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Numerical modeling of convective drying of food with spatially dependent transfer coefficient in a turbulent flow field

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A B S T R A C T

A numerical model is developed for prediction of transient moisture content of food materials. The moisture transfer is modeled considering diffusion of liquid water from inner layer to outer surface of the food material followed by evaporation of water from the surface to the dry air which flows over the moist food material. Discretization of transient heat and mass transfer governing equations are done using the finite-volume method (FVM). A 3-D code in MATLAB is developed to solve the simultaneous heat and mass transfer equations. The flow field over the moist food material is assumed to be turbulent and SST $k-\omega$ turbulence model is used for prediction of heat transfer coefficient using a computational fluid dynamics (CFD) commercial code. The sample moist food material is considered to be a rectangular shaped potato and the effects of temperature and velocity on drying behavior of the same are predicted. Different drying rate periods are identified. The numerical model is validated with experimental data with a reasonable agreement.

1. Introduction

Drying is the process of thermally removing moisture from a moist material by evaporation. Moisture held in moist food material as loose chemical combination, present as a liquid solution or trapped in the microstructure of the food material, which exerts a vapor pressure less than that of pure liquid is called bound moisture. Moisture in excess of bound moisture is called unbound moisture. Drying involves two processes to occur simultaneously, one is transfer of heat from the surrounding environment to evaporate the surface moisture and second is transfer of internal moisture to the surface of the food material and its evaporation due to process one. In first process, the removal of water as vapor from the material surface depends on the external conditions like air temperature, humidity, velocity, area of exposed surface, and pressure. In second process, the movement of moisture internally within the food material is a function of the physical nature of the food material, the temperature, and its moisture content. Drying rate depends on the rates of two processes mentioned above. Transport of moisture within the food material may occur by any one or more of the following mechanisms of mass transfer [1]: liquid diffusion (if the moist food material is at a temperature below the boiling point of the liquid), vapor diffusion (if the liquid vaporizes within material), Knudsen diffusion (if drying takes place at very low temperatures and pressures), hydrostatic pressure differences (when internal vaporization rates exceed the rate of vapor transport through the solid to the surroundings), combinations of the above mechanisms. Drying is an essential operation in the chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral processing, and wood processing industries, because drying extends product stability (prevention of growth and reproduction of undesirable microorganisms), enhances product quality (minimization of moisture mediated deterioration reactions, e.g. nutrient loss, product discoloration), and provide ease of handling the product (reduction in product weight and volume, decreased packing, storage and transportation costs) [2].

There has been a large amount of numerical work with varying degrees of complexities for prediction of drying rate of food products. The simplest model that is available in the literature considers only mass transfer [3–10] (no heat transfer) assuming that the drying occurs almost isothermally or the gradient of the temperature around the food material is too small to have any effect in the mass transfer process. The mass transfer is governed by the Fick's law of diffusion with a diffusion coefficient based on an Arrhenius form of equation which is a function of temperature.

In the next level of numerical model, simultaneous heat and mass transfer are considered with the effect of temperature

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Nomenclature

a	discretization coefficient
a_w	water activity
C	specific heat of moist food material (J/kg K)
C_p	specific heat of air (J/kg K)
D	moisture diffusivity of water in moist food material (m^2/s)
D_{va}	diffusivity of vapor in air (m^2/s)
h	heat transfer coefficient (W/m^2 K)
h_m	mass transfer coefficient (m/s)
h_{fg}	heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
L, B, H	length, breadth and height of moist food material (m)
Le	Lewis number
m_{dry}	dry mass of the food material (g)
m_{wet}	wet mass of the moist food material (g)
M	moisture content in food material (kg/kg of solid (db))
P_a	total ambient pressure (Pa)
P_v	partial vapor pressure (Pa)
Pr	Prandtl number
t	time (s)
T	temperature of moist food material (K)
u	velocity (m/s)
$\overline{u}, \overline{v}, \overline{w}$	time averaged velocity in x, y and z directions (m/s)
u', v', w'	fluctuating component of velocity in x, y and z directions (m/s)
Y	specific humidity (kg/kg of dry air)
x, y, z	distance along X, Y and Z direction

Greek symbols

α	thermal diffusivity (m^2/s)
μ	dynamic viscosity of drying air (Ns/m^2)
ρ	density (kg/m^3)
ϕ	relative humidity of drying air

Subscripts

o	initial condition
∞	conditions of drying air
i	interface between air and food material
m	moist food material

dependent diffusion coefficient [11–14]. Wang and Brennan [14] developed a 1-D mathematical model of simultaneous heat and moisture transfer for the prediction of moisture and temperature distributions during drying in a slab-shaped solid. The model took into account the effect of moisture-solid interaction at the drying surface by means of sorption isotherms of food. Non-constant physical and thermal properties were also incorporated in the model. The model was applied to the air drying of potatoes. They concluded that shrinkage had an influence on the drying behavior of potato and should be taken into account in predictive models.

In the recent time, numerical model has been developed with the consideration of variable heat and mass transfer coefficient [15–18] in 2D rectangular [15], cylindrical [16] and 3D geometries [17]. The variable convective coefficients were calculated using CFD simulations. The external flow and temperature fields were first numerically predicted solving simultaneous momentum and energy equations. From these distributions of temperature and velocity, the local distributions of the convective heat transfer coefficients were determined. Convective mass transfer coefficients were then calculated through the analogy between the thermal and concentration boundary layers. The simultaneous diffusive heat and mass transfer equations for internal temperature and moisture content field inside the moist food material were solved using these variable convective coefficients in the boundary conditions. Most of these analyses are for a lower air velocity range of 0.1–0.3 m/s with an assumption of laminar flow.

A more involved CFD model has been developed by Lamnatou et al. [19] for convective drying with consideration of laminar flow. The effect of drying on the relative positioning of a pair of porous blunt plates is investigated numerically based on a combination of a flow-heat transfer simulation with a suitable drying model.

In the most advanced recent model available in the literature, the heat and mass transfer is modeled with the consideration of heat loss because of evaporation. Islam et al. [20] developed a 1-D liquid diffusion model with surface evaporation and predicted optimum drying condition at different level of moisture content during drying by matching the energy demand for drying as determined by the drying kinetics. The evaporation of water from the surface of the moist food material is modeled considering water activity rate. The flow of air around the potato sample was assumed to be laminar. Only liquid transport is considered inside the food material in this work. A similar 1D model was proposed by Barati and Esfahani [21] with consideration of evaporation at the surface. Semi-analytical solutions were presented for carrot slabs with the effect of Biot number and relative humidity. In another work, an analytical model has been proposed by Ho et al. [22] where internal evaporation of liquid water is considered with both liquid and vapor transport inside a 2D potato sample. All these studies [20–22] considered a constant convective coefficient at the boundaries.

The velocity range considered for drying is in normally more than 0.5 m/s and in that velocity range, the flow field is turbulent. In that case, it is important to estimate the heat transfer coefficient with a proper turbulence model. None of the numerical work considered turbulent flow field of the drying air and hence thereby underestimated the heat and mass transfer rate from the air to moist food material. To the authors' knowledge, this is the only work which considers a turbulent flow field of air and thereby considers a more accurate convective boundary condition. Moreover, a 3-D numerical model with consideration of evaporation at the surfaces was never studied in the literature. This numerical work also closely simulates an experimental set up [23] developed at IIT Delhi and compares the numerical and experimental data reasonably well.

2. Mathematical model

2.1. Modeling of external flow and temperature field

Fig. 1 shows a moist food material kept inside a rectangular duct and exposed to the flow of hot air through the duct. The moist food material is placed centrally at the middle of the channel so that it gets maximum exposure to the air flow.

In this external flow model, prime objective is to find out the heat transfer coefficient at the surfaces of the moist food material. The solution domain for the CFD simulation is the duct without the moist food material. Therefore interior boundaries are placed around the moist food material to separate it out from the CFD simulation. The food material used in this work can be considered as a bluff body. Flow over the bluff bodies contains many complex phenomena such as separation, wake flow, vortex shedding, high