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Simulating the bulk storage of foodstuffs

Yongfu Xu, Dean Burfoot *

Silsoe Research Institute, Wrest Park, Silsoe, Bedfordshire MK45 4HS, UK

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Abstract

This paper presents a transient three-dimensional CFD model of heat and mass transfer in porous bulks of particulate foodstuffs. The mass, momentum and energy equations were solved to predict the air flows, temperature and moisture changes of the air and solids. The interaction between the air flows and the porous media were described by the Ergun equation. Moisture diffusion and heat transfer within the solids was predicted assuming the solids to be spheres, and the heat of respiration was included in the model as an empirically derived function of temperature. The predicted and measured temperature profiles across a bed of potatoes with a height of 2.4 m and a diameter of 0.7 m during forced cooling, from 15.5°C to 6°C, show similar spatial and temporal variations with a maximum difference of 1.4°C. Predicted weight loss of the bed in a 4-day test period was within 5% of the measured value.

Keywords: CFD simulation; Heat transfer; Mass transfer; Evaporation; Cooling; Food storage

Notation

A	surface area of a potato, m^2
a	specific surface area of a potato medium, $m^2\ m^{-3}$
c	specific heat, $J\ kg^{-1}\ K^{-1}$
D	diffusivity of vapour in air, $m^2\ s^{-1}$
D_{eff}	effective diffusivity of water through particle skin, $m^2\ s^{-1}$
D_p	diffusivity of water through solid particles, $m^2\ s^{-1}$
d_p	diameter of solid particles, m
H	enthalpy per unit mass, $J\ kg^{-1}$
h	latent heat, $J\ kg^{-1}$
h_m	mass transfer coefficient, $m\ s^{-1}$
h_t	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
K	permeability of a porous medium, m^2
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
L^*	characteristic length of a porous medium, $L^* = d_p\ \gamma\ /(1-\gamma\ )$
m	mass transfer rate, $kg\ m^{-3}\ s^{-1}$
F_{ht}	heat flux across a particle surface, $J\ s^{-1}$
F_{ms}	mass flux across a particle surface, $kg\ s^{-1}$
Nu	Nusselt number, $Nu = h_t\ d_p/k$
Pr	Prandtl number, $Pr = v/\alpha$
P	pressure, Pa
q	heating by respiration and conduction through the bulk, $J\ kg^{-1}\ s^{-1}$
q_1	heat of respiration, $J\ kg^{-1}\ s^{-1}$
R_i	resistance components, $N\ m^{-3}$
Ra	Rayleigh number, $Ra = gKd_p\beta(T_{ps} - T_a)/(\alpha v)$
Ra_m	mass transfer Rayleigh number, $Ra_m = gKd_p\beta_c\ (\rho_{v,ps} - \rho_{v,a})/(Dv)$
Re	Reynolds number, $Re = Ud_p/v$
r	radius, m
Sc	Schmidt number, $Sc = v/D$
Sh	Sherwood number, $Sh = h_m d_p\ /D$
t	time, s
T	temperature, K
u_i	fluid velocity components, $m\ s^{-1}$
U	fluid velocity, $m\ s^{-1}$
X_i	cartesian coordinates
Y	mass fraction of vapour, kg water/kg air
Greek	
α	thermal diffusivity, $m^2\ s^{-1}$
β	volumetric thermal expansion coefficient, K^{-1}
β_c	composition expansion coefficient of air/vapour, $m^3\ kg^{-1}$
γ	porosity of the porous medium
μ	fluid viscosity, $kg\ m^{-1}\ s^{-1}$
v	kinematic viscosity, $m^2\ s^{-1}$
ρ	density, $kg\ m^{-3}$
ρ_v	vapour mass concentration, $kg\ m^{-3}$
χ	moisture content, kg water/kg solid material
χ_0	initial moisture content, kg water/kg solid material
τ	share stress, $N\ m^{-2}$
ψ	water activity (partial pressure of the vapour/saturated vapour pressure)
Subscripts	
a	air/vapour flow
bp	bulk solid particles, e.g. potatoes
map	mass-averaged property of the solid particles inside a cell

* Corresponding author.

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p individual solid particle, e.g. a potato
ps surface of a solid particle
w water

1. Introduction

Most foodstuffs, such as grain, potatoes and onions, are stored in piles, silos or boxes. Key factors in the economic success of storage are minimising weight loss by evaporation, and restricting energy usage while avoiding disease and maintaining product quality. All of these factors are influenced by the temperature and moisture of the air in the store with the air flows governing the uniformity of the conditions. Improvements in store management systems are being sought and will require a better knowledge of the temporal and spatial variations of conditions within stores.

Numerous attempts have been made to predict heat and mass transfer processes in stored bulks of foodstuffs. These include one-dimensional models of heat and mass transfer (Bakker-Arkema, Bickert & Morey, 1967; Spencer, 1969; O'Callaghan, Menzies & Bailey, 1971) and two-dimensional models of air flows alone using finite difference methods (Brooker, 1961) and finite element methods (Marchant, 1976), and heat and moisture transfer in sealed bins (Casada & Young, 1994a,b). Other studies have considered three-dimensional problems. Sinicio, Jayas, Muir and Sanderson (1992) predicted three-dimensional air flows using a finite element method and Smith, Jayas, Muir, Alagusundaram and Kalbande (1992a,b) used a finite element method to predict the streamlines of air through a three-dimensional bulk and then used a one-dimensional finite difference model to predict temperature and moisture changes of the air and solids along each streamline. This method leads to some problems in interpolating between the streamlines and also implies movement of the solids as the streamlines are moved between successive iterations during the drying or storage period. Singh, Leonardi and Thorpe (1993) and Khankari, Patankar and Morey (1995) have considered air movement and heat and mass transfer in three-dimensional porous media within sealed containers.

The studies above have been carried out on grain bulks containing small particles within which large temperature and moisture gradients are not expected. Larger items of produce, such as potatoes, can show significant temperature gradients within individual tubers. Lerew and Bakker-Arkema (1978) presented a one-dimensional model for the heat and moisture transfer in a column of spherical food materials, e.g. potatoes and fruits, where internal temperature gradients exist within the materials.

In this paper, a transient three-dimensional heat and moisture transfer model, with air flow in an unconfined space of spherical particulate foodstuffs, is presented. The product conditions (temperature and moisture content) and its properties (conductivity and moisture diffusivity) vary spatially and are used to predict the local heat and mass transfer processes. The global migration of the heat and moisture throughout the storage volume are simulated by solving the Navier–Stokes equations of mass, momentum and energy. This model was tested against experimental results obtained in a bed of potatoes during cooling.

2. The CFD model

To carry out a CFD simulation, the entire store of foodstuffs is subdivided into imaginary control volumes called cells. The cells in the space around the bulk of foodstuffs contain only air whereas the cells inside the bulk contain both air and solid. This mixture of air and solids is treated as a porous medium to predict the air flows. Within each cell, the transfers of heat and moisture within a single solid particle and evaporation on its surface are predicted. That particle is considered as representative of all the particles within that particular cell. The following sections describe the equations for the transfers of air, heat and moisture between the cells and within the particles.

2.1. Air flow (air/water vapour mixture)

For homogeneous porous media with constant porosity, the continuity and momentum equations describing the air flow are:

$$\frac{\partial(\gamma\rho_{\rm a})}{\partial t} + \nabla(\rho_{\rm a}\gamma u_i) = m, \tag{1}$$

$$\frac{\partial(\gamma\rho_{\rm a}u_i)}{\partial t} + \nabla(\gamma\rho_{\rm a}u_iu_j - \gamma\tau_{ij}) = -\gamma\frac{\partial P}{\partial X_i} - R_i, \tag{2}$$

where m is the mass transfer rate per unit volume of a porous medium and is calculated later and R_i is the Darcy coefficient for multi-dimensional flow through a porous bulk (Ergun, 1952).

2.2. Heat transfer between control volumes

Heat is transferred through a porous medium by the movement of the air and by conduction through the air. Some heat is also transferred by conduction from the solid particles in one cell to the solid in neighbouring volumes. In mathematical terms

$$\frac{\partial(\rho H)}{\partial t} + \nabla(\gamma\rho_{\rm a}u_iH_{\rm a} - \gamma k_{\rm a}\nabla T_{\rm a}) = \nabla(k_{\rm bp}\nabla T_{\rm map}), \tag{3}$$

where subscript bp indicates the bulk properties of the solid particles, $T_{\rm map}$ is the mass-averaged temperature of the solid particles inside a cell, H is the total enthalpy of a porous cell and is the sum of the enthalpy of the solid particles and the air

$$\rho H = \gamma \rho_a H_a + (1-\gamma)\rho_{map} H_{map}. \quad (4)$$

The right-hand-side of Eq. (3) represents the heat conducted through the solids.

Substituting Eq. (4) into Eq. (3) and rearranging gives the energy equation for the air flow as

$$\frac{\partial(\gamma\rho_a H_a)}{\partial t} + \nabla(\gamma\rho_a u_i H_a - \gamma k_a \nabla T_a) = \nabla(k_{pb}\nabla T_{map}) - \frac{\partial[(1-\gamma)\rho_{map} H_{map}]}{\partial t}. \quad (5)$$

2.3. Moisture transfer between control volumes

The moisture in the air is transferred between neighbouring cells by the movement of the air and by diffusion, as given by

$$\frac{\partial(\gamma\rho_a Y)}{\partial t} + \nabla(\gamma\rho_a u_i Y - \gamma\rho_a D\nabla Y) = m, \quad (6)$$

where Y is the mass fraction of vapour and D is the diffusivity of vapour in air.

2.4. Moisture and heat transfer within a single particle

A single particle was considered as a sphere consisting of imaginary concentric shells with no variation of the air conditions around the individual particle over a specific time interval. Gradients of temperature and moisture content were formed across the surface of the particle and within the particle due to heat and mass transfer at the surface.

The transfer of moisture within the particle is by diffusion such that

$$\frac{\partial\chi}{\partial t} = \frac{1}{r^2}\left[\frac{\partial}{\partial r}\left(D_p r^2 \frac{\partial\chi}{\partial r}\right)\right], \quad (7)$$

where χ is the water content and D_p is the diffusivity of water inside solid particles.

When there is no condensation, the rate of mass transferred between the solids and air flow per unit volume of porous medium is related to the change of water content within the particle and, assuming no shrinkage of the particle, is given by

$$m = \frac{\rho_{bp}}{\rho_p V_p}\frac{\partial}{\partial t}\int_{V_p} \rho_w \chi \, dV, \quad (8)$$

where V_p is the volume of a particle.

Heat transfer within the particle is due to heat conduction and the diffusion of moisture

$$\frac{\partial(\rho_p H_p)}{\partial t} = q\rho_p + \left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 c_w \rho_w D_p T_p \frac{\partial\chi}{\partial r}\right)\right] + \left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k_p \frac{\partial T_p}{\partial r}\right)\right], \quad (9)$$

where T_p is the temperature inside a particle and $q\rho_p$ includes the heat of respiration and the heat conducted between cells (the term on the left hand side of Eq. (3)).

2.5. Mass and heat transfer at the surface of a particle

The boundary conditions at the surface of the particle show a balance between the moisture and heat reaching and leaving the surface of the particles.

Both forced and natural convections could occur inside one storage environment. Sherwood number Sh and Nusselt number Nu of the heat and mass transfer on a particle surface during forced convection are calculated using correlations given by Whitaker (1972):

$$\mathrm{Sh} = (0.5\mathrm{Re}^{1/2} + 0.2\mathrm{Re}^{2/3})\mathrm{Sc}^{1/3} \quad (10)$$

$$\mathrm{Nu} = (0.5\mathrm{Re}^{1/2} + 0.2\mathrm{Re}^{2/3})\mathrm{Pr}^{1/3} \quad (11)$$

for $10 < Re < 10^4$, where the Reynolds number Re is calculated using the characteristic length of the packed bed L^*. The correlations used for natural convection were given by Bejan (1995) as

$$\mathrm{Sh} = 0.362\mathrm{Ra}_m^{0.5}, \quad (12)$$

$$\mathrm{Nu} = 0.362\mathrm{Ra}^{0.5}. \quad (13)$$

The higher Nusselt number between Eqs. (11) and (13) and the associated Sherwood number are used for calculating the local heat and mass transfer.

The moisture flux F_{ms}, evaporated and diffused across the boundary layer on a particle surface into the air flow, is a boundary condition of Eq. (7) and given by

$$F_{ms} = h_m A(\rho_{v,ps} - \rho_{v,a}) = \frac{\mathrm{Sh}\, D\, A(Y_{ps} - Y)\rho_a}{d_p}, \quad (14)$$

where A is the surface area of a particle, h_m is mass transfer coefficient and Y_{ps} is the mass fraction of moisture at the surface of the particle. The value of Y_{ps} depends on the relative rates of diffusion of moisture from within the particle to the surface and the rate of evaporation of moisture at the surface. To carry out the calculation of Y_{ps} requires a relationship between the water and vapour concentrations at the surface, the sorption isotherm.

The heat flux across the boundary layer on a particle surface F_{ht}, which is a boundary condition of Eq. (9), is the sum of the heat transferred due to the temperature difference between air and the particle surface and the heat associated with the mass transfer

$$F_{ht} = h_t A(T_{ps} - T_a) - F_{ms}(h + c_a T_a - c_{a,ps} T_{ps}), \quad (15)$$

where h_t is heat transfer coefficient and T_{ps} the surface temperature of the particle.

2.6. Solution of momentum, continuity, mass and heat transfer equations

Heat and mass transfer inside foodstuffs during storage are transient processes. During the simulation, the air flow and energy and moisture Eqs. (1)–(6) are solved using the computational fluid dynamics package CFDS-CFX4 (AEA Technology, Harwell, Oxford, UK) and then the local heat and mass transfer rates are updated from the results of Eqs. (7) and (9) at the end of each time step. These transfer rates are then used in Eqs. (1)–(6) in the next time step. The number and shape of control volumes used to discretise the stores of foodstuffs and individual particles is dependent on the layout of the store and dimensions of the foodstuffs.

3. A test case: cooling a bed of potatoes

3.1. Experiment details

Experimental data are available on the forced air cooling of an insulated column of new potatoes (Fig. 1) from an initial temperature of 15.5°C using air at 6.7°C, 60% relative humidity and 9.2 m^3 h^{-1} (Misener & Shove, 1976a). The column has a diameter of 0.7 m and a height of 3 m and the height of the bed of packed potatoes is 2.4 m. The bed of potatoes has a bulk density of 390 kgm^{-3} and a porosity of 0.61. Misener and Shove (1976b) measured an average length of 95 mm and diameter of 51 mm for these tubers, which have surface areas equivalent to the spherical tubers with a diameter of 65 mm. The average velocity through the interstitial spaces between the potatoes is 0.0109 ms^{-1} and laminar flow is assumed. The initial water content of the potatoes, χ_0, was not reported and 80%, a typical value for new potatoes, is used in the model. Air temperature was measured up through the bed of potatoes after cooling for 24, 72 and 92 h and the weight of the bed was measured before and after the test.

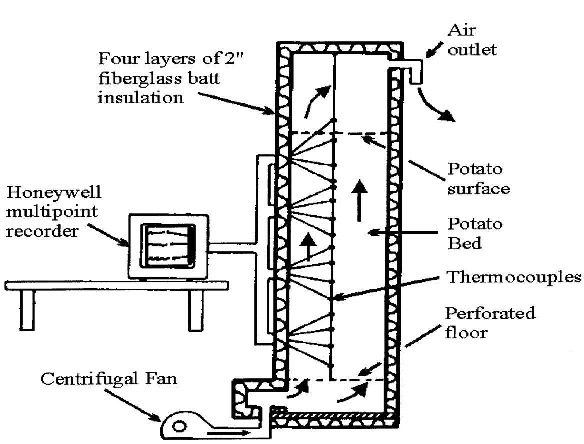

Fig. 1. Schematic diagram of the experimental arrangement used by Misener & Shove (1976a,b) to study the cooling of potatoes.

In the model, axial symmetry was assumed and the simulations were carried out for a radial section of the bed consisting of 256 (32×8) control volumes. Any difference in voidage of the bed near to the wall compared to that in the bulk was not considered in the model. Uniform velocity, temperature and moisture profiles were specified at the inlet.

3.2. Properties of the potato

The water diffusivity inside potatoes, D_p, is a function of temperature and water content. The diffusivity used here is a combination of the correlation produced by Ruan, Schmidt, Schmidt and Litchfield (1991) from NMR measurements while drying potato samples at constant temperature (40°C) and the temperature dependent correlation by Simal, Rossello, Berna and Mulet (1994)

$$D_p = 5.128 \times 10^{-3} e^{13.5\chi} \exp\left[-3151.5\left(\frac{1}{T_p} - \frac{1}{313.15}\right)\right].$$

The water diffusivity of the skin of potatoes has not been measured so the sensitivity of the predictions of temperature and moisture was considered using various values of diffusivity at the surface. These values were given by $D_{eff} = D_p/400$ or $D_{eff} = D_p/40$ (Burton, 1972, estimated that peeling results in a 300–500 fold increase in the rate of evaporation from the surface of potato).

There have been many measurements of the heat of respiration of potatoes. Data depend on the variety, maturity, and storage conditions of the potatoes. The following correlation was used in the model (Misener & Shove, 1976a)

$$q_1 = aT_p + b,$$

where $a = 6.99$ J kg^{-1} h^{-1} K^{-1} (USDA, 1963) and $b = 62.62$ J kg^{-1} h^{-1} (to provide agreement with Burton's (1966) data measured on matured new potatoes).

The specific heat capacity (Yamada, 1970) and thermal conductivity (Burton, 1972) and the thermal conductivity of potato bulks (Brugger, 1979) were calculated from

$$c_p = 904 + 3266\chi \text{ for } \chi > 0.5, \quad k_p = 0.58,$$
$$k_{bp} = k_p(1 - \gamma^{2/3}).$$

Sorption isotherm data for potato were taken from Mujumdar (1987) and extrapolated to provide a water activity of unity at a surface water content of 80%. The resulting curve for water activity ψ is given by

$$\psi = 1 \text{ for } \chi > 0.8$$
$$\psi = 1 - 0.28(0.8 - \chi) \text{ for } 0.3 \leqslant \chi \leqslant 0.8$$

There is uncertainty about the relevance of these equations to applications of storage. Mujumdar's data refers to mashed potato whereas potatoes in storage are whole and the sorption isotherm should strictly relate to the skin of the potato for which no data is available. To examine the sensitivity of the predictions of temperature and moisture profiles to variations in sorption data, predictions were also carried out using the following equations:

$\psi = 0.95$ for $\chi > 0.8$,

$\psi = 0.95 - 0.28(0.8 - \chi)$ for $0.3 \leqslant \chi \leqslant 0.8$.

The moisture diffusivity, thermal conductivity, density and viscosity of air and the latent heat of water vapour were taken from Bejan (1993).

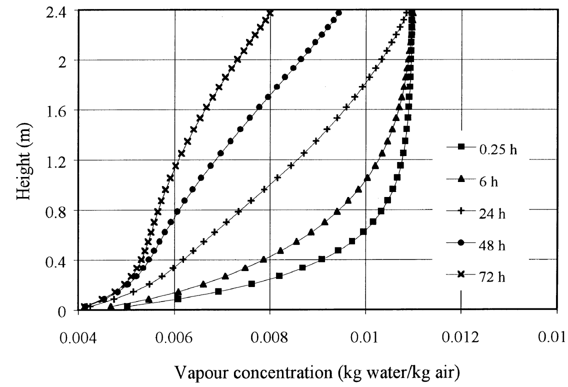

Fig. 3. Predicted moisture concentration in the air on the centre line along a bed of potatoes after cooling for various times. The potatoes, initially at 15.5°C, were cooled using air at 6.7°C and 60% relative humidity. The predictions are based on $D_{eff} = D_p/40$ and $\psi = 1$ at $\chi_0 = 0.8$.

4. Results and discussions

4.1. Simulation of the cooling front

Before the cooling test, the potatoes were kept at 15.5°C for 10 days so that the potatoes and surrounding air would be in thermal equilibrium. The simulation was begun with the air and potatoes at 15.5°C and 100% relative humidity throughout the bed. Cooler, less humid, air (6.7°C and 60% r.h.) was then forced into the bottom of the bed. When the cool air contacted the potatoes at the bottom of the bed, the rate of evaporation was high because of the large temperature and moisture differences between the air and the potato surfaces. Consequently, a cooling front with large gradients of temperature and moisture was predicted to develop (Figs. 2 and 3).

The cooling front was gradually pushed through the bed at a rate determined by the air flow rate and the heat and mass transfer processes. After 6 h, the temperature in the top of the column was greater than the initial temperature (15.5°C) due to the heat from respiration of the potatoes. After continuous cooling for 24 h, the air temperature at the top of the bed had fallen only slightly, to 15.4°C, because of the small difference between the vapour concentration in the air and that on the potato surfaces and because of the effect of the heat of respiration of the potatoes. The lowest air temperature, 6.4°C, was found near to the bottom of the column where moisture was evaporated from the potatoes and the potato surface temperature was approaching the local air wet bulb temperature. A cooling zone, where the air temperature dropped below the inlet air temperature due to evaporative cooling, had formed in the bottom section of the bed. As the air moved through the bed, the humidity of the air was gradually increased from a relative humidity of 60% at the bottom of the bed to just below 100% at the top (Fig. 3). Throughout the 92 h cooling period, the size of the cooling zone was increasing. The lowest temperature predicted inside the cooling zone was 5.3°C which occurred after 92 h.

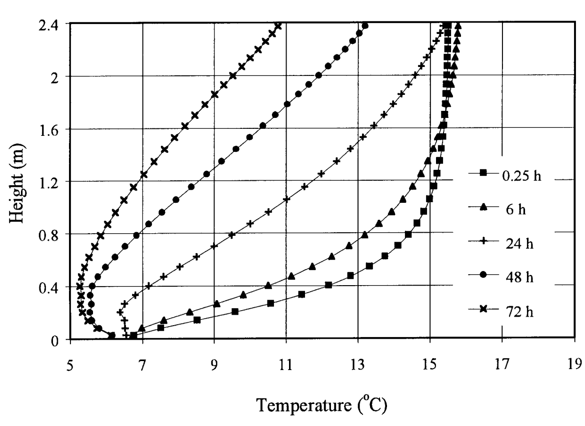

Fig. 2. Predicted air temperature on the centre line along a bed of potatoes after cooling for various times. The potatoes, initially at 15.5°C, were cooled using air at 6.7°C and 60% relative humidity. The predictions are based on $D_{eff} = D_p/40$ and $\psi = 1$ at $\chi_0 = 0.8$.

Radial gradients of temperature and moisture concentration also existed because of the slow down of the air flow near to the column wall. However, these radial gradients were very small because no heat was lost through the insulated wall of the column.

4.2. Temperature profiles and weight loss

Fig. 4(a) shows the temperature profiles measured by Misener and Shove (1976a) along the centre line of the column and the corresponding predictions obtained with $D_{eff} = D_p/40$ and $\psi = 1$ at initial water content $\chi_0 = 0.8$. After continuous cooling for 24 h, the predicted temperature gradient agrees well with the measurements along the whole column of potatoes. The air temperature measured at the bottom of the bed had dropped to

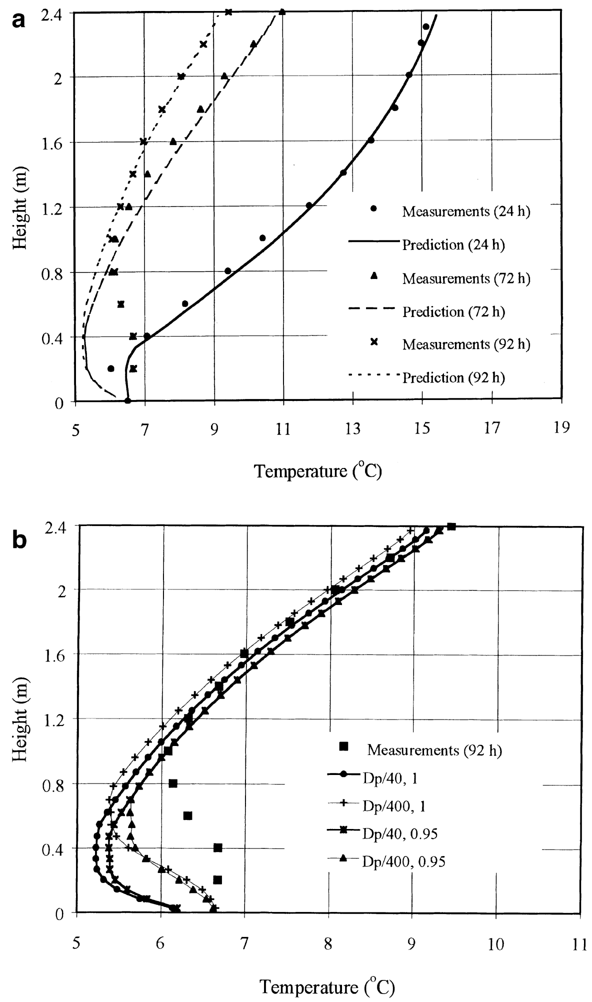

Fig. 4. Comparison of measured and predicted air temperature along a bed of potatoes during cooling: (a) Measurements after cooling for 24, 72 and 92 h and predictions made with $D_{\text{eff}} = D_p/40$ and $\psi = 1$ at $\chi_0 = 0.8$; (b) Measurements after cooling for 92 h and predictions made with D_{eff} values of $D_p/40$ and $D_p/400$ and $\psi = 0.95$ or 1 at $\chi_0 = 0.8$.

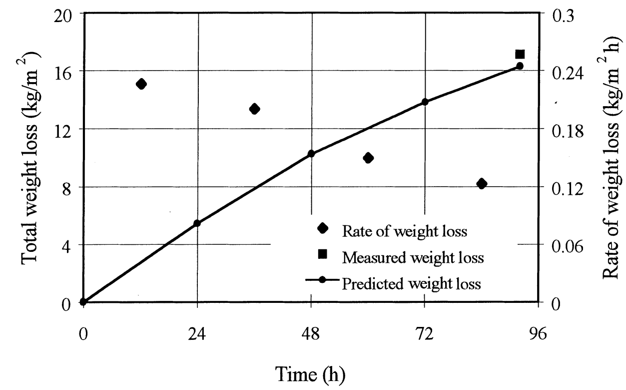

Fig. 5. Predicted rates of weight loss (averaged over 24 h), variations of the total weight loss of the potato bed with time and the weight loss measured after cooling the column of potatoes for 92 h. Predictions based on $D_{\text{eff}} = D_p/40$ and $\psi = 1$ at $\chi_0 = 0.8$.

6°C in the cooling zone and the lowest predicted temperature was 6.4°C. The difference between measured and predicted temperatures suggests that the evaporation rate at the bottom of the bed was slightly underpredicted by the model.

After 72 h, the temperatures were predicted reasonably along much of the column, but differences, up to 1.4°C, were found between measured and predicted data in the bottom third of the bed. The air temperature measured 0.2 m from the bottom of the bed was close to the inlet air temperature and was higher than both the measured and predicted temperature at the same position after 24 h. This increase of temperature suggests that evaporation had decreased probably due to earlier drying of the potato surfaces. The model did not fully predict this drying and consequently it continues to predict high evaporation rates after 72 h. Changes to the properties of the potato surfaces, such as reducing the skin water diffusivity to $D_p/400$ or the water activity to 0.95, provides some improvement in the predicted temperature profiles but those changes could not fully account for the higher temperatures measured in the bottom of the column, as shown in Fig. 4(b). In the experimental study, turbulence and possible flow fluctuations in the inlet cooling air could have been created by a centrifugal fan located upstream of the column of potatoes and this would have led to the high drying rate found at the early stages at the bottom of the bed and consequently lower drying rates in the later stages of the test. The model did not consider these effects since insufficient detail was available to provide a reliable simulation of the experimental arrangement.

The average rates of weight loss (weight loss per hour per square metre of the cross section of the potato bed) over each 24 h period of cooling were predicted (Fig. 5) and show the expected trend with the loss rate decreasing throughout the test period. The rate of loss over the last 24 h was almost half of that over the first 24 h of the test. This reduction is mainly caused by the lower temperature difference between the air and the potato surfaces in the later stages. The predicted total weight loss of the potato bed is shown in Fig. 5 and the value after 92 h was 16.3 kg m^{-2} which is within 4.5% of the measured value of 17.1 kg m^{-2}.

5. Conclusions

We have demonstrated the capability of the model to predict the temperature and moisture changes of potatoes during cooling. Some differences between measured and predicted temperatures were found near to the inlet of the air into the bed of potatoes and this may have been caused by over drying of the potatoes caused by turbulence and possible air speed fluctuations in the incoming air. Nonetheless, the predicted temperatures agree with measurements to within 1.4°C and show similar spatial variations. Weight loss, a major factor in the economic success of crop storage, is predicted reliably.

Knowledge of the temporal and spatial variations of conditions within stores of foodstuffs is vital to maintain quality and reduce the risk of disease. The model predicts temperature and moisture changes in agreement with measurements at a level that can realistically be expected of measuring instruments in commercial practice. It is in commercial applications, with more complicated geometries and operating strategies, and where measured data is difficult to obtain, that the model will find wide use. Condensation and the applications of the model validated here in commercial crop stores are being considered in the latest development of the model.

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