Mathematical modelling of thin layer hot air drying of apricot with combined heat and power dryer

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Abstract In this study thermal energy of an engine was used to dry apricot. For this purpose, experiments were conducted on thin layer drying apricot with combined heat and power dryer, in a laboratory dryer. The drying experiments were carried out for four levels of engine output power (25 %, 50 %, 75 % and full load), producing temperatures of 50, 60, 70, and 80 °C in drying chamber respectively. The air velocity in drying chamber was about 0.5 ± 0.05 m/s. Different mathematical models were evaluated to predict the behavior of apricot drying in a combined heat and power dryer. Conventional statistical equations namely modeling efficiency (EF), Root mean square error (RMSE) and chi-square (χ^2) were also used to determine the most suitable model. Assessments indicated that the Logarithmic model considering the values of $EF=0.998746$, $\chi^2=0.000120$ and $RMSE=0.004772$, shows the best treatment of drying apricot with combined heat and power dryer among eleven models were used in this study. The average values of effective diffusivity ranged 1.6260×10^{-9} to 4.3612×10^{-9} m²/s for drying apricot at air temperatures between 50 and 80 °C and at the air flow rate of 0.5 ± 0.05 m/s; the values of De_{eff} increased with the increase of drying temperature the effective diffusivities in the second falling rate period were about eight times greater than that in the first falling rate period.

Keywords Drying · Modeling · Apricot · Combined heat and power

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Introduction

Interest in combined heat and power technologies has grown among energy customers, regulators, legislators, and developers over the past decade as consumers and providers seek to reduce energy costs while improving service and reliability. Combined heat and power technology is a specific form of distributed generation, which refers to the strategic placement of electric power generating units at or near customer facilities to supply onsite energy needs. Combined heat and power technology enhances the advantages of distributed generation by the simultaneous production of useful thermal and power output, thereby increasing the overall efficiency.

Internal combustion engines are capable of burning a variety of fuels, including natural gas, oil, and alternative fuels to produce shaft power or mechanical energy. About two-thirds of the energy inputs to the engine wasted through exhaust gas and cooling system. Waste heat is generated in a process by the way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose (Pandiyarajan et al. 2011). Mechanical energy from the prime mover is most often used to drive a generator to produce electricity. Thermal energy from the system can be used in direct process applications or indirectly to produce steam, hot water, hot air for drying.

Fruits and vegetables are regarded as highly perishable food due to their high moisture content (Simal et al. 1997). Drying is one of the methods that is widely used to preserve fruits and vegetables. Longer persistence, product diversity and reduction in the size are the main reasons for drying fruits and vegetables and this can be expanded with improving product quality and drying methods. Drying of moist materials is a complicated process involving simultaneous heat and mass transfer (Yilbas et al. 2003). Many researches have attempted for drying the Food products especially apricot. Mathematical modeling of drying process is a good way to analysis and describing the

Fig. 1 Schematic diagram of drying equipment

products drying treatment. All parameters used in the model are directly related to drying conditions, drying time and energy required (Babalís and Belessiotis 2004). This process is very useful because doing all the experimental tests will be difficult, time consuming and costly. There are so many investigations about mathematical modeling of thin layer drying behavior of agricultural products, for example, tomato (Das Purkayastha et al. 2011), apricot (Toğrul and Pehlivan 2002), pumpkin (Tunde-Akintunde and Ogunlakin 2013), grape (Doymaz 2012), olive (Akgun and Doymaz 2005), carrot (Aghbashlo et al. 2009, Kumar et al. 2012), eggplant (Ertekin and Yaldiz 2004), apple pomace (Wang et al. 2007; Velickova et al. 2013), plum (Goyal et al. 2007), betel leave (Balasubramanian et al. 2011), sour cherry (Motavali et al. 2011), white mulberry (Akpınar 2008), oyster mushroom (Bhattacharya et al. 2013) and mango (Murthy and Manohar 2013).

However, there is no extensive and complete research on the drying of agricultural products using the exhaust's hot leaving gas in different engine operating powers and, therefore, in different drying temperatures. The objectives of this study are, investigating the drying of apricot slice with a combined heat

and power dryer and comparing mathematical models and determine the most suitable model for drying treatment.

Material and methods

Experimental apparatus

Drying experiments were carried out in a drying laboratory of Tarbiat Modares University. In this work from exhaust waste heat of an engine – generator was used for drying process. Equipment used in this dryer consist of a single cylinder engine that works with natural gas fuel, a generator that produces 2 kW of electricity, a dryer chamber which samples place in it, a fan to remove air from the dryer chamber, a digital balance for weighing samples, temperature sensor for measuring temperature and a PC to record hot air temperature and sample weight. Schematic diagram of the dryer is shown in Fig. 1.

Waste heat from the engine exhaust was directed into the dryer chamber. The heat is approached directly under the chamber page and the drier's chamber is warmed. Hot air is

Table 1 Mathematical models applied to the drying curves

No	Model name	Model	References
1	Lewis	$MR = \exp(-kt)$	(Ayensu 1997)
2	Page	$MR = \exp(-kt^n)$	(Doymaz 2004a)
3	Modified Page	$MR = \exp(-(kt)^n)$	(Demir et al. 2004)
4	Wang and Singh	$MR = 1 + a.t + b.t^2$	(Chen and Wu 2001)
5	Henderson and Pabis	$MR = a.\exp(-kt)$	(Chhinnan 1984)
6	Logarithmic	$MR = a.\exp(-kt) + c$	(Doymaz 2004b)
7	Approximation of diffusion	$MR = a.\exp(-kt) + (1-a).\exp(-k.b.t)$	(Ertekin and Yaldiz 2004)
8	Modified Page equation-II	$MR = \exp(-c(t/L^2)^n)$	(Diamante and Munro 1991)
9	Midilli et al.	$MR = a.\exp(-kt^n) + bt$	(Midilli et al. 2002)
10	Verma et al.	$MR = a.\exp(-kt) + (1-a).\exp(-gt)$	(Verma et al. 1985)
11	Modified Henderson ve Papis	$MR = a.\exp(-kt) + b.\exp(-gt) + c.\exp(-ht)$	(Karathanos 1999)

circulated inside the chamber and is removed from the chamber by a fan. Engine was run for a few minutes to reach steady state conditions, the drying experiment were performed at constant speed and four load levels, 25 %, 50 %, 75 % and full load.

Experimental material

Fresh apricot was obtained from Tehran local market in July 2012. The samples were stored in the refrigerator at 3 °C. Initial moisture content of the apricot was determined by drying in an air convection oven. About 77 g sample was placed in the oven at 80 °C for 12 h till the sample weight did not change anymore and the initial moisture was obtained to be 87 % (w.b.). All the experiments were replicated three times.

The experiments

The experiments were performed at 25 %, 50 %, 75 % and full load of engine output power. At 25 %, 50 %, 75 % and full load engine output power the temperatures generated in drying chamber, was about 50, 60, 70 and 80 °C respectively. The hot air velocity was 0.5 m/s which was circulated all over the drying chamber continuously. The apricots first sliced to two parts, and cores were removed. The initial weight of sample was 77 g, and mass variation was recorded every 5 min by a digital balance.

Mathematical modeling of drying curves

To evaluate the characters of the drying process, it is highly important for modeling the drying process. Therefore in this study, the drying curves obtained from experiments were

Fig. 2 Thin-layer drying curves of apricot at different engine output power

Fig. 3 Drying rate versus moisture content of apricot at different engine output power

fitted with 11 different models that commonly were used for describing the thin layer drying behavior (Table 1).

To find the best mathematical model, the moisture content data at different engine output powers were converted to (MR) that presents the dimensionless moisture ratio using Eq. (1).

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

where, M is the instantaneous moisture content ($\text{kg water kg}^{-1} \text{ dry matter}$) of the product, M_0 is the initial moisture content of the product and M_e is the equilibrium moisture content. The values of M_e are relatively negligible compared with M and M_0 for long drying time. Thus Eq. (1) has been simplified to Eq. (2) (Toğrul and Pehlivan 2004).

$$MR = \frac{M_t}{M_0} \quad (2)$$

Regression analyses for determining the most suitable model for drying thin layer apricots with combined heat and power dryer was carried out with using the conventional

Fig. 4 Drying rate versus drying duration of apricot at different engine output power

Table 2 Statistical results obtained from different thin-layer drying models

No	Loads (%)	Constants						χ^2	R ²	RMSE
1	25	k=0.01226						0.00227	0.97490	0.04762
	50	k=0.01386						0.00236	0.97409	0.04924
	75	k=0.01696						0.00560	0.94525	0.07629
	100	k=0.02734						0.00073	0.99153	0.02763
2	25	k=0.003439	n=1.282				0.00048	0.99470	0.02213	
	50	k=0.003469	n=1.317				0.00021	0.99764	0.01508	
	75	k=0.001866	n=1.533				0.00043	0.99578	0.02162	
	100	k=0.01567	n=1.149				0.00020	0.99769	0.01482	
3	25	k=0.012	n=1.282				0.00048	0.99470	0.02213	
	50	k=0.01354	n=1.317				0.00021	0.99764	0.01508	
	75	k=0.01659	n=1.533				0.00043	0.99578	0.02162	
	100	k=0.02686	n=1.149				0.00020	0.99769	0.01482	
4	25	a=-0.009038	b=2.045e-005				0.00013	0.99855	0.01160	
	50	a=-0.01026	b=2.653e-005				0.00012	0.99865	0.01143	
	75	a=-0.01173	b=2.847e-005				0.00041	0.99597	0.02112	
	100	a=-0.0206	b=0.0001119				0.00038	0.99552	0.02065	
5	25	a=1.081	k=0.01328				0.00152	0.98320	0.03947	
	50	a=1.092	k=0.01517				0.00140	0.98463	0.03850	
	75	a=1.126	k=0.01914				0.00359	0.96488	0.06236	
	100	a=1.039	k=0.02843				0.00055	0.99362	0.02465	
6	25	a=1.292	c=-0.2706	k=0.008126			0.00009	0.99905	0.00949	
	50	a=1.274	c=-0.2367	k=0.009759			0.00009	0.99897	0.00101	
	75	a=1.638	c=-0.5899	k=0.008486			0.00026	0.99743	0.00172	
	100	a=1.122	c=-0.1137	k=0.02209			0.00004	0.99953	0.00686	
7	25	a=-4.999	b=0.8774	k=0.02368			0.00051	0.99433	0.02324	
	50	a=-4.997	b=0.8686	k=0.02784			0.00026	0.99715	0.01684	
	75	a=0.8534	b=1.003	k=0.01695			0.00560	0.94525	0.07953	
	100	a=-0.2223	b=0.9588	k=0.02878			0.00072	0.99156	0.02917	
8	25	L=0.2456	c=9.377e-005	n=1.283			0.00048	0.99472	0.02244	
	50	L=1.107	c=0.004529	n=1.317			0.00021	0.99764	0.01531	
	75	L=10.8	c=2.756	n=1.533			0.00043	0.99578	0.02209	
	100	L=2.097	c=0.08593	n=1.149			0.00020	0.99769	0.01525	
9	25	a=0.8686	b=-0.005062	k=9.341	n=-10.37		0.00035	0.99437	0.00987	
	50	a=1.011	b=-0.000479	k=0.006052	n=1.161		0.00012	0.99665	0.01603	
	75	a=1.007	b=-0.0009606	k=0.003676	n=1.32		0.00029	0.99643	0.02830	
	100	a=0.9672	b=-0.0214	k=-0.002128	n=0.82		0.00071	0.99176	0.02970	
10	25	a=12.95	g=0.02282	k=0.02154			0.00051	0.99436	0.02318	
	50	a=-0.1258	g=0.01564	k=5.741			0.00074	0.98570	0.03346	
	75	a=-0.1862	g=0.02018	k=4.918			0.00269	0.97367	0.05515	
	100	a=5.369	g=0.04557	k=0.04091			0.00018	0.99790	0.01456	
11	25	a=1.106	b=-0.2853	c=0.1801	g=5.442	h=1.379	k=0.0136	0.00129	0.98569	0.03858
	50	a=4.232	b=-3.239	c=0.006784	g=0.02915	h=4.869	k=0.02357	0.00082	0.99125	0.03125
	75	a=-2.37	b=3.317	c=0.05284	g=0.03104	h=5.557	k=0.04572	0.00072	0.99291	0.03069
	100	a=0.07537	b=0.8669	c=0.1015	g=0.02745	h=0.04391	k=0.02748	0.00061	0.99289	0.02949

statistical calculations namely the chi-square (χ^2), root mean square error (RMSE) and modeling efficiency (EF). The

highest values of EF and the lowest values of χ^2 and RMSE, represent the best fitness with experimental data and

mathematical model (Akpınar et al. 2003). These statistical values can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^n (MR_{exp,i} - MR_{pre,i})^2}{N-n} \quad (3)$$

$$RMSE = \left[\frac{\sum_{i=1}^n (MR_{pre,i} - MR_{exp,i})^2}{N} \right]^{\frac{1}{2}} \quad (4)$$

$$EF = 1 - \frac{\sum_{i=1}^n (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^n (MR_{exp,i} - MR_{exp,i_{mean}})^2} \quad (5)$$

where, $MR_{exp,i}$ is the i th experimental moisture ratio, $MR_{pre,i}$ is the i th predicted moisture ratio, N is the number of observations, n is the number of constants in the drying model and $MR_{exp,i_{mean}}$ is the mean value of experimental moisture ratio.

Calculation of effective diffusivities

It has been accepted that the drying characteristics of biological products in falling rate period can be described by Fick's diffusion equation. The solution to this equation (Crank 1975) can be used for various regularly shaped bodies such as rectangular, cylindrical and spherical products, and the form of Eq. (6) can be applicable for particles with slab geometry by assuming uniform initial moisture distribution:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2}\right) \quad (6)$$

where D_{eff} is the effective diffusivity (m^2/s); L_0 is the half thickness of slab (m). For long drying periods the above equation can be simplified to Eq. (7):

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L_0^2}\right) \quad (7)$$

Eq. (8) is obtained by taking the natural logarithm of both sides:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \quad (8)$$

Diffusivities are typically determined by plotting experimental drying data in terms of $\ln MR$ versus drying time t in Eq. (8), because the plot gives a straight line with a slope as follows (Wang et al. 2007):

$$\text{slope} = \frac{\pi^2 D_{eff} t}{4L_0^2} \quad (9)$$

Results and discussion

Analysis of drying characteristics of apricot

Apricot was dried at 25 %, 50 %, 75 % and full load of engine output power in a combined heat and power dryer and the temperatures produced in drying chamber were at 50, 60, 70 and 80 °C respectively. The initial moisture content of apricot was about 6.7 ± 0.1 (d.b.), and the equilibrium moisture content was 0.088 ± 0.001 (d.b.) when no more change in weight was observed. For describing the apricot drying process, the moisture content at different drying conditions were converted to the dimensionless moisture ratio (MR). The drying curves of the apricots dried in the combined heat and power dryer are shown in Fig. 2. Obviously, within a certain temperature range (50–80 °C), increasing drying temperature speeds up the drying process, thus shortened the drying time. This result is similar to those of apricot products drying (Toğrul and Pehlivan 2002; Abdelhaq and Labuza 1987).

The time required to reach equilibrium moisture at 25 %, 50 %, 75 % and full load of engine output power were obtained for 190, 170, 125 and 95 min respectively. At starting the drying, initial moisture content of the apricot was high

Fig. 5 Average value of R^2 , χ^2 and RMSE for used

Fig. 6 Experimental and predicted moisture ratio changes with drying time at different engine output power

hence the loss of the humidity was high. During the drying process the product moisture content decreasing gradually which causes longer time needed in losing the moisture content. The engine output power was increased at equal intervals of 25 % from 25 to 100 % which caused a decrease in drying time by 20, 45 and 30 min correspondingly. The results showed that the reduction in drying time did not happen in the equal interval. In Figs. 3 and 4 it can be seen that a constant drying rate was not observed in drying the apricot samples and the moisture loss at beginning was faster comparing it with the end of drying process. This observation is in agreement with previous results on thin-layer drying of biological products (Tunde and Ogunlakin 2013, Bhattacharya et al. 2013)

The fuel consumption at full load is not economic and the temperature higher than 80 °C, causes disintegration of apricot (Toğrul and Pehlivan 2002). So, with regard to economic issues and product quality the 75 % of engine output power is the most suitable load for drying apricot.

Fitting of the drying curves

MATLAB 2011, curve fitting toolbox environment was employed to run standard drying curve fitting (Table 1) on the experimental data. The statistical results including models coefficients and equations used to assess the excellence model namely EF, RMSE and χ^2 are presented in Table 2. The average values of R^2 , χ^2 and RMSE for all drying models are shown in Fig. 5. Logarithmic model offering maximum average value of EF and minimum average value of RMSE and χ^2 namely 0.998746, 0.004772 and 0.000120 respectively as shown in Table 2 and Fig. 5.

Considering the direct effects of engine output power on logarithmic equation constants and coefficients (k , a and c at Eq. (10) regression analysis was used to determine the relationship between the coefficients and the loads. Regression

equations obtained from the parameters versus load (L) are as follows:

$$MR = a \exp(-kt) + c \quad (10)$$

$$a = -1E-05L^3 + 0.0023L^2 - 0.1162L + 2.954 \quad R^2 = 1 \quad (11)$$

$$k = 2E-07L^3 - 3E-05L^2 + 0.0015L - 0.0142 \quad R^2 = 1 \quad (12)$$

$$c = 1E-05L^3 - 0.0023L^2 + 0.1138L - 1.9081 \quad R^2 = 1 \quad (13)$$

where, MR is the moisture ratio, k is the drying rate constant (min^{-1}), t is the time (min), a and c are the experimental constants.

With considering the value of $EF=0.998746$, $RMSE=0.004772$ and $\chi^2=0.000120$ compatibility of experimental data with logarithmic model is revealed. Thus the moisture ratio of apricots that are drying in the combined heat and power dryer can be estimated with high accuracy in each moment. It can be seen from Fig. 6 that, logarithmic model was in a good agreement with the experimental results at all drying conditions.

In Fig. 7, the data predicted by the logarithmic model versus the experimental data is plotted. As can be seen the points have been arranged on a straight line with an angle of 45° to the horizontal axis that shows the good agreement between the calculated and experimental results. Accordingly, the Logarithmic model was selected as a suitable model to describe the characteristics of thin layer drying of apricot dried in combined heat and power dryer.

Fig. 7 Experimental and predicted moisture ratio values at different engine output power for the logarithmic model

Fig. 8 Ln MR versus drying duration of apricot at different engine output power

Determination of effective diffusivities

The results obtained have shown that internal mass transfer resistance due to presence of a falling rate-drying period controls drying time. Therefore, the values of effective diffusivity (D_{eff}) at different engine output power could be obtained by using Eqs. (8) and (9), the slope needed for Eq. (9) is given in Fig. (8). The average values of effective diffusivities of apricot in the drying process at 25 % to full load of engine output power varied in the range of 1.6260×10^{-9} to $4.3612 \times 10^{-9} \text{ m}^2/\text{s}$ (Table 3). As is expected, the values of D_{eff} increased with the increase of drying temperature. These results were in agreement with the previous investigations that the values of effective diffusivities lie within the general range of 10^{-11} to $10^{-9} \text{ m}^2/\text{s}$ for food materials (Abdelhaq and Labuza 1987; Madamba et al. 1996). In this study during drying, two falling rate periods were observed, each period occurs in a constant slope (Fig. 8) from which the effective diffusion coefficients are calculated. The dividing point between the first and second falling rate periods was at about 42 % (wb) of moisture content. The effective diffusivities in the first falling rate period ranged from $2.4307 \times$

10^{-10} to $1.1157 \times 10^{-9} \text{ m}^2/\text{s}$ whereas the effective diffusivities in the second falling rate period ranged from 3.0089×10^{-9} to $7.6068 \times 10^{-9} \text{ m}^2/\text{s}$ about eight times greater than that in the first falling rate period (Table 3). These values are correspond with conclusions obtained for previous investigation (Simal et al. 1994).

Conclusions

- 1- Drying behavior of thin layer apricot in combined heat and power dryer at 25 %, 50 %, 75 % and full load of engine output power was investigated. Among eleven models, Logarithmic model considering the values of $EF=0.998746$, $\chi^2=0.000120$ and $RMSE=0.004772$ was the most suitable model.
- 2- Variety, drying air temperature is significant factor in drying time. Therefore engine output power is an important factor that effects on apricot drying time and logarithmic coefficient. Higher engine output power resulted in a shorter drying time.

Table 3 Values of effective diffusivities obtained for apricot at different temperatures

loads	Temperature (°C)	average of two periods	effective diffusivity (m^2/s)	
			1st period	2nd period
25 %	50	1.6260×10^{-9}	2.4307×10^{-10}	3.0089×10^{-9}
50 %	60	2.3790×10^{-9}	3.0991×10^{-10}	4.4482×10^{-9}
75 %	70	2.6557×10^{-9}	5.6976×10^{-10}	4.7416×10^{-9}
Full load	80	4.3612×10^{-9}	1.1157×10^{-9}	7.6068×10^{-9}

- 3- The fuel consumption at full load was high and it was not economic and the temperature higher than 80 °C, causes disintegration of apricot. So with regard to economic issues and product quality the 75 % of engine output power is the best load for drying the apricot.
- 4- the average values of effective diffusivity ranged 1.6260×10^{-9} to 4.3612×10^{-9} m²/s for drying apricot at air temperatures between 50 and 80 °C and at the air flow rate of 0.5 ± 0.05 m/s; the values of D_{eff} increased with the increase of drying temperature the effective diffusivities in the second falling rate period were about eight times greater than that in the first falling rate period

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References

- Abdelhaq EH, Labuza TP (1987) Air drying characteristics of apricots. *J Food Sci* 52(2):342–345
- Aghbashlo M, Kianmehr MH, Khani S, Ghasem M (2009) Mathematical modelling of thin-layer drying of carrot. *Int Agrophysics* 23(4):313–317
- Akgun NA, Doymaz I (2005) Modelling of olive cake thin-layer drying process. *J Food Eng* 68(4):455–461
- Akpınar EK (2008) Mathematical modelling and experimental investigation on sun and solar drying of white mulberry. *J Mech Sci Technol* 22(8):1544–1553
- Akpınar E, Midilli A, Bicer Y (2003) Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modeling. *Energy Convers Manag* 44(10):1689–1705
- Ayensu A (1997) Dehydration of food crops using a solar dryer with convective heat flow. *Sol Energy* 59(4–6):121–126
- Babalıs SJ, Belessiotis VG (2004) Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. *J Food Eng* 65(3):449–458
- Balasubramanian S, Sharma R, Gupta RK, Patil RT (2011) Validation of drying models and rehydration characteristics of betel (Piper betel L.) leaves. *J Food Sci Technol* 48(6):685–691
- Bhattacharya M, Srivastav P, Mishra H (2013) Thin-layer modeling of convective and microwave-convective drying of oyster mushroom (*Pleurotus ostreatus*). *J Food Sci Technol* 1–10
- Chen C, Wu PC (2001) Thin layer drying model for rough rice with high moisture content. *J Agric Eng Res* 80(1):45–52
- Chhinnan MS (1984) Evaluation of selected mathematical models for describing thin-layer drying of in-shell pecans. *Trans ASAE* 27: 610–615
- Crank J (1975) *The mathematics of diffusion*. Clarendon, Oxford, England
- Das Purkayastha M, Nath A, Deka B, Mahanta C (2011) Thin layer drying of tomato slices. *J Food Sci Technol* 1–12. doi:10.1007/s13197-011-0397-x
- Demir V, Gunhan T, Yagcioglu AK, Degirmencioglu A (2004) Mathematical modelling and the determination of some quality parameters of air-dried bay leaves. *Biosyst Eng* 88(3):325–335
- Diamante LM, Munro PA (1991) Mathematical modeling of hot air drying of sweet potato slices. *Int J Food Sci Technol* 26:99
- Doymaz İ (2004a) Drying kinetics of white mulberry. *J Food Eng* 61(3): 341–346
- Doymaz İ (2004b) Effect of dipping treatment on air drying of plums. *J Food Eng* 64(4):465–470
- Doymaz İ (2012) Sun drying of seedless and seeded grapes. *J Food Sci Technol* 49(2):214–220
- Ertekin C, Yaldiz O (2004) Drying of eggplant and selection of a suitable thin layer drying model. *J Food Eng* 63(3):349–359
- Goyal RK, Kingsly ARP, Manikantan MR, Ilyas SM (2007) Mathematical modelling of thin layer drying kinetics of plum in a tunnel dryer. *J Food Eng* 79:176–180
- Karathanos VT (1999) Determination of water content of dried fruits by drying kinetics. *J Food Eng* 39(4):337–344
- Kumar N, Sarkar BC, Sharma HK (2012) Mathematical modelling of thin layer hot air drying of carrot pomace. *J Food Sci Technol* 49(1):33–41
- Madamba PS, Driscoll RH, Buckle KA (1996) The thin-layer drying characteristics of garlic slices. *J Food Eng* 29(1):75–97
- Midilli A, Kucuk H, Yapar Z (2002) A new model for single layer drying. *Dry Technol* 20(7):1503–1513
- Motavali A, Najafi G, Abbasi S, Minaei S, Ghaderi A (2011) Microwave–vacuum drying of sour cherry: comparison of mathematical models and artificial neural networks. *J Food Sci Technol* 1–9. doi:10.1007/s13197-011-0393-1
- Murthy T, Manohar B (2013) Hot air drying characteristics of mango ginger: prediction of drying kinetics by mathematical modeling and artificial neural network. *J Food Sci Technol* 1–10. doi:10.1007/s13197-013-0941-y
- Pandiyarajan V, Chinna Pandian M, Malan E, Velraj R, Seeniraj RV (2011) Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system. *Appl Energy* 88:77–87
- Simal S, Rossello C, Berna A, Mulet A (1994) Heat and mass transfer model for potato drying. *Chem Eng Sci* 22(49):3739–3744
- Simal S, Deyá E, Frau M, Rosselló C (1997) Simple modelling of air drying curves of fresh and osmotically pre-dehydrated apple cubes. *J Food Eng* 33(1–2):139–150
- Toğrul İT, Pehlivan D (2002) Mathematical modelling of solar drying of apricots in thin layers. *J Food Eng* 55(3):209–216
- Toğrul İT, Pehlivan D (2004) Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. *J Food Eng* 65(3):413–425
- Tunde-Akintunde TY, Ogunlakin GO (2013) Mathematical modeling of drying of pretreated and untreated pumpkin. *J Food Sci Technol* 50(4):705–713
- Velickova E, Winkelhausen E, Kuzmanova S (2013) Physical and sensory properties of ready to eat apple chips produced by osmo-convective drying. *J Food Sci Technol* 1–11. doi:10.1007/s13197-013-0950-x
- Verma LR, Bucklin RA, Endan JB, Wratten FT (1985) Effects of drying air parameters on rice drying models. *Trans ASAE* 28:296–301
- Wang Z, Sun J, Liao X, Chen F, Zhao G, Wu J, Hu X (2007) Mathematical modeling on hot air drying of thin layer apple pomace. *Food Res Int* 40:39–46
- Yilbas BS, Hussain MM, Dincer I (2003) Heat and moisture diffusion in slab products to convective boundary condition. *Heat Mass Transf* 39:471–476