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Numerical analysis of convective drying of a moving moist object

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ABSTRACT

Convective drying of a moving moist object is investigated numerically solving the conservation equations of mass, momentum, energy and air moisture concentration based on a k–ϵ turbulence model in the external region of the object as well as the conservation equations of energy and object moisture concentration in the internal region. The external and internal conservation equations are coupled to the heat and mass transfer conditions on the object surface including the effects of evaporation and water activity. The numerical results show that the analogy between heat and mass transfer for the convective drying is valid only when the object temperature is close to the equilibrium temperature. The simple analytical formulations developed for the total drying rate are found to compare well with the numerical results. The effects of object velocity and thickness and the wall heat flux on the drying rate are quantified.

1. Introduction

Hot air drying of a moving moist object is a popular water removal process for manufacturing various materials and handling bio products which are carried on a conveyor belt or a rotating drum. The convective drying process includes heat transfer to the wet object, evaporation of its moisture, and mass transfer to the surrounding air [1]. Its predictive model is essentially important to optimize the design parameters in various drying applications.

Shiravi et al. [2] presented a numerical model for analysis of superheated steam jet drying of a moist slurry film on a rotating drum. The heat and mass transfer in the moist film was obtained by solving one-dimensional unsteady conservation equations of energy and object moisture mass. The external convection heat transfer rate on the object boundary surface was evaluated by computing the two- or three-dimensional conservation equations of mass, momentum and energy in the external steam region. The mass transfer rate on the object surface was obtained from their experimental data.

Lu and Shen [3] investigated paper drying on a rotating drum by solving one-dimensional transient conservation equations of energy and object moisture mass with the effect of drum rotation. They estimated the air-side heat transfer coefficient on the object surface from the Dittus and Boelter's correlation instead of solving the conservation equations in the external air region and the mass transfer coefficient from the analogy between heat and mass transfer.

A more comprehensive study of drum drying of a sludge film was conducted by Islam et al. [4] including the effects of sludge film thickness, drum rotational speed and drying air velocity on the drying performance. The sludge film thickness was found to be the most critical parameter to determine the final moisture content. Their numerical model also employed one-dimensional temperature and moisture diffusion equations in the sludge film and the empirical correlations to evaluate the heat and mass transfer coefficients on the object surface. The water activity, which is defined as the ratio of partial vapor pressure on the object surface to the saturated vapor pressure at the same temperature, was included in the calculation of the evaporation rate on the object surface. Burmester and Eggers [5] carried out a similar analysis for coffee drying in a vacuum belt dryer using one-dimensional unsteady conservation equations in the object and the empirical correlations for the external heat and mass transfer coefficients.

Several researchers presented numerical methods to solve multi-dimensional conservation equations of energy and moisture mass in an object and to compute the external heat and mass transfer coefficients on the object boundary rather than to use the corresponding empirical correlations. Kaya et al. [6] solved two-dimensional conservation equations of energy and moisture mass inside a stationary object using the air-side heat transfer coefficient, which was computed from the conservation equations of mass, momentum and energy in the external region. The mass transfer coefficient was obtained from the analogy between heat

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Nomenclature

c	specific heat
D	diffusion coefficient
h_{fg}	heat of vaporization
k	turbulent kinetic energy
H	height
h_t	convection heat transfer coefficient
h_m	convection mass transfer coefficient
L	length
Le	Lewis number
M	molecular mass
Nu	Nusselt number
p	pressure
q	heat flux
Re	Reynolds number
Sh	Sherwood number
T	temperature
u	velocity in the x-direction
x, y	cartesian coordinates
Y	water vapor mass fraction

Greek symbols

α	volume fraction
ϵ	turbulent dissipation rate
λ	thermal conductivity
μ	dynamic viscosity
ρ	mass density
ϕ	water activity
ω	liquid water mass fraction based on dry solid

Subscripts

eq	equilibrium state
g	gas or air and water vapor mixture
i	inlet
int	object surface or object-air interface
l	liquid water
max	maximum
o	object or outlet
s	solid
sat	saturation
v	vapor
w	bottom wall
∞	free stream

and mass transfer. They used the FLUENT CFD code to compute the external flow and temperature fields. The numerical approach was extended by Mohan and Talukdar [7] for convective drying in a three-dimensional case and by Ateeque et al. [8] to include the effects of evaporation and water activity.

More complete numerical approaches to simultaneously solve the conservation equations in the internal and external regions of a moist object were also reported in the literature [9–15]. The internal and external conservation equations are coupled by the matching conditions of temperature, heat and mass fluxes on the object surface. However, the complete numerical approaches were limited to the drying of stationary objects.

In this work, the complete numerical analysis including the effects of evaporation and water activity is extended to the convective drying of a moving object. The analogy between heat and mass transfer used in the previous numerical models [3–8] for the convective drying is tested for its validity. The effects of object velocity and thickness are included in the analysis to find the optimum conditions to maximize the drying rate.

2. Numerical analysis

The present numerical approach is based on the FLUENT CFD code to solve the conservation equations for convective drying and a UDF (user defined function) sub-program developed in our previous work [15] to treat the heat and mass transfer boundary conditions on the object surface. The approach is extended to analyze the convective drying of a moving moist object, as depicted in Fig. 1. In this work, the following assumptions are made: (1) the flow, temperature and moisture fraction fields are two-dimensional and steady; (2) the gas phase is an ideal mixture of air and water vapor; (3) the gas flow is incompressible and turbulent considering the Reynolds number is very large, $\mathrm{Re} = \rho_g u_\infty H_g/\mu_g \simeq 2.4 \times 10^4$ in the present case; (4) the object is a porous solid containing liquid water and the contribution of vapor to the heat and mass transfer inside the object is negligible; (5) the evaporation occurs on the object surface; and (6) the moist object does not shrink.

2.1. Governing equations in the gas region outside a moist object

Based on the k–ϵ turbulence modeling for the high Reynolds number condition, the conservation equations of mass, momentum, turbulent kinetic energy k, turbulent dissipation rate ϵ, energy, and water vapor mass fraction in the external gas region of the object are written as

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho_g \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot (\mu_g + \mu_t)[\nabla \mathbf{u} + (\nabla \mathbf{u})^T] \tag{2}$$

$$\rho_g \mathbf{u} \cdot \nabla k = \nabla \cdot \left[\left(\mu_g + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k - \rho_g \epsilon \tag{3}$$

$$\rho_g \mathbf{u} \cdot \nabla \epsilon = \nabla \cdot \left[\left(\mu_g + \frac{\mu_t}{\sigma_\epsilon}\right)\nabla \epsilon\right] + C_{1\epsilon}\frac{\epsilon}{k}G_k - C_{2\epsilon}\rho_g\frac{\epsilon^2}{k} \tag{4}$$

$$\rho_g c_g \mathbf{u} \cdot \nabla T = \nabla \cdot \left[\left(\lambda_g + \frac{c_g \mu_t}{\mathrm{Pr}_t}\right)\nabla T\right] \tag{5}$$

$$\rho_g \mathbf{u} \cdot \nabla Y = \nabla \cdot \left[\left(\rho_g D_g + \frac{\mu_t}{\mathrm{Sc}_t}\right)\nabla Y\right] \tag{6}$$

where

$$\mu_t = c_\mu \rho_g \frac{k^2}{\epsilon}, \quad G_k = \mu_t[\nabla \mathbf{u} + (\nabla \mathbf{u})^T] : (\nabla \mathbf{u})$$

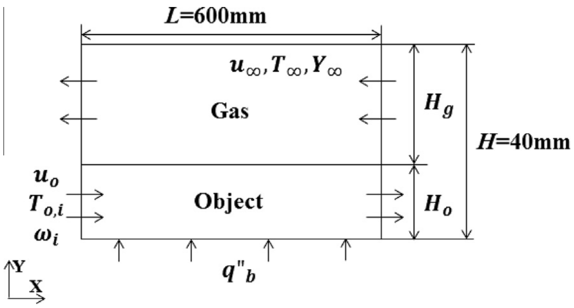

Fig. 1. Computational domain for analysis of convective drying of a moving moist object.