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CONCURRENT DRYING OF SOYBEAN SEEDS: THE EFFECT OF THE RADIAL AIR PROFILE

A. J.Assis*, T. S. Lira, V. V. Murata and M. A. S. Barrozo

Faculdade de Engenharia Química, Universidade Federal de Uberlândia.
Av. João Naves de Ávila 2121, CEP 38408-100, Uberlândia - MG, Brazil
Phone: (034)3239-4292, Fax: (034)3239-4188
E-mail: masbarrozo@ufu.br
E-mail: ajassis@ufu.br

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Abstract - The aim of this work was to analyze the heat and mass transfer between the air and soybean seeds in a concurrent moving bed dryer with an air profile that is not flat. The modelling of heat and mass transfer in moving bed dryers is generally based on the application of mass and energy balance equations for both solid and fluid phases (two-phase model). In the establishment of these equations some classical hypotheses such as that the fluid velocity profile is flat, are assumed. The main goal of this work was to verify the validity of this assumption by means of an experimental and simulation study in a concurrent moving bed, using soybean seeds as particles. In this work, the radial air profile was taken into account by means of a suitable empirical correlation and a mechanistic model validated by experimental results. The numerical solution of the one-dimension boundary value problem was obtained by means of a computational code based on axial integration through the DASSL code. By comparison of the experimental data and the simulated responses for air temperature and seed moisture content, it was possible to verify the significant effect of air velocity distribution.

Keywords: Concurrent drying; Soybean seeds; Radial air profile.

INTRODUCTION

Soybeans are currently one of the most important agricultural food sources in the world. Their importance in grain production has been increasing due to their high yield capacity and lower harvest cost in comparison to other grains. Their high quality as a source of protein makes them the primary food in the fight against hunger, and they may be found in many densely populated and underdeveloped areas.

In recent years, research on the moving bed technique, specially on its application in agricultural dryers, has intensified (Barrozo, 1995; Barrozo, Murata and Costa, 1998). This technique requires a lower investment and a lower consumption of energy and causes less mechanical damage to the seeds than other techniques. The classic configurations of moving bed dryers are crosscurrent, concurrent and countercurrent flow, according to the relative directions of seed and air flows. Configurations with parallel flow have some advantages over those with crosscurrent flow, such as obtaining more homogeneous products as well as achieving a better use of energy (Souza, 2001).

The so-called two-phase model (Barrozo, 1995; Barrozo, Murata and Costa, 1998) is used to describe heat and mass transfer between air and soybean seeds in the moving bed dryer. This model comprises the mass and energy balance equations applied to both fluid and solid phases and requires constitutive equations for the coefficient of heat transfer between these two phases, the drying kinetics and the equilibrium moisture content of the solid material. In establishing these equations some classic hypotheses,

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*To whom correspondence should be addressed such as that the fluid velocity profile is flat, are assumed. Velocity profiles within a packed bed, as reported in the literature (Fahien and Stankovich, 1979; Vortmeyer and Schuster, 1983; Zotin and Freire, 1986; Negrini et al., 1999), are strongly affected by the voidage distribution in the bed. The high-velocity zones correspond to the high voidage regions and upon increasing the flow, the peak velocities become more pronounced.

The main goal of this work was to verify the effect of a fluid velocity profile that is not flat by means of an experimental and simulation study in a concurrent moving bed, using soybean seeds as particles. The radial air profile was taken into account by means of a suitable empirical correlation and a mechanistic model validated by experimental results. By comparison of the experimental data and the simulated responses for air temperature and seed moisture content, it was possible to prove the significant effect of air velocity distribution.

MATHEMATICAL MODELLING

To describe heat and mass transfer between air and soybean seeds in moving bed dryers, the two-phase mathematical model was developed based on the following assumptions (Barrozo, 1995; Barrozo, Murata and Costa, 1998):

- the steady state is achieved;
- air and solids flow mainly in one direction;
- internal diffusion is the predominant mechanism of mass transfer;
- grain shrinkage is negligible during the drying process;
- convection is the predominant mechanism of heat transfer;
- heat losses are negligible;
- the interstitial air velocity profile is flat ;
- the solids flow rate is uniform.

Some of these assumptions are made to simplify the mathematical model and comparing numerical model results to experimental data obtained in the equipment can validate them. However, the two latter assumptions, i.e., that the solids flow rate is uniform and that the interstitial air velocity profile is flat, should be verified by experimental studies of fluid dynamics in a moving bed of particles. Souza (2001) has shown that these two assumptions are valid in moving bed dryers with large dryer diameter-to-particle diameter ratios. Decreasing this ratio, the effect of the dryer wall on bed porosity becomes important and the interstitial air velocity tends to increase near the dryer wall due to the significant variation in bed porosity (higher in regions near the dryer wall and lower in regions close to the center of the bed; very close to the wall, the velocity is zero, which characterizes the so-called “slip condition”).

In the present work, this dryer wall effect on fluid flow was taken into account by assuming that the dryer is composed of concentric sliding zones and that within each one the air velocity is flat, but the average value is different from those of the neighbouring zones. This assumption allows use of the one-dimensional model developed for the case of the flat air velocity profile, thus avoiding the need to solve the more complicated two-dimensional model, described by partial differential equations, which would be required if the assumption of sliding zones were not taken into account. Figure 1 shows a sketch of the concurrent flow moving bed assumed in the modelling.

Application of the aforementioned assumptions in conjunction with mass and energy balances for both fluid and solid phases, taking into consideration the dryer represented in Figure 1, results in the following equations:

a) Mass balance:

Fluid phase:

$$G_{fi}\frac{dW_i}{dx} = f_m\ a \tag{1}$$

Solid phase:

$$G_s\frac{d\overline{M_i}}{dx} = -f_m\ a \tag{2}$$

b) Energy balance:

Fluid phase:

$$\frac{dT_{fi}}{dx} = -\frac{ha\ (T_{fi} - T_{si})}{G_{fi}\ (Cp_f + W_i Cp_v)} \tag{3}$$

Solid phase:

$$\frac{dT_{si}}{dx} = \frac{ha\ (T_{fi} - T_{si})}{G_s\ (Cp_s + \overline{M}_i Cp_l)} - \frac{f_m\ a\ (\lambda + Cp_v T_{fi} - Cp_l T_{si})}{G_s\ (Cp_s + \overline{M}_i Cp_l)} \tag{4}$$

The inlet air humidity, seed moisture content and air and seed temperatures are assumed to be constant in all layers, resulting in the following model boundary conditions:

$$W_i(0) = W_0 \tag{5a}$$

$$\overline{M}_i(0) = \overline{M}_0 \tag{5b}$$

$$T_{f\,i}(0) = T_{f\,0} \tag{5c}$$

$$T_{si}(0) = T_{s0} \tag{5d}$$

Equations for the Heat Transfer Coefficient, Equilibrium Moisture Content and Drying Kinetics

The coefficient of heat transfer between air and soybean seeds in a concurrent moving bed dryer is estimated using the correlation proposed by Sartori (1986), as follows:

$$Nu = 0.84 Pr^{1/3} Re^{0.65} \tag{6}$$

As shown in earlier work (Barrozo, 1995), the equilibrium moisture content of soybean seeds is described well by the modified Halsey equation as follows:

$$\overline{M}_{eq} = \left(\left(-\exp\left(\begin{matrix}-0.00672 * T_s + \\ +3.02\end{matrix}\right)\right) / \ln(UR)\right)^{\frac{1}{1.508}} \tag{7}$$

where $\overline{M}_{eq}$ is calculated for dry basis, UR is given as a mass ratio and T_S is in °C.

The numerical parameters in Equation (7) were estimated with regression analysis methods by fitting the modified Halsey equation to the experimental equilibrium data on soybean seeds.

The diffusive model, represented by Equation (8), is the one used to describe the drying kinetics of soybean seeds.

$$MR = \frac{\overline{M} - \overline{M}_{eq}}{\overline{M}_0 - \overline{M}_{eq}} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[\frac{-n^2 \pi^2 D_{ef}\, t}{R_p^{\ 2}}\right] \tag{8}$$

Based on experimental data obtained in a thin layer dryer of soybean seeds, Barrozo (1995) estimated the effective diffusivity coefficient, D_{ef}. The variation in this coefficient with temperature is obtained by reparametrization of the Arrhenius equation, as shown in Equation (9):

$$D_{ef} = \exp(\beta) \exp\left(-T' \exp(\gamma)\right) \tag{9}$$

where $T' = (1/T_f - 1/T^*)$, $T^* = 273$ K , T_f is in Kelvin and D_{ef} is in cm^2/min. The β and γ parameters, estimated by the least squares methods, are 13.185 and 8.36, respectively.

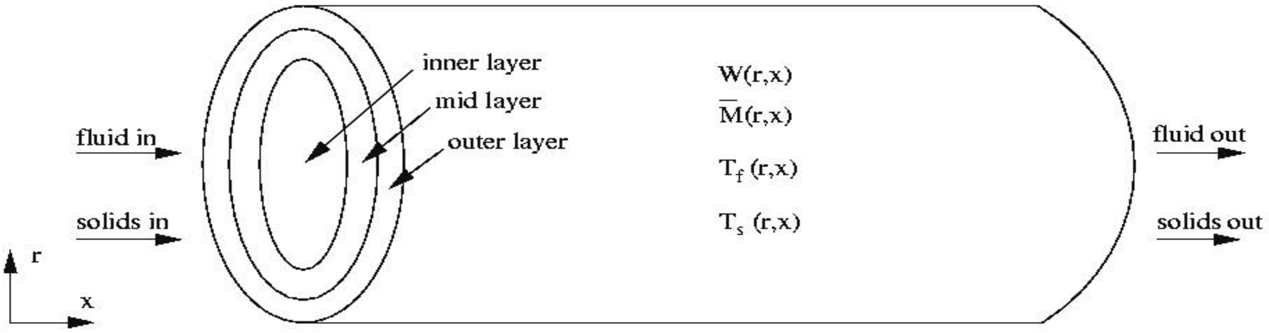

Figure 1: Sketch of the concurrent flow moving bed with sliding layers used in modelling.

Porosity and Velocity Pprofile

The void fraction data of Benenati and Brosilow (1962) for uniform spherical particles have the typical oscillatory variation in void fraction in the region of the wall, and Equation (10) is an empirical fit of these data:

$$\varepsilon(x) = 0.38 + 0.62 e^{-1.70 x^{0.434}} \cos(6.67 x^{1.13}) \tag{10}$$

where $x = (1-\zeta)\delta/2$ is the number of d_p from the wall. Nevertheless, according to Vortmeyer and Schuster (1983) quite different observations are made for the porosity function of a packed bed consisting of glass spheres with small deviations from the spherical structure, as one could expect with soybean seeds. In this case the porosity function oscillates only once before reaching the average porosity and is then approximated by the following equation for a circular tube, where C has to be adjusted according to ε_o:

$$\varepsilon = \varepsilon_o\left[1 + C\exp\left(1 - 2\frac{R-r}{d_p}\right)\right] \qquad (11)$$

Vortmeyer and Schuster (1983) used the differential equation which describes the artificial flow profile within a porous medium bounded by a rigid wall proposed by Brinkman, who extended Darcy's law by a viscosity term in order to include the viscous forces near the wall. Later, the Brinkman model was extended to higher flow rates by incorporating the Ergun pressure drop equation. Using the exponential porosity profile shown in Equation (11) above, Vortmeyer and Schuster (1983) proposed an approximative analytical solution to Brinkman's extended equation, using the variational method, as follows:

$$\frac{v_z}{<V>} = B_1\left[1 - \exp\left(a\frac{R-r}{d_p}\right)\left(1 - n\frac{R-r}{d_p}\right)\right] \qquad (12)$$

$$B_1 = \frac{1}{2}R^{*2}\left[\begin{array}{l}\dfrac{R^{*2}}{2} - \left(aR^* + 1\right)\left(nR^* - 1\right)\dfrac{1}{a^2} + \\ +n\left(\dfrac{R^{*2}}{a} + \dfrac{2R^*}{a^2} + \dfrac{2}{a^3}\right) - \\ -e^{-aR^*}\dfrac{1}{a^2}\left(1 - R^*n + n\dfrac{2}{a}\right)\end{array}\right]^{-1} \qquad (13)$$

where

$$R^* = \frac{R}{d_p}, \quad a = \frac{4n}{4-n}, \quad Re = \frac{Gd_p}{\mu}$$

If $0.1 \le Re \le 1$,

$$n = 112.5 - 26.31Re + 10.97Re^2 - 0.1804Re^3$$

If $1 < Re \le 1000$,

$$n = -1803 + 201.62(\ln Re + 4) - 3737(\ln Re + 4)^{1/2} +$$
$$5399(\ln Re + 4)^{1/3}$$

If $Re > 1000$, $n = 27$

Several researchers have experimentally measured variations in radial velocity, such as Fahien and Stankovich (1979) who correlated experimental data for a wide range of d_p, d_t and Reynolds' numbers in terms of the single parameter $\alpha = d_t / d_p$, as follows:

$$V^* = \frac{v_z}{<V>} = \frac{A_1 + A_2 r^{*(B+1)} - A_3 r^{*(B+2)}}{A_1 + \dfrac{2A_2}{B+3} - \dfrac{2A_3}{B+4}} \qquad (14)$$

where

$$B = 0.45\alpha^{1,5}$$
$$A_1 = \frac{1}{B+2} - \frac{\alpha - 1}{\alpha\left(B+1\right)}$$
$$A_2 = \frac{\alpha - 1}{\alpha\left(B+1\right)}$$
$$A_3 = \frac{1}{B+2} \text{ and } r^* = \frac{r}{r_t} \left(\text{with } r_t = \frac{d_t}{2}\right)$$

Reporting on Brinkman's extended equation Johnson and Kapner (1990) proposed a suitable simplification in order to achieve only one differential second-order equation with boundary conditions to describe the velocity profile within the bed. The porosity profile used was that given in Equation (10), and by numerical solution a quite oscillatory velocity profile was found.

A detailed comparison of the three velocity profile models described above and experimental data for a countercurrent dryer filled with soybeans can be found elsewhere (Assis et al., 2004). Using Equations (12) and (14), as well as experimental data (Souza, 2001), it could be seen that the correlation proposed by Fahien and Stankovich (1979) is in better agreement with data than the solution proposed by Vortmeyer and Schuster (1983) (see Figure 2).

So, in this work, the Fahien and Stankovich (1979) correlation was chosen for the velocity profile of the sliding bed.

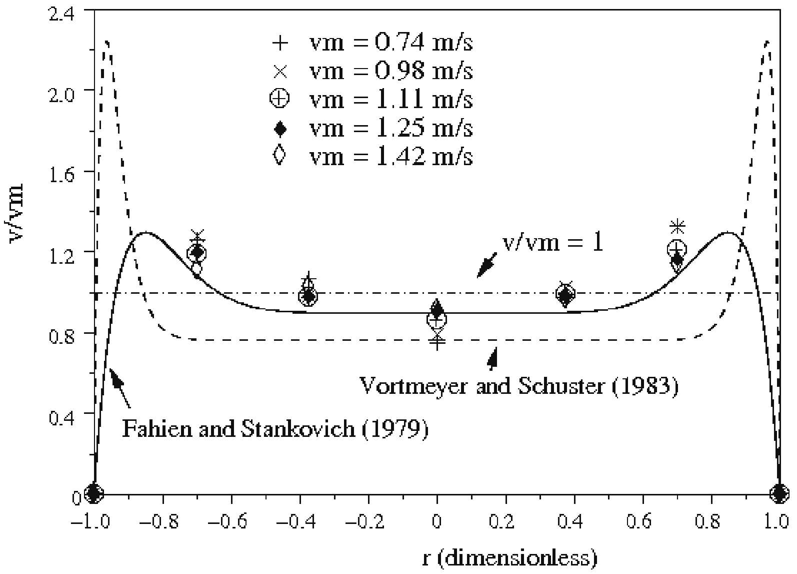

Figure 2: Experimental and predicted radial velocity profiles.

Numerical Solution

As shown in earlier work (Barrozo, Murata and Costa, 1998), numerical solution of the model can be obtained using the DASSL code (Brenan et al., 1996). This code developed in FORTRAN computer language implements BDF (backwards differentiation formulas) methods for solving a general set of algebraic differential equations with index zero or index one, such as those represented by Equations (1) to (9).

RESULTS AND DISCUSSIONS

The experiments were conducted with soybean seeds of the Brazilian Doko variety with d_p = 6 mm and $\rho = 1.17x10^3$ kg/m^3, artificially moisturized by the contact with air close to their saturation point, using a dryer with d_t/d_p = 13.3. A detailed description of the experimental method employed to collect the experimental data will not be presented here, but it can be found elsewhere (Felipe and Barrozo, 2003).

In order to study the effect of radial air profile, the moving bed was divided into six concentric layers (δ = r/R = 0-0.5; 0.5-0.6; 0.6-0.7; 0.7-0.8; 0.8-0.9; 0.9-1 in dimensionless units). Air velocity was then calculated with Equation (14) using the average radial positions for each range mentioned above.

Figures 3 and 4 compare simulated model results to experimental data for the variables, air temperature and seed moisture content, respectively, for the radial positions mentioned, along axial direction. It can be seen that the temperature profile in the axial direction depends on position of the radius, and next to the wall, where the velocity is significantly lower (see Figure 2), the temperature profile is strongly affected. The experimental data were obtained in the central region of the dryer, but due to the characteristic of the experimental apparatus employed it is hard to assure that all data were really from this region; thus, it is accepted that small deviations from that region could have occurred and this could explain the small deviations between experimental and predicted results. Furthermore, several parameters, such as air and solids density and heat capacity, were considered constant throughout the dryer in development of the model. Nevertheless, as these parameters are affected by the temperature profile they can be expected to contribute to deviations between simulated and measured data. In spite of this, the average deviations between experimental and simulated data for air temperature and seed moisture content are close to the measurement uncertainties of these variables. Therefore, in the range of these measurement uncertainties, the model prediction is satisfactory and an imprecise conclusion can be drawn about the model assumptions.

Figure 5 shows simulated radial profiles for air temperature in two axial positions (x = 0.3 and 0.8). It is clear that there are temperature gradients in the radial direction, thereby affecting the transport mechanism of mass and heat transfer throughout the bed. As a consequence of this, seed quality will be affected, as shown by Felipe and Barrozo (2003).

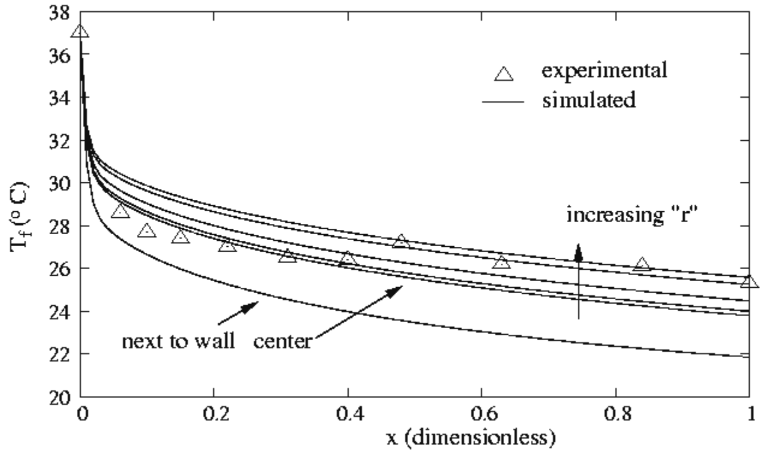

Figure 3: Axial profiles for air temperature (experimental and simulated).

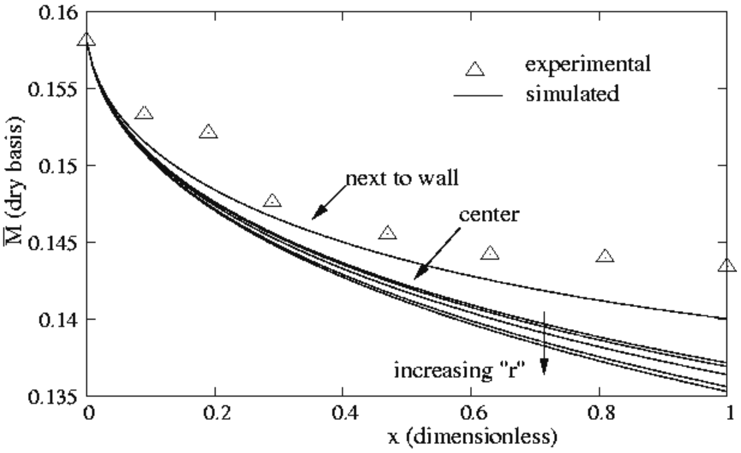

Figure 4: Axial profiles for average volumetric seed moisture (experimental and simulated).

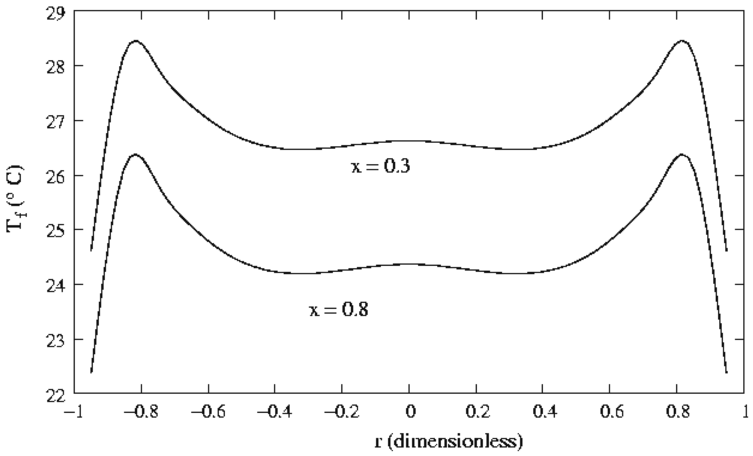

Figure 5: Radial profiles for air temperature (simulated).

CONCLUSIONS

The method presented in this work is suitable for studying and analyzing the mechanisms of heat and mass transfer between air and soybean seeds as well as the effect of the air velocity profile during the drying operation in concurrent moving beds.
Deviations from the flat air velocity profile were taken into account using empirical and mechanistic equations found in the literature that describe the air profile as a function of radius. Predicted air temperature profiles were obtained using those equations after comparing them with experimental data. Using concentrically sliding layers the model developed to predict axial variations in moisture and temperature for both solid and fluid phases was extended to include the air velocity profile, thereby avoiding the need to use a two-dimensional complex model described by partial differential equations.

The predicted results obtained through simulation were compared with experimental data obtained in the central region of the dryer for air temperature and seed moisture content, resulting in acceptable agreement. Furthermore, radial air temperature profiles were obtained in two distinct axial positions in order to show the effect of air velocity profile on relevant drying variables such as air temperature.

NOMENCLATURE

a	interfacial transfer area per bed volume unit; const. eq. (12)	m^{-1}
Cp	specific heat	$m^{-2}K^{-1}s^{-2}$
D_{ef}	effective mass diffusivity of the water inside the grain	m^2s^{-1}
d_p	diameter of the sphere of equal volume	m
d_t	dryer diameter	m
f_m	local drying rate per unit area	kg $m^{-2}s$
G_f	mass flux of dry gas	kg $m^{-2}s^{-1}$
G_s	mass flux of dry solid	kg $m^{-2}s^{-1}$
h	heat transfer coefficient	kg $K^{-1}s^{-3}$
L	length of the bed	m
$\overline{M}$	average volumetric seed moisture	$kg_{water}/kg_{dry\ solid}$
MR	moisture number	(-)
Nu	Nusselt number	(-)
Pr	Prandtl number	(-)
Q	flow rate	kg^1s^{-1}
R_p	particle radius	m
R	dryer radius	m
Re	Reynolds number	(-)
t	time variable	s
T	temperature	K
UR	relative humidity of the air	(-)
v, v_z	axial fluid velocity	m s^{-1}
<V>	mean axial velocity	m s^{-1}
x	coordinate of the direction of the grain flow	m
x'	(x/L) position of bed	(-)
W	absolute air humidity	$kg_{water}/kg_{dry\ air}$

Greek Symbols

β	parameter that represents the variation in effective diffusivity with temperature	(-)
γ	parameter that represents the variation in effective diffusivity with temperature	(-)
μ	viscosity, kg m^{-1} s^{-1}	(-)
ρ	density, kg m^{-3}	(-)
ε	void fraction	(-)
ζ	= r/R, dimensionless radial coordinate	(-)
δ	= R/R_p, radial aspect ratio	(-)
		(-)

Subscript

Eq	equilibrium	(-)
f	fluid	(-)
int	interstitial	(-)
l	liquid	(-)
0	inlet conditions	(-)
s	solid	(-)
v	vapor	(-)
i	sliding zone “i” considered in the dryer modelling	(-)

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