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Transient numerical study of the effect of ambient temperature on 2-D cereal grain storage in cylindrical silos

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ABSTRACT

A numerical study was performed on the transient heat and mass convection of grain storage in a cylindrical silo. Temperature gradients were induced by the heat of respiration, and thermal gradients were generated by variations of the temperature surrounding the cavity. The model was developed using the equations of heat, mass, and momentum transport for multiphasic media. The equation that represents the environmental temperature along the day-night cycle was obtained via a least squares regression using statistical data. In this study, the effects of different geometric ratios (A) and Rayleigh (Ra) numbers on the isotherms, flow patterns, and concentration isolines were analyzed. The governing equations were solved using discretization of the spatial coordinates by orthogonal collocation with Legendre polynomials and an implicit-trapezoidal formulation for time. The resulting algebraic system was solved by employing the Newton–Raphson with LU factorization method. A computer code called NEWIMPC2 in the FORTRAN 90 language was developed; this code was used to calculate the dynamics and hot regions in the bulk mass grain in the cavity. The thermodynamic properties for sorghum were used in the simulation, although the model is applicable to any cereal grains. For simulation data, typical prevailing conditions in the Bajio, an agricultural region located in Guanajuato State, were used. When the geometric ratio (A) increases, the hot nucleus is displaced toward the top of the cavity. In the case of Rayleigh numbers (Ra), a small increase significantly increases the stiffness of the parabolic equations. The ambient temperature has a significant effect on the formation of hot regions inside the cavity. When Ra increases, an increase can be observed in the temperature of the hot nucleus, with this temperature reaching 31 °C near the top wall of the enclosure. There was no evidence of the formation of multicellular flows.

1. Introduction

Population growth throughout the world, and particularly in Mexico, has motivated researchers to improve the technological support to enhance the quality of life. Cereal grains are important not only in the daily life of people but also for livestock feeding, where it is necessary to have higher quality and quantity of grains. Nevertheless, it is known that Latin America loses approximately 20% of stored grains to the absence of storage control and a lack of technological knowledge regarding proper storage (Jiménez-Islas et al., 2004).

The existing models for grain storage are very complex because to obtain a realistic solution, it is necessary to consider the equations of heat, mass, and momentum transport as well as the boundary conditions that simulate the environmental temperature. Most of the studies in the literature are limited to systems of heat and momentum transport, with some studies referring to the types of boundary conditions that represent the environmental effects. For this reason, the development of models for transport and the solution in terms of differential equations and boundary conditions is not trivial.

In the storage of grains in silos, heat, and mass transfer are coupled. Therefore, an optimum design for the conservation of cereals requires an understanding of the transport phenomena that are present in the storage of grains, the environmental conditions of the stream flows, and the temperature and concentration profiles in the silo (Singh and Thorpe, 1993; Jiménez-Islas et al., 1996; Alabadan and Oyewo, 2005). The process of respiration of grain continues during the storage for a long time, and the interaction

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Nomenclature

A	Height/radius ratio, L/R
a_v	Grain–air interfacial area, $m^2\,m^{-3}$
a_w	Water activity, dimensionless
$\mathbf{C}$	Permeability tensor, m^2
C_A	Concentration of component A (water vapor or grain moisture), $kg\,m^{-3}$
C_p	Specific heat, $J\,kg^{-1}\,K^{-1}$
$\mathbf{D}$	Diffusivity tensor, $m^2\,s^{-1}$
D	Diffusivity scalar, $m^2\,s^{-1}$
Da	Darcy number, $K\,R^{-2}$
Fo	Fourier number or dimensionless time, $\alpha t/R^2$
$\mathbf{G}$	Acceleration of the gravity, $m\,s^{-2}$
$\mathbf{K}$	Effective thermal conductivity tensor, $W\,m^{-1}\,K^{-1}$
K	Permeability of the porous media, m^2
k_{eff}	Thermal conductivity of the porous media, $W\,m^{-1}\,K^{-1}$
k_y	Mass transfer coefficient, $m\,s^{-1}$
L	Height of the cavity, m
Le	Lewis number, α/D_{eff}, α/D_a
m_v	Mass flow of evaporated water, $kg\,m^{-3}\,s^{-1}$
N	Buoyancy mass/temperature ratio, $\beta_{C\rho o}\,(Y_1 - Y_0)/\beta(T_1 - T_0)$
P_0	Volumetric generation of water by respiration, $kg\,m^{-3}\,s^{-1}$
Pr	Prandtl number, $C_p\mu/k_{eff}$
P_o^v	Vapor pressure, mm Hg
p	Pressure, Pa
Q_0	Volumetric heat of respiration of the cereal grain, $J\,m^{-3}\,s^{-1}$
Ra	Rayleigh number for porous media, $\rho_o gK\beta(T_h - T_c)R/(\mu\alpha)$
Ra_f	Rayleigh number for homogeneous fluid, $\rho_o g\beta(T_1 - T_0)R^3/\mu\alpha$
R	Radius of the cylindrical enclosure, m
T	Temperature of the fluid, °C, K
$\mathbf{u}_r$	Dimensionless radial velocity
$\mathbf{u}_z$	Dimensionless axial velocity
$\mathbf{v}_r$	Velocity vector in radial coordinate, $m\,s^{-1}$
$\mathbf{v}_z$	Velocity vector in axial coordinate, $m\,s^{-1}$
W	Dimensionless humidity in the grain, $(X - X_0)/(X_1 - X_0)$
X	Humidity of the grain on a dry basis, kg H_2O/kg dry grain
x	Humidity of the grain on a wet basis, kg H_2O/kg dry grain
Y	Absolute humidity of the air, kg H_2O/kg dry air
Y_i	Absolute humidity of air in the interface grain–air, kg H_2O/kg dry air.

Greek symbols:

A	Thermal diffusivity of the porous media, $k_{eff}/\rho C_p$
β	Volumetric coefficient of thermal expansion, $K - 1$
β_C	Volumetric coefficient of mass expansion, $m^3\,kg^{-1}$
λ_v	Latent heat of vaporization of water, $J\,kg^{-1}$
μ	Viscosity of the fluid, $kg\,m^{-1}\,s^{-1}$
ρ	Density, $kg\,m^{-3}$
ρ_a	Density of dry air, $kg\,m^{-3}$
ζ	Dimensionless axial coordinate, z/L
ξ	Dimensionless radial coordínate, r/R
ψ	Dimensionless stream function
ω	Dimensionless vorticity
θ	Dimensionless temperature, $(T - T_0)/(T_1 - T_0)$
φ	Dimensionless absolute humidity in air, $(Y - Y_0)/(Y_1 - Y_0)$

Subscripts:

A	Air
eff	Property for effective media
β	Air
max	Maximum value
min	Minimum value
0	Reference state or property evaluated at time zero
1	Property evaluated in the lateral or top wall of the silo

between air humidity and temperature is important. Grain stored at more than 15% moisture respires faster than dry grain, forming hot regions that are favorable for fungal growth and insect attacks (Jamieson and Jobber, 1993).

The external temperature of the storehouse does not have a direct effect on grain stored in large silos, but it does affect grain stored in small deposits or containers constructed with metallic walls. These walls are heated by the sunrays, which generate additional temperature gradients, inducing favorable conditions for fungi and insect reproduction (Lindblad and Druben, 1979; Jiménez-Islas et al., 2004, Jian et al, 2009). In recent years, there have been some studies on the effects of temperature gradients produced by environmental conditions together with the heat of respiration of the grain (sorghum) (Jiménez-Islas et al., 2004). Momentum, energy, and mass equations for porous media show the variable that controls the dynamics of storage is the moisture content in the grain.

Gastón et al. (2005) reported a two-dimensional model based on the finite element method to predict the evolution of the temperature distribution of a mass of grains (wheat) stored in a cylindrical silo of 140 ton, taking into account the seasonal variations in the ambient temperature, the solar radiation, and the wind. The predictions indicate that the central region of the silo is less susceptible to seasonal changes, which have more influence on the quality of the grains near the top surface or the galvanized walls. This region equals approximately 40 ton of grain, which is 28% of the total stored grain.

Alabadan and Oyewo (2005) performed a comparative analysis of the temperature variation for wooden and metal silos in the tropical regions of Nigeria. The variations in temperature were studied for a period of 130 days (July to November) using stored corn. As expected, the temperature variation was smaller in wooden than in metallic silos. The temperatures increased at the end of the storage period; this increase was due to the change in the relative humidity of air (humid to dry), implying a metallic silo at high temperatures cannot maintain acceptable conditions for grain storage throughout the year.

There are experimental studies that demonstrate the importance of boundary conditions on the heat transfer in a square cavity filled with air (Ching et al., 2006). In these studies, the authors found that the temperature increase at the top wall causes the formation of an independent flow in this region and a secondary flow near the boundary composed of the vertical walls. Therefore, this kind of flow causes significant effects on the heat transfer in this region. Abalone et al. (2006) used daily values of temperature, environmental relative humidity, and wind velocity, obtained from monthly statistical averages, and used them as boundary conditions for the storage of grains in silos. They found that the ambient temperature has more influence in the area near the walls of the storehouse, generating suitable conditions for the proliferation of