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Full Length Research Paper

Biot number - lag factor (Bi-G) correlation for tunnel drying of baby food

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To obtain mass transfer coefficients of three baby food mixtures on cereal basis in a tunnel dryer, Bi-G drying correlation can be used. Experimental moisture content values for three mixtures at three different air temperatures (60, 80 and 100°C) and air velocities (0.5, 1.0 and 1.5 m/s) during tunnel drying were collected. Effective moisture diffusivities coefficients were calculated in two ways and for mixtures 1, 2 and 3 and ranged between 1.51 × 10^{-8} to 52.7 × 10^{-8} m^2/s, 1.05 × 10^{-8} to 64.9 × 10^{-8} m^2/s and 0.107 × 10^{-8} to 53.1 × 10^{-8} m^2/s, respectively. At lower drying temperature, moisture diffusivities values calculated in two ways agreed better than at higher temperature. The influence of baby food composition on mass transfer parameters was observed.

Key words: Baby food, exponential drying model, mass transfer coefficients, tunnel drying.

INTRODUCTION

Drying represent one of the oldest and still important way of food preservation (Ježek et al., 2008). Besides drying as a technology, there is growth of various innovative technologies like ultrasound, high hydrostatic pressure, extrusion, pulsed electric fields and tribomechanical activation for food preservation which could be used for various purposes mostly in a way of pretreatment or enhanced processing (Herceg et al., 2004; Brnčić et al., 2006; Bosiljkov et al., 2011). Dehydrated baby food is one of the most important daily baby meals. Dehydrated baby food can be produced using various techniques like spray drying and drum drying. Products produced in these ways have very low moisture content (2 to 5%, wet basis). It is known that the main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput by optimizing the design and operating conditions (Brnčić et al., 2004; Sun et al., 2005). Both aforementioned drying methods, spray drying and drum drying consume high quantity of energy. During the last three decades, the rise of energy prices was accompanied by increasingly stringent legislation on pollution, working conditions and safety. To optimize energy consumption, new drying methods and dryer design are required (Strumillo et al., 1995; Brnčić et al., 2010) as much as new methods for pre-treatment of foodstuffs before drying. Extrusion cooking could be taken into consideration for producing of directly expanded food that is acceptable as enriched snack (Brnčić et al., 2009, 2009b). Quantitative understanding of the fundamental mechanism of the moisture distributions and heat transport within the product is crucial for process design, quality control and energy savings (McMinn, 2004). Developing drying models and determining moisture transport parameters are of particular interest for efficient mass transfer analysis (Mrkić et al., 2002, 2007; Ježek et al., 2006). Several heat and mass transfer models were reviewed together with obtained drying parameters (Saravacos and Maroulis, 2001).

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Nomenclature: **A,** Constant; **B,** constant; **Bi,** Biot number (dimensionless); **c,** parameter in linear function; **D,** moisture diffusivity (m^2/s); **Fo,** Fourier number (dimensionless); **G,** lag factor (dimensionless); **K,** drying constant (1/s); **k,** moisture transfer coefficient (m/s); **L,** characteristic dimension, slab half thickness (m); **μ,** root of the transcendental characteristic equation; **R^2,** correlation coefficient; **RH,** relative humidity; **RMSE,** root mean square error; **S,** drying coefficient (1/s); **t,** drying time (s); **T,** air temperature (°C); **Y,** dimensionless moisture content; **X,** moisture content (kg/kg, dry basis); **Exp,** experimental; **I,** initial; **1,** first characteristic value.

To characterize the mass transfer during the drying regular geometry solid objects (infinite slab, infinite cylinder and sphere) Dincer and Dost (1995, 1996) developed and verified analytical model. Based on analogy between cooling and drying profiles drying process parameters (drying coefficient S and lag factor G) were introduced. Dincer and Hussain (2004) developed new Biot number Bi and lag factor G (Bi-G) correlation to determine the mass transfer parameters for solids drying processes using a large number of experimental data. The new correlation was found to be suitable for use in practical drying application. McMinn (2004) used new correlation in the drying of lactose powder.

The published data of moisture diffusivity values in food products show a huge variability from 10^{-12} to 10^{-8} m^2/s (Zogzas et al., 1996). In literature, no detailed studies were found to predict mass process parameters of dehydrated cereal-based baby food during tunnel drying.

The aim of this work was to determine the mass transfer parameters using Bi-G correlation at different drying temperatures and air velocities during tunnel drying. New correlation will enable designers and operators an accurate and simple analytical tool to conduct design analysis and relevant calculations. Designers and engineers will be able to provide the optimum solution to various aspects of drying operations (process control, operating conditions and energy use) without undertaking actual experimental trials (Dincer, 1998). The reducing of experimental drying trials for mixtures of baby food is very important, because the components which are added, especially vitamins and minerals, are very expensive.

Effective moisture diffusivity was calculated by using drying constant obtained in semi-log plot of experimental data and from model equations.

MATERIALS AND METHODS

Experiment

The drying experiments on baby food were performed in a pilot-plant tunnel dryer designed and manufactured at the Faculty of Food Technology and Biotechnology in Zagreb, Croatia. The dryer consist of a tunnel, electrical heater and fan, and is equipped with controllers for controlling temperature and air velocity.

The components of mixture 1 were water, wheat flour (30%), sugar (8%), corn starch and vitamins, the components of mixture 2 were water, wheat flour (25%), soya flour, milk powder, sugar (4%) and vitamin mixture and the components of mixture 3 were water, corn flour (37%), powdered sugar (3%), vitamins and mineral mixture. The chemical analysis of the three wet mixtures showed that mixture 1 consisted of water (56%), proteins (3.5%), sugars (38.9%), fats (0.53%) and ash (0.15%). Mixture 2 consisted of water (61%), proteins (6.3%), sugars (27%), fats (4.76%) and ash (0.79%) and mixture 3 of water (65%), proteins (2.7%), sugars (30.2%), fats (0.89%) and ash (0.25%). Because of the added soya flour, mixture 2 characterized higher percent of fats and proteins, while mixture 1 had higher sugar content. All percentages are given on wet basis. The initial moisture content was determined by the AOAC method no. 931.15 (AOAC, 1990).

50 g of wet mixtures were prepared 30 min before drying. To conduct the drying experiments at 60, 80 and 100°C (+-1°C) and at air velocity 0.5, 1.0 and 1.5 m/s, wet mixtures were placed into aluminum trays (size: diameter 100 × height 5 mm). Moisture loss was recorded at 1 min interval during 1 h and later at 5 min interval till the end of the drying by digital balance of 0.01 g accuracy (Mettler-Toledo, model PB602-L, Switzerland). The drying was continued until the variation in the moisture content loss was less than 0.01 g during three measurements. Relative humidity RH (%) of the air in the tunnel dryer was measured by Testo 177-H1 (Lenzkirch, Germany). Experiments were conducted in triplicates.

Data analysis

The moisture transfer characteristics of the baby food samples were evaluated using semi-logarithmic plots (lnY-t) and the Bi-G correlation proposed (Dincer and Hussain, 2004).

The experimental data were non-dimensionalised using equation (Doymaz and Pala, 2002; Velić et al., 2004; Mrkić et al., 2007):

$$Y = \frac{M}{M_i} \quad (1)$$

Semi-logarithmic plots lnY-t were constructed and described by linear function (Mrkić et al., 2007):

$$lnY = -Kt + c \quad (2)$$

The value K (s^{-1}) drying constant can be used to determine moisture diffusivity D for a slab of thickness L by the equation (Marinos-Kouris and Maroulis, 1995):

$$D = \frac{KL^2}{\pi^2} \quad (3)$$

Where, L is slab half-thickness (m).

Using least-square method, the dimensionless moisture content Y was expressed in terms of lag factor G and drying coefficient S.

$$Y = G\exp(-St) \quad (4)$$

The moisture diffusivity D was computed using the model developed by Dincer and Dost (1996):

$$D = \frac{SL^2}{\mu_1^2} \quad (5)$$

Where, μ_1 is a simplified expression for the roots of the characteristic equation for a slab geometry:

$$\mu_1 = -419.24G^4 + 2013.8G^3 - 3615.8G^2 + 2880.3G - 858.94 \quad (6)$$

To verify and apply the model, the dimensionless moisture distribution Y was calculated for slab geometry (Dincer and Dost, 1996):

$$Y = A_1B_1 \quad (7)$$

Where,

$$A_1 = G = e^{\frac{0,2533\,Bi}{1,3\,Bi}} \quad (8)$$

Table 1. Drying parameters obtained from linear model of drying curve in semi-logarithmic plot *lnY-t*.

Baby food	Drying condition			Drying parameter	
	T (°C)	v (m/s)	RH (%)	K	D × 10^{-8} (m^2/s)
Mixture 1	60	0.5	32	0.009	2.28
	60	1.0	34	0.0111	2.81
	60	1.5	34	0.0116	2.94
	80	0.5	38	0.0125	3.17
	80	1.0	31	0.0137	3.47
	80	1.5	29	0.0196	4.96
	100	0.5	39	0.0170	4.31
	100	1.0	42	0.0203	5.14
	100	1.5	38	0.0254	6.43
Mixture 2	60	0.5	26	0.0079	2.00
	60	1.0	33	0.0079	2.00
	60	1.5	43	0.0084	2.13
	80	0.5	41	0.0144	3.65
	80	1.0	40	0.0146	3.70
	80	1.5	38	0.0170	4.31
	100	0.5	39	0.0203	5.14
	100	1.0	36	0.0186	4.71
	100	1.5	37	0.0274	6.94
Mixture 3	60	0.5	29	0.0005	0.127
	60	1.0	28	0.0004	0.107
	60	1.5	31	0.0006	0.152
	80	0.5	38	0.0004	0.107
	80	1.0	29	0.0004	0.107
	80	1.5	28	0.0005	0.127
	100	0.5	27	0.0007	0.177
	100	1.0	31	0.0008	0.203
	100	1.5	33	0.0007	0.177

$$B_1 = e^{-\mu_1^2 F_0} \quad (9)$$

$$F_0 = \frac{Dt}{L^2} \quad (10)$$

The moisture transfer coefficient k was calculated from Biot number Bi definition:

$$k = \frac{D\ Bi}{L} \quad (11)$$

The Biot number was calculated from the relation between Biot number Bi and lag factor G (Bi-G) (Dincer and Hussain, 2004):

$$Bi = 0{,}057\ G^{26{,}7} \quad (12)$$

Using root mean square error RMSE the predicted moisture ratio was compared to experimental moisture ratio (McMinn, 2006; Srikiatden and Roberts, 2008):

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(Y_{exp,i} - Y_{predict,i})^2\right]^{\frac{1}{2}} \quad (13)$$

As RMSE approaches zero, the closer the prediction is to the experimental data (Srikiatden and Roberts, 2008).

RESULTS AND DISCUSSION

For all experiments, drying curves were fitted well (R^2>0.94) with straight lines described by Equation 2. In all cases straight lines with constant slope K were obtained, which indicates that drying of mixtures 1, 2 or 3 took place in one falling rate period with constant moisture diffusivity D. Table 1 shows the values of K and D obtained from Equation 3. The values of effective diffusion coefficient D for food materials are in the range

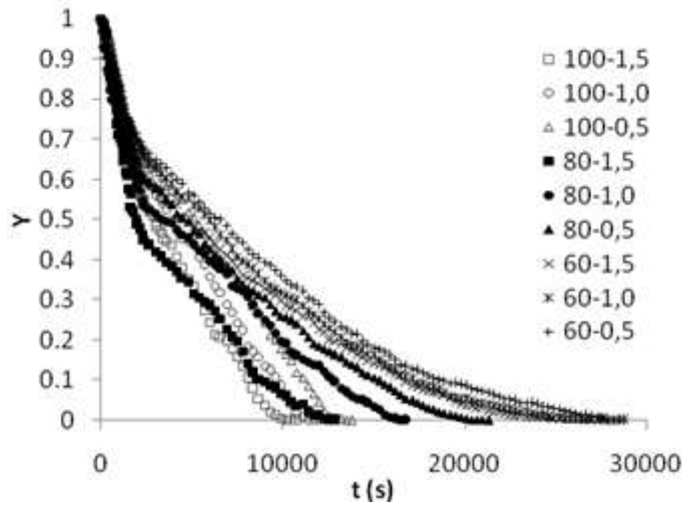

Figure 1. Experimental average dimensionless moisture content of mixture 1 dried under different drying conditions.

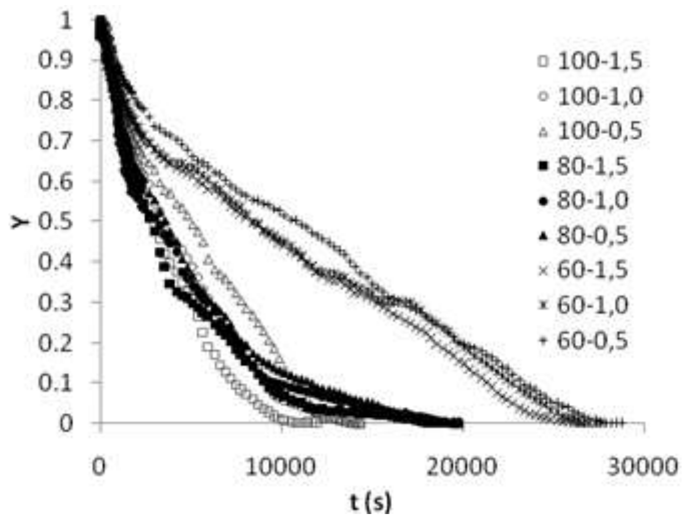

Figure 2. Experimental average dimensionless moisture content of mixture 2 dried under different drying conditions.

of 10^{-13} to 10^{-6} m^2/s, and most of them are accumulated in the region 10^{-11} to 10^{-8} (Marinos-Kouris and Maroulis, 1995). The values D for mixtures 1 and 2 were in this region also, but values for mixture 1 were in the region of 10^{-7}. This indicates that the binding water capacity of mixture 3 is weaker than of the other two mixtures. The reason for that can be different physical structure and composition of mixture 3 that influence the moisture transfer characteristics. From Table 1, it can clearly be seen that the moisture diffusivity is an increasing function of temperature (Marinos-Kouris and Maroulis, 1995) and increasing function of air velocity.

Figure 1 shows the experimental average dimensionless moisture content of mixture 1 under different drying conditions. Drying curves show that the rate of drying increased with increasing drying air temperature and velocity. High effect of air velocity on drying rate was observed in all cases. At the same temperature with increasing the air velocity, the drying rate was increased also. At the beginning of drying, differences in shape of drying curves were smaller while at the end of the processes, the differences were higher. This indicates that the influence of temperature and air velocity on drying kinetics is higher towards the end than at the beginning of the process. For broccoli drying, influence of temperature on drying kinetics was lower towards the end than at the beginning of the process (Mrkić et al., 2007).

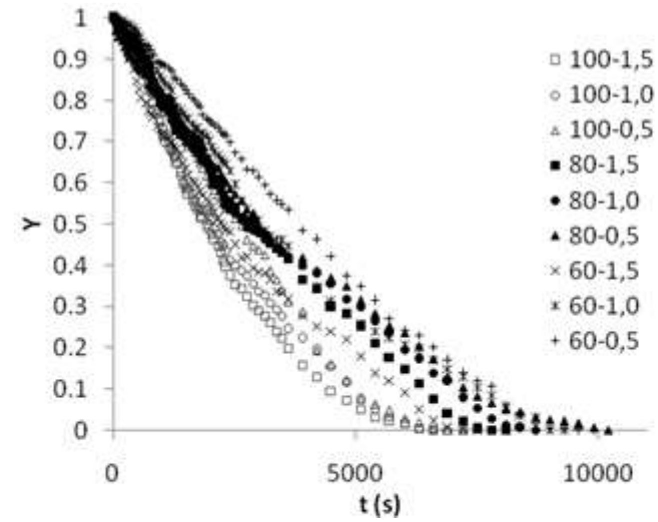

Figure 3. Experimental average dimensionless moisture content of mixture 3 dried under different drying conditions.

Figure 2 shows the experimental average dimensionless moisture content of mixture 2 under different drying conditions. The influence of air temperature on drying kinetics was not pronounced at 100 and 80°C. At 60°C, the influence of the temperature can be seen, because the drying took place longer than at 80 and 100°C, respectively. Figure 3 shows the experimental average dimensionless moisture content of mixture 3 under different drying conditions. From the beginning of drying, the influence of air temperature and velocity can be clearly seen. With increasing air temperature and velocity, the time required to achieve certain moisture content decreased.

Table 2 shows calculated drying parameters of regression model using Equation 4. The experimental moisture content was turned dimensionless. The received data were more than the regressed against time. The drying coefficient S and lag factor G were obtained. The lag factor G is an indicator of the magnitude of both internal and external resistance to moisture transfer from the product and the drying coefficient S indicates the drying capability of the solid object (Dincer and Dost, 1995). An increase of S values is observed with increase in the air velocity and temperature. An increase of S

Table 2. Drying parameters of regression model.

Baby food	Drying condition			Drying parameter			
	T (°C)	v (m/s)	RH (%)	G	S	R^2	RMSE
Mixture 1	60	0.5	32	0.9212	0.0066	0.9950	0.0689
	60	1.0	34	0.9206	0.0072	0.9984	0.0774
	60	1.5	34	0.9211	0.0078	0.9922	0.0601
	80	0.5	38	0.9193	0.0084	0.9935	0.0575
	80	1.0	31	0.9222	0.0097	0.9874	0.0435
	80	1.5	29	0.9500	0.0159	0.9867	0.0522
	100	0.5	39	1.0969	0.0111	0.9827	0.0418
	100	1.0	42	1.0301	0.0119	0.9914	0.0658
	100	1.5	38	1.0284	0.0154	0.9938	0.0579
Mixture 2	60	0.5	26	0.9215	0.0045	0.9861	0.0824
	60	1.0	33	0.9243	0.0048	0.9864	0.0683
	60	1.5	43	0.9483	0.0052	0.9859	0.0699
	80	0.5	41	1.0469	0.0133	0.9148	0.0598
	80	1.0	40	0.9512	0.0133	0.9953	0.0354
	80	1.5	38	0.9659	0.0147	0.9989	0.0351
	100	0.5	39	1.0245	0.0129	0.9958	0.0742
	100	1.0	36	1.0179	0.0103	0.9883	0.0817
	100	1.5	37	1.0253	0.0166	0.9958	0.0788
Mixture 3	60	0.5	29	1.1096	0.0136	0.9822	0.0959
	60	1.0	28	1.0969	0.0156	0.9914	0.0803
	60	1.5	31	1.0625	0.0202	0.9936	0.0692
	80	0.5	38	1.0499	0.0149	0.9918	0.0830
	80	1.0	29	1.0452	0.0159	0.9910	0.0706
	80	1.5	28	1.0424	0.0170	0.9896	0.0755
	100	0.5	27	1.0412	0.0196	0.9799	0.0923
	100	1.0	31	1.0411	0.0237	0.9934	0.0783
	100	1.5	33	1.0439	0.0258	0.9919	0.0809

value with air temperature was observed during the drying of lactose powder using different methods (McMinn, 2004). Values of lag factor G were higher than 1 at higher temperature (100°C) by drying of mixtures 1 and 2 and lower than 1 at lower temperature (60 and 80°C). For mixture 3, all lag factors G values were higher than 1, what verify the presence of internal resistance to mass transfer within the baby food slab. Good agreement between the observed and predicted results can be observed (R^2>0.98). Only a few data; mixture 2 at 80°C and 0.5 m/s and mixture 3 at 100°C and 0.5 m/s had lower degree of correlation (R^2<0,98). The influence of drying temperature, air velocity and relative humidity on coefficients G and S was analyzed by ANOVA test for all mixtures. It was found that in all mixtures, the drying temperature had significant positive effect ($p<0.05$) on the drying coefficients G and S. The influence of air velocity and relative humidity on coefficients G and S was not significant ($p>0.05$), while only for mixture 3, the influence of air velocity was significant ($p<0.05$). In Figure 3, the influence of air velocity can be seen and the results of ANOVA test were consistent. The reason for insignificant influence of air velocity and relative humidity on the coefficients G and S in all other cases could be that their values are very close. Mrkić et al. (2007) reported about insignificant influence of air velocity on coefficients G and S during broccoli drying.

Table 3 shows mass transfer parameters calculated using the lag factor G. The proposed Bi-G correlation was used to determine Biot number Bi. Biot number is one of the most important dimensionless numbers in drying that indicates the resistance to moisture diffusion inside the material. For mixture 1 at 60 and 80°C, Bi values were Bi<0.1 which indicates negligible internal resistance to the mass diffusivity within the solid object. At 100°C, Bi values were 0.1<Bi<100 indicating that finite internal and surface resistance were present. Mixture 2 shows similar behavior like mixture 1. For mixture 3, all Bi values are in the range of 0.1<Bi<100 indicating the present of internal and external resistance to moisture diffusivity within the

Table 3. Mass transfer parameters.

Baby food	Drying condition			Drying parameter			
	T (°C)	v (m/s)	RH (%)	μ_1	Bi	D × 10^{-8} (m^2/s)	k × 10^{-5} (m/s)
Mixture 1	60	0.5	32	-1.6539	0.0064	1.51	0.0039
	60	1.0	34	-1.6763	0.0063	1.60	0.0041
	60	1.5	34	-1.6562	0.0064	1.76	0.0045
	80	0.5	38	-1.7212	0.0061	1.78	0.0043
	80	1.0	31	-1.6211	0.0066	2.31	0.0061
	80	1.5	29	-0.8062	0.0146	15.2	0.0895
	100	0.5	39	0.8196	0.6821	10.4	2.83
	100	1.0	42	0.4432	0.1272	38.1	1.93
	100	1.5	38	0.4279	0.1216	52.7	2.56
Mixture 2	60	0.5	26	-1.6425	0.0065	1.05	0.0027
	60	1.0	33	-1.5476	0.0071	1.24	0.0035
	60	1.5	43	-0.8472	0.0139	4.54	0.0254
	80	0.5	41	0.5713	0.1958	25.6	2
	80	1.0	40	-0.776	0.0152	13.9	0.0839
	80	1.5	38	-0.447	0.0228	46.2	0.421
	100	0.5	39	0.3923	0.1098	52.3	2.29
	100	1.0	36	0.3280	0.0924	59.7	2.20
	100	1.5	37	0.4002	0.1122	64.9	2.92
Mixture 3	60	0.5	29	0.8640	0.9261	11.4	4.23
	60	1.0	28	0.8196	0.6821	14.5	3.97
	60	1.5	31	0.6664	0.2910	28.4	3.31
	80	0.5	38	0.5638	0.1904	29.5	2.24
	80	1.0	29	0.5598	0.1876	31.9	2.39
	80	1.5	28	0.5396	0.1743	36.5	2.54
	100	0.5	27	0.5313	0.1693	43.4	2.94
	100	1.0	31	0.5307	0.1689	52.5	3.55
	100	1.5	33	0.5513	0.1818	53.1	3.86

product.

Using the lag factor G, the μ_1 was calculated from Equation 6. The μ_1 values are detailed in Table 3.

Furthermore, using μ_1, S and L values, the moisture diffusivity was calculated by Equation 5. The calculated diffusivities are shown in Table 3. Comparing diffusivities values obtained through Equations 3 and 5, some differences were seen. At higher temperature, differences between the two methods of calculation were greater for mixtures 1 and 2, but for mixture 3 the obtained differences were much greater. The variability in moisture diffusivity values by the same samples can be explained by using different methods of calculation, and Zogzas and Maroulis (1996) reported it in their work also.

Dincer and Hussain (2002) noticed a wide variation of moisture diffusivities data of the same foodstuffs using different methods of its estimation. The same conclusion was reported by drying of broccoli (Mrkić et al., 2007). In this work, the calculated values of moisture diffusivities are in the range of values for food materials presented by Marinos-Kouris and Maroulis (1995).

The moisture transfer coefficient k was determined using Equation 11 and values are presented in Table 3. Calculated values ranged between 0.0039 × 10^{-5} to 2.83 × 10^{-5} m/s for mixture 1, 0.0027 × 10^{-5} and 2.92 × 10^{-5} m/s for mixture 2 and 2.24 × 10^{-5} and 4.23 × 10^{-5} m/s for mixture 3 depending on air temperature and velocity.

Through Equation 7, Bi-G correlation was verified. The predicted dimensionless moisture content was calculated using A_1 value from Equation 8 and B_1 value from Equation 9. The agreement between the experimental and predicted values is given in Table 4. As shown, the results of the model agreed very well with the experimental data, except for the values for mixture 1 dried at 100°C R^2<0.80.

Conclusion

The developed Bi-G correlation was capable of calculating mass transfer coefficients. The exponential model excellently fitted the experimental values of

Table 4. Agreement between experimental and predicted values calculated through Equation 7.

Baby food	Drying condition			Drying parameter	
	T (°C)	v (m/s)	RH (%)	R^2	RMSE
Mixture 1	60	0.5	32	0.9953	0.1705
	60	1.0	34	0.9958	0.1854
	60	1.5	34	0.9923	0.1955
	80	0.5	38	0.9560	0.3261
	80	1.0	31	0.9875	0.1913
	80	1.5	29	0.9868	0.0869
	100	0.5	39	0.7956	0.2373
	100	1.0	42	0.7929	0.3029
	100	1.5	38	0.9585	0.2115
Mixture 2	60	0.5	26	0.9870	0.1521
	60	1.0	33	0.9869	0.2119
	60	1.5	43	0.9864	0.1814
	80	0.5	41	0.9977	0.0867
	80	1.0	40	0.9953	0.1367
	80	1.5	38	0.9989	0.0699
	100	0.5	39	0.9968	0.0985
	100	1.0	36	0.9889	0.0954
	100	1.5	37	0.9963	0.0398
Mixture 3	60	0.5	29	0.9425	0.2941
	60	1.0	28	0.9649	0.2945
	60	1.5	31	0.9683	0.2365
	80	0.5	38	0.9576	0.2762
	80	1.0	29	0.9652	0.2985
	80	1.5	28	0.9584	0.3052
	100	0.5	27	0.9599	0.3020
	100	1.0	31	0.9744	0.2761
	100	1.5	33	0.9828	0.2808

non-dimensional moisture content for all the three mixtures at different air temperatures and velocities. Calculated D values using lag factor and drying coefficient and using only drying coefficient were very close to each one at 60 and 80°C for mixture 1 and 60°C for mixture 2. For other conditions, D values differed 10 times or more. The influence of baby food composition on mass transfer parameters was observed.

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