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Mathematical modelling of mixed mode natural convection solar drying of tomato slices

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Abstract
The objective of the present investigation was to study the drying kinetics of tomato (*Lycopersicon Esculentum*) slices at different drying loads in a fabricated mixed mode natural convection solar dryer. Tomato slices were dried to the safe level moisture content in a period of 20 h, 23 h and 30 h with the drying loads of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2, respectively. The solar dryer was constructed at a low cost with locally obtainable materials. Nine different thin layer mathematical models were chosen to fit to the experimental data. The models were compared using the correlation coefficient (R^2), root mean square error (RSME) and the reduced chi-square (χ^2). Among all these models, the approximation of Two-term was shown a better fit to the experimental drying data compared to other model for 2 kg/m^2 and 4 kg/m^2 whereas the Logarithmic model was shown a better fit for a 6 kg/m^2 of drying load. The dryer efficiency increased from 17.33% to 35% with increased in drying loads from 2 kg/m^2 to 6 kg/m^2.

Keywords: Diffusivity, Dryer efficiency, Mathematical modelling, Solar dryer

1. Introduction
Drying is one of the oldest methods of food preservation practiced by humans and it extends the shelf life of the food product. Drying process makes the seasonal food available throughout the year to meet the thirst of food lovers. It also reduces transportation cost by lowering the weight and volume, packing size, storage space (Demir and Sacilik, 2010) [9]. In drying, heat and mass transfer occurs simultaneously in which moisture is removed from food products and carried away by hot drying air. Solar energy being the renewable energy is used by human by directly drying the food produce in the hot sun. It requires large area, results in uneven control of drying, involves high labour cost and also product quality is degraded because of dust, insects, birds and other foreign matter (Basunia and Abe, 2001) [5]. To overcome these difficulties, improvement of sun drying has led to evolution of solar drying protecting the food from contamination and weather conditions while retaining the nutritional qualities as such (Ukegbu and Okereke, 2013) [29].

Tomato (*Lycopersicon esculentum*) is considered as one of the most important vegetables occupying second position amongst the vegetable crops in terms of production (Abano *et al*., 2011) [1]. It is a perishable vegetable that contains higher moisture content so that it is necessary to dehydrate it without changing nutritional and sensory characteristics to use in off season. Dried tomatoes can be made into powder and is used as an ingredient in the manufacturing of different food products. At the market, rejection rates for tomatoes are 23% for good grades (Singh and Singla, 2011) [25]. The prediction of drying rate of the specific crops under various conditions is important for the design of the drying systems. Full-scale experimentation for different products is sometimes costly and not possible. The use of a simulation model is a valuable tool for predicting the performance of solar drying systems (Basunia and Abe, 2001) [5].

The design of the dryer equipment in terms of optimum drying times can be achieved through the use of mathematical models, promoting a better understanding of the drying mechanisms (Olanipekul *et al*., 2015) [19]. Extensive work has been carried out on mathematical modelling of thin layer drying of different agricultural food products such as apple (Wang *et al*., 2007) [30], red chilli (Kaleemullah and Kailappan, 2005) [15], organic apple (Sacilik and Elicin, 2006) [26], prickly pear peel (Lahsasni *et al*., 2004) [17], plum (Doymaz, 2004) [12], apricot (Togrul and Pehlivan, 2002; Togrul and Pehlivan, 2003) [27, 28], grape (Yaldiz *et al*., 2001) [32] and Pineapple (Reddy *et al*., 2017) [21].

This study was undertaken to investigate the thin-layer drying characteristics of tomato in a mixed mode natural convection solar dryer to fit the experimental data to mathematical models available in literature under different load conditions.

2. Material and methods
2.1 Drying procedure
A mixed mode natural convection solar dryer (Fig. 1) was fabricated at College of Agricultural Engineering, Sangareddy, Medak district, Telangana state of India. It is situated on the latitude of 17.6294 °N, longitude of 78.0917 °E and at an elevation of 621 m above mean sea level. The dimension of the dryer was 1300 mm×525 mm. Tomato (*Lycopersicon Esculentum*) used for the drying experiment were procured from a local market and stored in a refrigerator at 5±1 °C. Selection was based on visual assessment of uniform colour and geometry. Prior to drying, the individual tomatoes were then cut into uniform thickness of 6±1 mm using stainless steel knife**.** The initial moisture content of the tomatoes was determined according to AOAC (2000) [4]. The drying experiments were conducted during the month of April to May. During the drying process, the moisture loss of samples was determined by means of a digital electronic balance (Testing Instrument Pvt. Ltd., India) having an accuracy of ±0.001 g. The two trays were loaded with equal amount of tomato slices. During the experiments, temperatures were measured for every 10 min interval using digital thermometer.

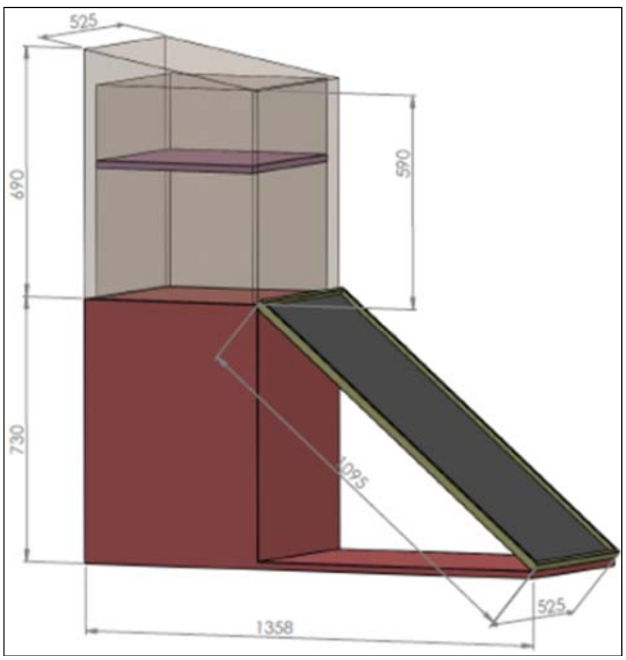

Fig 1: Mixed mode natural convection solar dryer

Moisture content on wet basis (M_{wb}) of fresh sample was calculated using the following equation

$$M_{wb} = \frac{(m_i - m_f)}{m_i} \times 100 \tag{1}$$

The recorded moisture contents for each sample were then used to plot the drying curves. The drying rate of tomato slices was calculated using following equation.

$$DR = \frac{\Delta M}{\Delta t} \tag{2}$$

Where
ΔM = loss of the mass of the crop (kg water/kg dry matter)
Δt = interval of time (min)

2.2 Dryer efficiency
The efficiency of the dryer for mixed mode type was calculated using the following equation

$$\eta_s = \frac{m_w h_{fg}}{IAt} \tag{3}$$

Where η_s is the dryer efficiency, h_{fg} is latent heat of vaporisation of water, kJ/kg, I is solar intensity, W/m^2, A is solar collector area and surface area of glass at the top, m^2, t is time of drying, h.

3. Mathematical modelling
The drying kinetics of tomato slices was expressed in terms of empirical models, where the experimental data were plotted in the form of dimensionless moisture ratio (MR) against drying time (expressed in min) for infinite slab (Crank, 1975; Doymez, 2009) [7] is

$$MR = \frac{M(t) - M_\infty}{M_o - M_\infty} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \pi^2 \frac{D_{eff} t}{4L^2} \right) \tag{4}$$

Where, MR is moisture ratio (dimensionless), M_t is moisture content at time t (kg water/kg solids), M_e is equilibrium moisture content (kg water/kg solids), M_o is initial moisture content, *n* = 1, 2, 3,... the number of terms taken into account; D_{eff} is the effective moisture diffusivity (m^2/s), and L is half the thickness of slice of the sample (m), t is the drying time, h. For longer drying periods for infinite slab, the equation is simplified to first term of series only, without much affecting the accuracy of the prediction (Akpinar, 2006) [2].

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4L^2} \right) \tag{5}$$

The above equation can also be written in a more simplified form as

$$MR = \frac{M - M_e}{M_o - M_e} \tag{6}$$

During drying of tomato, the equilibrium moisture content was not determined because this value is relatively small compared to M or M_o (Doymaz, 2009) [13], so the equilibrium moisture content was assumed to be zero. Hence, the moisture ratio was simplified according to Kingsly *et al*. (2007) [16] to given below equation

$$MR = \frac{M}{M_o} \tag{7}$$

The experimental set of (MR, t) were fitted to 9 different empirical drying models widely used in scientific literature shown in Table 1 to analyse the thin layer drying kinetics of tomato slices. Three primary criteria used to determine the goodness of fit for selected models (Table 1) in the layer drying were; the correlation coefficient (R^2), root mean square error (RMSE) and reduced chi-square (χ^2).The goodness of fit to the models was determined based on highest R^2, lowest χ^2 and RMSE. Several authors have been used these criteria to select the best models for drying sultana grapes (Yaldiz *et al*., 2001) [32], potato slices (Srivastava *et al*., 2015) [26], sweet potato slices (Diamante and Munro, 1993) [10], apricot (Togrul and Pehlivan, 2002) [27], Pineapple (Reddy *et al*., 2017) [21]. The different statistical evaluation [Equations 8, 9 and 10] to describe the goodness of fit of the dried tomato slices (Rayaguru and Routray, 2012; Roberts *et al*., 2008) [20, 22] were as follows:

$$R^2 = \frac{N\sum_{i=1}^{N} MR_{pred,i} MR_{expt,i} - \sum_{i=1}^{N} MR_{pred,i} \sum_{i=1}^{N} MR_{exptX,i}}{\sqrt{\left(N\sum_{i=1}^{N} MR^2_{pred,i} - \left(\sum_{i=1}^{N} MR_{pred,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR^2_{expt,i} - \left(\sum_{i=1}^{N} MR_{expt,i}\right)^2\right)}} \quad (8)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{ecpt,i} - MR_{pred,i}\right)^2} \quad (9)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{expt,i} - MR_{pred,i}\right)^2}{N - z} \quad (10)$$

Where $MR_{expt,i}$ and $MR_{pred,I}$ are the experimental and predicted dimensionless MR respectively, N is the number of observations, and z is the number of model constants. The drying rate constants and coefficients of the model equations were determined with nonlinear regression analysis using curve fitting tool in MATLAB software package (R2015a (8.5.0.197613)) and the goodness of fit of the curves was determined with correlation analysis.

3.1 Estimation of effective moisture diffusivity

The complete profile of drying consists of two stages; the first stage of drying, a constant rate period, and a falling rate period (Bon *et al*., 1997) [6]. During drying, diffusion is a complex process and it can be defined from Fick's second law as given below:

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \quad (11)$$

Where M = moisture content (kg of water/kg of dry matter).
The falling rate period of biological materials is best described by Fick's second law of diffusion (Crank 1975; Roberts *et al*., 2008) [7, 22]. The effective moisture diffusivity was estimated by using analytical solution of Fick's second law for unsteady state diffusion. This analytical solution of above equation is solved by considering tomato slice as an infinite slab geometry, assuming uniform initial moisture distribution, constant temperature and diffusivity coefficient, and negligible external mass transfer resistance (Crank, 1975; Doymez, 2009) [7]. The solution for above equation is given in equation [4]. Effective moisture diffusivity (D_{eff}) of the tomato slices was obtained from the slope (m) of the plot of ln (MR) against the drying time. The plot of ln (MR) versus time results in a straight line with negative slope and D_{eff} is calculated from the following expression

$$m = \frac{\pi^2 D_{eff}}{4L^2} \quad (12)$$

4. Results and Discussion

4.1 No-load condition

It was observed that the average maximum and average minimum temperature inside the dryer was 51 °C and 37 °C, respectively. Relative humidity for the corresponding temperatures was 52% and 68%. Similarly, outside the dryer, the ambient temperatures of maximum and minimum observed to be 40 °C and 30 °C. Hence, inside the drier, there is an increase in temperature of about 11 °C as compared to the outside ambient temperature. The average solar radiation was observed to be 1084.257 W/m^2.

4.2 Drying kinetics under different drying loads

During drying of tomato slices with loads of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2, the weather was generally sunny and no rain appeared. The maximum and minimum temperature inside the solar dryer during the drying periods of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2 were observed to be 50.5 °C and 37 °C; 51.5 °C and 37 °C; 51.7 °C and 37 °C, respectively. The average solar insolation during drying of these loads in a dryer was observed to be 1097.62 W/m^2, 1041.37 W/m^2 and 1114.25 W/m^2, respectively.
Fig. 2 shows the reduction in moisture content from 93.67% to 7.76% (w.b.) in 20 h, 7.65% (w.b.) in 23 h and 7.56% (w.b.) in 30 h of duration for 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2, respectively. Fig. 3 represents the plot of moisture ratio against time for the drying load of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2. This drying curve shows that moisture ratio decreased exponentially with increased in drying time. It was observed that load of 6 kg/m^2 was associated with higher moisture ratio followed by 4 kg/m^2 and 2 kg/m^2. It can also be observed that the removal of moisture was faster at the beginning hour due to the availability of free unbound moisture than immediate following hours. This observation is in agreement with previous results on thin-layer drying of apple pomace (Wang *et al*., 2006) [30].

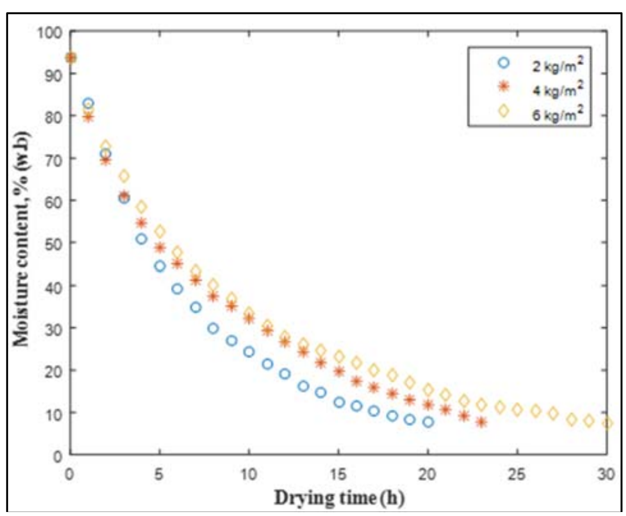

Fig 2: Variation of moisture content with drying time for different drying loads

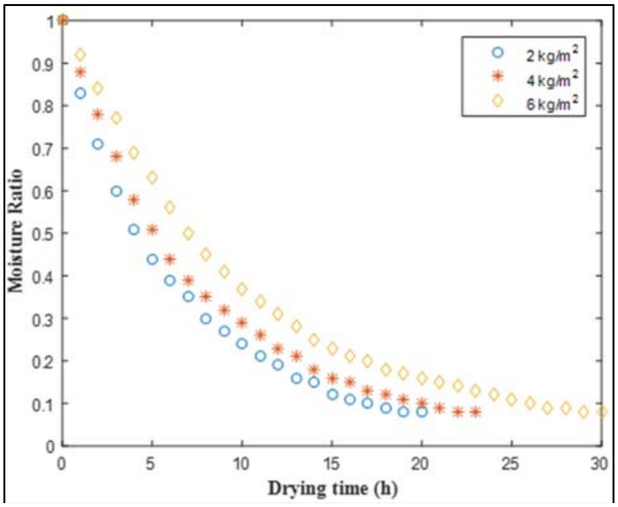

Fig 3: Comparison of moisture ratio with drying time for different drying loads

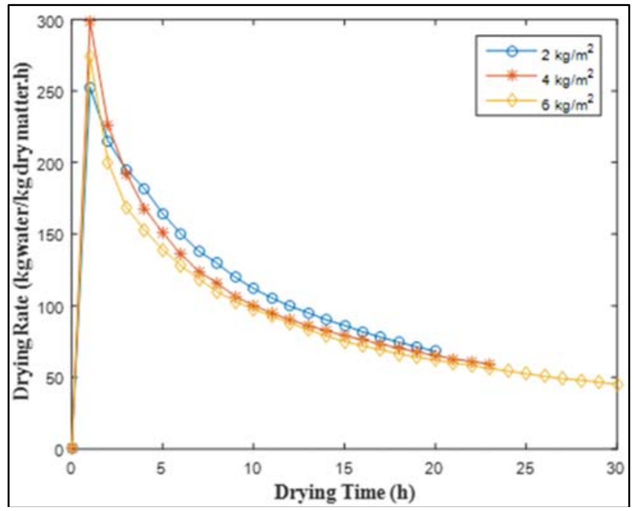

Fig 4: Comparison of drying rate with drying time for different drying loads

Variation of drying rate with respect to drying time is shown in Fig. 4. Initially, the rate of drying was more and was found to be decreasing as drying time proceeds. The drying rate was significantly affected by all drying loads. It can be observed that the drying of tomato took place in the falling rate period as there is no much constant rate period, thus indicating that the drying rate is controlled by liquid diffusion from interior parts of solid to surface (Diamante and Munro, 1993) [10]. In general, the internal mass transfer was there by molecular diffusion or vapours diffusion or by capillary forces in the interior region of the product and the water was evaporated as it reached the surface. These results were in agreement with the results for sultana grape (Yaldiz *et al*., 2001) [32], apricot (Akpinar *et al*., 2004) [3], plum (Doymaz, 2004) [12] and prickly pear peel (Lahsasni *et al*., 2004) [19].

4.3 Fitting of the drying curves

The moisture content data observed during the experiment were converted into the moisture ratio (MR) and fitted to the nine models as listed in Table 1. The statistical results of the different models, including the drying model constants and the comparison criteria used to evaluate goodness of fit, namely, R^2, χ^2 and RSME are presented in Table 2 for 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2. We need the lower value of χ^2, RMSE to reach zero and higher value of R^2 for the better goodness of the fit. The Two-term was the best fitted model among all mathematical models for load of 2 kg/m^2 and 4 kg/m^{2}with highest R^2 as 0.99971 and 0.99943; lowest χ^2 as 2.03×10^{-5} and $4.17\times10^{-5}$and lowest RMSE as 0.0045 and 0.008459, respectively whereas for a load of 6 kg/m^2, Logarithmic model was best suited compared to other models with highest R^2 as 0.99935 and lowest $\chi^2$and RMSE as $4.78\times10^{-5}$and 0.006914 respectively.

Table 1: Mathematical models applied to the drying curves

Model name	Model Expression	References
Henderson and Pebis	MR=a*exp(-k*x)	Mercali *et al*., (2010)
Logarithmic	MR=a*exp(-k*x)+c	Akpinar (2006) [2]
Modified Page	exp(-(k*x)^n)	Yaldiz *et al*., (2001) [32]
Newton	exp(-k*x)	Westerman *et al*., (1973)
Page	MR=exp(-k*x^n)	Diamante *et al*., (2010) [11]
Pegleg	1-x/(a+b*x)	Mercali *et al*., (2010)
Silva *et al*.	exp(-a*x-b*sqrt(x))	Da Silva *et al*., (2014)
Two-term	MR=a exp(-k_1x) + b exp(-k_2x)	Henderson (1974)
Two-term exponential	a exp(-k*x)+(1-a)exp(-k*a*x)	Sharaf-Eldeen *et al*., (1980)

Table 2: Statistical parameters for different mathematical models for a drying load of 2 kg /m^2, 4 kg /m^2 and 6 kg /m^2

Model Name	Model constants	R^2	RMSE	χ^2
2 kg /m^2				
Henderson and Pebis	k=0.1412, a=0.9546	0.99478	0.01958	3.83×10^{-4}
Logarithmic	k=0.1676, a=0.9258, c=0.05421	0.99851	0.01074	1.15×10^{-4}
Modified Page	k=0.1964, n=0.8653	0.99957	0.00562	3.15×10^{-5}
Newton	k=0.1486	0.99161	0.02419	5.85×10^{-4}
Page	k=0.19634, n=0.8653	0.99957	0.00562	3.15×10^{-5}
Pegleg	a=4.953, b=0.8228	0.9995	0.00603	3.63×10^{-5}
Silva *et al*.	a=0.1131, b=0.09593	0.99899	0.00862	7.43×10^{-5}
Two-term	k1=0.1149, k2=0.3955, a=0.7318, b=0.268	0.99975	0.0045	2.03×10^{-5}
Two-term exponential	k=0.3627, a=0.3063	0.99974	0.00441	6.20×10^{-5}
4 kg /m^2				
Henderson and Pebis	k=0.1412, a=0.9546	0.99478	0.019575	2.03×10^{-4}

Logarithmic	k=0.1398, a=0.9614, c=0.04161	0.99933	0.007293	5.32×10^{-5}
Modified Page	k=0.12694, n=0.93282	0.99877	0.009676	9.36×10^{-5}
Newton	k=0.1256	0.99696	0.014891	2.22×10^{-4}
Page	k=0.1458, n=0.9328	0.99877	0.009676	9.36×10^{-5}
Pegleg	a=6.293,b=0.7859	0.99764	0.013413	1.80×10^{-4}
Silva *et al*.	a=0.1128,b=0.03709	0.99823	0.01163	1.35×10^{-4}
Two-term	k1=0.07882, k2=0.1809, a=0.399, b=0.6102	0.9995	0.006459	4.17×10^{-5}
Two-term exponential	k=0.1937,a=0.4668	0.99939	0.006818	2.37×10^{-4}
	6 kg /m^2			
Henderson and Pebis	k=0.09536, a=1.004	0.99792	0.012585	1.58×10^{-4}
Logarithmic	k=0.1059, a=0.9844, c=0.03603	0.99939	0.006914	4.78×10^{-5}
Modified Page	k=0.09526, n=0.98037	0.99804	0.012188	1.49×10^{-4}
Newton	k=0.095	0.9979	0.012424	1.54×10^{-4}
Page	k=0.09976, n=0.9804	0.99804	0.012188	1.49×10^{-4}
Pegleg	a=8.664, b=0.7638	0.9946	0.020261	4.10×10^{-4}
Silva *et al*.	a=0.09412, b=0.002912	0.99791	0.012605	1.59×10^{-4}
Two-term	k1=0.08209, k2=0.08089, a=9.258, b= 8.274	0.99712	0.015321	1.70×10^{-4}
Two-term exponential	k=0.1211, a=0.5781	0.99857	0.010413	1.60×10^{-4}

Fig. 5 illustrates the comparison between experimental moisture ratio and predicted moisture ratio by Two-term model for 2 kg/m^2 and 4 kg/m^2, respectively and by Logarithmic model for 6 kg/m^2. It can be observed that there is very good agreement between calculated and experimental data, which indicates that the Two-term and Logarithmic model could adequately describe the drying behaviour of tomato at different loading rates of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2, respectively.

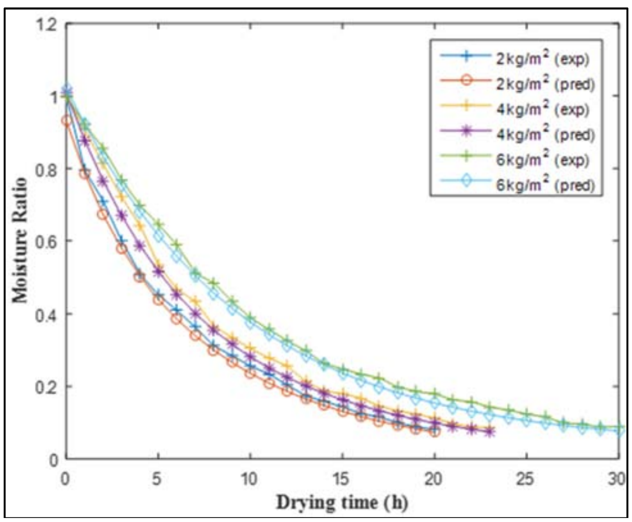

Fig 5: Comparison of the experimental and predicted moisture ratio against drying time at different drying loads

4.4 Effective moisture diffusivity

The effective moisture diffusivity was computed by using the graph of ln (MR) against time for different loads is shown in Fig. 6. The moisture diffusivity of tomato in natural convection drying were decreased with increased in drying loads of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2. The maximum value of D_{eff} was obtained as 3.209×10^{-7} m^{2}s^{-1} during the experiment for a loading rate of 2 kg/m^2. The minimum value of D_{eff} was found to be 2.201×10^{-7} m^2 s^{-1} was for 6 kg/m^2. According to reports (Wang *et al*., 2007) [30], the values of effective diffusivity fall within the range of 10^{-11} to 10^{-6} m^2/s for all agricultural and food products.

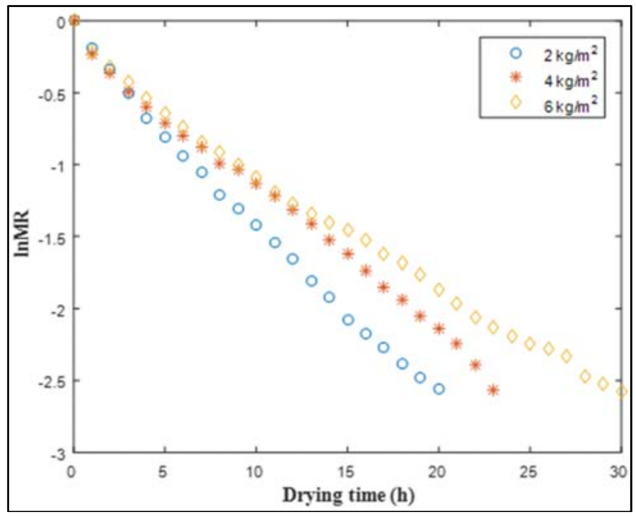

Fig 6: Comparison of ln (MR) with drying time for different drying loads

4.5 Dryer overall efficiency

The overall efficiency of the drying is affected by several factors such as drying time, climatic conditions (solar radiation and temperature), the drying characteristics of the dried materials, and structure of the drying devices etc. In the present research work, the efficiency of mixed mode natural convection solar dryer for three loads of 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2 was found to be 17.33%, 30.37% and 35%, respectively. During drying process, it was observed (graph is not presented here) that higher efficiency was observed at initial stage of drying, later stage this dryer efficiency was decreased due to decrease in moisture content. Moreover, the efficiency was more at a drying load of 6 kg/m^2 might be due to highest drying time and more amount of moisture loss in sample whereas efficiency was less at 2 kg/m^2 might be due to less drying time and less amount of moisture loss.

5. Conclusion

The drying characteristics of the tomato slices were studied in a fabricated mixed mode natural convection solar dryer for different drying loads with nine mathematical models to fit the experimental data. The results indicate that the Two-term model was best to fit the drying data for 2 kg/m^2 and 4 kg/m^2, whereas Logarithmic model for 6 kg/m^2. The drying process took place in falling rate period. The moisture diffusivity ranges from 3.209×10^{-7} m^{2}s^{-1} to 2.201×10^{-7} m^{2}s^{-1}. The drying rate gradually decreased with increased load. The efficiency of the mixed mode natural convection solar dryer for 2 kg/m^2, 4 kg/m^2 and 6 kg/m^2 was observed to be 17.33%, 30.37% and 35%, respectively.

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