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Development of a new *Bi–Di* correlation for solids drying

I. Dincer *, M.M. Hussain

Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals (KFUPM), Box 127, Dhahran 31261, Saudi Arabia

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Abstract

In this article, a recently developed Biot number–Dincer number (*Bi–Di*) correlation for drying applications is presented. The developed correlation is used to determine the moisture diffusivities and moisture transfer coefficients for products subjected to drying. A large number of experimental data taken from various sources in the literature has been utilized for the development of this correlation. Dimensionless moisture distributions were obtained for three regular shaped objects such as slab, cylinder and sphere to verify them with the available experimental measurements. The results show a considerably high agreement between the predicted values from the correlation and measured experimental observations. Thus, the present correlation is considered to be of great importance to design engineers and operators in estimating the moisture transfer parameters in a reasonably simple manner.

1. Introduction

The dehydration of fruits and vegetables is very important in the production of convenience foods, which have become a major part of the western world. The removal of moisture prevents the growth and reproduction of microorganisms causing decay and health risks and minimizes many of the moisture mediated deteriorative reactions. It brings about substantial reduction in weight and volume minimizing for packing, storage and transportation costs and enables storability of the product under ambient temperature.

One of the major concerns in the drying process is the provision of optimum processing conditions for good quality products, which can be made possible by analyzing the moisture transfer and moisture transfer parameters in terms of moisture diffusivity and moisture transfer coefficient. Accurate determination of moisture transfer parameters is important in order to obtain good quality dried products leading to energy savings. Decreasing energy consumption in the drying process will decrease the environmental impact in terms of pollutants and hence protect the environment [1].

Despite numerous theoretical and experimental studies on the determination of drying profiles for various food products, limited data on moisture transfer parameters are available in the literature [2–4], with a wide variation of reported values, due to the complexity of the foods and methods of estimation [5]. The present study aims to develop a unique correlation between Biot number and Dincer number for determining the moisture transfer parameters for products subjected to drying in a simple and accurate manner.

2. Analysis

The dimensionless moisture content values as a function of time can be expressed in exponential form as:

$$\Phi = G\exp(-St), \tag{1}$$

where G is the lag factor, which gives an indication of internal resistance in the solid to moisture transfer during drying and S is the drying coefficient representing the drying capability of the solid object.

* Corresponding author. Tel.: +966-3-860-4497; fax: +966-3-860-2949.

E-mail address: idincer@kfupm.edu.sa (I. Dincer).

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Nomenclature

a, b	constants in Eq. (7)
A, B	constants in Eq. (12)
Bi	Biot number for moisture transfer (dimensionless)
D	moisture diffusivity ($m^2\ s^{-1}$)
Di	Dincer number (dimensionless)
Fo	Fourier number for moisture transfer (dimensionless)
G	lag factor (dimensionless)
k	mass transfer coefficient ($m\ s^{-1}$)
M	moisture content (kg per kg)
S	drying coefficient (s^{-1})
t	time (t)
U	flow velocity of drying air ($m\ s^{-1}$)
Y	characteristic dimension (m)
Greek symbols	
Φ	dimensionless moisture content
μ	root of the transcendental characteristic equation
Subscripts	
e	equilibrium
i	initial
1	refers to the first characteristic value

The dimensionless moisture content can be represented in terms of moisture content at any point of the solid object as:

$$\Phi = (M - M_e)/(M_i - M_e). \quad (2)$$

The Biot number for moisture transfer can be defined as a function of moisture transfer coefficient, moisture diffusivity and characteristic dimension as

$$Bi = kY/D. \quad (3)$$

The moisture diffusivity (D) relation developed by Dincer and Dost [3] for slab, cylindrical and spherical objects is given as

$$D = (SY^2)/(\mu_1^2). \quad (4)$$

The moisture transfer coefficient for slab, cylindrical and spherical products can be obtained from Biot number definition as

$$k = (DBi)/Y. \quad (5)$$

In the present study, a new Biot number–Dincer number (Bi–Di) correlation was developed, where Dincer number (Di) is a dimensionless number and initially developed for cooling applications, representing the effect of flow velocity of the cooling fluid on the cooling coefficient of the regular and irregular products [6] as $Di = U/CY$. It is already known that both cooling and drying processes have similar nature due to the fact that in cooling the temperature of the product is reduced from a certain level to another; and in drying the moisture content is reduced from a certain point to another. Based on this analogy, the Dincer number can now be applied to a drying process, representing the influence of the flow velocity of the drying fluid on the drying coefficient of the product subjected to drying. It is therefore defined as follows:

$$Di = U/SY. \quad (6)$$

It is known that the Biot number is one of the most significant dimensionless parameters in drying, indicating the resistance to moisture diffusion within the product. Apparently, it is a function of both product and drying medium properties. Based on this landmark, the strong relationship is evident between the Biot and Dincer numbers. In this regard, we aim to develop a new drying correlation in the following form

$$Bi = aDi^{-b}, \quad (7)$$

where a and b are non-dimensional constants of the regression.

3. Results and discussion

This section discusses the methodology for calculating the drying process and moisture transfer parameters and presents the development of Biot number–Dincer number correlation.

The procedure employed in estimating the process parameters is as follows:

- The experimental moisture content values were non-dimensionalized using Eq. (2).
- The dimensionless moisture content values and drying time are regressed in the exponential form of Eq. (1) using the least square curve-fitting method. Hence, lag factor (G) and drying coefficient (S) are found.
- The characteristic roots (μ_1's), which appear in the moisture diffusivity relation, are determined using the newly developed expressions as follows [7]:

For slab:

$$\mu_1 = -419.24G^4 + 2013.8G^3 - 3615.8G^2 + 2880.3G - 858.94. \quad (8)$$

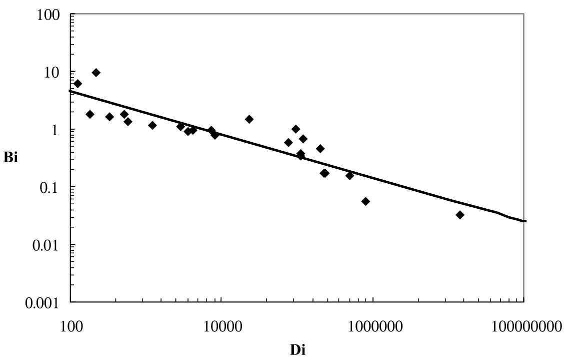

Fig. 1. *Bi–Di* diagram for food products subjected to drying.

For cylinder:

$$\mu_1 = -3.4775G^4 + 25.285G^3 - 68.43G^2 + 82.468G - 35.638. \quad (9)$$

For sphere:

$$\mu_1 = -8.3256G^4 + 54.842G^3 - 134.01G^2 + 145.83G - 58.124. \quad (10)$$

- The moisture diffusivity values are then calculated using Eq. (4).
- Knowing the velocity of the drying fluid, drying coefficient and characteristic dimension of the product, Dincer number (*Di*) is calculated using Eq. (6).
- Using the experimental drying data taken from various literature sources, the Biot number–Dincer number correlation was obtained for several kinds of food products subjected to drying (Fig. 1) with the correlation coefficient over 0.8 as:

$$Bi = 24.848Di^{-3/8}. \quad (11)$$

Finally, the moisture transfer coefficients are calculated using Eq. (5).

4. Illustrative example

The purpose of this example is to show how the present correlation can be utilized in determining the moisture transfer parameters using the existing experimental moisture data of a solid product. In order to explain the application of the correlation, previous experimental moisture measurements of prune, okra and potato as slab, cylinder and sphere, respectively, will be used. The thermophysical properties employed in the experiments are given in Table 1.

The following procedure is employed to determine the moisture transfer parameters and dimensionless moisture distribution:

- The lag factor (G) and drying coefficient (S) are determined by regressing the experimental dimensionless moisture content values against the drying time using the least square curve-fitting method.
- The Dincer number is calculated using Eq. (6)
- Using the present correlation, Biot numbers are estimated for slab, cylinder and sphere.
- The characteristic roots are then evaluated using the relations in Eqs. (8)–(10) for different objects.
- The moisture diffusivities are then calculated using the Eq. (4).
- The moisture transfer coefficients are calculated using Eq. (5).
- Finally the dimensionless moisture distribution is obtained as (see Dincer and Dost [3] for details):

$$\Phi = A_1 B_1, \quad (12)$$

where for slab:

$$A_1 = G = \exp((0.2533Bi)/(1.3 + Bi)) \quad (13)$$

for cylinder:

$$A_1 = G = \exp((0.5066Bi)/(1.7 + Bi)) \quad (14)$$

for sphere:

$$A_1 = G = \exp((0.7599Bi)/(2.1 + Bi)), \quad (15)$$

and for all products,

$$B_1 = \exp(-\mu_1^2 Fo), \quad (16)$$

where

$$Fo = Dt/Y^2. \quad (17)$$

The values of the drying coefficient (S), lag factor (G), Biot number (Bi), root of the characteristic equation (μ), moisture diffusivity (D) and moisture transfer coefficient (k) for the slab, cylindrical and spherical products were obtained using the above listed methodology and these are tabulated in Table 2. It is important to emphasize

Table 1
Thermophysical properties of experimental data

Shape	Temperature (°C)	Velocity (m s^{-1})	Characteristic dimension (Y) (m)	References
Slab	60	3	0.0075	Tsami and Katsioti [8]
Cylinder	80	1.2	0.003	Gogus and Maskan [9]
Sphere	40	1	0.009	Mclaughlin and Magee [10]

Table 2
Obtained drying process and moisture transfer parameters for the samples

Process parameters	Product		
	Slab	Cylinder	Sphere
S (1/s)	7×10^{-5}	0.0001	0.0009
G (dimensionless)	1.0016	1.1981	1.0074
Di (dimensionless)	5714285.714	4000000	123456.79
Bi (dimensionless)	0.0745	0. 0851	0.3119
μ_1 (dimensionless)	0.1407	1.2593	0.2781
D ($m^2\ s^{-1}$)	1.9889×10^{-7}	5.6752×10^{-10}	9.4259×10^{-7}
k ($m\ s^{-1}$)	1.9756×10^{-6}	1.6098×10^{-8}	3.2665×10^{-5}

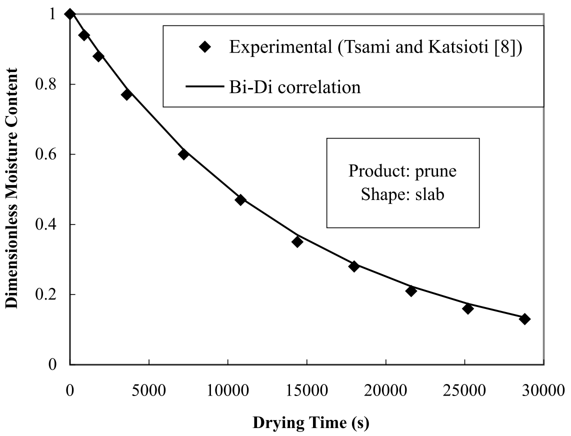

Fig. 2. Measured and calculated dimensionless center moisture distribution of slab.

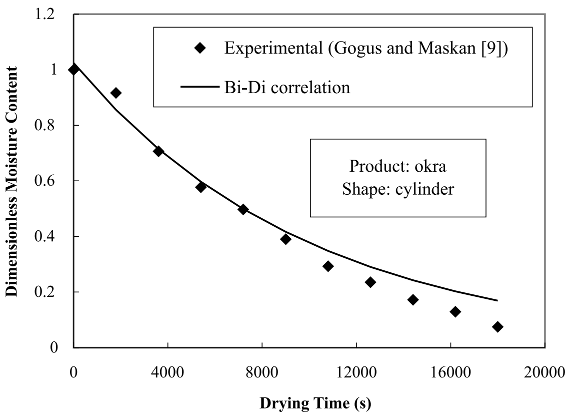

Fig. 3. Measured and calculated dimensionless center moisture distribution of cylinder.

that the moisture content data of these three products were not employed in the development of the present correlation. Thus, these can help determine the applicability and accuracy of the present correlation.

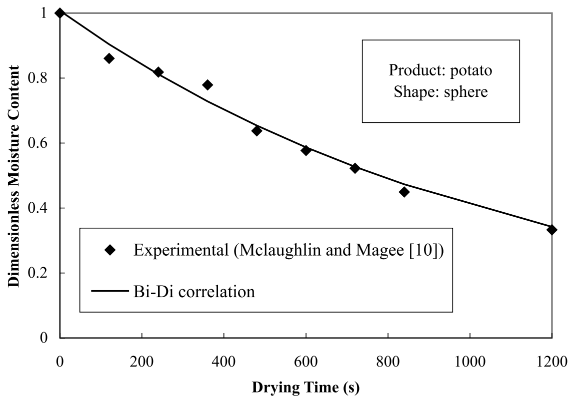

Fig. 4. Measured and calculated dimensionless center moisture distribution of sphere.

Here, applicability of the *Bi–Di* correlation has been verified. In this regard, using the obtained data in Table 2 we calculate the dimensionless average moisture content profiles for these slab, cylindrical and spherical products subject to drying at different conditions and compare these calculated dimensionless moisture content profiles with the experimental dimensionless moisture content values. Both calculated and experimental profiles are shown in Figs. 2–4. The average error between predicted and measured moisture content values for slab, cylinder and sphere were found to be ±3.38%, ±14.84% and ±1.31% with respect to measured values, respectively. While the agreement between the calculated values and experimental data for cylindrical product is very good, an excellent agreement appears for slab and spherical products.

5. Conclusions

In this paper development of new drying correlation has been discussed. The application of the developed correlation is presented by means of illustrative examples, to determine the moisture transfer parameters i.e., moisture diffusivity and moisture transfer coefficients.

Moreover, dimensionless center moisture distribution was obtained for slab, cylinder and sphere. The obtained moisture distribution profiles were compared with the experimental data and found out to be in good agreement with it. Thus the present correlation can be used with reasonable accuracy and confidence for such drying applications.

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