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HEAT AND MASS TRANSFER COEFFICIENTS DURING DRYING OF APPLE CYLINDERS BY NATURAL CONVECTION

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ABSTRACT

Apple cylinders were dried by combined natural convection and infrared radiation at two temperature levels. Convection seems to dominate and a pseudo-convective model appears to be adequate when temperature is low (40°C). At high temperature, however, radiation becomes important as is shown by an increase on surface temperature above air temperature and radiation equations are required to describe the process. Heat and mass transfer coefficients at lower temperature were measured taking in account the temperature profiles in the sample and its shrinkage with the moisture removal. Parameters for an equation involving Nu, Gr, and Pr dimensionless numbers valid for the experimental conditions employed were determined.

INTRODUCTION

Simultaneous heat and mass transfer is an important food processing operation (drying, smoking, frying, cooking, for example). Many physical, chemical, and nutritional changes are function of temperature, moisture, moisture profiles, and time. Therefore, undesirable effects could be minimised, and the process could be better controlled if temperature and moisture distributions in foods with respect to time could be accurately predicted. There are many models in the literature to predict the moisture and temperature distributions during these processes (Rossen and Hayakawa, 1977). Most of the drying models have been established under simplifying assumptions like no shrinkage, isotropic behaviour constant transport parameters and physical properties. Most of such models are only valid under forced convection drying. When infrared drying (ID) is used, radiation distribution in the dryer is assumed homogeneous and an average radiation intensity is assumed, perpendicular to the surface.

Infrared processing is quite common in the food industry, besides drying. Examples are the mass baking of bread, cakes, cookies and the pre-cooking of ready-meals prior to freezing.

THEORY

During heat processing of foods with warm air, where dehydration is normally present, external heat and mass transfer coefficients vary according to operational conditions, such as air flow rate, temperature and humidity and also the geometry of the material. At low air velocities (< 2 m/s) and large gradient temperature between air and solid, heat exchange takes often place by convection and radiation simultaneously. In these conditions, it is necessary to determine experimentally the surface temperature of the solid which differs from the wet bulb temperature (Kondjoyan et al., 1993). The surface boundary conditions are:

Mass:

$$-\rho_b D_{eff} \left.\frac{\partial X}{\partial y}\right)_{y=0} = k'(a_w - \varphi) \qquad (1)$$

Energy:

$$-k_b \left.\frac{\partial T}{\partial y}\right)_{y=0} = h_c(T_s - T_e) - \lambda k'(a_w - \varphi) + \varepsilon\sigma(T_s^4 - T_i^4) \qquad (2)$$

Simultaneous heat transfer by natural convection and radiation can be described according to Kern, (1965) by a combined coefficient:

$$Q = (h_c + h_r)A(T_e - T_s) \qquad (3)$$

The convection coefficient, h_c is given by:

$$Nu = \frac{h_c R}{k} \qquad (4)$$

where Nu is the Nusselt number:

$$Nu = a(Gr\,\mathrm{Pr})^m \qquad (5)$$

Grasshoff number (Gr):

$$Gr = \frac{R^3 \rho_a^2 g \beta \Delta T}{\mu^2} \qquad (6)$$

and Prandtl number (Pr):

$$\mathrm{Pr} = \frac{c\mu}{k} \qquad (7)$$

In equation (3) h_r is given by:

$$h_r = \frac{5.67 \cdot 10^{-8} \varepsilon (T_i^4 - T_s^4)}{(T_i - T_s)} \qquad (8)$$

It is known the analogy between heat and mass transfer coefficients (Ozisik, 1985):

$$\frac{h_c}{k'} = c(Le)^{0.66} \rho_a \qquad (9)$$

where Le number is given by:

$$Le = \frac{k}{cD\rho_a} \qquad (10)$$

In this work a combined heat transfer coefficient $h = h_c + h_r$ was used to investigate the comparative extension of radiation transfer with respect to natural convection.

Apple samples, as well as many other types of foods, shrink and deform during dehydration, and the transfer coefficients are dependent upon them. Thus, the dimensions of cylinders have to be measured during dehydration.

EXPERIMENTAL

Apple (*Golden delicious* variety) with an initial water content in the range of 0.85-0.89 (w/w, wet basis) were used in this study (determined at 70 °C under < 100 mm Hg). Cylinders were produced using n 12.5 ± 0.1 mm cork borer. The apple cylinders had constant height of 40 ± 0.1 mm. Radius and volume changes were determined following Sjöholm and Gekas, 1995. Top and bottom surfaces were sealed with glue to prevent moisture removal through them. The samples were dehydrated at two temperatures (40 and 80 °C). An infrared dryer (Sartorius MA 30) was used. This equipment was linked to a monitoring system which is able to follow both sample weight and air + sample temperature profiles, using home-made type K microthermocouples both linked to a OM 800 data acquisition system (Omega Engineering) as shown in Figure 1.

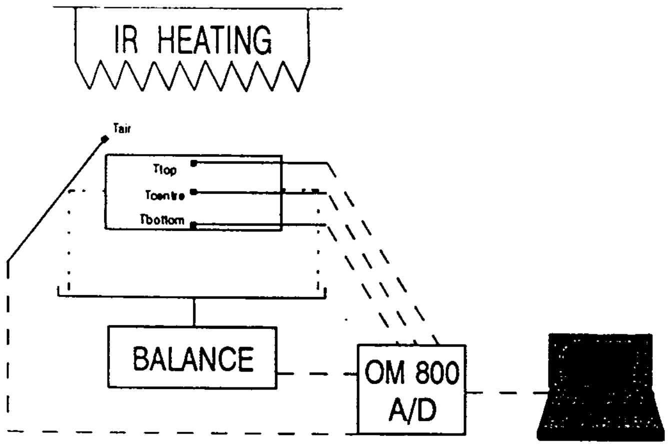

Figure 1 Diagram of experimental system linked to a monitoring system

RESULTS

Drying curves for different experimental conditions are shown in Figures 2 and 3 (40 and 80 °C, respectively). It is clearly seen that drying temperature is an important variable influencing the operation rate.

From the drying kinetics, the mass flux of water, J_m, lost by the apple cylinder to the air is easily determined from

$$A = dl.\pi = (1.67 \cdot 10^{-3}.X + 0.0023) \cdot 0.04 \cdot \pi \quad (14)$$

The mass transfer coefficient k' obtained experimentally is shown against moisture content in Figure 6. In this Figure it is also plotted the mass transfer coefficient calculated in absence of radiation assuming constant properties at the solid surface, using equation (9) and the following expression to evaluate the heat transfer coefficient (Kern, 1965):

$$Nu = 1.09(Gr \cdot \Pr)^{0.2} \quad (15)$$

The parameters in equation (15) were obtained for the range of $1<Gr \cdot Pr<10^4$ used in this experiments It can be observed that the mass transfer coefficient in presence of radiation is larger than when there is only natural convection. This difference decreases with the moisture content suggesting a growing influence of internal resistance to mass transfer.

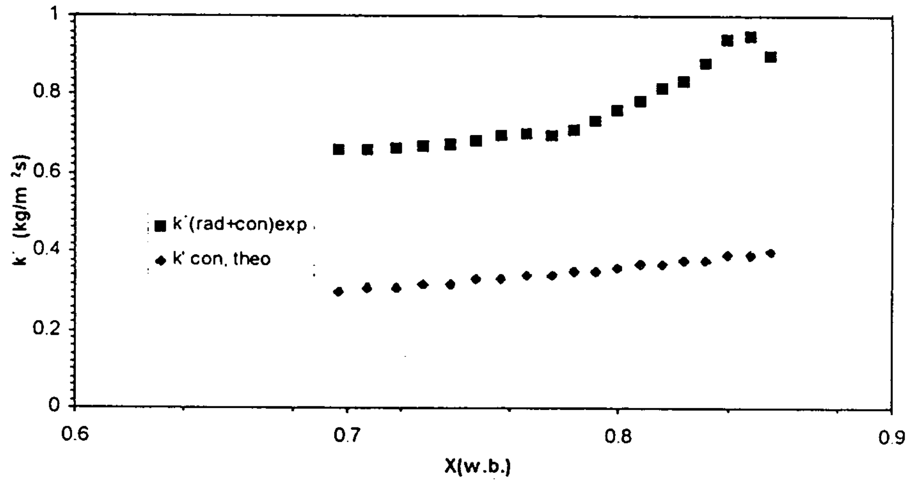

Figure 6. Change of mass transfer coefficient with moisture content. Experimental results compared to results calculated for natural convection.

With physical properties data were taken from Lide (1992) the relation between heat and mass transfer at the experimental conditions employed (40 °C) in presence of radiation (equation 9) leads to

$$h' = 1.20 \cdot k' \quad (16)$$

introducing this relation in the equation (5) parameters a and m for existing experimental conditions are obtained:

$$Nu = 6.46 \cdot (Gr \cdot \Pr)^{0.3} \quad (17)$$

CONCLUSIONS

Experimental data on heat and mass transfer during drying of apple cylinders in conditions of simultaneous natural convection and radiation allowed the determination of a global mass transfer coefficient. By comparing these experimental coefficients with values predicted from well established correlations valid for simple natural convection, it was possible to estimate the effect produced by radiation. By increasing the heating output mass transfer an inversion on the surface temperature was observed showing the increased importance of radiation with respect to convection in this condition These results show to what extent simple convection transfer analysis can lead to significant differences in heat and mass transfer fluxes in the presence of radiation.

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NOTATION

a_w	water activity	-
A	area	m^2
c	specific heat of air	$J\cdot kg^{-1}\cdot K^{-1}$
d	diameter	m
D	mass difussivity	$m\cdot s^{-1}$
h	overall heat transfer coefficient	$W\cdot m^{-2}\cdot s^{-1}$
J_m	mass flux exchanged between cylinder and air	$kg\cdot m^{-2}\cdot s^{-1}$
k	thermal conductivity of air	$W\cdot m^{-1}\cdot K^{-1}$
k'	overall mass transfer coefficient	$m\cdot s^{-1}$
Q	heat per time unit	W
R	radius	m
t	time	s
T	temperature	K
X	moisture content (dry basis)	-

Greek symbols

β	thermal volumetric expansion coefficient	K^{-1}
ε	emissivity	-
φ	relative humidity	-
μ	dynamic viscosity of air	$kg\cdot m^{-1}\cdot s^{-1}$
ρ	density	$kg\cdot m^{-3}$
σ	Stephan-Boltzmann constant	$W\cdot m^{-2}\cdot K^{-4}$

Subscripts

a	air
b	body
c	convection
eff	effective
i	infrared emission
s	surface
r	radiation

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