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ASSESSMENT OF THE SIMPLIFIED EQUATIONS USED FOR THE DETERMINATION OF μ_1 AND BIOT NUMBER IN UNIDIRECTIONAL DRYING CALCULATIONS IN SOLIDS

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Abstract

The accuracy of the two simplified methods; Dincer and Dost (1996) and Dincer and Hussain (2004), used for the determination of the first root of the characteristic equation and the Biot numbers from experimental lag factor data in unidirectional drying of solids has been investigated. The tabulated values relating the lag factor to the first root of the characteristic equation and Biot number were taken as basis in the assessment. None of the methods considered yielded accurate predictions for the complete lag factor range. The calculation of μ_1 and Biot number from the tabulated values of lag factors has been recommended.

Keywords: *Biot, mass coefficient, drying, food*

KATILARDA TEK BOYUTLU KURUTMA HESAPLAMALARINDA μ_1 ve BIOT SAYISININ BELİRLENMESİ İÇİN KULLANILAN BASİTLEŞTİRİLMİŞ DENKLEMLERİN DEĞERLENDİRİLMESİ

Özet

Katıların tek boyutta kurutulmasında deneysel lag faktör verilerinden karakteristik eşitliğin birinci kökünü ve Biot sayılarının öngörülmesini belirlemek için kullanılan iki basitleştirilmiş yöntemin, Dincer and Dost (1996) ve Dincer and Hussain (2004), doğruluğu incelenmiştir. Karakteristik eşitliğin birinci kökü ve Biot sayısı ile ilgili tablolaştırılmış değerler, öngörüler için temel alınmıştır. İncelenen yöntemlerden hiçbiri tüm lag faktör aralığı için doğru öngörülerde bulunamamıştır. μ_1 ve Biot sayılarının, lag faktörlerin tablolaştırılmış değerlerinden hesaplanması önerilmiştir.

Anahtar sözcükler: *Biot, kütle katsayısı, kurutma, gıda*

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1.INTRODUCTION

Moisture diffusivity and convective mass transfer coefficient are two important parameters in drying calculations. Moisture diffusivity, structure and the dimensions of the solid specify the internal mass transfer resistance, whereas the convective mass transfer coefficient specifies the external mass transfer resistance. The estimation of these parameters is important in drying calculations in which the moisture content history has to be accurately predicted. Simple, dependable models are essential for practical drying calculations.

Dincer and his coworkers published numerous papers on drying modeling: [1] proposed an analytical model to estimate the mass transfer parameters moisture diffusivity and convective mass transfer coefficient from experimental centerline moisture content data. [1] method utilized the first term of the unidirectional unsteady state diffusion equation for solids having constant physical properties [2];

$$\Phi = A_1 e^{-\mu_1^2 Fo} \tag{1}$$

Φ is the dimensionless moisture content defined by Eqn.(2). A_1 is the lag factor, μ_1 is the first root of the characteristic equation. Fo is the mass transfer Fourier number defined by Eqn. (3):

$$\Phi = \frac{X_{CL} - X_{eq}}{X_{ini} - X_{eq}} \tag{2}$$

$$Fo = \frac{D_{eff} t}{y^2} \tag{3}$$

where D_{eff} is the effective diffusivity, t is the drying time and y is the characteristic length; half thickness for an infinite slab, radius for infinite cylinder and sphere. Eqn. (1) is valid only for Fo >0.2 [2]. [1] have defined a drying coefficient S as

$$S = \mu_1^2 \frac{D_{eff}}{y^2} \tag{4}$$

Eqn. (1) may be written as the following in terms of the drying coefficient S as

$$\Phi = A_1 e^{-St} = Ge^{-St} \tag{5}$$

If experimental centerline moisture content versus time data are available, ln (Φ) vs t should yield a straight line for Fo ≥ 0.2 for constant effective diffusivity. The intercept of the resulting straight line will be lnG and the slope will be equal to the drying coefficient S. The lag factor G and the first root of the characteristic equation μ_1 are only a function of mass transfer Bi number (Bi $=k_c y/D_{eff}$), and μ_1 and G are not independent from one another. In other words, when G has been determined experimentally, Bi number and μ_1 can be evaluated from this value by the utilization of the tabulated values [2]. However, [1] have not used the tabulated values for the evaluation of Biot number and μ_1. They have used the following simplified equations to calculate the effective diffusivities and mass transfer coefficients for the three basic shapes;

For an infinite slab

$$A_{1s} = \exp(0.2533 Bi_s / (1.3 + Bi_s)) \quad 0.1 \langle Bi_s \langle 100 \tag{6}$$

$$\mu_{1s} = a\tan(0.64043 Bi + 0.380397) \quad 0 \langle Bi_s \langle 100 \tag{7}$$

$$\mu_{1s} = \frac{\pi}{2} \qquad Bi \rangle 100 \tag{8}$$

For an infinite cylinder

$$A_{1c} = \exp(0.5066Bi/(1.7+Bi)) \quad 0.1\langle Bi\langle 100 \tag{9}$$

$$\mu_{1c} = ((3/4.188)\times\ln(6.796Bi+1))^{\frac{1}{1.4}} \quad 0\langle Bi\langle 10 \tag{10}$$

$$\mu_{1c} = [\ln(1.737792\mathrm{Bi}+147.32)]^{\frac{1}{1.2}} \quad 10\langle \mathrm{Bi}\langle 100 \tag{11}$$

For a sphere

$$A_{1sp} = \exp\left(\frac{0.7599Bi}{2.1+Bi}\right) \quad 0.1\langle Bi\langle 100 \tag{12}$$

$$A_{1sp} = 2 \quad \mathrm{Bi}\rangle 100 \tag{13}$$

$$\mu_{1sp} = (1.1223\times\ln(4.9Bi+1))^{\frac{1}{1.4}} \quad 0\langle Bi\langle 10 \tag{14}$$

$$\mu_{1sp} = \left[\frac{5}{3}\ln(2.199501\mathrm{Bi}+152.4386)\right]^{\frac{1}{1.2}} \quad 10\langle \mathrm{Bi}\langle 100 \tag{15}$$

In the implementation of the [1] model, for example for an infinite slab, A_{1s} (G) will be determined from experimental centerline moisture content data. Then the Biot number may be determined from Eqn. (6) and μ_{1s} may be determined from Eqn. (7) or (8). Once μ_{1s} has been estimated, the effective diffusivity Deff may be determined from Eqn. (4) using the experimental drying coefficient S. [1] presented additional equations to calculate the mass transfer coefficients from the experimental lag factors. [3] have shown that these additional equations used in the calculation of mass transfer coefficients were erroneous. [3] have corrected these equations and called this corrected method "Modified Dincer and Dost method". The mass transfer coefficient may also be calculated from the definition of the Biot number after the estimation of the diffusivity.

Although [1] model in the modified form can be used to calculate the mass transfer parameters, it has been verified with limited experimental data. [4] have applied the same procedure to the evaluation of effective diffusivities and convective mass transfer coefficients in drying woods with infinite slab and infinite cylinder shape. [5] modelled mass transfer during convective, microwave and combined microwave- convective drying of solid slabs and cylinders by [1] method. They concluded that [1] method is an effective means by which moisture transfer parameters may be calculated for convective, microwave and combined convective microwave drying of slabs and cylindrical potato samples. However, a systematic assessment of [1] method for the entire Biot number range for the three basic simple shapes has not been done.

[6] developed a new model which they called Biot number (Bi)-lag factor (G) correlation to estimate the moisture transfer parameters and hence moisture content variations. [6] claimed that the proposed correlation was valid for infinite slabs, infinite cylinders, spheres, cubes, etc.

[6] have presented new regression equations for the first root of the characteristic equation. For the three basic shapes, these equations were

For an infinite slab

$$\mu_{1s} = -419.24G^4 + 2013.8G^3 - 3615.8G^2 + 2880.3G - 858.94 \tag{16}$$

For an infinite cylinder

$$\mu_{1c} = -3.477G^4 + 25.285G^3 - 68.43G^2 + 82.468G - 35.638 \tag{17}$$

For a sphere

$$\mu_{1sp} = -8.3256G^4 + 54.842G^3 - 134.01G^2 + 145.83G - 58.124 \quad (18)$$

[6] have proposed the following equation based on literature data for different geometries; infinite slab, cylinder sphere, cubic, etc. for the calculation of Biot number from the experimental G values. The proposed equation was

$$Bi = 0.0576(G)^{26.7} \quad (19)$$

The so called Bi- G correlation has been proposed in drying calculations for the three basic shapes; infinite slab, infinite cylinder and sphere. However, the verification of the correlation has been carried out with limited literature data: one experimental data for one shape.

[6] method has been used by various researchers for different geometries at different Biot number ranges [7; 8]. [7] concluded that the Biot number- lag factor (Bi- G) correlation was capable of determining the moisture diffusivity and mass transfer coefficient values for selected lactose powder drying systems in a simple and accurate manner. [8] stated that Bi- G correlation can be used to estimate the mass transfer coefficients in tunnel drying of baby food. However, [9] evaluated the moisture transfer parameters by Bi-G correlation; then, the obtained parameters were substituted to Fick's second law of diffusion model, and the model was numerically calculated with convective boundary condition. They have concluded that the Bi-G correlation should be further improved to obtain more accurate moisture transfer parameters. [10] based on experimental data on convective drying of carrot slices and numerical solution of the Fick’s second law concluded that Bi-G correlation can’t be used to accurately estimate the convective mass transfer coefficient and the moisture diffusion coefficient.

[1] method and Bi- G method proposed by [6] are based on the experimental determination of the lag factor G from centerline moisture history data. After the determination of G, the Biot number Bi and the first root of the characteristic equation μ_1 are calculated from simplified equations given above. A thorough comparison of the predictions of these simplified equations with the actual tabulated values for G, Bi and μ_1 have not been performed. Therefore, the assessment of the simplified equations proposed by [1] and [6] was the objective of this paper. The percent errors resulting from the use of the simplified equations for an almost complete range of G (1.001 to 1.2731 for infinite slab; 1.001 to 1.6015 for infinite cylinder and 1.01 to 1.999 for sphere) will be evaluated and the validity intervals of the simplified equations will be determined.

2. MATERIALS AND METHODS

Tabulated values given in [2] were used as a basis to assess the simplified equations. Therefore, a simple FORTRAN program was prepared which accepted the tabulated G, μ_1 and Bi values [2] as input data for infinite slabs, infinite cylinders and spheres. G which can be experimentally obtained from drying data was taken as the independent variable. μ_1 and Bi were the dependent variables. An interpolation subroutine FUN1 [11] was used. G value was increased starting from 1.0 by very small increments, ie. 0.001 until the A_1 value corresponding to a Biot number of 100 was reached (1.2731 for infinite slab, 1.6015 for infinite cylinder and 1.9990 for spheres). The interpolated μ_1 and Bi values were computed and printed at definite intervals. A total of 29 tabulated values were used for each variable. The interpolated values for , μ_1 and Bi were taken as the basis for comparison and the following % error definitions were used to quantify the agreement between the predictions of the simplified equations with the tabulated values.

$$\%E\mu_{1Din} = \frac{\mu_{1Din} - \mu_{1\text{int}}}{\mu_{1\text{int}}} \times 100 \text{ and } \%EBi_{Din} = \frac{Bi_{Din} - Bi_{\text{int}}}{Bi_{\text{int}}} \times 100 \quad (20)$$

where $\mu_{1\text{int}}$ and Bi_{int} are the interpolated values obtained from the experimental lag factor values, μ_{1Din} are the values of the first root of the characteristic equations calculated from the simplified equations (7), (8), (10), (11), (14) and (15) depending on the geometry and Biot number range. Bi_{Din} is the Biot number calculated from the simplified equations (6), (9) and (12) depending on the geometry

Similarly for the Bi- G method, the following percent errors were defined

$$\% E\mu_{1G} = \frac{\mu_{1G} - \mu_{1\text{int}}}{\mu_{1\text{int}}} \times 100 \quad \text{and} \quad \% EBi_G = \frac{Bi_G - Bi_{\text{int}}}{Bi_{\text{int}}} \times 100 \qquad (21)$$

where $\mu_{1\text{int}}$ and Bi_{int} are the interpolated values obtained from the experimental G values, μ_{1G} are the values of the first root of the characteristic equations calculated from the simplified equations (16), (17) and (18) depending on the geometry. Bi_G is the Biot number calculated from the simplified equation (19) claimed to be valid for the three basic shapes.

3. RESULTS AND DISCUSSION

Table 1 shows the level of agreement between the interpolated Bi_s and μ_{1s} values and the corresponding values calculated from the corresponding equations given in [1] and [6] for infinite slabs.

If we assume that the acceptable error range is ± 10 %, then the following comments can be made:

The simplified equations given by [6] for μ_{1s} can be used safely at all G values. The simplified equations for μ1s given in [1] may only be used if G is greater than 1.03. The performances of the Biot number correlations are much less satisfactory: Biot number calculated by [1] method, Eqn. (6), is only accurate in a very narrow G range; 1.096 < G < 1.115. Similarly, the Biot number vs G correlation given in Eqn. (19) is valid for 1.115 < G < 1.163

Table 1. The level of agreement between the interpolated Biot numbers and μ_{1s} values and the corresponding values calculated from the simplified equations for infinite slabs.

A1 (G)	Bi_{int}	$\% EBi_{Din}$	$\% E\mu_{1Din}$	$\% EBi_G$	$\% E\mu_{1G}$
1.01	0.061	-13.2	60.5	22.7	-0.7
1.05	0.338	-8.4	-4.4	37.4	7.8
1.10	0.784	0.1	-7.8	-6.4	5.9
1.15	1.520	5.3	-2.1	58.2	2.2
1.20	2.679	24.7	3.3	a	2.0
1.25	6.398	50.5	4.3	a	4.1
1.26	9.096	49.0	3.2	a	3.7
1.27	20.626	5.7	0.3	65.1	1.6
1.2731	100.0	-71.7	-2.5	-63.0	-0.9

a % error is greater than 100 %.

The performances of the simplified equations given in [1] and [6] are given in Table 2 for infinite cylinders. Again, the Bi- G correlation proposed by [6] was only accurate in a very narrow range: 1.024 <G < 1.062. The accuracy of the simplified Biot expression proposed by [1] was accurate in a wider range, namely 1.09 < G < 1.32. The performance of the simplified equations used in estimating μ_{1c} were much better compared to the Biot – lag factor expressions: the ranges in which the predictions by the simplified equations were ± 10 % of the tabulated values were calculated to be 1.01 < G < 1.54 for [1] method and 1.06 < G < 1.32 for [6] method.

The performances of the simplified equations given in [1] and [6] are given in Table 3 for spheres. The Bi- G correlation proposed by [6] was not accurate at any G value. The accuracy of the simplified Biot expression proposed by [1] was accurate in a wider range, namely 1.09 < G < 1.32. The performance of the simplified equations used in estimating μ_{1s} values were much better compared to the Biot number expressions: The calculated μ_{1s} from the simplified equations given in [1] were accurate for 1.02 < G < 1.87. The simplified equation proposed by [6] for the first root of the characteristic equation was accurate at all G values.

Table 2. The level of agreement between the interpolated Biot numbers and μ_{1c} values and the corresponding values calculated from the simplified equations for infinite cylinders

A_{1c} (G)	Bi_{int}	% EBi_{Din}	% $E\mu_{1Din}$	% EBi_G	% $E\mu_{1G}$
1.01	0.04	-15.7	-9.1	85.9	-0.3
1.05	0.207	-12.7	7.5	2.2	-11.7
1.10	0.433	- 8.9	8.1	69.7	-4.7
1.15	0.680	-4.7	6.6	a	0.1
1.20	0.958	-0.2	5.3	a	2.6
1.25	1.327	0.9	4.8	a	3.8
1.30	1.708	7.0	3.9	a	2.9
1.40	2.764	21.7	3.1	a	-1.5
1.35	2.144	15.3	3.1	a	0.8
1.45	3.610	29.6	3.4	a	-4.5
1.50	4.913	38.8	4.2	a	-7.7
1.55	7.776	40.3	83.7	a	-11.8
1.60	48.09	-54.6	68.4	a	-19.0
1.6015	100.0	-77.3	66.7	a	-19.9

a % error is greater than 100 %.

Table 3. The level of agreement between the interpolated Biot numbers and μ_{1sp} values and the corresponding values calculated from the simplified equations for spheres

A_{1c} (G)	Bi_{int}	% EBi_{Din}	% $E\mu_{1Din}$	% EBi_G	% $E\mu_{1G}$
1.01	0.033	-16.4	-19.7	a	-3.4
1.05	0.169	-14.6	0.4	25.6	-10.6
1.10	0.342	-12.0	3.7	a	-3.5
1.15	0.522	-9.3	4.2	a	1.0
1.20	0.709	-6.4	4.0	a	3.0
1.25	0.905	-3.5	3.6	a	3.5
1.30	1.130	-2.0	3.8	a	3.5
1.35	1.373	-0.1	3.9	a	2.9
1.40	1.664	3.3	3.5	a	1.5
1.45	1.858	8.2	2.8	a	-0.1
1.50	2.145	12.0	2.5	a	-1.2
1.60	2.842	19.8	2.7	a	-1.7
1.70	3.793	28.2	3.2	a	-0.8
1.80	5.279	35.9	4.3	a	0.9
1.90	8.430	35.5	a	a	2.0
1.95	14.718	3.5	a	a	1.1
1.99	30.439	-34.1	a	a	-1.0
1.999	100.	-78.4	97.5	a	-2.9

a % error is greater than 100 %.

Illustrative example given in [6]

[6] have used the following literature data given in Table 4 to illustrate the implementation of their model

Table 4 Experimental Data Used by Dincer and Hussain (2004) in the implementation of their model

Shape	Infinite slab	Infinite cylinder	Sphere
Air temperature, K	323.15	332	378.15
Air relative humidity, %	-	-	11
Air velocity, m/s	0.5	2	-
Characteristic dimension y, m	0.0025 (half thickness)	0.005 (radius)	0.03 (radius)
Drying coefficient S, 1/s	0.0002	0.0006	0.0046
G	1.1503	1.0181	1.2864
Reference	[12]	[13]	[14]

Implementation of the present model

Infinite slab

Table 1 may be consulted to see whether the simplified equations may be used to calculate the Biot number and μ1s: The experimental G value is 1.1503. Table 1 shows that the μ1s and Bis values calculated by the simplified equations given in [1] (Eqns. (6) and (7)) are close to the interpolated values. Therefore these equations may be used to calculate μ1s and Bis. Table 1 also shows that the simplified equation given in [6] for estimating μ_{1s} will yield an accurate value which in turn will result in an accurate diffusivity value. However the Biot value expression given in [6] will yield an inaccurate Biot value resulting in an inaccurate mass transfer coefficient value.

Infinite cylinder

Table 2 may be consulted to see whether the simplified equations may be used to calculate the Biot number and μ_{1s}: The experimental G value is 1.0181. Table 2 shows that the μ_{1c} and Bi_c values calculated by the simplified equations given in [1] (Eqns. (9) and (10)) are close to the interpolated values. Therefore these equations may be used to calculate μ1s and Bis. The diffusivity values and the mass transfer coefficients calculated by the [1] method will be accurate values. Table 2 also shows that the simplified equation given in [6] for estimating μ1c (Eqn. (17) will yield an accurate value which in turn will result in an accurate diffusivity value. However the Biot value expression given in [6] will yield an inaccurate Biot value resulting in an inaccurate mass transfer coefficient value.

Sphere

Table 3 may be to see whether the simplified equations may be used to calculate the Bit number and μ_{1sp}: The experimental G value is 1.2864. Table 3 shows that the μ_{1s} and Bi_s values calculated by the simplified equations given in [1] (Eqns. (12) and (14)) are close to the interpolated values. Therefore these equations may be used to calculate μ_{1s} and Bi_s. The diffusivity values and the mass transfer coefficients calculated by the [1] method will be accurate values. Table 3 also shows that the simplified equation given in [6] for estimating μ1s (Eqn. (17) will yield an accurate value which in turn will result in an accurate diffusivity value. However the Biot value expression given in [6] will yield an inaccurate Biot value resulting in an inaccurate mass transfer coefficient value.

Table 5 shows the comparison of the μ_1 and Biot numbers calculated by [1] and [6] models with the interpolated values of μ1 and Bi number for the experimental data in Table 4.

As may be observed from Table 5 both methods; [1] and [6] yield similar μ_1 values which means similar diffusivity values (Eq. (4)). However, The Biot numbers estimated from the Bi- G correlation (Eq. (19)) were larger than the interpolated and [1] Biot numbers, especially for the sphere data. This means that the mass transfer coefficients calculated by the Biot- G correlation will be much larger compared to the values calculated by interpolation and by [1] method.

The diffusivities and the mass transfer coefficients calculated from Table 5 are given in Table 6. As previously discussed, the diffusivity values in Table 6 show that for the given G and S values [1] and [6] methods may be used to calculate the diffusivities. [1] method also yielded mass transfer coefficients in agreement with the ones obtained from tabulated values when they were calculated from the definition of the mass transfer Biot number. The same mass transfer coefficient values can also be calculated from the modified Dincer and Dost method [3]. However, Bi-G correlation given in Eqn.(19) yielded erroneous mass transfer coefficients.

Table 5. Comparison of the μ1 and Biot numbers calculated by Dincer and Dost (1996) and Dincer and Hussain (2004) models with the interpolated values of μ_1 and Bi number

Shape	G	S,1/s	μ_{1int}	μ_{1Din}	μ_{1G}	Bi_{int}	Bi_{Din}	Bi_G
Infinite slab	1.1503	0.0002	0.9741	0.9538	0.9952	1.525	1.607	2.421
Infinite cylinder	1. 0181	0.0006	0.3790	0.3750	0.3399	0.073	0.062	0.093
Sphere	1.2864	0.0046	1.6001	1.6580	1.6552	1.064	1.041	47.9

Table 6. Comparison of the diffusivities and the mass transfer coefficients calculated by Dincer and Dost (1996) and Dincer and Hussain (2004) models with the values calculated from the interpolated values of μ_1 and Bi number

Shape	G	S, 1/s	D_{int}, m^2/s	D_{Din}, m^2/s	D_{BiG}, m^2/s	k_{cint}, m/s	k_{cDin}, m/s	k_{cBiG}, m/s
Infinite slab	1.1503	0.0002	$1.32 x 10^{-9}$	$1.37 x 10^{-9}$	$1.26 x 10^{-9}$	$8.04 x 10^{-7}$	$8.83 x 10^{-7}$	$1.22 x 10^{-6}$
Infinite cylinder	1.0181	0.0006	$1.04 x 10^{-7}$	$1.07 x 10^{-7}$	$1.30 x 10^{-7}$	$1.53 x 10^{-6}$	$1.33 x 10^{-6}$	$2.41 x 10^{-6}$
Sphere	1.2864	0.0046	$1.62 x 10^{-6}$	$1.51 x 10^{-6}$	$1.51 x 10^{-6}$	$5.73 x 10^{-5}$	$5.23 x 10^{-5}$	$2.42 x 10^{-3}$

[7] reported experimental data for thin layers of lactose powders dried under convective, microwave, combined convective- microwave and combined vacuum- microwave conditions. Table 7 summarizes the experimental data obtained by [7]. The diffusivities and mass transfer coefficients obtained by interpolation from the experimental G data, and percent errors in the diffusivities predicted by [1] and [6] methods, and mass transfer coefficients predicted by modified Dincer and Dost method [3] and [6] methods are also shown in Table 7.

Percent mean errors, standard deviations, minimum and maximum percent errors between the diffusivities and the mass transfer coefficients calculated from the interpolated μ1 and Biot numbers and the corresponding values calculated by [1] and [6] methods are shown in Table 8. As may be observed from Table 8 [1], and [6] methods yield more accurate diffusivity values compared to the mass transfer coefficients. However, [6] has no superiority over the [1] method.

[15] presented experimental data on convective drying of broccoli infinite slabs. They have reported experimental G and S values and calculated the diffusion coefficients from Eqn. (16) and Eqn.(4). Biot numbers were calculated from a correlation proposed by Dincer and Hussain (2002) [16] shown below:

$$Bi = 24.888 Di^{-3/8} \qquad (22)$$

where Di is Dincer number defined in Eqn.(23) .

$$Di = \frac{v}{Sy} \qquad (23)$$

Table 7. The experimental data of McMinn(2004) and comparison of the diffusivities and mass transfer coefficients calculated by interpolation, Modified Dincer and Dost (2015) and Dincer and Hussain (2004) methods.

Exp. #	r ,m	G	S, 1/s	$D_{int,}\times10^9$ m^2/s	$k_{cint}\times10^4$ m/s	$\%ED_{Din}$	$\%ED_{Bi-G}$	$\%Ekc_{Din}$*	$\%Ekc_{Bi-G}$
1	0.0030	1.286	0.0001	0.37	0.12	-1.9	-6.1	-1.9	-55.3
2	0.0030	1.268	0.0003	1.23	0.07	-1.8	-3.9	8.8	78.2
3	0.0030	1.279	0.0004	1.49	0.50	-1.9	-1.6	-1.9	-59.6
4	0.0015	1.116	0.0002	0.63	0.004	14.2	-8.2	17.8	2.8
5	0.0030	1.045	0.0003	9.92	0.0099	5.9	-12.7	-3.5	-45.7
6	0.0045	1.242	0.0002	2.32	2.70	-8.9	-7.5	34.5	232.4
7	0.0150	1.341	0.0001	9.30	0.62	-1.9	-28.7	-1.9	3.7
8	0.0060	1.370	0.0001	1.49	0.25	-1.9	-32.1	-1.9	74.8
9	0.0015	1.336	0.0002	0.19	0.12	-1.9	-27.5	-1.9	-4.6
10	0.0015	1.061	0.0002	1.20	0.0034	15.7	-14.5	8.0	-43.7
11	0.0030	1.398	0.0002	0.74	0.25	-1.9	-28.2	-1.9	217.3
12	0.0030	1.343	0.0001	0.37	0.12	-1.9	-29.1	-1.9	7.3
13	0.0030	1.131	0.0003	3.31	0.013	9.8	-6.2	12.4	20.4
14	0.0030	1.166	0.0004	0.034	0.020	0.4	-3.2	12.3	88.2
15	0.0030	1.166	0.0005	4.26	0.025	0.4	-3.2	12.3	88.2
16	0.0030	1.100	0.0005	7.31	0.019	17.7	-10.8	17.8	-16.5
17	0.0015	1.140	0.0006	1.54	0.014	7.1	-5.2	10.4	33.5
18	0.0030	1.146	0.0006	5.88	0.028	5.5	-4.6	9.9	43.9
19	0.0015	1.144	0.0008	1.99	0.019	6.0	-4.9	10.0	40.3
20	0.0030	1.250	0.0005	2.43	0.052	-8.1	-7.7	38.3	221.4
21	0.0015	1.151	0.0005	1.18	0.017	4.1	-4.2	9.9	53.5
22	0.0030	1.249	0.0002	0.98	0.020	-8.3	-7.7	38.1	224.4
23	0.0150	1.166	0.0005	105.8	0.13	0.4	-3.2	12.3	88.1
24	0.0015	1.270	0.0004	0.40	0.055	-0.5	-3.0	5.4	60.6
25	0.0030	1.108	0.0005	6.75	0.020	16.0	-9.6	17.9	-7.4
26	0.0030	1.086	0.0005	8.60	0.018	19.3	-12.9	16.3	29.5
27	0.0030	1.199	0.0005	3.39[7]	0.030	-6.1	-3.8	16.6	166.3

* Calculated by the Modified Dincer and Dost Method (Ilıcalı and Icier, 2015)

where v is the drying air velocity. The mass transfer coefficients were calculated from the definition of the Biot numbers. However, the experimental G values reported in [15] were between 1.000 and 1.006.

Table 8. Percent mean errors, standard deviations, minimum and maximum percent errors between the diffusivities and the mass transfer coefficients calculated from the interpolated μ1 and Biot numbers for McMinn (2004) data and the corresponding values calculated by Dincer and Dost (1996) and Dincer and Hussaiın (2004) methods

	$\%ED_{Din}$	$\%ED_{Bi-G}$	$\%Ekc_{Din}$*	$\%Ekc_{Bi-G}$
Mean error, %	2.8	-8.6	10.6	59.9
Standard deviation, %	8.1	11.9	11.8	88.0
Minimum error, %	-8.9	-32.1	-3.5	-59.6
Maximum error, %	19.3	-1.6	38.3	221.7

* Calculated by the Modified Dincer and Dost Method (Ilıcalı and Icier, 2015)

According to the tabulated Bi, G and μ1 values given in [2], these G values (A1 values) correspond to Biot numbers less than 0.04 indicating negligible internal resistance. The Biot number range predicted by Eqn. (22) was 0.206 and 0.3228. Erroneous drying parameters will be obtained from erroneous predictions.

4. CONCLUSIONS

Two simplified analytical models, [1] and [6], developed for the calculation of mass transfer parameters in solids undergoing unidirectional drying has been assessed. Assessment has been carried out by comparing the first roots of the characteristic equations and the Biot numbers predicted by [1] and [6] methods with the actual tabulated values given in [2]. It was observed that one of these methods can be used in the full Biot number range. The performance of Bi- G correlation, Eqn. (16) has been found to be poor for the three geometries considered, infinite slab, infinite cylinder and sphere. The use of the tabulated values of the first root of the characteristic equation and Biot numbers for the evaluation of the mass transfer parameters is recommended.

5. NOMENCLATURE

A lag factor, dimensionless
Bi mass transfer Biot number, $k_c y/D$, dimensionless
D diffusivity, m^2/s
Di Dincer number, v/(Sy), dimensionless
Fo mass transfer Fourier number, Dt/y^2, dimensionless
k_c mass transfer coefficient, m/s
S drying coefficient, 1/s
v drying air velocity, m/s
t time, s
X moisture content, kg moisture//kg dry solid
y characteristic dimension, half thickness for slab, radius for cylinder and sphere
$\% EBi_{Din}$ % error in the predicted Biot numbers by Dincer and Dost (1996) method
$\% EBi_{G}$ % error in the predicted Biot numbers by the Bi - G correlation
$\% E\mu_{1Din}$ % error in the predicted characteristic roots by Dincer and Dost (1996) method
$\% E\mu_{1G}$ % error in the predicted characteristic roots by the Bi - G correlation.
$\%ED_{Din}$ % error in the predicted diffusivities by Dincer and Dost (1996) method
$\%ED_{Bi-G}$ % error in the predicted diffusivities by the Bi - G correlation

$\%Ekc_{Din}$ % error in the predicted mass transfer coefficients by Dincer and Dost (1996) method
$\%Ekc_{Bi\text{-}G}$ % error in the predicted mass transfer coefficients by the Bi - G correlation

Greek Letters
Φ dimensionless moisture content
μ root of the characteristic equation

Subscripts
1 first
c cylinder
CL centerline
Din Dincer and Dost (1996) method
Eff effective
Eq equilibrium
ini initial
int interpolated
G lag factor
s slab
sp sphere

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