statistically modeled based on the response surface methodology (RSM) using Statgraphics Centurion software. The regression model developed for thermal properties is included in the flash drying model to analyze the thermal behavior and perform a validation of the model by comparison of the simulation results to the experimental data obtained for a flash dryer at bench scale.

2. Materials and Methods

2.1. Experimental Determination of the Phosphate Thermal Properties

2.1.1. Sample Preparation. Phosphate particles obtained from the phosphate ore are mainly composed of bone phosphate lime (BPL) and oxides of calcium and magnesium. The ore is valuable when containing a higher fraction
of BPL. The samples used for the experiments were sieved using an electronic siever Analysette 3, Fritsch [37], equipped with sieves \( r \) ranging from 40 \( \mu \)m to 300 \( \mu \)m. A duration of 20 minutes at 2 Hz was used for sieving the samples. The sieving results showed that the fraction of the sample having a mesh diameter less than 80 \( \mu \)m is 2\%. This proportion was therefore neglected in the present study after 3 repeated tests showing the same results. The density of the sample is 1400 kg/m\(^3\), measured using a water displacement method. The size distribution (Figure 1) was studied by sieve analysis considering particles as spheres.

Particles were initially dried at 130°C for 48 h in a convection oven until no mass variation was observed. Water was then added to reach the desired moisture content level. The phosphate particles and water were fully blended in a convection oven until no mass variation was observed.

2.1.2. Thermal Conductivity Measurement. Thermal conductivity (TC) was measured with a C-Therm TCI analyzer [39] which relies on the modified transient plane source method (MTPS). The setup (Figure 2) consists of a sensor connected to the control unit which converts the signal and transmits it to the computer. The sensor chip is made of 96\% aluminum oxide coated with a thin sealing glass layer. The sensor operates by applying a one-directional heat flow to the sample. The sample absorbs a quantity of this heat, while the remaining results in a temperature rise of up to 3 K at the sensor surface [40]. The temperature rise is measured by recording the voltage drop at the sensor/sample interface. In fact, the sensor operates both as the heating source and as the voltage sensor.

Samples were filled in a 50 ml beaker until reaching a volume of 30 ml (following the supplier instructions). To ensure a better contact between the sensor and the sample, a 500 g weight was placed on the top of the sensor, enabling to compact better the sample and to avoid any heat exchange with the surrounding environment.

Calibration of the sensor was performed using three standards (distilled water, Pyrex, and Pyroceram), yielding results similar to manufacturer’s values. The apparatus provides direct reading of the TC value based on the mean value of 10 measures.

2.1.3. Specific Heat Capacity Measurement. Specific heat capacity was measured using DSC Q20 (TA Instruments) with the modulated temperature option. Measurement by DSC was based on sample heating and calculation of the temperature difference between a reference (empty pan) and a sample. The experimental setup (Figure 3) consists of two sample holders (sample and reference) mounted inside a furnace, being heated radially. Two thermocouples are connected to each holder, while a thermoelement is connected between the two holders to measure the temperature difference measured as voltage [41].

Measurements were performed by placing 24.3 mg of the sample into a standard aluminum pan (40 \( \mu \)L) [42], which was then sealed hermetically. During measurement, the furnace was continuously purged with 60 mL/min of dry nitrogen gas to eliminate any water vapor. Specific heat capacities were calibrated with sapphire following the manufacturer’s instructions [43], yielding to a calibration constant of 0.752. Specific heat was measured in the temperature range of 30 to 100°C at a linear heating rate of 3°C/min, with the modulation conditions of a 120-second period and ±1°C amplitude.

Specific heat of the phosphate particles was obtained as a direct output of the DSC apparatus, using TA Instruments Universal Analysis 2000 software.

2.1.4. Response Surface Methodology and Experimental Design. Experimental design is the best approach to obtain the maximum of information with the minimum number of tests. Several techniques are used to generate an experimental design, but the central composite design (CCD) remains the most widespread technique used to establish a second-order polynomial for the output function without having to resort to a full factorial design [44].

The response surface methodology (RSM) [45, 46] is a statistical approach that correlates several variables to a response function. It enables to test the effect of the variables and their interaction on the output while developing a mathematical model. Thus, the output function (Y) can be correlated to the variables (\( X_1, X_2, \ldots, X_n \)) by means of the quadratic model:

\[
Y = \beta_0 + \sum_{i=1}^{N} \beta_i X_i + \sum_{i=1}^{N} \beta_i^2 X_i^2 + \sum_{i<j}^{N} \beta_{ij} X_i X_j + \epsilon,
\]

with \( \beta_0, \beta_i, \beta_i^2, \) and \( \beta_{ij} \) denoting the regression coefficients for the intercept, linear, quadratic, and interaction terms, respectively. \( \epsilon \) represents the statistical error due to many sources, among which is the measurement error.

The validity of each of the preceding regression model is tested using the Fisher test, which compares the regression and experimental variances [47], with the rejection threshold set usually at 5\%.

The factors and their limits considered for thermal conductivity and specific heat characterization are presented in Table 1.

2.2. Application of the Phosphate Characterization to the Flash Drying Analysis: Performance Model Development. In order to develop a performance model featuring a higher precision, the mathematical model of phosphate flash drying requires an accurate determination of the particle properties. The model is based on coupled transfers of heat, mass, and momentum between drying air and phosphate [5].

The thermal property regression results obtained from the experimental approach will be incorporated into the code of the flash dryer model using MATLAB software for its resolution. Simulation results are validated against experimental data obtained on a bench-scale solar flash dryer.
The bench scale is coupled to a 29 kWth parabolic trough collector system [48] and installed at Green Energy Park (GEP-Ben Guerir).

The bench-scale flash dryer (Figure 4) consists of a drying chamber, air fan blower, a cyclone, and air filter, along with a draft fan responsible for the conveying of the drying air and phosphate particles along the dryer. Drying air was heated indirectly through a spiral crimped air-to-oil.

Table 1: Factors and their limits for thermal conductivity and specific heat measurement.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Code</th>
<th>Unit</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter</td>
<td>$X_1$</td>
<td>μm</td>
<td>100–300</td>
</tr>
<tr>
<td>Moisture content</td>
<td>$X_2$</td>
<td>%</td>
<td>0.8–29.1</td>
</tr>
<tr>
<td>Temperature</td>
<td>$X_3$</td>
<td>°C</td>
<td>21–100</td>
</tr>
</tbody>
</table>

Figure 1: Particle size distribution.

Figure 2: C-Therm TCi apparatus for thermal conductivity measurement.

Figure 3: DSC apparatus for specific heat measurement. (a) Schematic diagram. (b) DSC Q20, TA Instruments.
heat exchanger [49], yielding to a maximum air temperature of 126°C with an average air absolute humidity of 0.010 kg water/kg dry air.

The dryer was instrumented with thermocouples, which were inserted at five locations along the dryer length (0, 0.3, 0.7, 1.2, and 1.6 m), to measure the air temperature. A data acquisition system (OMEGA OMB-DAQ-2416) [50] was connected to the thermocouples to record the temperatures. Concerning the moisture content, the experimental tests will be limited to the initial and final moisture content.

3. Results and Discussion

3.1. Thermal Conductivity Statistical Modeling. The experimental variance was evaluated at the central point of the experimental design, corresponding to \( d_p = 200 \mu m \) and \( MC = 15\% \), using 4 duplicate tests prepared in the same conditions. Results show a mean estimation of the thermal conductivity of 0.191 W/m K and a standard deviation of 0.0073. A coefficient of variation of 3.8% is found, corresponding to the standard error divided by the sample mean estimate.

The thermal conductivity values obtained through the experimental design are given in Table 2. A statistical analysis performed using Statgraphics Centurion software [51] yielded the regression coefficients and variance for each model. Table 3 summarizes the stepwise multiple linear regressions describing the experimental results which satisfy the Fisher test. A correlation not considering the temperature (equation (4)) is preferred as temperature is a perturbation variable in the present work, and its study field is limited.

\[
k = 0.18 - 4.0 \times 10^{-4} d_p + 4.7 \times 10^{-4} MC^2.
\]  

Figure 5 shows the response surface plot for the thermal conductivity of phosphate particles against particles’ size and moisture content. Thermal conductivity increases with moisture content, which can be explained by the fact that adding water to the material leads to the air expulsion from the pores. As the air has low thermal capacity \( k_{air} = 0.028 \text{ W/m-K} \) compared to water \( k_{water} = 0.664 \text{ W/m-K} \), the pores filled with water are more conductive. Thus, the thermal conductivity is more important.

It can also be observed from Figure 5 that the thermal conductivity decreases with the particle size, a trend similar to other works [12, 52]. This phenomenon may be explained as follows: for solids with an important particle size, the volume of air filling the pores is greater, yielding to a decrease in the thermal conductivity since the presence of air in the pores adds an “insulation” character to the bulk sample.

3.2. Specific Heat Capacity Statistical Modeling. The experimental variance was evaluated through 3 repeated tests at the central point corresponding to a diameter of 200 \( \mu m \) with 17.9 mg \( \pm \) 0.01 mg of particles in the temperature range 35–100°C. The results of repeated tests were evaluated at three different temperatures which enabled the calculation of the coefficient of variation, estimated to be 2%.

Table 4 presents the measured specific heat of phosphate particles (100, 200, and 300 \( \mu m \)) in the temperature range between 35 and 100°C. As shown in Figure 6, the specific heat capacity increases linearly with increasing temperature but decreases with particle diameter. Table 5 gives the regression coefficients correlating the specific heat capacity to temperature and particle diameter.

A more general model was fitted to correlate all experimental data of various particle diameters with
temperature variation. This yielded the following equation in the form

\[ C_p = A(d_p) + B(d_p) * T, \]  

(5)

with \( A(d_p) = 0.511 - 1.4910^{-9}d_p^3 \) and \( B(d_p) = 8.5610^{-4} + 5.110^{-6}d_p - 1.4910^{-9}d_p^2 \).

The relative percentage deviation (RPD) was also calculated, estimated to a maximal value of 0.32%, indicating thus very good fitting of the experimental data.

As expected, the results show that the specific heat capacity increases with increasing temperature. This phenomenon may be explained as follows: as the temperature increases, more energy is supplied to bring the rotation and
Table 4: Experimental results of the specific heat capacity of phosphate particles.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Specific heat capacity (J/g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 µm</td>
</tr>
<tr>
<td>38</td>
<td>0.555</td>
</tr>
<tr>
<td>42</td>
<td>0.561</td>
</tr>
<tr>
<td>45</td>
<td>0.564</td>
</tr>
<tr>
<td>50</td>
<td>0.570</td>
</tr>
<tr>
<td>55</td>
<td>0.576</td>
</tr>
<tr>
<td>60</td>
<td>0.582</td>
</tr>
<tr>
<td>65</td>
<td>0.588</td>
</tr>
<tr>
<td>70</td>
<td>0.595</td>
</tr>
<tr>
<td>75</td>
<td>0.601</td>
</tr>
<tr>
<td>80</td>
<td>0.607</td>
</tr>
<tr>
<td>85</td>
<td>0.613</td>
</tr>
<tr>
<td>90</td>
<td>0.619</td>
</tr>
<tr>
<td>95</td>
<td>0.625</td>
</tr>
<tr>
<td>100</td>
<td>0.630</td>
</tr>
</tbody>
</table>

Table 5: Regression coefficients for the specific heat capacity.

<table>
<thead>
<tr>
<th>Particle diameter (µm)</th>
<th>A</th>
<th>Standard deviation</th>
<th>B</th>
<th>Standard deviation</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.509293</td>
<td>4.51 × 10⁻⁴</td>
<td>12.17 × 10⁻⁴</td>
<td>6.384E – 06</td>
<td>p ≤ 0.001</td>
</tr>
<tr>
<td>200</td>
<td>0.49956</td>
<td>1.30 × 10⁻³</td>
<td>12.80 × 10⁻⁴</td>
<td>1.846E – 05</td>
<td>p ≤ 0.001</td>
</tr>
<tr>
<td>300</td>
<td>0.470696</td>
<td>3.01 × 10⁻⁴</td>
<td>10.45 × 10⁻⁴</td>
<td>4.263E – 06</td>
<td>p ≤ 0.001</td>
</tr>
</tbody>
</table>

vibration of the molecules, yielding thus to the increase of their internal energy. As specific heat is defined as the slope of the internal energy plot with temperature, an increase in the internal energy implies thus an increase in the specific heat.

On the contrary, the specific heat decreases with increasing the particle size. This observation can be explained by the fact that heating larger particles requires more heat to generate the rotation of the atoms than smaller particles absorbing the same heat flow. The internal energy of the larger particles is thus less, implying a reduction in their specific heat capacity.

3.3. Flash Drying Analysis and Validation of the Performance Model. Thermal properties determined above were used to analyze the phenomenon occurring during phosphate particles’ flash drying, showing that the phosphate particles exhibit a relatively low thermal conductivity which presents a poor thermal conductor. This fact explains the convective feature of flash drying, where moisture removal is governed by the convective transfers of free moisture at the surface of the particles, rather than the conduction inside the pores. The calculation of the thermal effusivity and diffusivity for phosphate particles from the present experimental data, at ambient temperature and dry state, yields to the following values: \( D = 14.310^{-6} \text{ m}^2/\text{s} \) and \( \varepsilon = 291 \text{ J/m}^3 \cdot \text{C} \cdot \text{s}^{1/2} \). As the thermal effusivity enables quantifying the ability of a material to change temperature when receiving a heat flow with a nonuniform distribution, two phenomena are combined: a heat flow is absorbed according to the specific heat capacity, and later, this heat flow is transferred to adjacent areas according to the thermal conductivity.

In order to validate the mathematical model, experimental tests were organized following an experimental design, where air temperature, phosphate mass flow rate, and product moisture content were varied in the range of 100–126 °C, 45–72 kg/h, and 14–18%, respectively, as shown in Table 6. Particles collected from the cyclone after drying were analyzed using a moisture analyzer [38] to measure the final moisture content.

Simulations were performed with MATLAB using the fourth-order Runge–Kutta function to solve the model’s equations. Detailed comparison of simulation results and experimental data is given for the test N°1, as shown in Figures 7 and 8. It can be noted in test N°1 that the measured moisture content at the dryer outlet is 0.76%, while the simulated moisture content is 0.78%, showing an error of 2.5%. On the contrary, the measured temperatures at different positions are 101.5, 81.26, 74.36, 68.2, and 63.25 °C against simulations of 101, 79.6, 70.4, 64, and 60.6 °C. Simulation results fall among the average error bars of ±2.2 °C for the thermocouple. For this test, an average error of 3.6% is estimated for the temperature measurement, as shown in Table 7.

Subsequent test results are reported in Table 6. For all tests, the model average error for moisture content and temperature estimation is 2% and 4.5%, showing good fitting for practical purposes.

Considering the Biot number as an important parameter in conjugate heat and mass transfer, it was calculated in function of the model outputs. The calculation shows an
Table 6: Parameter variation for the experimental tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Theoretical design variables</th>
<th>Experimental test variables</th>
<th>Moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T ) (°C)</td>
<td>( Q_p ) (kg/h)</td>
<td>( MC ) (%)</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>60</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>71.82</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>45</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>55</td>
<td>14.31</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>40</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>65</td>
<td>17</td>
</tr>
</tbody>
</table>

Figure 7: Moisture content profile along the dryer length: simulation vs. experimental.

Figure 8: Temperature profile along the dryer length: simulation vs. experimental.

Table 7: Temperature error calculation for each position (test N°1).

<table>
<thead>
<tr>
<th>Position</th>
<th>Corresponding dryer length (m)</th>
<th>Air temperature (°C)</th>
<th>Error calculation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Experimental</td>
<td>Simulated</td>
</tr>
<tr>
<td>Z1</td>
<td>0</td>
<td>101.5</td>
<td>101</td>
</tr>
<tr>
<td>Z2</td>
<td>0.3</td>
<td>81.26</td>
<td>79.56</td>
</tr>
<tr>
<td>Z3</td>
<td>0.7</td>
<td>74.36</td>
<td>70.40</td>
</tr>
<tr>
<td>Z4</td>
<td>1.2</td>
<td>68.2</td>
<td>63.98</td>
</tr>
<tr>
<td>Z5</td>
<td>1.6</td>
<td>63.25</td>
<td>60.61</td>
</tr>
</tbody>
</table>
average value of 14 indicating a “thermally thick substance” [53], which is characterized by a slow heat conduction inside the material compared to heat convection at its surface. The obtained value confirms the analysis discussed above concerning the thermal behavior of phosphate particles along the flash dryer.

4. Conclusion

This paper presents the experimental characterization of thermal properties for phosphate particles for the performance analysis of the phosphate flash dryer. In this context, the thermal conductivity and specific heat capacity of phosphate particles were investigated through experimental measurements with moisture content, temperature, and particle size variation in the range 1–30%, 35–100°C, and 100–300 μm, respectively. These properties were studied through a response surface methodology.

The thermal conductivity was measured using the transient plane source method, while the specific heat capacity was measured using the DSC. The experimental results of the thermal properties were fitted using a multilinear regression. The developed correlations for the thermal properties were incorporated into the phosphate flash drying model. This model was simulated and compared to experimental data obtained in the present work. The main results are presented as follows:

Thermal conductivity increased with moisture content and temperature, showing good agreement with the literature results, while an inversional effect was observed with particle diameter.

Regarding the specific heat capacity tendency, it increased linearly with temperature while decreased with increasing particle size.

The regression models of the thermal properties were found statistically significant, having a relative percentage deviation of 3.8% and 0.32% for the thermal conductivity and specific heat capacity, respectively. Considering the results of the phosphate thermal properties, an analysis of the phenomenon occurring in the flash dryer showed that the particles exhibit a poor thermal conductor aspect, thus explaining the necessity to operate convective drying for surface moisture removal.

Simulation results were compared with experimental data obtained on the bench-scale flash dryer, showing good agreement with a relative error of 2% and 4% for moisture content and drying air estimation; the validated model will be used in the future work to evaluate the performance of the industrial flash dryer and to design an industrial solar flash dryer.

Nomenclature

- \( A \): Area (m²)
- \( C \): Heat capacity (J/kg)
- \( C_d \): Drag coefficient
- \( d_p \): Particle diameter (m)
- \( f \): Frictional coefficient
- \( g \): Gravity acceleration (m/s²)
- \( G \): Mass flow rate (kg/s)
- \( k \): Thermal conductivity (W/m K)
- \( K(\theta) \): Incidence angle modifier (IAM)
- \( h \): Convective heat transfer coefficient (W/m²·K)
- \( H \): Air humidity (kg/kg)
- \( L_v \): Latent heat of vaporization (J/kg)
- \( MC \): Moisture content (kg/kg)
- \( P \): Pressure (Pa)
- \( Q \): Heat (W)
- \( T \): Temperature (°C)
- \( V \): Velocity (m/s)

Greek letters

- \( \varepsilon \): Volume fraction
- \( \rho \): Density (kg/m³)

Subscripts

- A: Air
- P: Particle

Abbreviations

- MC: Moisture content
- TC: Thermal conductivity
- ID: Internal diameter

Data Availability

The experimental data used to support the findings of this study are included within the article.

Additional Points

Highlights. (i) Characterization of the thermal properties of phosphate particles: thermal conductivity and specific heat capacity; (ii) experimental approach using the modified transient plane source, differential scanning calorimetry, and experimental design; (iii) effect of temperature, moisture content, and particle size on the thermal properties; (iv) performance analysis of phosphate flash drying; and (v) validation of the developed phosphate flash drying model using own bench-scale tests.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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