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Predicting condensation in bulks of foodstuffs

Yongfu Xu, Dean Burfoot *

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

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Abstract

The bulk storage of foodstuffs, such as potatoes, is common but unfortunately condensation in bulk stores is often observed. Condensation has been shown to initiate diseases on the foodstuff with subsequent loss of quality or amount of saleable produce. A numerical model was developed to calculate the air flows, temperature and moisture changes in bulk stores, and solved using a computational fluid dynamics code in order to predict the conditions under which condensation is likely to occur. The model was able to predict the position of condensation in a typical bulk potato store and it also showed how condensation would occur in other regions if different operational policies were used. The model showed that condensation occurs due to variations in the air flow, and hence cooling front, in the bulk and that it could be restricted by increasing the period of forced convection or, more novel, directing cool air into the regions of slow air movement.

Keywords: Storage; Condensation; CFD simulation; Potatoes; Air flows

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, $Pr = \nu/\alpha$
P	pressure, Pa
Q	heat transfer rate between air and potatoes, $J\ m^{-3}\ s^{-1}$
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, $Ra = gKd_p\beta(T_{ps} - T_a)/(\alpha\nu)$
Ra_m	mass transfer Rayleigh number, $Ra_m = gKd_p\beta_c(\rho_{v,ps} - \rho_{v,a})/(D\nu)$
Re	Reynolds number, $Re = Ud_p/\nu$
r	radius, *m*
Sc	Schmidt number, $Sc = \nu/D$
Sh	Sherwood number, $Sh = h_m d_p/D$
t	time, *s*
Δt	time step, *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/vapor, $m^3\ kg^{-1}$
γ	porosity of the porous medium
δ	thickness of condensation film, m
μ	fluid viscosity, $kg\ m^{-1}\ s^{-1}$
ν	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	shear 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

* Corresponding author. Tel.: +1-525-860000; fax: +1-525-861697; e-mail: dean.burfoot@bbsri.ac.uk

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map	mass-averaged property of the solid particles inside a cell
p	individual solid particle, e.g. a potato
ps	surface of a solid particle, e.g. a potato
w	water

1. Introduction

Many raw foodstuffs are stored in bulk either in boxes, bins or piles. Condensation of moisture on the foodstuff can lead to the development of diseases and the growth of microorganisms with consequent loss of quality and saleable produce. For example, potatoes may suffer from 'soft rotting' caused by *Erwinia carotovora*. Each time condensation occurs it is usually in the same place in a given store as noted by Hylmö, Persson and Wikerb (1976), who found that condensation in commercial bulk potato stores frequently arises in strips which lie in the top layers between, not above, the air ducts. However, the region of condensation may move during the storage period. There is a need to understand the causes of condensation which can lead to high losses, and to provide advice on methods of preventing it.

Condensation occurs when the temperature of the potato surface is below the dew point temperature of the air nearby. In large bulks, the spatial variation of the temperature of the potatoes depends on the air flow and the transfer of heat and moisture within the bulk. To understand the complex interactions between these transfer processes, and so understand the process of condensation and predict the regions where it may occur, it is necessary to construct a mathematical model of the transfer processes. One-dimensional (Bakker-Arkema, Bickert & Morey, 1967; O'Callaghan, Menzies & Bailey, 1971), two dimensional (Casada & Young, 1994a,b), and three dimensional (Smith, Jayas, Muir, Alagusundaram & Kalbande, 1992a,b; Khankari, Patankar & Morey, 1995) models of heat and mass transfer in granular bulks have been developed. However, the application of these models is restricted to bulks of small particulates, such as grains, where the temperature within individual grains can be considered uniform. More recently, Xu and Burfoot (1999) developed a model to predict the air flows, temperature and moisture changes in three-dimensional bulks of larger solids, such as potatoes. That work, like many others, did not consider condensation and the aim of the present work is to include this important phenomenon. Furthermore, we aim to show that our model can be used to predict the regions of condensation as observed by Hylmö et al. (1976) and commonly found in commercial potato stores.

2. Mathematical model

The equations describing the transfers of air, heat and moisture within porous bulks, such as bulk potatoes, without condensation are presented by Xu and Burfoot (in press) and summarised in Table 1. In this model, the store of foodstuffs is subdivided into a set of imaginary control volumes called cells. Some of the cells contain air while others contain air and solid spherical particles (potatoes). The latter mixture is treated as a porous medium and the flow resistance of that medium is described by the Darcy coefficient in Table 2. In this model, one solid within each cell is considered to calculate the local heat and mass transfer rates and is treated as a representative of all of the others within that cell. The equations needed to describe the condensation process are given below.

Condensation occurs only when the air/moisture mixture experiences a temperature or pressure change that is sufficient to cause the local moisture concentration to exceed saturation. Condensation then brings the local moisture concentration down to the saturation value. Assuming film condensation, the change of film thickness due to the condensation within one time step of simulation is then given by

$$\Delta\delta = \frac{-m\,\Delta t}{a\,\rho_{\mathrm{w}}} \tag{1}$$

where m is the rate of mass transfer between the air and the potato per unit volume of porous medium; it is negative for condensation and positive for evaporation.

The condensation film maintains the surface relative humidity at saturation. In the model, there is no absorption of water into the potato from the film of condensation and the film temperature equals the temperature of the local potato surface so there is no heat transferred between them. The enthalpy received by the air flow during condensation is given by

$$Q = h_{\mathrm{t}}\,a(T_{\mathrm{ps}} - T_{\mathrm{a}}) - m(h + C_{\mathrm{a}}T_{\mathrm{a}} - C_{\mathrm{a,ps}}T_{\mathrm{ps}}) \tag{2}$$

where $c_{\mathrm{a,ps}}$ is the specific heat capacity of the air/vapour mixture at the surface of the potato. The first term on the right hand side represents the convective transfer between the potato surface and the air, and the second term represents the enthalpy changes due to mass transfer between air and potato when no condensation has occurred or between air and the condensation film if condensation has formed on the potato surface. These equations, and those in Tables 1 and 2, were solved using the computational fluid dynamics package CFX-4.1 (AEA Technology, Harwell, Oxford, UK).

Since the heat and mass transfer and the occurrence of condensation in crop stores are always time-dependent processes, the equations presented in Tables 1 and 2 are solved at each time step and then local heat and mass transfer rates are updated after each solution. These transfer rates are then used in the next solution of the equations and this procedure is repeated for each time step throughout a storage period.

Table 1
Equations describing the transfers of air, heat and moisture in bulks of porous media (Xu & Burfoot, in press)

Transfer process	Equation
Air flow continuity (air/water vapour mixture)	$\frac{\partial(\gamma\rho_a)}{\partial t} + \nabla(\rho_a \gamma u_i) = m$
Air flow momentum (air/water vapour mixture)	$\frac{\partial(\gamma\rho_a u_i)}{\partial t} + \nabla(\gamma\rho_a u_i u_j - \gamma\tau_{ij}) = -\gamma\frac{\partial P}{\partial X_i} - R_i$
Energy equation for the air flow (air/water vapour mixture)	$\frac{\partial(\gamma\rho_a H_a)}{\partial t} + \nabla(\gamma\rho_a u_i H_a - \gamma k_a \nabla T_a) = \nabla(k_{bp}\nabla T_{map}) - \frac{\partial(1-\gamma)\rho_{map}H_{map}}{\partial t}$
Moisture transfer in the air	$\frac{\partial(\gamma\rho_a Y)}{\partial t} + \nabla(\gamma\rho_a u_i Y - \gamma\rho_a D\nabla Y) = m$
Heat transfer within single spherical particle	$\frac{\partial(\rho_p H_p)}{\partial t} = q\rho_p + \left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 c_w \rho_w D_p T_p \frac{\partial\chi}{\partial r}\right)\right] + \left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k_p \frac{\partial T_p}{\partial r}\right)\right]$
Mass transfer within single spherical particle	$\frac{\partial\chi}{\partial t} = \frac{1}{r^2}\left[\frac{\partial}{\partial r}\left(D_p r^2 \frac{\partial\chi}{\partial r}\right)\right]$
Heat and mass transferred at surface of particles	$F_{ht} = h_t A\left(T_{ps} - T_a\right) - F_{ms}\left(h + c_a T_a - c_{a,ps} T_{ps}\right)$ $F_{ms} = h_m A\left(\rho_{v,ps} - \rho_{v,a}\right) = \mathrm{Sh}\, D\, A\, \rho_a\left(Y_{ps} - Y\right)/d_p$

3. Experiment

Hylmö et al. (1976) noted that condensation had been observed in commercial bulk potato stores and this phenomenon occurred in strips in the top layer of the potatoes. The regions of condensation were found to lie between, and not above, the air ducts and the condensation occurred after stopping the fans. This is a problem that is generally recognised although condensation can be found in other regions. Hylmö et al. (1976) report on observations in a store measuring 100×20 m containing 5600 ton of potatoes in a pile of 4 m depth. The potatoes were ventilated at 70 m^3 $tonne^{-1}$ h^{-1} through ducts located on 4 m centres (Fig. 1). The initial conditions of the potatoes and the ambient air conditions are not reported. However, after cooling for 8 h, the wet bulb temperature of the incoming air was 3.4°C and the temperature of the top layer of potatoes directly above the ducts was 5°C while it was 6°C halfway between the ducts. Ventilation was stopped at this time and condensation was observed later on the top layer of the potatoes halfway between the ducts.

4. Computations

Air flows, and the associated transfer of heat and moisture, are always three-dimensional and time dependent in crop stores. We have simplified the problem because complete information about the store observed by Hylmö et al. is not available and a direct simulation of the whole process would be lengthy and require a huge computing resource. The three-dimensional problem was reduced to a two-dimensional case (Section A-A in Fig. 1) by assuming that the air flow around each duct was periodic along the store i.e. all of the ducts behave the same, and that the flow was constant along each duct. The latter assumption may be doubtful in the regions near to the walls of the store. The computational mesh of cells created for the simulation is shown in Fig. 2. All of the boundary conditions were symmetrical about the centre line so this was specified as a plane of symmetry and only half of the section was used in the simulation. A wall without frictional resistance was the boundary condition applied at the side of the computational domain. The distance between the top of the bed of potatoes and the roof of the store was not known and in the simulation a distance of 2 m was given to provide almost fully developed flow at the exit of the computational domain. The simulation included forced air cooling for 8 h followed by natural convection.

At the inlet, a mass flow boundary condition was specified for the air flow and the temperature and moisture were assumed to be uniform across the duct during the period of forced ventilation. The initial temperature of the potatoes was 6°C and the incoming

Table 2
Equations used to calculate the properties of the air or potatoes and the surface transfer coefficients

Property or transfer coefficient	Equation
Darcy coefficient describing resistance of porous medium to air flow	$R_i = \frac{\mu}{K} u_i + b\rho U u_i$ where $K = \frac{d_p^2 \gamma^3}{150(1-\gamma)^2}$ $b = \frac{1.75(1-\gamma)}{\gamma^3 d_p}$
Surface heat and mass transfer coefficients for forced convection	$\mathrm{Nu} = (0.5\mathrm{Re}^{1/2} + 0.2\mathrm{Re}^{2/3})\mathrm{Pr}^{1/3}$ $\mathrm{Sh} = (0.5\mathrm{Re}^{1/2} + 0.2\mathrm{Re}^{2/3})\mathrm{Sc}^{1/3}$ for $10 < \mathrm{Re} < 10^4$
Surface heat and mass transfer coefficients for natural convection	$\mathrm{Nu} = 0.362\mathrm{Ra}^{1/2}$ $\mathrm{Sh} = 0.362\mathrm{Ra}_m^{1/2}$
Moisture diffusivity inside potatoes	$D_p = 5.128 \times 10^{-13} e^{13.5\chi} e^{-3151.5\left(\frac{1}{T_p} - \frac{1}{313.15}\right)}$
Moisture diffusivity of potato skin	$D_{eff} = D_p/40$
Heat of respiration of stored potatoes	$q_1 = 6.99T_p - 17.7(\mathrm{J\ Kg^{-1}\ h^{-1}})$
Specific heat capacity of potato	$c_p = 904 + 3266\chi$ for $\chi > 0.5$
Thermal conductivity of potato	$k_p = 0.58$
Thermal conductivity of potato bulk	$k_{bp} = k_p(1 - \gamma^{2/3})$
Sorption isotherm for potato	$\begin{cases} \psi = 0.95 & \text{for } \chi > 0.8 \\ \psi = 0.95 - 0.28(0.8 - \chi) & \text{for } 0.3 \leqslant \chi \leqslant 0.8 \end{cases}$

air was at 3.6°C and 90% relative humidity. After the period of forced ventilation, the air velocity at the inlet duct was reduced to zero and the ambient air temperature and relative humidity of 0°C and 100% respectively were used as boundary conditions at the top of the computational domain.

A time step of 1 sec was used in the simulation of forced ventilation and 0.5 sec for natural convection. The cpu time on a DEC Alphastation 250 with 196 MB of RAM was 36 h for the forced convection and 48 h for the natural convection period.

5. Results and discussion

In the store observed by Hylmö et al., the air flow across the potato pile was not uniform. Air near to the duct was moving faster than the air in the side region, and the air movement was very slow near to the floor halfway between two neighbouring ducts. This flow pattern, which changed slightly as more potatoes were cooled, resulted in parabolic distributions of air temperature and moisture across the potato pile. The cooling front penetrated the potato pile much easier and faster in the centre than at the side and consequently a warm region having both a high temperature and moisture concentration was formed at the side. Fig. 3 shows the predicted distributions of air flow, temperature and moisture across the potato pile after cooling for 8 h. Above the pile,

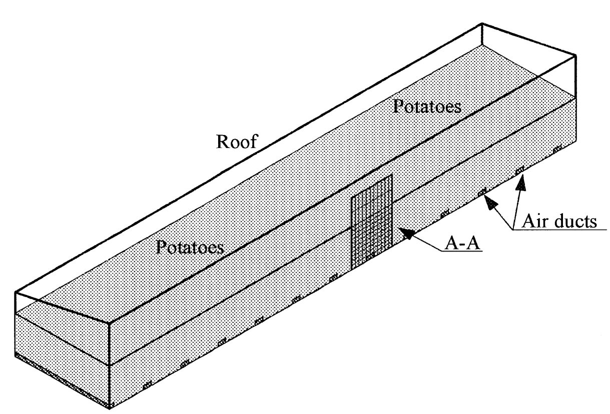

Fig. 1. Schematic diagram of a quarter section of a bulk potato store as used in the test by Hylmö et al. (1976). The hatched region is represented in the numerical model in the way shown in Fig. 2.

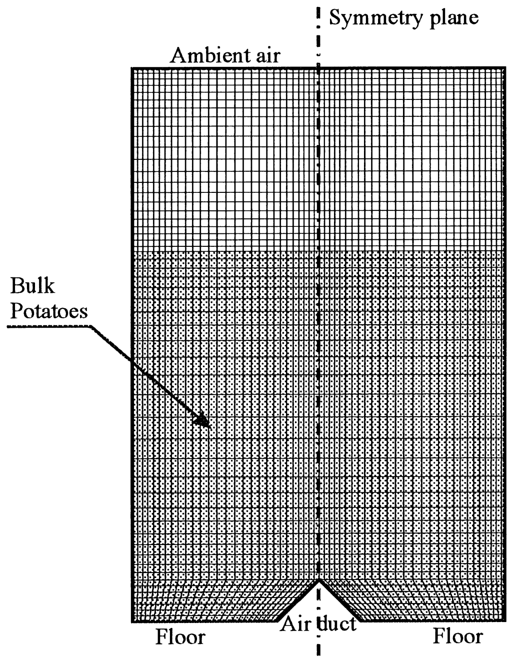

Fig. 2. Two-dimensional domain representing the bulk store investigated by Hylmö et al. Flows were symmetrical about the centre line so, only half of the section was used in the simulations.

air moved towards the side because of the strong buoyancy caused by the warm region at this stage. The air temperature in the centre of the computational domain was about 0.8°C lower than the temperature at the side, at the mid-height of the pile. The predicted temperature in the top layer of potatoes above the supply duct was 4.9°C and it was 5.9°C mid-way between the ducts (the side of the computational domain). These predictions agree well with the measurements by Hylmö et al. of 5°C above the supply duct and 6°C mid-way between the ducts. Fig. 4 also shows good agreement between the measured and predicted temperatures at the top and the bottom of the centre line of the pile after the cooling period.

After forced cooling for 8 h, the air flow rate at the inlet was reduced to zero in 5 sec to transfer the simulation from forced convection to natural convection. Air at the top of the computing domain, having a temperature of 0°C and 100% relative humidity, started to fall onto the potato pile in the central region and cooled the potatoes at the top. It then rose towards the ceiling at the side because air moved out of the pile from the warm region due to buoyancy. Consequently, a small amount of cooling air was drawn into the potato pile at the top of the central region and formed a gentle circulation inside. This small amount of cooling air reached equilibrium with the surrounding potatoes very quickly while circulating through the pile and so the cooling effect on the warm region was very weak at this time.

As more potatoes in the top layer of the pile were cooled by the falling cold air, the flow patterns above and within the pile changed accordingly. The region where the air was falling above the pile began to gradually move away from the centre towards the side. Fig. 5 shows the air flows and temperature near

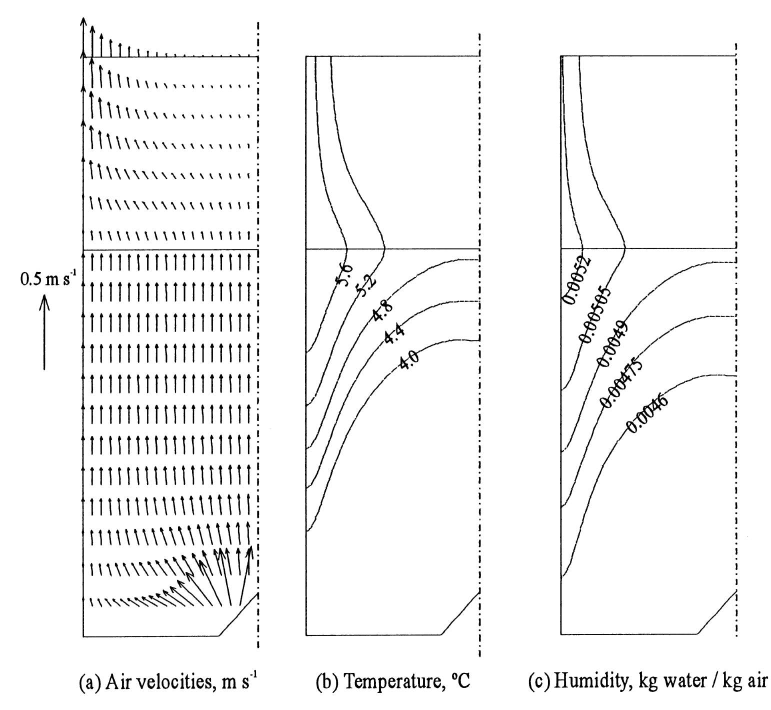

Fig. 3. Predicted patterns of air flow, temperature (°C) and humidity (kg water/kg air) through the potato pile after forced cooling for 8 h.

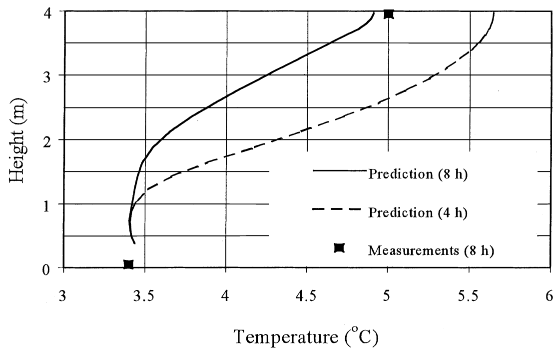

Fig. 4. Predicted and measured air temperatures on the centre line of the pile after forced cooling for 4 and 8 h.

to the top of the pile after 3.5 h of natural convection. The change of flow pattern increased the size of the region of cooled potatoes in the top layer but the potato temperature in the warm region had changed very little. After a further 1.5 h of natural convection, the region of falling cold air moved further towards the side and the air temperature in the top layer had dropped to around 4°C (Fig. 6). Condensation then occurred at the top of the pile halfway between neighbouring ducts, as observed by Hylmö et al., because the cooled potatoes and cold air on the top encountered the rising warmer air from the warm region. The greatest thickness of the condensation film predicted at that time was 83.2 μm.

The performance of the store was examined further by varying the operational parameters within the model. Results revealed that if ventilation had been stopped after 6 h then condensation would have occurred earlier and would have been found within the potato pile instead of at the top of it. At this time, the cooling front was still largely within the potato pile even in the central region and condensation would have occurred in that region when warm air in the top layer of the pile was convected backwards across the cooling front by the gentle circulation mentioned above. However, when cooling for 8 h, the cooling front in the central region had already passed through the pile and the danger of condensation within the pile therefore was removed. This explains why the location of condensation can vary.

The main cause of condensation was a warm region produced by the non-uniformity of air distribution during forced cooling. Above-floor ducts, as used in the current simulation, and flush floor ducts (built into the floor and covered with spaced slats) are both used in the potato industry. Simulations were carried out to compare the effectiveness of these two types of duct. The results showed that the overall uniformity of the air flow across the pile can only be improved marginally by using above-floor ducts compared to in-floor ducts. The warm region found in bulk stores could be eliminated by lengthening the period of forced ventilation but this would result in increased moisture loss from the potatoes near to the ducts. Reducing the risk

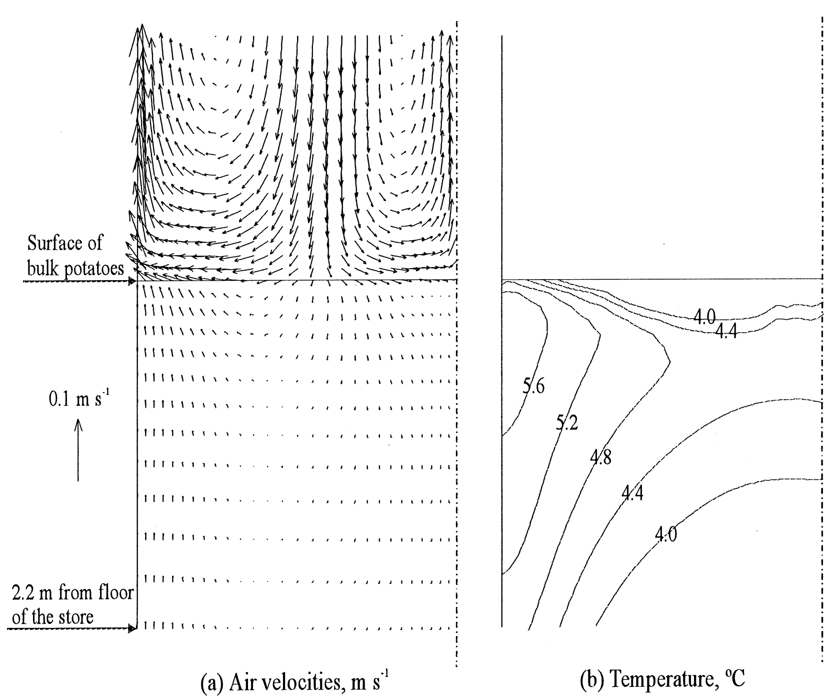

Fig. 5. Predicted patterns of air flow and temperature near to the top of the potato pile after forced ventilation for 8 h and natural convection for 3.5 h.

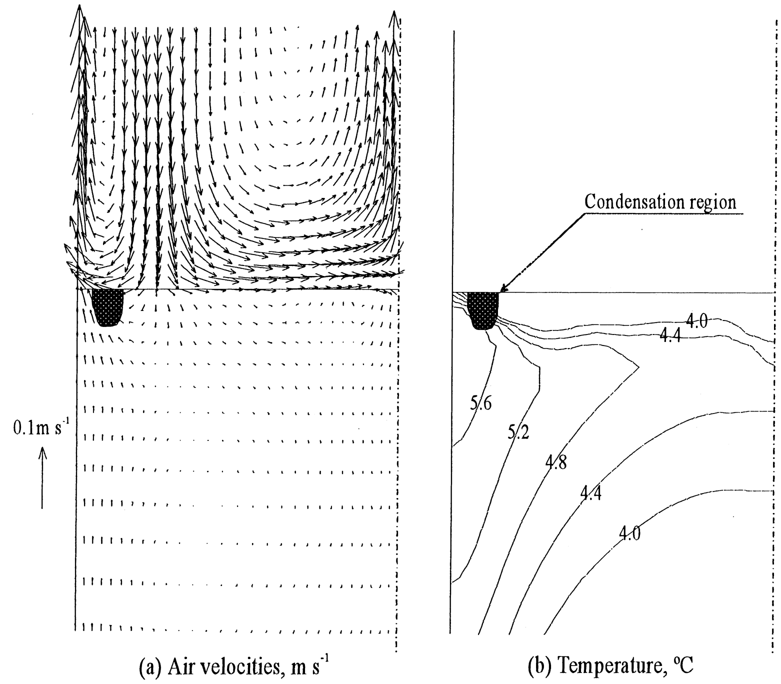

Fig. 6. Predicted patterns of air flow and temperature around the top of the potato pile after forced cooling for 8 h followed by natural convection for 5 h and the occurrence of condensation at this stage.

of condensation could be achieved by either reducing the distance between neighbouring ducts or by diverting some cooling air into the region of slow air movement.

6. Conclusions

Considerable computing resources were required to predict the air flows, temperature and moisture changes in the bulk of potatoes and this forced the use of a 2-dimensional model. Nonetheless, we have shown how condensation develops and why it can be found in various regions of the bulk, but most commonly at the top of the bulk and mid-way between the air supply ducts. The variations in air flow, leading to differences in the movements of the cooling front, are the main cause of condensation. Increasing the period of forced ventilation to ensure that the cooling front has passed through the entire bulk of the potatoes is the easiest way to restrict condensation but produces increased moisture loss. Directing air into regions where there is currently the least air flow is a more novel solution.

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