A Fully Coupled Multiphase Model for Infrared-Convective Drying of Sweet Potato

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Abstract

Background

Combined infrared and convective drying is a promising technology in dehydrating heat-sensitive foods, such as fruits and vegetables. This novel thermal drying method, which involves the application of infrared (IR) energy and hot air during a drying process, can drastically enhance energy efficiency and improve overall product quality at the end of the process. Understanding the dynamics of what goes on inside the product during drying is important for further development, optimization and upscaling of the drying method. In this study, a multiphase porous media model considering liquid water, gases and solid matrix was developed for the
combined infrared and hot-air drying (CIR-HAD) of sweet potato slices in order to capture the relevant physics and obtain an in-depth insight on the drying process. The model was simulated using MATLAB with user-friendly GUI interface for easy coupling and faster computational time.

Results

The gas pressure for CIR-HAD was higher centrally and decreased gradually towards the surface of the product. This implies that drying force is stronger at the product core than at the product surface. Phase change from liquid water to vapour occurs almost immediately after the start of the drying process for CIR-HAD. The evaporation rate as expected was observed to increase with increased drying time. Evaporation during the CIR-HAD increased with increasing distance from the centerline of the sample surface. The simulation results of water and vapour flux revealed that moisture transport around the surfaces and sides of the sample is as a result of capillary diffusion, binary diffusion and gas pressure in both the vertical and horizontal directions. The nonuniform dominant infrared heating caused the heterogeneous distribution of product temperature. These results suggest that CIR-HAD of food occur in a non-uniform manner with high vapour and water concentration gradient between the product core and the surface.

Conclusions

This study provides better insight into the physics and phase changes of food during CIR-HAD. The multiphase model has the advantage that phase change and impact of CIR-HAD operating parameters can be swiftly quantified. Such modelling approach is thereby significant for further development and process optimization of CIR-HAD towards industrial upscaling.
1. Introduction

Drying is one of the oldest process technologies for preserving fruits and vegetables. This process involves the reduction of moisture from a material due to concomitant heat and mass transfer process. Conventionally, drying of fruits and vegetables is often carried out using sun and solar drying for rural farmers, and forced hot-air convective drying for agro-allied and manufacturing industries\(^1\). The hot-air drying method has been demonstrated to be less energy efficient\(^2\)–\(^4\) and often result in a low quality final dried products due to elevated temperature and longer drying duration\(^5\). The sun and solar drying methods are also time-consuming and result in a product of lesser nutritional qualities compared to other standard drying methods\(^5\).

The combined infrared (IR) and hot air drying (HAD) (CIR-HAD) method have received considerable interest in dehydrating fruits and vegetables. This method involves the continuous application of IR radiation together with forced hot air during the entire drying process. CIR-HAD has been proven to be more efficient in terms of cost, energy consumption and final product quality compared to conventional HAD, and infrared drying (IRD)\(^7\). However, the continuous application of IR energy may also result in product overheating and non-uniform drying rate \(^8\). This means that depending on the dryer configuration, some parts of a product will dry faster than other parts. This even becomes more problematic when drying a large amount of products as the drying rate will possibly reduce downstream. In order to avoid this condition from occurring, it is imperative to understand what
takes place inside a product during CIR-HAD. To quantify this, an adequate model that will describe the underlying physics during CIR-HAD is required.

Current works conducted on CIR-HAD are experimental. Although there are a few studies on modelling and simulation of CIR-HAD, most of these modelling studies only focused on empirical\textsuperscript{9-11} and single-phase theoretical models\textsuperscript{12-14} without any insight on the phase change during the entire drying process. Khan et al.\textsuperscript{15} stated that multiphase theoretical models can adequately describe individual phase change both at micro and macro levels, and can also provide an in-depth understanding of the heat, mass and momentum transfer.

In recent years, different researchers have developed multiphase models for convective drying\textsuperscript{16,17}, microwave drying\textsuperscript{18,19}, refractance window drying\textsuperscript{20}, and intermittent microwave convective drying\textsuperscript{21,22}. However, studies on the multiphase modelling of fruits and vegetables for combined IR and HAD are limited. Based on the author’s best knowledge, there is no known study on multiphase modelling of food during CIR-HAD. For further development and upscaling of the CIR-HAD technology, a multiphase model is required to provide useful information and detailed insight on the heat and mass transfer physics behind the drying of fruits and vegetables. In this study, we investigated the multiphase modelling of sweet potato slices during continuous CIR-HAD, considering liquid water, and vapour transport. The study quantifies the success of the model by evaluating the simulated moisture and temperature evolution in comparison with experimental data. A user-friendly GUI MATLAB program for easy coupling of the underlying physics and reduction of computational time was developed and used for the physics-based finite element simulation.
2. **Multiphase model development**

This section describes the equations used for the multiphase modelling of sweet potato slices considering the heat, mass and momentum transfer processes during combined IR and HAD. The multiphase equations used for this study were based on principles similar to those deployed in the development of a multiphase model for microwave drying\(^{21,22}\). The drying transport mechanism, model assumptions, model parameters, and input conditions are also illustrated. The infrared heat generation model was based on the model developed by Onwude et al.\(^{12}\). The multiphase model considered coupling liquid water, vapour and air transport processes in the sweet potato slice core. The model also expanded to capture diffusion, convective air transfer, water and vapour evaporation for the mass and energy conservation. Darcy’s equation was used to develop momentum conservation, while the evaporation-condensation phenomenon was developed using a non-equilibrium formula of evaporation which was considered to be uniformly distributed throughout the model domain.

2.1 **Problem definition and model assumptions**

Figure 1 shows a computation domain of sweet potato slice during CIR-HAD, showing the heat and mass transport process. A 2D axisymmetric cylindrical geometry of a 3D sliced sweet potato sample represented the computational domain. The sweet potato slice was assumed to be a porous media that had liquid water, air and water vapour transportable phases. Heat and mass transport process occurred at all boundaries except the symmetrical boundary (\(r=0\)) (Figure 1). Equal temperatures in solid, liquid and gas phases were assumed because all these phases were continuous with a valid local thermal equilibrium. Convective flow occurred because of capillary flow, evaporation and gas pressure gradient, which was
responsible for liquid water transport during the drying process. The gas pressure gradient and binary diffusion occurred during the drying process resulting in vapour and air transport. The non-equilibrium condition occurred during evaporation. It is obvious that shrinkage occurs during the drying of food, it was however not considered in this study. The multiphase modelling of combined infrared and hot-air drying is already very complex and the inclusion of shrinkage would further complicate the model simulation process. As it is the foremost multiphase model to describe the combined infrared and hot-air drying process, it already makes sense to start with a simplified model. Besides, the consideration of shrinkage may provide better prediction, all the transport phenomena that occur during the drying process would be the same. Therefore, this study focused on understanding the transport phenomena during the combined infrared and hot-air drying of sweet potato.
2.2 Governing equations

The model formulations, input parameters, initial and boundary conditions are all presented in this section. The heat generation term due to infrared $Q_{inf}$ is also discussed in this section.

**Mass and momentum balance**

The sum of gas volume, water and solid phases is represented as elementary volume, $\Delta V$ ($m^3$) and is given as follows:

$$\Delta V = \Delta V_g + \Delta V_w + \Delta V_s$$

where, $\Delta V_g$ is the gas volume ($m^3$), $\Delta V_w$ is the water volume ($m^3$), and $\Delta V_s$ is the solid volume ($m^3$).

The apparent porosity ($\varphi$) is referred to as the volume ratio of gas and water in the sample. It can be estimated using Equation 2 as:

$$\varphi = \frac{\Delta V_g + \Delta V_w}{\Delta V}$$

The gas saturation ($S_g$) and water saturation ($S_w$) are referred to as the pore volume ratio of gas and water phase, respectively and can be expressed as:

$$S_g = \frac{\Delta V_g}{\Delta V_g + \Delta V_w} = \frac{\Delta V_g}{\varphi \Delta V}$$

and

$$S_w = \frac{\Delta V_w}{\Delta V_w + \Delta V_g} = \frac{\Delta V_w}{\varphi \Delta V} = 1 - S_g,$$
respectively.

The mass concentrations \((kgm^{-3})\) of air \((c_a)\), water \((c_w)\), and vapour \((c_v)\) are expressed as follows:

\[
c_a = \frac{p_aM_a}{RT} \varphi S_g,
\]

\[
c_w = \rho_w \varphi S_w,
\]

and

\[
c_v = \frac{p_vM_v}{RT} \varphi S_g,
\]

respectively.

where \(p_a\) is the air partial pressure (Pa), \(R\) is the universal gas constant \((Jmol^{-1}K^{-1})\), \(T\) is the sample temperature (K), \(\rho_w\) is the water density \((kgm^{-3})\), \(p_v\) represents vapour partial pressure (Pa), \(M_a\) denotes air molar mass \((kgmol^{-1})\), and \(M_v\) represents vapour molar mass \((kgmol^{-1})\).

The mass conservation equation for liquid water is based on capillary diffusion, flow due to gas pressure, and liquid water evaporation to vapour. This equation can be expressed as \(^{23}\):

\[
\frac{\partial}{\partial t}(\rho_w \varphi S_w) + \nabla \cdot (\vec{n}_w) = -R_{\text{evap}}
\]

Where \(\vec{n}_w\) represents water flux \((kg/m^2s)\), and \(R_{\text{evap}}\) is the liquid water evaporation to water vapour \((kg/m^2s)\).

According to Bear \(^{24}\), the liquid water total flux \((P_w)\) is as a result of liquid pressure gradient \((P_w = P - P_c)\) and can be expressed according to Darcy’s Law as:

\[
\vec{n}_w = -\rho_w \frac{k_{w}k_{r,w}}{\mu_w} \nabla P_w
\]
Substituting for $P_w$, Equation 9 becomes:

$$\vec{n}_w = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P_c$$  \hspace{1cm} (10)

where $k_w$ represents water intrinsic permeability ($m^2$), $k_{r,w}$ denotes water relative permeability, $\mu_w$ is known as water viscosity (Pa.s), $P$ denotes total gas pressure (Pa), and $P_c$ represents capillary pressure (Pa).

The capillary pressure is responsible for holding the water within the product pore. During drying, the capillary pressure is highly affected by moisture and temperature gradient\textsuperscript{21,22}. Occasionally, the capillary pressure is also affected by the pore diameter. Considering that there are few studies on the relationship between capillary pressure, moisture content and temperature\textsuperscript{25}, this study shades more light on the interaction between temperature and moisture content on capillary pressure. Therefore, a further breakdown of Equation 10 becomes:

$$\vec{n}_w = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial P_c}{\partial c_w} \nabla c_w + \rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial P_c}{\partial T} \nabla T$$  \hspace{1cm} (11)

Equation 11 can be substituted into Equation 8 neglecting capillary diffusivity due to temperature gradient (thermal diffusivity), which has been reported to be insignificant when compared with capillary diffusivity due to water concentration gradient\textsuperscript{25}. Thus, Equation 8 can be written as:

$$\frac{\partial}{\partial t} \left( \rho_w \varphi S_w \right) + \nabla \left( -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial P_c}{\partial c_w} \nabla c_w \right) = -R_{\text{evap}}$$  \hspace{1cm} (12)

Equation 12 is also known as liquid water concentration. The capillary diffusivity due to water concentration $D_c$ can be expressed as:

$$D_c = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial P_c}{\partial c_w}$$  \hspace{1cm} (13)

Therefore, the liquid water concentration can be expressed as:
\[
\frac{\partial}{\partial t}(\rho_w \varphi S_w) + \nabla \left( -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P - D_c \nabla c_w \right) = -R_{\text{evap}}
\]  

(14)

Based on the derivation of the conservation of liquid water, the conservation of water vapour can be expressed in terms of mass fraction \( w_v \), as\(^{21} \):

\[
\frac{\partial}{\partial t}(\rho_g \varphi S_g w_v) + \nabla \left( \tilde{n}_v \right) = R_{\text{evap}}
\]

(15)

where \( \rho_g \) represents the density of gas (\( \text{kgm}^{-3} \)), \( w_v \) denotes the vapour mass fraction and \( \tilde{n}_v \) indicates vapour mass flux (\( \text{kg/m}^2\text{s} \)).

A binary mixture such as gas, \( \tilde{n}_v \) can be expressed as\(^{26} \):

\[
\tilde{n}_v = -\rho_g w_v \frac{k_{r,g}}{\mu_g} \nabla P - \rho_g \varphi S_g D_{\text{eff,g}} \nabla w_v
\]

(16)

where, \( k_g \) denotes gas intrinsic permeability (\( \text{m}^2 \)), \( \mu_g \) denotes gas viscosity (\( \text{Pa.s} \)), \( k_{r,g} \) represents gas relative permeability, and \( D_{\text{eff,g}} \) denotes binary diffusivity of vapour and air (\( \text{m}^2/\text{s} \)).

Therefore, the mass balance equation for the conservation of water vapour considering binary diffusion, bulk flow, and phase change can also be written as:

\[
\frac{\partial}{\partial t}(\rho_g \varphi S_g w_v) + \nabla \left( -\rho_g w_v \frac{k_g k_{r,g}}{\mu_g} \nabla P - \rho_g \varphi S_g D_{\text{eff,g}} \nabla w_v \right) = R_{\text{evap}}
\]

(17)

The gas-phase consists of air and vapour mixture. On estimating the value of the mass vapour fraction (\( w_v \)) and applying the equations stated above, the mass fraction of air (\( w_a \)) can then be obtained using the following relation:

\[
w_a = 1 - w_v
\]

(18)
Continuity equation for gas phase

The gas pressure ($P$) is calculated from the overall mass balance for the gas phases during combined CIR-HAD and can be expressed as:

$$\frac{\partial}{\partial t}(\rho_g \phi_S) + \nabla \cdot (\vec{n}_g) = R_{evap}$$

(19)

where $\vec{n}_g$ is the gas flux, and is given by,

$$\vec{n}_g = \rho_g \frac{k_g k_{r.g}}{\mu_i} \nabla P$$

(20)

here, $\rho_g$ is the density of gas-phase and is given as:

$$\rho_g = \frac{PM_g}{RT}$$

(21)

where $M_g$ represents the weight of the gas molecules (kg/mol).

Energy balance equation

It has been assumed that all transport phases possess the same thermal equilibrium. Therefore, the equation for the balance of energy for CIR-HAD can be written as:

$$(\rho_{eff} C_{p,eff}) \frac{\partial T}{\partial t} + \nabla \cdot (\bar{n}_g h_g + \bar{n}_w h_w) = \nabla \cdot (k_{eff} \nabla T) - h_{fg} R_{evap} + Q_{inf}$$

(22)

where $\rho_{eff}$ is the effective density (kg/m$^3$), $C_{p,eff}$ denotes effective specific heat capacity (J/kg/K), $h_g$ means gas enthalpy (J), $h_w$ is the water enthalpy (J), $T$ denotes the temperature of each phase (K), $k_{eff}$ represents effective
thermal conductivity (W/m/K), $h_{fg}$ represents latent heat of evaporation (J/kg), $Q_{inf}$ denotes the volumetric infrared heat source (W/m$^3$) calculated as shown in Equation 23

$$Q_{inf} = q_{inf}/V$$  \hspace{1cm} (23)

Where V denotes the sample volume which is a function of IR penetration depth (m$^3$)

2.3 Model parameters and properties

**Infrared energy source**

The infrared heat generation ($q_{inf}$) was estimated according to Lambert’s Law 27, written as:

$$q_{inf} = q_o \exp(-\alpha \delta)$$  \hspace{1cm} (24)

where $\alpha$ overall absorption coefficient is calculated from the relationship between the infrared emitter emissivity ($\varepsilon_{IR}$), the emissivity of the sample ($\varepsilon_s$) and the shape view factor between the infrared emitter and the sample$^{12}$. $\delta$ characterizes the depth at which the infrared energy penetrates the sweet potatoes (m), and $q_o$ is the IR incident power from the IR emitter to the sample surface, details of its derivation can be found in Onwude et al.$^{12}$. The IR penetration depth has been reported to be relatively small due to IR wavelength$^{27}$. IR depth of 0.004m has been used in our previous publication$^{27}$ whose accuracy has been proven.

**Thermophysical properties**

Thermo-physical properties of the mixture were estimated from the average of the weighted-volume of all the phases as given in the below expressions$^{21}$:

$$\rho_{eff} = \varphi (\rho_g S_g + \rho_w S_w) + (1 - \varphi) \rho_s$$  \hspace{1cm} (25)
\[ C_{p,\text{eff}} = \varphi (\rho_g C_{pg} + C_{pw} S_w) + (1 - \varphi) C_{ps} \]  

(26)

and

\[ k_{\text{eff}} = \varphi (k_{th,g} S_g + k_{th,w} S_w) + (1 - \varphi) k_{th,s} \]  

(27)

where \( \rho_s \) represents the density of sweet potato \( \left( \frac{kg}{m^3} \right) \), \( C_{pg} \) denotes specific heat capacity of gas \( (J/kg/K) \), \( C_{pw} \) is the specific heat capacity of water \( (J/kg/K) \), \( C_{ps} \) is the specific heat capacity of solid \( (J/kg/K) \) \( k_{th,g} \) is the thermal conductivity of gas \( (W/m/K) \), \( k_{th,w} \) is the thermal conductivity of water \( (W/m/K) \) and \( k_{th,s} \) is the thermal conductivity of sweet potato \( (W/m/K) \).

**Evaporation rate**

The evaporation rate was estimated using a non-equilibrium equation 28. This also agrees with the theory of the statistical rate of evaporation for pure water surface 22,29 and can be expressed as:

\[ R_{evap} = K_{evap} \frac{M_v}{R T} (p_{v,eq} - p_v) \]  

(28)

where \( K_{evap} \) is the evaporation rate constant \( (1/s) \), \( M_v \) denotes the weight of the vapour molecules \( (kg/mol) \), \( p_{v,eq} \) denotes equilibrium vapour pressure \( (Pa) \) and \( p_v \) represents the pressure of the vapour \( (Pa) \).

The equilibrium vapour pressure \( (p_{v,eq}) \) of sweet potato was estimated using the sorption isotherm according to Equation 2930:

\[ p_{v,eq} = p_{v,\text{sat}}(T) \exp \left( -0.027M^{-1.656} + 0.011 \exp(-1.29M)M^{-1.513} \ln(p_{v,\text{sat}}) \right) \]  

(29)
where $M$ is the moisture content of sweet potato (kg/kg dry basis) and $p_{v,\text{sat}}$ is the saturated vapour pressure (Pa). The moisture content ($M$) is also related to $C_w$ through Equation 30:

$$M = \frac{C_w + C_v}{(1 - \varphi)\rho_s}$$  \hspace{1cm} (30)

Hyland and Wexter\textsuperscript{31} presented an equation for the saturated vapour pressure of water and this can be expressed as:

$$p_{v,\text{sat}} = \exp\left(\frac{-5800.2}{T_{ab}} - 5.5163 - 0.048640T_{ab} + 0.000041765T_{ab}^2 - 1.4452 \times 10^{-8}(T_{ab})^3 + 6.5460\ln T_{ab}\right)$$  \hspace{1cm} (31)

where $T_{ab}$ is the temperature measured in Kelvin.

Furthermore, vapour pressure ($p_v$) can be estimated from partial pressure relation as given in Equation 32:

$$p_v = X_v P$$  \hspace{1cm} (32)

where $X_v$ is the vapour mole fraction given by:

$$X_v = \frac{w_v M_a}{w_v M_a + w_a M_v}$$  \hspace{1cm} (33)

**Initial and boundary conditions**

The following initial conditions were used for this study:

$$C_{w0} = \rho_w \varphi S_{w0}$$  \hspace{1cm} (34)

$$W_{v0} = 0.0262$$  \hspace{1cm} (35)

$$P_0 = P_{\text{amb}}$$  \hspace{1cm} (36)

$$M_0 = 3.4 \text{ kg/kg}$$  \hspace{1cm} (37)

and
The conditions representing the boundaries of transportation (Figure 1.) are given for mass conservation of liquid water (Equation 14) and water vapour (Equation 17), respectively as:

\[ T_0 = 301K \]  

\[
\bar{n}_w = h_m \varphi S_w \frac{(p_v - p_{vair})}{RT}
\]  

(39)

\[
\bar{n}_v = h_m \varphi S_g \frac{(p_v - p_{vair})}{RT}
\]  

(40)

where \( p_{vair} \) is the air vapour pressure (Pa) and \( h_m \) denotes the coefficient of mass transfer (m/s).

During the drying of agricultural crops, the boundary pressure equals the pressure at ambient condition. Thus, the boundary condition for gas-phase mass balance (Equation 19) can be expressed as:

\[
P = P_{amb}
\]  

(41)

where \( P_{amb} \) is the ambient pressure (Pa)

During CIR-HAD, heat is transferred by convection and lost from the sample surface due to evaporation. Therefore, the boundary condition for energy equations (Equation 22) is given as\(^{21}\):

\[
q_{surf} = h_T(T - T_{air}) + h_m \varphi S_w \frac{(p_v - p_{vair})}{RT} h_{fg}
\]  

(42)

where \( h_T \) represents the coefficient of heat transfer (\( Wm^{-2}K^{-1} \)). The heat and mass transfer coefficients were obtained from experimental drying data as described in Onwude et al\(^{12}\).

**Permeability**
Permeability is a measure of the capacity and ability of a porous media to allow the transport of water because of a pressure gradient. This is a very important property concerning the modelling and simulation of the transport process in food during dehydration. As such, its value can be used to describe the extent of pressure generated in a product. However, only a few studies considered the inclusion of this property in model development\textsuperscript{21,22,32}. The permeability of porous media is often expressed in terms of intrinsic permeability of water, which is an intensive property that serves as a function of the material structure. Permeability of a material is often derived experimentally by applying Darcy’s law of laminar flow or can be derived as a function of porosity using mathematical models.

In this study, the intrinsic water permeability \( k_w \) was expressed in terms of porosity based on the Kozeny-Carman model and is given as\textsuperscript{33}:

\[
k_w = 5.578 \times 10^{-12} \frac{\varphi^3}{(1 - \varphi)^2} \quad 0.39 < \varphi < 0.77 \tag{43}
\]

Meanwhile, intrinsic permeability for gas \( k_g \) was considered to be constant and is given as\textsuperscript{21,33}:

\[
k_g = 4.0 \times 10^{-12} \text{ m}^2 \tag{44}
\]

On the other hand, the relative water and gas permeabilities can be estimated from water saturation as expressed in Equation 45 and 46, respectively\textsuperscript{21,33}:

\[
k_{r,w} = S_w^3 \tag{45}
\]
\[
k_{r,g} = 1.01e^{-10.86S_w} \tag{46}
\]
where $k_{r,w}$ denotes the water relative permeability ($m^2$) and $k_{r,g}$ represents relative permeability of gas ($m^2$).

**Effective gas diffusivity**

Effective gas diffusivity was estimated based on porosity and gas saturation using the following equation \(^{21,22,28}\):

$$D_{eff_g} = D_{av} (S_g \varphi)^{4/3}$$ \hspace{1cm} (47)

where $D_{av}$ represents binary diffusivity ($m^2/s$) given as \(^{18,34}\):

$$D_{av} = \frac{2.13 \bar{P} (T/273)^{1.8} (S_g \varphi)^{3-\varphi}}{\varphi}$$ \hspace{1cm} (48)

**Liquid Water Capillary Diffusivity (LWCD)**

LWCD is also a very significant phenomenon with respect to the drying of agricultural crops. This is because the dominant force during drying is the capillary force, which is related to the liquid water force\(^{21,28}\). It can be seen from Equation 13, that liquid water capillary diffusivity depends on the capillary pressure and the mass concentration of water. According to Joardder et al.\(^{22}\), an increase in the moisture content results in increased water capillary diffusivity. However, the liquid water capillary diffusivity is not proportional to the effective moisture diffusivity at lower moisture region as is the case with materials with significant vapour diffusion. As such, it becomes indispensable to integrate the capillary diffusivity in transport models. In this study, the liquid water capillary diffusivity ($D_c$) was expressed as a function of moisture content \(^{35}\) as given in Equation 49:

$$D_c = 10^{-8} \exp(-2.8 + 2M)$$ \hspace{1cm} (49)
The model prediction ability was measured based on the coefficient of determination ($R^2$), and root mean square error (RMSE)

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(\hat{M}_{\text{pred}} - \hat{M}_{\text{exp}})^2}{\sum_{i=1}^{N}(\hat{M}_{\text{pred}} - \bar{M})^2}$$  \hspace{1cm} (50)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\hat{M}_{\text{pred}} - \hat{M}_{\text{exp}})^2}{N}} \times 100$$  \hspace{1cm} (51)

**Parameter values and constants**

The values of input parameters and other relevant properties used for the multiphase simulation of sweet potato during CIR-HAD are presented in Table 1.

**Table 1. Parameters and values used for the multiphase simulation of sweet potato during CIR-HAD.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value (unit)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample density, $\rho_s$</td>
<td>1082 (kg/m$^3$)</td>
<td>$^{36}$</td>
</tr>
<tr>
<td>Sample thickness</td>
<td>0.004 (m)</td>
<td>Current study</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.04 (m)</td>
<td>Current study</td>
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<tr>
<td>Initial temperature $T_0$</td>
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<td>Current study</td>
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<td>Drying air temperature, $T_{air}$</td>
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<td>Drying air velocity</td>
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<td>Mass transfer coefficient, $h_m$</td>
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<td>Parameters</td>
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<td>Equivalent porosity, $\varphi$</td>
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<td>Vapour mass fraction, $W_v$</td>
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<td>Initial water saturation, $S_{w0}$</td>
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<td>Initial gas saturation, $S_{g0}$</td>
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<td>Evaporation rate</td>
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<td>Molecular weight (vapour) $M_v$</td>
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<td>Molecular weight (air), $M_a$</td>
<td>$28.966 (g mol^{-1})$</td>
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<td>Ambient pressure, $P_{amb}$</td>
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<td>Thermal conductivity of sweet potato, $k_{th,s}$</td>
<td>$0.0397 + 1.0695 \left(\frac{M}{M + 1}\right) + 0.003T - 0.649 \left(\frac{M}{M + 1}\right)^2$</td>
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<td>Specific heat capacity of air, $C_{pw}$</td>
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<td>1,005.04 $\left(\frac{J}{kgK}\right)$</td>
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<td>Parameters</td>
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<td>Reference</td>
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<tr>
<td>------------------------------------------------</td>
<td>------------------</td>
<td>-----------</td>
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<td>The viscosity of vapour and air, $\mu_g$</td>
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<tr>
<td>Infrared bulb emissivity, $\varepsilon_{IF}$</td>
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<td>27</td>
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</table>

2.4 Model implementation and computer simulation

Figure 2 illustrates the flowchart of the developed multiphase simulation model for CIR-HAD of sweet potato. The mathematical models and phase simulation were solved with MATLAB program (version R2016b, MathWorks, Natick, Massachusetts, USA) using finite element method (FEM) and differential solver. The multiphase models were written in MATLAB files considering evaporation, mass flux, infrared heat source, gradients, and the differential solver.

The MATLAB programming steps included: (i) creating system domain, (ii) creating the finite element mesh (tetrahedral after several sensitivity tests), allowing for easy modification of the maximum edge size, the mesh growth, edge triangulation and maximum iteration, (iii) defining the mathematical models (Equation 1-49), (iv) developing global functions and matrix, (v) defining all boundary conditions and input parameters, (vi) numerical solution using differential solver, and (vii) coupling and integrating with graphical user interface (GUI).
Figure 2. A flow chart showing the working steps of the multiphase model simulation.

Multiphase simulation for CIR-HAD of sweet potato involves defining the material geometry, constants and input parameters (Figure 3.). After which the mathematical models are fully coupled for energy balance, mass and momentum balance, the continuity equation for gas phase, evaporation rate, effective diffusivity of gas and liquid water and capillary diffusivity of gas and liquid water. The program then solves the model based on time.
steps. The results are then displayed (graphs, data and contour) for various drying phenomenon including moisture distribution, temperature distribution, liquid water flux, vapour water flux, gas pressure. The simulation for this study was done on Windows 10 Lenovo Yoga Laptop, with Intel® Core™ i3-4030U CPU@ 1.90GHz, 8GB RAM, and 500GB disk space. Each simulation run took a total time of about 1-5 hours.

**Figure 3.** The interface of the developed multiphase MATLAB based simulation program.

3. **Materials and methods**

3.1 **Drying experiments**

The experimental sweet potato drying data of Onwude et al.\textsuperscript{42} was used for the model validation. Sweet potato slices were spread on a stainless steel
mesh in the drying chamber of IR combined hot-air dryer. Onwude et al. described the details of the materials used, CIR-HAD dryer, the drying experiments and the measuring instruments for air velocity, air temperature, sample temperature, relative humidity and infrared intensity used in this study (Figure 4). The drying experiments were conducted at an air velocity of 1.2 m/s, air temperature of 60 °C, relative humidity of 45 ± 2%, 1100 W/m² infrared intensity, and 30 cm distance between the sample surface and IR emitter. For each experimental run, the drying continued until the final moisture content reached 0.02 kg/kg (dry basis).

Figure 4. A Schematic of Combined Infrared and Hot-Air Dryer (A=Load cell; B=Infrared bulb; C=hot-air Fan/blower; D=Sweet potato sample; E=Drying tray; F=Drying system; G=Drying chamber; H=Computer system; I=Digital Control panel for drying system; J=Control panel for Infrared) (figure not to scale)

4. Results and discussion
4.1 Drying kinetics and temperature prediction
The simulated and experimental drying kinetic results for sweet potato slices during CIR-HAD is shown in Figure 5. From the figure, it can be seen that the CIR-HAD of sweet potato slices took place during the falling rate period with short drying time. A similar result was obtained by Onwude et al.\textsuperscript{27}. The developed multiphase model satisfactorily predicted the moisture changes of sweet potato with $R^2 > 0.98$ and $< 5\%$ relative error. Compared to single-phase shrinkage and temperature-dependent models\textsuperscript{27}, there was no much difference as the multiphase model gave very good prediction as can be seen in Figure 5. As the single-phase model is diffusion based, this result already gives us an idea that diffusion is the dominant mechanism of mass transfer for CIR-HAD. The no-shrinkage assumption for the multiphase model did not significantly affect the prediction ability for moisture transfer.

![Figure 5. Simulated and experimental moisture changes of sweet potato slices during CIR-HAD.](image)
Figure 6 shows the simulated and experimental average temperature data during combined IR and HAD. The simulation results agreed reasonably with the experimental data ($R^2 = 0.956$). However, a slightly higher temperature prediction by the model after 20 minutes of drying can be seen in the figure. This may be because of differences in the average temperature data, which consisted of collected data at the surface of the sample for the experimental result, and the average value of all finite element nodes from the multiphase physical model. A similar observation was reported for the multiphase modelling of microwave drying\textsuperscript{32}. In addition, the slight discrepancy between the experimental and simulation temperature results may be because of solid deformation, which was not considered in this model. Yuan et al.\textsuperscript{43} reported a similar finding for convective drying of apple slices. They observed inconsistency between experimental temperature data with those obtained from simulation runs. Compared to the single-phase shrinkage and temperature-dependent models\textsuperscript{27}, the multiphase model resulted in better prediction of average sample temperature using the experimental data set for this study.
Figure 6. Average simulated and experimental temperature for sweet potato slices during CIR-HAD

4.2 Temperature evolution inside the sample

From Figure 6 above, we can see that the average temperature of the sample varied with time. To further gain insight into the temperature distribution within the product, Figure 7 illustrates the temperature evolution along the radial axis of the sample at different drying times. The temperature inside the sample may be non-uniform and, hence, a function of the radial distance.

From Figure 7, at the start of the drying process (0-10s), the temperature at the sample surface is higher than that in the sample core and also on the sample sides. This could be as a result of the forced hot-air heating. As
drying continued, infrared radiation penetrates the sample and further heat is generated within the sample core. The temperature inside the sample (from the right-side) can be seen to be higher than that of the sample surface after 400s of drying. This effect continued even after 800sec, but this time more towards to sample core. The central temperature rising rate of sweet potato slices was faster than the peripheral temperature rising rate after 800s – 1000s. At these points, the temperature in the sample interior was higher than that at the exterior during CIR-HAD. This higher interior temperature towards the sample-bottom core could be due to increased evaporation cooling and higher absorption rate due to higher moisture content. The temperature profile for CIR-HAD of sweet potato shows that the regions of high temperatures are located towards the middle and bottom of the sample, indicating the presence of significant electron and magnetic field density near those locations. This behaviour has been demonstrated by Onwude et al. for the single-phase heat and mass transfer modelling of sweet potato during CIR-HAD. Kumar et al. also reported similar findings for the multiphase modelling of apple slices during intermittent microwave convective drying. Generally, the temperature evolution at different drying time has shown uneven heating (asymmetric profile) due to infrared radiation during CIR-HAD. This result offers profound insight regarding the over-heating of heat-sensitive food during continuous CIR-HAD, suggesting that a temperature redistribution is needed (intermittent application of IR).
4.3  Moisture distribution inside the sample

The final nutritional, sensory and shelf-life quality of dried food are related to the average moisture content but also the moisture distribution in different parts of the product. Often, we see that spoilage of dried food starts from one part of the food and spreads to other parts with time. Therefore, to mitigate this effect and control the drying process both at the micro and macro scale, more intuition into the moisture concentration gradient during CIR-HAD process becomes indispensable.

Figure 8 shows the evolution of water concentration of sweet potato sample at different drying time (10–1000s). Random moisture movement both within the product and at the product surface was observed, hence both diffusion and convection mass transfer occur. As expected, the figure shows...
higher moisture concentration inside the sample at the start of the drying process (10s) compared to the sample surface. The moisture level can be seen to spread sideways from the center of the product (100s). Gradual reduction of the moisture concentration inside the product occurred as drying continues with almost the same water content level throughout the sample after 400s. At this point, there is increased heat generation inside the sample due to infrared heating (see Figure 7 above), as well as increased evaporation rate at the sample surface (see below-section 4.4, 4.5). With further heat generated within the sample core as drying continued (1000s), the moisture concentration reduced further inside the sample compared to the sample surface and sides.

An interesting perception is demonstrated for 100s - 800s, where the moisture concentration at the centerline-surface is higher than the other parts to the surface edges. This finding implies that evaporation during the CIR-HAD in this study increases with increasing distance from the centerline of the sample surface. Again, confirming the non-inform drying rate of CIR-HAD within the product as earlier observed, even though the moisture level gradient only ranged from 0.01-1kg/m³.
Figure 8 Simulated moisture concentration in sliced sweet potato at different drying times during CIR-HAD

4.4 Gas pressure and evaporation rate

Figure 9(a) shows the gas pressure spatial distribution within sweet potato slices for CIR-HAD. The gas pressure for CIR-HAD was higher centrally and decreased gradually towards the surface. This is because the gas transport is restricted to lower gas porosity, leading to higher total gas pressure. Similar results have been reported by Joardder et al.\(^{21,22}\) for the microwave hot-air drying of food.
The evaporation rate of sweet potato during CIR-HAD is shown in Figure 9b. The figure shows that the evaporation rate increased with drying time as also observed for microwave convective drying\textsuperscript{22}. This is due to a greater vapour pressure difference between the sample and drying environment. In addition, the steady increase in the evaporation rate with drying time also indicate the presence of non-equilibrium condition throughout the drying process. This phenomenon cannot be explained using a single-phase model\textsuperscript{27}. It is worthy to note that the importance of equilibrium vapour pressure and the vapour pressure parameters in the developed non-equilibrium multiphase model cannot be overemphasised as earlier stated by Zhang & Datta\textsuperscript{44}. Therefore, the nonequilibrium multiphase models are more realistic when compared to the single-phase diffusion model for representing physical problems.

4.5 Mass fraction of vapour in the sample
Contrarily to what has been reported in the literature\textsuperscript{22}, the vapour mass fraction of a porous media during drying is not constant. This is because phase change occurs during drying and the moisture concentration within the product varies with time, as already discussed above. The mass fraction is independent of temperature until phase change occurs. Figure 10 shows the mass fraction of vapour for sweet potato sample during CIR-HAD at different drying times (10s-1000s). The vapour mass fraction increases with increased drying time, corresponding to an increase in evaporation (Figure 9b). At the start of the drying process (10s-100s), the vapour mass fraction is higher at the sample surface compared to the core of the sample (Figure 10). During this time, the temperature of the sample surface is also higher than that at the sample core (Figure 7). Since mass fraction is independent of temperature until phase change occurs, it then means that phase change from liquid water to vapour occurs almost immediately after the start of the drying process for CIR-HAD. This insight further shows the synergetic contribution of IR and convective heating for CIR-HAD, which makes this drying process rapid.

From Figure 10, the mass fraction of vapour (10s-400s) increases sideways from the centreline to the sample edges. This implies that evaporation during the CIR-HAD increases with increasing distance from the centerline. At 400s, the same mass fraction of vapour can be observed throughout the sample (with 0.00004 radial gradient). This corresponds with the uniform moisture distribution as was already discussed above (Figure 8). As drying progresses, heat is conducted through the food to the liquid-vapour interface, where an abrupt temperature drop takes place due to evaporation. The vapour mass fraction component in the gas mixture is greatest at the sample core. Due to increased diffusion and convection,
with increased drying time (800s-1000s), the vapour mass fraction increases with increasing distance from the sample surface, with higher concentration at the bottom.

![Figure 10. Spatial gradient of mass fraction of vapour for sweet potato slices during CIR-HAD](image)

**4.6 Liquid water and vapour fluxes**

Figure 11 shows the liquid water fluxes due to capillary diffusion and gas pressure in sweet potato during CIR-HAD along the vertical and horizontal directions at different drying times. The figure shows that the liquid water fluxes along both the vertical and horizontal directions is higher towards the sample sides (radius =15mm from the center) and decreases radially towards the surfaces at the initial drying period (400s). A similar finding was reported for microwave convective drying of apple\(^2\). The liquid water
flux at 400s drying time is zero on the side edges of the sample and mostly positive afterwards. This indicates that the water flux is moving from the product sides and center towards the radial middle (10-15mm) of the product. It is interesting to note that the moisture flux near the centreline is higher than those at the surfaces after drying for 1000s (Figure 11). This result corresponds to that of moisture concentration as discussed above (Figure 8), implying that increased liquid water increased the drying rate, resulting in a reduction in moisture concentration. The increase in the concentration gradient during CIR-HAD result in faster drying rate when compared with convective hot-air drying. This finding further suggests that capillary diffusion and gas pressure are less dominant in the center of the sample at the start of the drying process. However, as the drying continues capillary diffusion and gas pressure becomes more dominant towards the sample centerline.

![Figure 11 Liquid water flux spatial distribution for sliced sweet potato during CIR-HAD](image)

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Figure 12 illustrates the spatial distribution of vapour fluxes for sweet potato during CIR-HAD. The figure shows that the vapour fluxes for both vertical and horizontal direction are positive during the drying process (0-100s). The vapour flux is higher towards the right side of the sample after drying for 1000s (radius = 15mm) and gradually decreases towards the centreline in both directions. The vapour flux at this point can be seen to move from the product center (-0.000006 kg/m²/s) to the product surface (0.0000015 kg/m²/s) in both directions (Figure 12). Similar results have been reported for microwave drying 21, and heating 45. Binary diffusion and gas pressure are more dominant at the sides of the sample during the drying process.

Figure 12. Vapour flux spatial distribution for sliced sweet potato during CIR-HAD

In summary, we can see that the distribution of the vapour flux differs from that of the water flux during the drying of food using CIR-HAD. These trends
are due to the different mass diffusivities in each of the phases. At the start of the drying process, the vapour fluxes due to binary diffusion and gas pressure are the only fluxes for moisture transport at the sample surfaces in all directions (Figure 12). At this stage, the dominant mechanism for moisture transport in the sample core is the water fluxes due to capillary diffusion and gas pressure gradient in both the vertical and horizontal directions (Figure 11). As drying continued for about 100s, the transport of moisture to the sample center during CIR-HAD is only by water fluxes due to capillary diffusion and gas pressure (Figure 11). On the other hand, both water and vapour fluxes cause moisture transport around the surfaces and sides of the sample in both the vertical and horizontal directions. This interesting result further gives additional insight into the different role of the mass transfer mechanism during the drying of food using combined infrared and hot-air drying technique.

4.7 Effects of operating conditions

From the discussion above, we identify the product temperature and moisture profile to be of significance during the CIR-HAD of sweet potato. Based on this, we quantify the effect of varying the model air temperature and the depth of IR penetration on the product temperature and drying kinetics of sweet potato (Figure 13).

Figure 13a shows that changes in the drying air temperature significantly affects the moisture content of sweet potato during CIR-HAD. An increase in the drying air temperature from 40 °C to 60 °C after 1000s resulted in about 2.2% reduction in the moisture content. A stronger sensitivity of sample temperature to drying air temperature is shown in Figure 13b.
Increasing the air temperature from 40 °C to 60 °C caused a significant increase in the sample temperature by about 46%.

The moisture changes of sweet potato during CIR-HAD was not too sensitive to the IR penetration depth at the start of the drying process (Figure 13c). However, the effect increased as drying continued, just as discussed above. On the other hand, the sample temperature was sensitive to IR penetration depth throughout the drying process (Figure 13d). Overall, the effect of IR penetration depth on the CIR-HAD drying of food became prominent as drying progressed, whereas the drying air temperature was effective from start till the end of the drying process. These results further explain the reason why moisture concentration in the product core is very high at the start of the drying process (Figure 8). Since IR internal generation of heat takes prominent as drying progresses, it makes sense to have less effect on moisture distribution at the start of the drying process.
Figure 13. Moisture content and temperature of the food as a function of time for different drying air temperature and infrared penetration depth: [a] moisture profile ($T_{\text{air}}=40-60^\circ\text{C}$); [b] temperature profile ($T_{\text{air}}=40-60^\circ\text{C}$); [c] moisture profile ($\text{IR-depth}=0.003-0.005\text{m}$); [d] temperature profile ($\text{IR-depth}=0.003-0.005\text{m}$)

5. Conclusions

A non-equilibrium multiphase model for combined infrared and hot-air drying (CIR-HAD) of sweet potato was developed. The model was validated with experimental moisture content and temperature drying data. We quantify the evaporation rate, gas pressure, liquid water and vapour fluxes during the CIR-HAD of sweet potato, which is not possible using the much simpler single-phase model. This will allow more rationale fine-tuning of drying conditions to give desirable quality parameters. To pave the way for further development of CIR-HAD technology, this study concludes with the following:
• A multiphase porous media model considering Lambert’s law for electromagnetic heat generation can adequately be used to describe the drying behaviour and drying mechanism of food during CIR-HAD.

• The temperature distribution is uneven within the food product during the CIR-HAD duration.

• The phase change from liquid water to vapour occurs almost immediately after the start of the drying process for CIR-HAD.

• At the start of the drying process, the vapour fluxes are the only fluxes for moisture transport at the sample surfaces in all directions. The dominant mechanism for moisture transport in the sample core is water fluxes.

• Both water and vapour fluxes cause moisture transport around the surfaces and sides of the sample during the drying process.

• The moisture and temperature profile were sensitive to the model drying air temperature and IR penetration depth, with air temperature being the more dominant model parameter.

Declaration of Competing Interest
The authors confirm that there is no conflict of interest associated with this research

Acknowledgement
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List of Nomenclatures
Moisture concentration \( (kg/m^3) \)

The temperature of each phase \( (K) \)

Density \( (kg/m^3) \)

Specific heat capacity of sweet potato \( (J/kgK) \)

Thermal conductivity \( (W/mK) \)

Volumetric infrared heat source \( (W/m^3) \)

Heat absorbed by sweet potato \( (W) \)

Absorption coefficient

Infrared penetration depth \( (mm) \)

Infrared emitter emissivity

The emissivity of the sweet potato

View factor between the surface of the IR bulb and sample

View factor between IR emitter and the wall

View factor between the sample and the wall

Stefan-Boltzmann radiation constant

The temperature of the emitter \( (^\circ C \text{ or } K) \)

The temperature of the sample surface \( (^\circ C \text{ or } K) \)

Total thermal resistivity

The initial mass of sample \( (kg) \)

Mass of dried sample \( (kg) \)

Heat transfer coefficient \( (W/m^2K) \)

Mass transfer coefficient \( (m/s) \)

Drying air temperature \( (^\circ C \text{ or } K) \)

Latent heat of evaporation \( (J/kg) \)

Specific heat capacity \( (J/kgK) \)

Thermal conductivity of product \( (W/mK) \)

Sample initial surface area \( (m^2) \)

Sample surface area at a time, \( t \) \( (m^2) \)

Density of water \( (kg/m^3) \)

The density of sweet potato \( (kg/m^3) \)

The activation energy \( (kJ/mol) \)

Universal gas constant \( (J/mol/K) \)

Diffusion integration constant \( (m^2/s) \)

Density of air \( (kg/m^3) \)

Dynamic viscosity of air \( (kg/m \cdot s) \)
\( \mu_w \) Dynamic viscosity of water (kg/m. s)
\( \mu_v \) Dynamic viscosity of vapour (kg/m. s)
\( v \) Drying air velocity (m/s)
\( k_a \) Thermal conductivity of air (W/ (K.m))
\( C_{pa} \) Specific heat capacity of the air \( \left( \frac{J}{kgK} \right) \)
\( a_w \) Water activity
\( \Delta V \) The sum of the gas, water and solid volume \( (m^3) \)
\( \Delta V_g \) The volume of gas \( (m^3) \)
\( \Delta V_w \) The volume of water \( (m^3) \)
\( \Delta V_s \) The volume of solids \( (m^3) \)
\( \varphi \) Apparent porosity
\( S_g \) Gas saturation
\( S_w \) Water saturation
\( K_{evap} \) Evaporation constant
\( M_v \) The molecular weight of vapour \( (kg \text{ mol}^{-1}) \)
\( M_a \) The molecular weight of air \( (kg \text{ mol}^{-1}) \)
\( M_g \) The molecular weight of gas \( (kg \text{ mol}^{-1}) \)
\( P_{amb} \) Ambient pressure (Pa)
\( P_w \) The total flux of liquid water
\( R_{evap} \) Liquid water evaporation to water vapour \( (kg/m^3s) \)
\( K_g \) Intrinsic permeability of gas \( (m^2) \),
\( P_{va} \) Air vapour pressure (Pa)
\( D_{va} \) Binary diffusivity \( (m^2/s) \)
\( C_{pv} \) Specific heat capacity of vapour \( \left( \frac{J}{kgK} \right) \)
\( C_{pw} \) Specific heat capacity of water \( \left( \frac{J}{kgK} \right) \)
\( K_{th,s} \) Thermal conductivity of sweet potato \( \left( \frac{W}{mk} \right) \)
\( K_{th,g} \) Thermal conductivity of the gas \( \left( \frac{W}{mk} \right) \)
\( K_{th,w} \) Thermal conductivity of water \( \left( \frac{W}{mk} \right) \)
\( W_v \) Vapour mass fraction
\( LWCD \) Liquid water capillary diffusivity

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