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DETERMINATION OF HEAT TRANSFER COEFFICIENT FOR BABY FOOD DRIED IN TUNNEL DRYER

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Abstract

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Baby food represent one of the most important final food products because of the sensitivity of production, nutritive issues, textural and structural properties and at the end people's choice for this kind of foodstuff.

In this work, a new Nusselt-Reynolds-Prandtl-Dincer correlation for the calculation of the heat transfer coefficient *h* was developed and successfully applied for the drying of baby food mixtures. The new correlation contains both fluid and material characteristic properties.

The proposed correlations can be used for drying of baby foods in tunnel dryer at the drying (air) temperature $60\ °C<T<100\ °C$, air velocities $0,5\ m/s<v<1,5\ m/s$, $Re >10000$ and $3000<Di<60000$.

Key words: baby food, convective drying, heat transfer coefficient, temperature profile

Nomenclature:
A – total area available for the heat transfer (m^2)
C – heating coefficient (s^{-1})
c_p – specific heat of air (kJ/kg K)
c_{pm} – specific heat of the material (kJ/kg K)
c_{pw} – specific heat of water (kJ/kg K)
c_{pp} – specific heat of proteins (kJ/kg K)
c_{pf} – specific heat of fat (kJ/kg K)
c_{pc} – specific heat of carbohydrates (kJ/kg K)
c_{pa} – specific heat of ash (kJ/kg K)
D – hydraulic diameter of the tunnel dryer (m)
Di – Dincer number
h – heat transfer coefficient (W/m^2 K)
L – material thickness (m)
Nu – Nusselt number
Pr – Prandtl number
Re – Reynolds number
t – time (s)
T – material temperature (°C)
T_{air} – air temperature (°C)
T_i – initial material temperature (°C)
v – air velocity (m/s)
V – volume of the object (m^3)
x_w – mass fraction of water (%, wet basis)
x_p – mass fraction of proteins (%, wet basis)
x_f – mass fraction of fat (%, wet basis)
x_c – mass fraction of carbohydrates (%, wet basis)
x_w – mass fraction of ash (%, wet basis)
Z - dimensionless center temperature distribution
α, β, γ, δ – constants
μ – air viscosity (Pa s)
ρ – air density (kg/m^3)
ρ_m – material density (kg/m^3)
ρ_w – water density (kg/m^3)
ρ_p – protein density (kg/m^3)
ρ_f – fat density (kg/m^3)
ρ_c – carbohydrate density (kg/m^3)
ρ_a – ash density (kg/m^3)
λ_{air} – thermal conductivity of air (W/m K)
ω – lag factor

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Introduction

Heating is one of the most important processes during the drying of food products. Drying of such materials is a complex process involving simultaneous heat and mass transfer inside the material (Ježek et al., 2008). The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum efficiency by optimizing the design and operating conditions (Sun et al., 2005; Mrkić et al., 2008). Dehydrated baby food is one of the most important daily baby meals, which can be produced using various techniques like spray drying and drum drying (Jurendić and Tripalo, 2011). Hence, foodstuffs could also be produced and enriched with various proteins within complex bioreactors like extruders and dried immediately after expansion (Brnčić et al., 2008a; 2008b). During the last three decades, the rise of energy prices has been accompanied by increasingly stringent legislation on pollution, working conditions and safety (Jurendić and Tripalo, 2011). To reduce and optimize energy consumption the development of new drying techniques can be of great importance like introducing hi-intensity ultrasound as non-thermal technology as pre-treatment for enhanced drying of various foods (Brnčić et al., 2010) or high hydrostatic pressures (Bosiljkov et al., 2010).

During the convective drying of food materials, transient convective heat transfer occurs between the medium and the food material. Transient heat transfer is of significant practical interest because of the vast amount of heating applicants (Dincer, 1996). The heat transfer rate is a function of external heat transfer coefficient and the thermal conductivity of material (Jaturonglumlert and Kiatsiriroat, 2010). Convective heat transfer coefficient and thermal diffusivity are important parameters in design, optimization and analysis of food processes and processing equipment (Waananen et al., 1993; Erdoğdu, 2008). Thermal diffusivity represents a ratio of three parameters (thermal conductivity, density and specific heat), and also defines how fast heat propagates through a material (Singh, 1982). Study of thermal processing of food materials requires prior knowledge of convective heat transfer coefficient and thermal diffusivity since the information of these parameters is rarely available (Erdoğdu, 2008).

The convective heat transfer coefficient depends on characteristics of the final food product (shape, dimension, structure and texture), changes in surface temperature and roughness, and characteristics of fluid flow (velocity and turbulence) (Erdoğdu, 2008; Brnčić et al., 2009). Since so many parameters influence the convective heat transfer coefficient, an experimental and empirical approach is required in order to obtain the heat transfer coefficient.

In literature, a large number of empirical equations and approaches is available which can be used to determine heat transfer coefficients for different geometries and thicknesses of food materials which are dried under different processing conditions (Marinos-Kouris and Maroulis, 1995). Several heat transfer models were reviewed with drying parameters proposed by Saravacos and Maroulis (2001). Different experimental and theoretical approaches for determination of heat transfer coefficients during drying are reported by Bialobrzewski (2006), Ježek et al (2006), Jaturonglumlert and Kiatsiriroat (2010), Kaya et al. (2008), Pavón-Melendez et al. (2002) and Srikiatden and Roberts (2008).

Another route of estimating heat transfer coefficients is determination of the internal temperature profiles (Dincer, 1996). With this approach a new dimensionless number, called Dincer number Di, was introduced. Di expresses the effect of flow velocity v of heating or cooling fluids on the heating and cooling coefficient C of solid samples with regular or irregular shape (Dincer, 1996). In addition to development of the Dincer number, an adapted Nusselt and Dincer correlation $Nu=f(Di)$ for cooling of food products was developed. Coefficient C describes the heating or cooling capability of the solid object and has a direct effect on the heat transfer coefficient (Dincer, 1996).

The aim of this study was to develop a new correlation $Nu=f(Re, Pr, Di)$ for the determination of heat transfer coefficients of three different baby food samples at different drying temperature and air velocity. Compared with state of the art Nusselt number $Nu=f(Re, Pr)$ (Saravacos and Maroulis, 2001) the correlation $Nu=f(Di)$ (Dincer, 1996) does not include air properties (thermal conductivity, density, specific heat, viscosity) and vice versa, state of the art Nusselt number $Nu=f(Re, Pr)$ does not contain material specific properties as considered in *Nu=f(Di)* correlation. An adapted correlation will include air as well as material specific properties, and will provide design and operation with an accurate analytical tool to conduct relevant calculations in order to reduce additional experimental demand. The reducing of experimental trials for mixtures of baby food is very important because the components, which are added, especially vitamins and minerals, are very expensive (Jurendić and Tripalo, 2011). Moreover, determination of heat transfer coefficients for baby food mixtures is of particular interest because such data do not exist in literature.

Materials and Methods

Three different humid mixtures of baby foods were dried in a tunnel dryer. Mixture 1 consists of water, wheat flour (30 %), sugar (8%), corn starch and vitamins, mixture 2 consists of water, wheat flour (25 %), soya flour, milk powder, sugar (4%) and vitamin mixture and the components of mixture 3 are water, corn flour (37 %), powdered sugar (3%), vitamins and mineral mixture. All percentages are given on a wet basis. Table 1 shows the chemical analysis of wet mixtures 1, 2 and 3. The initial moisture content was determined by AOAC method no. 930.15 (AOAC, 1990).

Experiment

The experiments were conducted in a pilot-plant tunnel dryer designed and manufactured at the University of Zagreb, Faculty of Food Technology and Biotechnology, Croatia (Figure 1).

The dryer consists of a tunnel, electrical heater and fan and is equipped with controllers for air temperature, air velocity and material temperature. 50 ± 0.1 g of wet mixtures were prepared 30 minutes before drying.

Table 1
Chemical composition of mixtures 1, 2 and 3 before drying in % (wet basis)

Mixture	Water	Protein	Carbo-hydrates	Fat	Ash
1	56.00	3.50	38.90	0.53	0.15
2	61.00	6.30	27.00	4.76	0.79
3	65.00	2.70	30.20	0.89	0.25

To conduct the drying experiments at 60°C, 80°C and 100°C (±1°C) and an air velocity 0.5, 1.0 and 1.5 m/s, the humid mixtures (thickness 0.005 m) were placed into aluminum trays (size: 100 mm in diameter and 5 mm high). The material temperature was recorded in 1 min. intervals for 1 hour and later in 5 min. intervals until the end of drying by a thermometer of 0.01°C accuracy (COLE-PARMER, model 8502-25, Chicago, USA), with the sensor immersed into the material. Moisture content was also recorded together with temperature with a digital balance of 0.01 g accuracy (Mettler-Toledo, model PB602-L, Switzerland). Drying was continued until moisture content loss was less than 0.01 g in three consecutive measurements. At this point the temperature recording was stopped. Measurements were conducted in triplicate and the mean temperature values were taken to conduct further analysis.

Data analysis

Heat transfer coefficients were determined with three different calculation methods. The first method was applying the correlation proposed by Dincer (1996), the second was the Nusselt correlation *Nu=f(Re, Pr)* (Saravacos and Maroulis, 2001) and finally direct estimation of the heat transfer coefficient *h* (Srikiatden and Roberts, 2008) was applied. Direct estimation of the heat transfer coefficient *h* was assumed more precise, because it considers air as well as material properties.

For the estimation of the heat transfer coefficient the dimensionless centre temperature distribution *Z* of the material was determined according to (Dincer, 1996):

$$Z = \frac{T - T_{air}}{T_i - T_{air}} \quad (1)$$

A regression analysis in the exponential form was applied to this temperature distribution using the least-squares curve fitting technique (Dincer, 1996):

$$Z = \omega \exp^{(-Ct)} \quad (2)$$

The Dincer number *Di* was determined (Dincer, 1996) with the heating coefficient *C* from Eq. (2):

$$Di = \frac{v}{CL} \quad (3)$$

The Nusselt number *Nu* was then calculated with the following correlation (Dincer, 1996):

$$Nu = 2.2893 \times 10^{-4} Di^{1.0047} \quad (4)$$

The heat transfer coefficient *h* was also calculated with the Nusselt correlation of Eq. (5) (Saravacos and Maroulis, 2001), with the Reynolds number according to Eq. (6) and the Prandtl number from Eq. (7). According to Eq. (6) a *Re* number of *Re>10000* for turbulent airflow was assumed:

$$Nu = 0.0366 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.33} \quad (5)$$

with $$\mathrm{Re} = \frac{\rho v D}{\mu} \quad (6)$$

and $$\mathrm{Pr} = \frac{c_p \mu}{\lambda_{air}} \quad (7)$$

Parameter *D* represents the hydraulic diameter of the tunnel dryer, calculated through *D=4a/P*, where *a* represents cross-sectional area of the dryer, $a=l^2$, and *P* is dryer perimeter *P=4l,* where *l* is equal to *0.5 m* and hence *D=0.5 m*.

The heat transfer coefficient *h* was also determined with Eq. (8) (Srikiatden and Roberts, 2008):

$$\frac{T - T_{air}}{T_0 - T_{air}} = \exp\left[-\left(\frac{hA}{\rho_m c_{pm} V}\right)t\right] \quad (8)$$

The plot $\ln[(T-T_{air})/(T_0-T_{air})]$ vs. time *t* gives a straight line with a slope of $hA/\rho_m c_{pm} V$, where $A=7.85\times10^{-3}\ m^2$ and $V=3.93\times10^{-5}\ m^3$. The heat transfer coefficient *h* was then calculated from the slope.

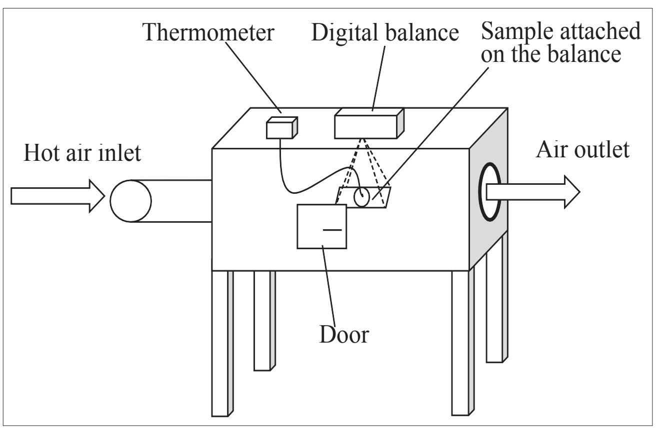

Fig. 1. Schematic sketch of tunnel dryer

Density ρ_m and specific heat c_{pm} of the material are calculated as follows (Srikiatden and Roberts, 2008; Singh, 2007):

$$\rho_m = \frac{1}{\frac{x_w}{\rho_w} + \frac{x_p}{\rho_p} + \frac{x_f}{\rho_f} + \frac{x_c}{\rho_c} + \frac{x_a}{\rho_a}} \quad (9)$$

$$c_{pm} = x_w c_{pw} + x_p c_{pp} + x_f c_{pf} + x_c c_{pc} + x_a c_{pa} \quad (10)$$

With the *h* values from Eq. 8 verification of applicability of Eqs. 4 and 5 for the calculation of heat transfer coefficients was done. These *h* values were then used for calculation of *Nu* number in the new correlation.

Since Eq. 4 does not take into account air properties such as thermal conductivity, viscosity, density and specific heat, and Eq. 5 does not take into account additional material and process properties contained in the heating coefficient *C*, (which is part of Dincer number *Di)* there is a need to develop new a correlation that will consider fluid and material properties.

Because of the reasons mentioned above, it is necessary to generalize the correlation *Nu=f (Re, Pr)* and to develop a new Nusselt number *Nu=f (Re, Pr, Di)* as suggested in the following correlation:

$$Nu = \alpha + \mathrm{Re}^{\beta} \, \mathrm{Pr}^{\gamma} \, Di^{\delta} \quad (11)$$

The new correlation contains both air (*Re* and *Pr* numbers) and material properties (*Di* number) therefore the development of such a correlation seems to be eligible.

Heat transfer coefficients *h* were calculated as follows (Dincer, 1996):

$$h = \frac{Nu \, \lambda_{air}}{L} \quad (12)$$

with λ_{air} values of λ_{air} *(60°C)=0.0285 W/m K*, λ_{air} *(80°C)=0.0299 W/m K* and λ_{air} *(100°C)=0.0314 W/m K*, respectively.

The relative error *E* was then calculated to determine the fitting quality of different models (Srikiatden and Roberts, 2008):

$$E(\%) = \frac{100}{n} \sum_{i=1}^{n} \frac{\left|M_{\exp,i} - M_{predict,i}\right|}{M_{\exp,i}} \quad (13)$$

Results and Discussion

Figure 2 shows that material temperature depends strongly on the drying (air) temperature. With increasing air temperature T_a, the material temperature T gradually increases.

Towards the end of drying, material temperature and air temperature were almost identical. The same observation was reported by Sun et al. (2005). At higher air temperatures material temperatures increases faster than at lower air temperatures. Increasing the air temperatures led to decreasing drying times. The influence of air velocity on the drying time was observed at higher temperature (80 °C and 100 °C), where increasing air velocity caused shorter drying time. At 60 °C the influence of different air velocity on the drying time cannot be observed.

Figure 3 shows temperature values of dried material (mixture 2) during convective tunnel drying when varying temperature and air velocity. The influence of different drying temperature on material temperature was similar for mixture 1, because of similar composition of both mixtures.

Figure 4 shows the experimental temperature trend for mixture 3. The influence of air velocity on the material temperature for drying air temperature T=60°C can be clearly observed. As mentioned above it was not possible to indicate a difference during drying of mixture 1 (Figure 2) and mixture 2 (Figure 3).

Less drying time for mixture 3 (Figure 4) than for mixtures 1 and 2 is needed. This can be explained by the different composition and structures of materials. In mixture 3 corn flour dominates, while in the other two mixtures wheat and soya flour dominates. This is probably due to zein protein present in corn, which is a relatively hydrophobic and thermoplastic material (Ghanbarzadeh et al., 2007). Therefore, corn flour particles cannot bind higher quantities of water, water is mostly present as free water, and it evaporated faster, resulting in shorter drying times.

Table 1 and Table 2 show the chemical composition of three samples before and after drying. It can be seen that different components used in those recipes strongly influence the chemical composition of all mixtures.

Table 3 shows equations applied for calculation of the thermo-physical properties of the three mixtures. The results of calculations are shown in Table 4.

It can be observed that the density of material is lower at the beginning, however increases towards the end of drying. Saravacos and Maroulis (2001) reported

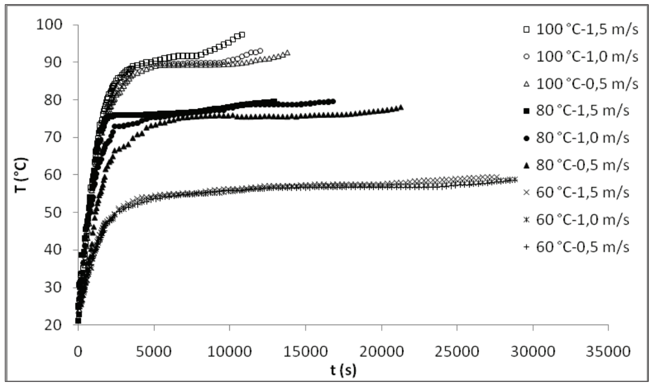

Fig. 2. Experimental temperature values for mixture 1

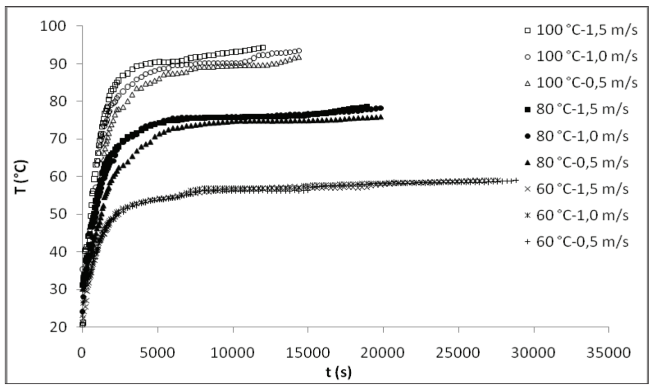

Fig. 3. Experimental temperature values for mixture 2

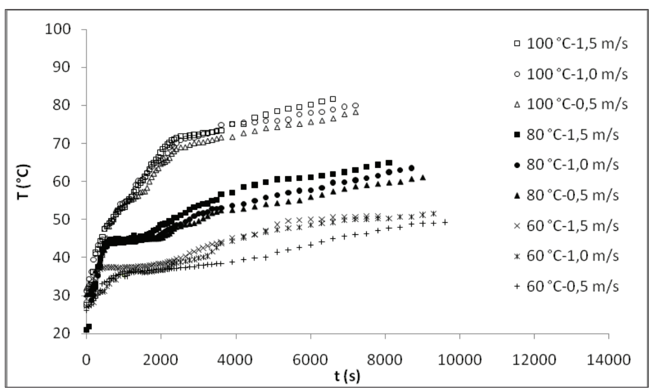

Fig. 4. Experimental temperature values for mixture 3

a similar conclusion. From studying starch materials, they observed that at higher material moisture content, the water reduces the material density by swelling the starch granules. Baby foods that have been studied contain starch materials and therefore behave in a similar way to other starch materials reported by Saravacos and Maroulis (2001).

Specific heat values decreased during drying because of the very low moisture content in dry products. For further calculations, average values of density and specific heat were used.

Heat transfer coefficients *h* were calculated in four different ways. Using Eq. 4, which was proposed by Dincer (1996), Nusselt number *Nu* values were obtained. Table 5 shows calculated heat transfer coefficient *h* values. In this correlation coefficient *C* contains material characteristic properties. As shown in Table 5 the *C* values vary with material composition, processing temperature and air velocity. At higher drying temperature and air velocities, *C* values are higher than for reverse process conditions. Similar characteristic of *C* values was observed by Dincer (1996), in cooling of other food products (tomato, pear, cucumber, grape, fig, banana and carrot). At the same temperature, heat transfer coefficients *h* values decreased with decreasing air velocity. Kaya et al. (2008) reported that similar behavior of heat transfer coefficient *h* during kiwi drying was observed.

Heat transfer coefficients *h* obtained from Eq. 5 seem to be redundant. This can be seen in Table 5. Independent of dried material and drying temperature *h* values are expectedly identical. Application of the algorithm seems to be inadequate in this case, because this correlation includes fluid and process properties only.

Table 2
Chemical compositions of mixtures 1, 2 and 3 after drying in % (wet basis)

Mixture	Water	Protein	Carbo-hydrates	Fat	Ash
1	2.75	7.83	86.98	1.18	0.34
2	2.67	15.75	67.45	11.88	1.97
3	1.97	7.74	87.09	2.57	0.73

Table 3
Equations for the determination of thermo-physical properties (Singh, 2007)

Property	Equation
Density ρ, kg/m^3	$\rho_w = 997.18 + 3.1439 \times 10^{-3}T - 3.7574 \times 10^{-3}T^2$ $\rho_p = 1329.9 - 5.184 \times 10^{-1}T$ $\rho_f = 925.59 - 5.184 \times 10^{-1}T$ $\rho_c = 1599.1 - 3.1046 \times 10^{-1}T$ $\rho_a = 2423.8 - 2.8063 \times 10^{-1}T$
Specific heat cp, kJ/kg K	$c_{pw} = 4.1762 - 9.0864 \times 10^{-5}T + 5.4731 \times 10^{-6}T^2$ $c_{pp} = 2.0082 + 1.2089 \times 10^{-3}T - 1.3129 \times 10^{-6}T^2$ $c_{pf} = 1.9842 + 1.4733 \times 10^{-3}T + 4.8008 \times 10^{-6}T^2$ $c_{pc} = 1.5488 - 1.9625 \times 10^{-3}T + 5.9399 \times 10^{-6}T^2$ $c_{pa} = 1.0926 - 1.8896 \times 10^{-3}T + 3.6817 \times 10^{-6}T^2$

Table 4
Thermo-physical properties of mixtures 1, 2 and 3 before and after drying

		Before drying		After drying		Average	
Mixture	T_{air}, °C	ρ_m , kg/m^3	c_{pm}, kJ/kg K	ρ_m, kg/m^3	c_{pm}, kJ/kg K	ρ_m, kg/m^3	c_{pm}, kJ/kg K
1	100	1155.44	3107.00	1516.57	1777.00	1336.01	2442.00
	80	1168.03	3089.00	1523.98	1759.00	1346.01	2424.00
	60	1178.16	3072.00	1531.17	1737.00	1354.67	2404.00
2	100	1093.97	3273.00	1381.53	1855.00	1237.75	2564.00
	80	1106.53	3255.00	1389.88	1837.00	1248.21	2546.00
	60	1116.69	3238.00	1398.05	1816.00	1257.37	2527.00
3	100	1108.68	3332.00	1495.64	1778.00	1302.16	2555.00
	80	1121.60	3314.00	1502.93	1759.00	1312.27	2537.00
	60	1131.90	3298.00	1510.06	1738.00	1320.98	2518.00

In order to test the capability of both Eq. 4 and Eq. 5 for calculation of *h*, the calculation method reported by Srikiatden and Roberts (2008) was used. Using this method was reasonable as it takes into account some process properties (temperature, time) and some material properties (density, specific heat, surface area and volume). Table 5 shows that the estimated *h* values are much higher than *h* values calculated through Eq. 4 and lower than *h* values obtained from Eq. 5. Therefore, proposed *Nu=f (Di)* and *Nu=f (Re, Pr)* correlations cannot be used for the practical application in baby food dried in tunnel dryers. However, by combining both process and material properties (as used in the slope method) determination of heat transfer coefficient *h* using a new correlation is recommended.

h values obtained from Eq. 8 vary with drying temperature, air velocity, mixture type and composition. At higher drying temperature and air velocity heat transfer coefficient values are higher, which was expected from the convective drying theory.

It can be observed that depending on calculation technique, heat transfer coefficient values *h* vary significantly. This is a consequence of the fact that each calculation method considers only a finite number of

Table 5
Heating coefficient *C* and heat transfer coefficient values

Mixture	T_{air}, °C	v, m/s	C, s^{-1}	Nu=f(Di) h ($W/m^2 K$)	Nu=f(Re,Pr) h ($W/m^2 K$)	Slope h ($W/m^2 K$)	Nu=f(Re,Pr,Di) h ($W/m^2 K$)
1	100	15.00	0.04	11.95	832.31	334.41	232.42
	100	1.00	0.03	8.21	620.60	261.03	203.77
	100	0.50	0.03	4.07	370.04	225.12	206.53
	80	1.50	0.07	6.57	832.31	394.79	414.15
	80	1.00	0.05	5.86	620.60	306.70	243.31
	80	0.50	0.03	4.17	370.04	179.45	204.08
	60	1.50	0.03	15.75	832.31	156.32	207.74
	60	1.00	0.03	11.15	620.60	128.64	188.27
	60	0.50	0.02	6.09	370.04	123.75	181.02
2	100	1.50	0.04	10.65	832.31	277.69	249.19
	100	1.00	0.03	9.57	620.60	196.76	194.49
	100	0.50	0.02	6.62	370.04	182.48	178.39
	80	1.50	0.04	12.34	832.31	198.62	228.51
	80	1.00	0.04	7.90	620.60	197.03	206.71
	80	0.50	0.02	6.51	370.04	160.49	178.86
	60	1.50	0.03	14.10	832.31	154.10	215.55
	60	1.00	0.03	9.82	620.60	150.93	193.22
	60	0.50	0.03	5.12	370.04	139.80	188.76
3	100	1.50	0.01	53.87	832.31	277.81	185.47
	100	1.00	0.01	39.59	620.60	236.22	176.19
	100	0.50	0.01	19.99	370.04	212.93	168.11
	80	1.50	0.01	83.55	832.31	216.39	184.85
	80	1.00	0.00	64.26	620.60	183.11	175.87
	80	0.50	0.00	38.42	370.04	131.50	167.62
	60	1.50	0.00	92.17	832.31	181.28	184.78
	60	1.00	0.01	52.30	620.60	176.29	175.96
	60	0.50	0.00	38.97	370.04	129.72	167.61

process or material properties. Bialobrzewski (2006) reported different calculation methods for the estimation of h values. The intention of this work was to develop a new correlation, which will co-inside with both process and material properties.

Table 6 shows the coefficient of correlation *(R^2)* values obtained because of fitting data with the slope method. The R^2 values are in the range $0.72<R^2<0.98$, which indicate satisfactory goodness of fit.

Since *Nu=f(Re, Pr)* correlation (Eq. 5) contains air and process parameters (thermal conductivity, viscosity, specific heat, density and air velocity) and *Nu=f(Di)* correlation (Eq. 4) and material properties (heating parameter C) than the slope method (Eq. 8), the development of a new correlation according to *Nu=f(Re, Pr, Di)* seems to be adequate.

It is therefore necessary to find the dependence of *Nu=f (Re, Pr, Di)*. For this purpose, Nusselt number *Nu* was estimated with Eq. 12, heat transfer coefficient *h* values were taken from Table 5 (slope method). Reynolds number *Re*, Prandtl number *Pr* and Dincer number *Di* were calculated through Eqs. 6, 7 and 3. Through nonlinear regression (*Statistica 6* software), the constants of Eq. 11 were estimated. Therefore, the suggested correlation has the following form:

$$Nu = 29.388 + \mathrm{Re}^{-0.762}\,\mathrm{Pr}^{-92.278}\,Di^{-2.635} \qquad (14)$$

With the new correlation the Nusselt number *Nu* values were calculated and used to predict heat transfer coefficient values *h* (Table 5). Predicted *h* values calculated through the new correlation show much better agreement with *h* values (slope method) than *h* values calculated through Eqs. 4 and 5. Table 7 shows the errors *E (%)* for *h* values calculated through different models. The majority of *h* values is in the range of $167<h<250$ $W/m^2 K$.

The values are in agreement with data reported by Saravacos and Maroulis (2001) for air-drying of food in constant rate period. Hussain and Dincer (2002) reported *h* values between $25<h<250$ $W/m^2 K$ during drying of cylindrical food objects. It can be seen that *h* values calculated with the new correlation agree very well with data reported by Saravacos and Maroulis (2001) and Hussain and Dincer (2002). Consideration of the Dincer number *Di* in determining heat transfer coefficient *h* seems to be eligible. The new correlation considers fluid, process and material properties and its application in determining the heat transfer coefficient of starch based food materials could be of importance.

Table 6
Coefficient of correlation values for fitting with the slope method

Mixture	T_{air}, °C	v, m/s	R^2
1	100	1.50	0.84
	100	1.00	0.72
	100	0.50	0.73
	80	1.50	0.79
	80	1.00	0.92
	80	0.50	0.78
	60	1.50	0.90
	60	1.00	0.83
	60	0.50	0.80
2	100	1.50	0.79
	100	1.00	0.80
	100	0.50	0.82
	80	1.50	0.84
	80	1.00	0.81
	80	0.50	0.81
	60	1.50	0.88
	60	1.00	0.88
	60	0.50	0.89
3	100	1.50	0.89
	100	1.00	0.87
	100	0.50	0.85
	80	1.50	0.93
	80	1.00	0.92
	80	0.50	0.95
	60	1.50	0.96
	60	1.00	0.98
	60	0.50	0.95

Table 7
Relative error *E (%)* for different models

Mixture	Model		
	Nu=f(Di)	Nu=f(Re,Pr)	Nu=f(Re,Pr,Di)
1	95.77	187.14	25.06
2	94.89	233.17	16.44
3	71.22	215.28	17.45

Therefore, the new *Nu=f(Re, Pr, Di)* correlation can be used for the determination of heat transfer coefficient *h* of baby foods containing wheat, soya and corn flour, when they are dried under following conditions: drying (air) temperature *60<T<100 °C*, air velocity *0,5<v<1,5 m/s*, Reynolds number *Re>10000* and Dincer number *3000<Di<60000.*

Conclusions

The newly developed correlation *Nu=f (Re, Pr, Di)* seems to be more efficient than *Nu=f (Di)* or *Nu=f (Re, Pr)* correlations in estimation of heat transfer coefficient *h* during tunnel drying of baby food mixtures. This correlation takes into account specific material properties (heating parameter *C* and material temperature), process properties (air velocity *v*, drying temperature *T* and drying time *t*) and air properties (specific heat, density, thermal conductivity and viscosity). The new correlation can be used for practical applications in determination of heat transfer coefficient *h* for tunnel drying of baby food, dried under the mentioned conditions.

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