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Mathematical modelling of convective drying of fruits: A review

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A B S T R A C T

The convective drying of fruits is the most implemented drying technique to stabilize fruits and to increase their shelf life. The mathematical modelling of drying is a useful tool in process optimization and dryer design. The modelling involves the solution of complex partial differential equations of coupled heat, mass and momentum transfer, which can be solved by several numerical and analytical methods. The aim of this review is to present and analyse the main published researches on the modelling of the convective drying of fruits focused on theoretical models. The main parameters involved in the numerical modelling of fruit drying are presented, such as the main mathematical models in the conjugated or non-conjugated approach, the applications on different geometries and dimensions, the scale approach, the thermophysical and transport properties determination, the alternatives of numerical solutions, the main methods to determine convective transfer coefficients, and other modelling considerations such as the shrinkage inclusion and quality deterioration are presented and analysed in this review based on the studies reported in the literature in the past decade. Through their comparison and analysis, future perspectives and challenges in fruit drying modelling are discussed. The computational tools increase the accuracy in predicted values and the possibility to extrapolate the characteristics from a micro-scale level to a macro-scale level. The challenges for convective drying of fruit lead to overcoming the dependence on empirical models for drying parameters determination, the lack of shrinkage inclusion and 3D modelling by means of advanced procedures such as multi-scale and conjugated modelling. The definition of the application of the model is important. Simple models present an effective use in some cases of engineering applications. More complex models are closer to reality and useful to engineering and research purposes.

Contents

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Nomenclature

a_w	water activity
T_∞	air temperature (°C)
C_m	water capacity (kg kg^{-1}Pa^{-1})
x, y, z	coordinates (m)
C_μ	empirical turbulence model constant
X	moisture content ((kg kg^{-1}, dry basis, db)
C_p	specific heat (J kg^{-1} K^{-1})
w^*	dimensionless moisture content
C_∞	water concentration in air (mol m^{-3})

Greek symbols

C_o	water concentration in fruit (mol m^{-3})
α	thermal diffusivity (m^{2}s^{-1})
$C_{w,c}$	water content on wet base (kg kg^{-1})
ε	turbulent dissipation rate (m^2 s^{-3})
D_{eff}	effective moisture diffusivity (m^{2}s^{-1})
ϕ	porosity
D_c	water diffusion coefficient inside cells (m^{2}s^{-1})
θ	dimensionless temperature
h	heat transfer coefficient (W m^{-2} K^{-1})
ρ	density (Kg m^{-3})
h_{fg}	latent heat of evaporation (J kg^{-1})
ρ_s	density of solid product = dry mass/total volume (kg m^{-3})
h_l	enthalpy of liquid water (J kg^{-1})
$\rho_{w,c}$	wet base cell density (Kg m^{-3})
h_m	mass transfer coefficient (m s^{-1})
σ_κ	model parameter
I	net superficial incident radiation (W m^{-2})
ς	($\varkappa L_0^{-1}$)diffusion timescale(dimensionless)
J	Jacobian of the transformation (m^{-3})
τ	time in the transformed domain
k	turbulent kinetic energy (m^2 s^{-2})
ω	specific dissipation (s^{-1})
K_m	moisture permeability of the tissue (s)
$\varkappa$	thickness (m)
K_g	intrinsic permeability of gas (m^2)
η,μ	dynamic viscosity (N s m^{-2})
$K_{r,g}$	relative permeability of gas
μ_τ	turbulent viscosity (Kg m^{-1} s^{-1})
K_1-K_4	model coefficients
ξ,γ	axes of the system of generalized coordinates (dimensionless)
Le	Lewis number
λ	thermal conductivity (W m^{-1} K^{-1})
$\dot{m}$	evaporation rate (kg m^{-2}s^{-1})
ψ	water potential (Pa)
$\dot{m}_{v,loss}$	internal water vapor loss (kg s^{-1})

Subscripts

a_{11}- a_{22}	coefficients for the diffusion model in generalized coordinates
a	air
P	pressure (Pa)
c	cell
($\dot{Q}$)	volumetric heat generation (Wm^{-3})
g	gas
R	radius (m)
eq	equilibrium
RH	relative humidity of drying air (%)
pol	polyphenols
r, y	position in cylindrical coordinates (m, m)
PM	porous medium
u	shrinkage velocity (ms^{-1})
sol	solid
u	velocity (m s^{-1})
t	drying time (s)
T	absolute temperature (K)
$\bar{T}$	scaled temperature (dimensionless)

1. Introduction

Fruits are biological materials and the source of many biological, flavour and aroma compounds of interest in health and industry. Fruits can be consumed fresh or processed, and drying is one of the most used methods to stabilize fruits and their compounds. Dried fruit has been used as snack and ingredient to formulate functional foods, pharmaceuticals and cosmetic products. Drying is a unit operation to remove water from a product and consequently to reduce its water activity (Omolola et al., 2015). There are many advantages of fruit drying, such as: the inhibition of the growth of microorganisms and deterioration reactions by the water activity reduction (Caccavale et al., 2016) as well as the reduction of transport and storage costs due to product weight and volume decrease (Fernandes et al., 2011; Kaleta et al., 2013; Márquez and de Michelis, 2011; Tzempelikos et al., 2015).

Convective drying is the process of removing water with air via simultaneous heat, mass and momentum transfer. The required heat is conducted to the food by a stream of hot air. The energy is transferred to the surface of the product by convection and then is transferred inside the product by diffusion or convection, depending on the product structure. This heat flux causes a product temperature increase and water evaporation (Bezerra et al., 2015; García-Alvarado et al., 2014). The moisture is transferred from the product surface to the air by convection as water vapor and from inside the product by diffusion, convection or capillarity (Ertekin and Firat, 2015; Fernando et al., 2011). The drying rate and the dried product properties depend on the external conditions of the process such as air temperature, humidity, velocity and the air flux direction. Additionally, the drying rate depends on internal