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Research Paper

Determination of diffusion and convective transfer coefficients in food drying revisited: A new methodological approach

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It is usual to determine diffusion and convective transfer coefficients using classical approximate relationships involving dimensionless numbers. These approximate relationships were developed in the past, in order to avoid the difficulties associated with calculations of large series expansions and its corresponding expansion coefficients given by transcendental equations. However, the development of improved computing techniques has removed these difficulties, such that currently such calculations can be easily performed. An iterative methodology is proposed that takes advantage of current computational capabilities, avoiding to use approximate relationships. The proposed methodology is applied to generated data and also to experimental data from carrot drying. Additionally, a MATLAB® implementation of the proposed iterative methodology, along with the input data files corresponding to the results presented in this paper, is provided as supplementary material.

1. Introduction

In the development of suitable models for complex processes involving foods, which are applicable to a broad set of external conditions, the correct and accurate determination of the physical parameters involved is a central issue. Especially important in food engineering are heat and mass transfer processes, which are characterised by the corresponding diffusion and convective transfer coefficients.

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Nomenclature

Bi	Biot number
D	Effective diffusion coefficient (m^2 s^{-1})
D_i	Effective diffusion coefficient calculated at the i-th iteration (m^2 s^{-1})
F	Mass flow (g [water] (m^{-2} s^{-1})
Fo	Dimensionless time (Fourier number)
M	Dry basis moisture (g [water] g^{-1} [dry matter])
$\overline{M}$	Position averaged moisture (g [water] g^{-1} [dry matter])
M_0	Initial uniform moisture (g [water] g^{-1} [dry matter])
M_{eq}	Moisture at equilibrium (g [water] g^{-1} [dry matter])
M_ℓ	Moisture at food sample-air interface (g [water] g^{-1} [dry matter])
S_D	Generalised significant figures in diffusion coefficient
S_h	Generalised significant figures in mass transfer coefficient
T	Sample temperature (°C)
a	Intercept in the fitting to the straight line $y = a + bt$
b	Slope in the fitting to the straight line $y = a + bt$ (s^{-1})
h	Convective mass transfer coefficient (m^2 s^{-1})
h_i	Convective mass transfer coefficient calculated at the i-th iteration (m^2 s^{-1})
ℓ	Half thickness of the sample (mm)
ℓ_y	Half width of the sample (mm)
ℓ_z	Half height of the sample (mm)
t	Time (s)
t_i	The i-th time measured in the drying process (s)
v	Air velocity induced by the extractor fan (m s^{-1})
w_0	Initial sample weight in the drying process (g)
w_{dm}	Sample dry matter weight (g [dry matter])
w_{eq}	Sample weight at equilibrium in the drying process (g)
w_i	Sample weight at each time t_i in the drying process (g)
x	Position across thin layer sample thickness (mm)
y_i	The i-th ordinate value corresponding to the average dimensionless relative moisture at each time t_i in the drying process
Δ_i	Convergence of first term approximation for the i-th iteration
$\overline{\Phi}$	Average dimensionless relative moisture
$\overline{\Phi}_N$	The N terms series expansion approximation to the average dimensionless relative moisture
μ_n	The n-th positive root of the characteristic equation $\mu_n \tan\mu_n = \mathrm{Bi}$
ρ	Sample dry matter density (g [dry matter] m^{-3})
σ_D^2	Variance of the diffusion coefficient (m^2 s^{-1})
σ_h^2	Variance of the mass transfer coefficient (m s^{-1})
σ_i^2	Variance corresponding to the i-th ordinate value y_i in the drying process
σ_w^2	Variance corresponding to the instrumental error of the weighing device (g)

It is noteworthy that for industrial purposes, as is pointed out by Zhao et al. (2014), foods are usually dried to remove the moisture up to a certain level at which microbial spoilage and deteriorative chemical reactions are minimised, and accurate determination of diffusion and convective transfer coefficients is required in order to facilitate accurate designs.

Different methods have been described in the literature to obtain experimental values for these coefficients. Zhao et al. (2014) used a trial-and-error method based on a comparison of analytic and experimental drying curves, tuning the value of the diffusion coefficient until the matching of both curves is reached approximately. In similar fashion, Białobrzewski (2007) obtained both diffusion and convective transfer coefficients by comparing numerical (as opposed to analytical) and experimental drying curves. Note that analytical solutions are available only for some simple systems, whilst numerical solutions are available for any system. Conversely, analytical solutions have arbitrarily high accuracy, but the accuracy of numerical solutions is limited by numerical approximation, especially in the case of partial differential equations. Also, in order to obtain the convective transfer coefficient, the reaction engineering approach has been applied by considering drying as a competitive process between condensation and evaporation (Compaore et al., 2017). However, the most widely used method is the fitting of the experimental drying curves, in logarithmic form, to a straight line. For simple one-dimensional geometries, such as for slices or cylinders, by assuming the first term approximation in the series expansion solution, diffusion coefficient can be obtained from the corresponding slope (Karim & Hawlader, 2005; Mghazlia et al., 2017; Sampaio et al., 2017; Srikiatden & Roberts, 2006). Additionally, by using approximate relationships involving dimensionless numbers, in particular the Biot number, convective transfer coefficient is also obtained (Dhalsamant, Tripathy, & Shrivastava, 2017; Guiné, Cruz, & Mendes, 2014; Tripathy & Kumar, 2009). Note that, in order to obtain the correct values of the coefficients, it is important that the experimental conditions correspond to the mathematical conditions under which the analytical solution was obtained. However, it is not common to find in the literature details explaining the drying experimental methodology which could fulfil such conditions.

Moreover, it is important to determine the accuracy of the resulting coefficients and the corresponding significant figures. Note that the instrumental error of the experimental data will propagate in the calculations when the coefficients are obtained, such that the significant figures in the initial experimental data will decrease (or at best remain the same) in the calculated coefficients. In this regard, as is well known, the calculability of diffusion and convective transfer coefficients depends on the Biot number, therefore this issue should be analysed in any method for the determination of diffusion and convective transfer coefficients.

In drying experiments, since the mass diffusion coefficient (and also convective mass transfer coefficient) depends on temperature, in order to calculate the mass diffusion