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RESEARCH PAPER

Mathematical modeling of infrared assisted hot air drying of ginger slices

P. V. ALFIYA* AND **S. GANAPATHY**
Department of Food and Agricultural Process Engineering, Tamil Nadu Agricultural University, COIMBATORE (T.N.) INDIA

ABSTRACT

Infra-red assisted hot air drying studies were conducted on ginger slices of diameter 20±2.5 mm and thickness 5±0.5 mm. Drying experiments were executed under infra-red and hot air temperature of 60 ^{0}C with two levels of air velocities: 0.8 m/s and 1.4 m/s. the drying rate was found to increase proportionately with the drying air velocity, thereby minimising the total drying time. Time taken for drying ginger slices from an initial moisture content of 442 per cent (d.b.) to a final moisture content of 8.4 per cent (d.b.) at 0.8 m/s air velocity was 300 min. Whereas, it took 210 min to lower the moisture content of ginger from 433.33 per cent (d.b.) to 6.67% (d.b.) under the drying air velocity of 1.4 m/s. Infrared drying temperature of 60 ^{0}C in combination with air velocity of 0.8 m/s showed better results for quality evaluation with reduced drying times. Logarithmic model fitted the experimental data well for the whole range of temperatures (R^2= 0.9989, RMSE= 0.0119 and λ^2= 0.000140574).

Key Words : Infra-red, Ginger drying, Logarithmic model, Moisture ratio, Drying rate

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Ginger (*Zingiber officinale* Rose.) is a widely used spice mainly found in Asia. India is a leading producer of ginger in the world with a production of 7.60 lakh tonnes from an area of 142000 hactares; the productivity being 5.4 MT per hectare. Thirty per cent of the ginger produced is converted to dried ginger and 20 per cent is consumed as seed material (Sundari *et al.*, 2013). Indian dried ginger is known in international market under the trade name of Cochin ginger (NUGC) and Calicut ginger (NUGK). But the crude and imperfect methods adopted in the country for the production of dried ginger, reduces the export market potential. Hence, improved drying technology is needed in the area to achieve high turnover in ginger export. Sun drying is the commonly adopted method of drying ginger which has many disadvantages. Availability of sunshine, space requirements, pest and disease infestations, uncontrolled drying conditions, time consumption and quality factors accounts to this (Jayashree *et al.*, 2014). Also, the yield of dry ginger is about 19-25 per cent of fresh ginger depending on the variety and climatic zone (Midilli, 2001). In order to fulfil the quality and food product requirement

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* **Author for correspondence**
P.V. Alfiya, Central Institute of Fisheries Technology, COCHIN (T.N.) INDIA

of the growing population, efficient and affordable drying methods should be practiced.

Effectiveness of crop drying have been improved by adopting combined mode of drying such as convective and microwave assisted methods (Giri and Prasad, 2007). Studies on the application of infra-red (IR) for combined mode of drying of food materials have been reported (Hebbar *et al.*, 2004) very recently. When infra-red and hot air drying methods are combined, by virtue of high density and penetrative depth of the former, the moisture migration towards the surface becomes rapid. Further, the moisture gradient is maintained by the convective air flow across the surface. Studies on energy and quality aspects of barley during infra-red assisted hot air drying showed a substantial reduction in energy consumption (Afzal *et al.*, 1999). Continuous type combined infra-red and hot air dryer was developed by Hebbar *et al.*, 2004 for fruits and vegetables. Combined infrared and hot air dying studies on onions indicated an improvement in product quality as compared to hot air drying alone (Praveenkumar *et al.*, 2005). Therefore, this work aims to study the drying characteristics and hot air assisted infra-red drying of ginger and establishes the best fit model to the drying data.

RESEARCH METHODOLOGY

Plant material:

Raw ginger (*Zingiber officinale*) was procured from Calicut. The rhizomes of ginger were properly washed under running water and excess moisture on surface was wiped off with a filter paper. Ginger was made into circular pieces of 20 mm diameter. These samples were used for infra-red assisted hot air drying studies.

Infrared dryer:

A batch type infrared and hot air dryer fabricated at the Food and Agricultural Process Engineering Department of Tamil Nadu Agricultural University, Coimbatore was used for experimentation. Dryer was fitted with quartz lamps (Wavelength=1.1-1.2 µm). a thermostat was used to control the drying temperatures in the system. To ensure uniform power intensity, the position of samples and the distance between source and samples were fixed for all the experimental runs. 500 g of cleaned and sliced ginger was spread in a single layer uniformly over the mild steel tray for each drying trials. The samples were drawn at regular intervals of 30 minutes for moisture analysis.

The experiments were carried out at drying temperature of 60 ^{0}C for different air velocities (0.8 and 1.4 m/s). ginger samples were mixed intermittently (every 5 minutes) for uniform drying without affecting the steady state conditions. The slices were cooled to room temperature (27±2 ^{0}C) in a desiccator to prevent them from absorbing moisture from atmosphere.

Selection of drying temperatures and air velocities:

Spices are generally dried at temperatures between 50 to 70 ^{0}C (Hoque *et al.*, 2013). Drying time was longer at lower temperatures which often resulted in browning of products. At the same time, case hardening was found to be an obstacle to high temperature drying. This caused outer surface to be over dried resulting in disintegration of moisture diffusion from interior part of the product during drying. Final dried material could not be regarded as quality one because of non-uniform drying. Therefore, temperature level of 60 ^{0}C was selected for safe drying.

Smaller velocities of air flow were not effective in penetrating into product and cause evaporation of moisture. A too high rate of air velocities had a negative effect due to evaporative cooling from surfaces. The air velocities were kept at levels of 0.8 m/s and 1.4 m/s which were found to have a desirable effect on mass transfer rates (Praveenkumar *et al.*, 2005).

After completion of drying, samples were collected, cooled in a desiccator to ambient temperature and then sealed in ploythene bags.

Drying characteristics of ginger:

Determination of dry basis moisture content:

$$\mathbf{MC\,(d.b)} = \frac{\mathbf{Ww}}{\mathbf{Wd}}\,\mathbf{x\,100} \qquad .....(1)$$

MC % (d.b) : Moisture content, present dry basis

W_w: Weight of water evaporated to make ginger bone-dry condition, g

W_d: Weight of dry matter content present in ginger, g.

Determination of drying rate:

$$\mathbf{k} = \frac{\mathbf{Ww}}{\mathbf{T}} \qquad .....(2)$$

K: Drying rate, g/h

W_w: Quantity of moisture evaporated, g

T: Time taken (for drying) to remove water Ww g of moisture, h.

Determination of moisture ratio:

$$\mathbf{MR} = \frac{\mathbf{M - Me}}{\mathbf{Mo - Me}} \qquad .....(3)$$

MR: Moisture ratio, dimensionless value
M: Moisture content at any time t, % (db)
M_e: Equilibrium moisture content, % (db)
M_o: Initial moisture content, % (db).

Modelling of drying characteristic curves:

From the drying data collected during different drying experiments moisture ratio values were determined and plotted against drying time. The resulted experimental values were tested and verified with eight well known drying models to determine the best fit model to determine the best fit model to describe the drying experiments.

Non-linear regression procedure was performed on all drying curves to estimate the parameters associated with the selected models using software MATLAB (2012). The co-efficient of determination R^2 was primary criterion for selecting the best fit model to describe drying data. The goodness of fit for each model was evaluated based on root mean square error (RMSE) and Chi-square (λ^2).

RESULTS AND REMONSTRATION

The results obtained from the present investigation as well as relevant discussion have been summarized under following heads :

Drying rate curves in hot air assisted infrared drying of ginger:

The reduction in drying time during hot air assisted infrared drying of ginger at 60 ^{0}C is shown in Fig. 1. The drying time requird for drying of ginger from initial moisture content of 442 per cent (db) to a final moisture content of 8.4 per cent (db) at 0.8 m/s air velocity was 300 minutes. The combination of drying temperature at 60 ^{0}C and air velocity at 1.4 m/s required 210 minutes to lower the moisture content of ginger from 433.33 per cent (db) to 6.67 per cent (db). The increase in drying air velocities resulted in increased rates of heat and mass transfer leading to a reduction in drying times during hot air assisted infrared drying of onion slices (Praveenkumar *et al.*, 2005). A reduction of 30 per cent in drying time was observed when the drying air velocities were increased from 0.8 m/s to 1.4 m//s, respectively. Similar trends were observed by Mazza and LeMaguer (1980) during the convection drying of onion slices. Faster drying rates were also observed by Mongpraneet *et al*. (2002) during far IR onion drying under vacuum.

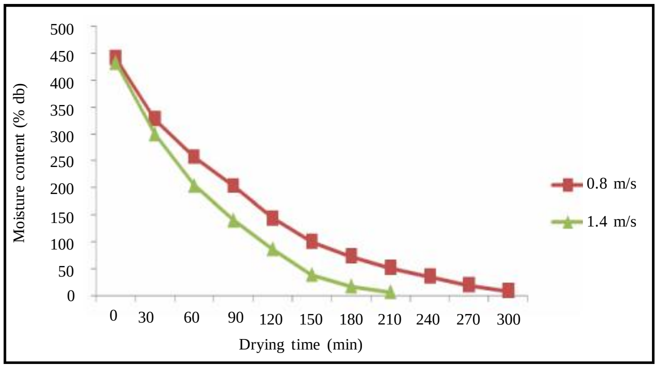

Fig. 1 : **Drying curve of ginger at 60°C**

Moisture ratio studies :

From the drying data collected, moisture ratio were determined and shown in Fig. 2 for drying temperature of 60 ^{0}C at air velocities 0.8 m/s and 1.4 m/s. moisture ratio recorded a maximum value of 1.00 just before starting of drying experiment and recorded a value of 0.009 and 0.0153 for velocities 0.8 m/s and 1.4 m/s, respectively, at the time of establishing equilibrium moisture content with drying conditions prevailed at the time of drying. in between, moisture ratio recorded a gradual and continuous decrease in its value.

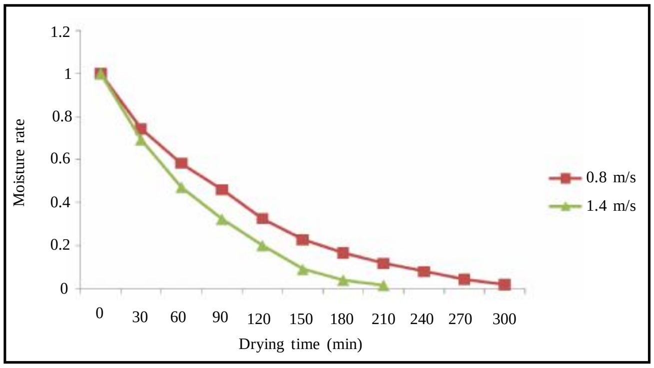

Fig. 2 : **Moisture ratio vs. drying time curve during drying of ginger**

Modelling of drying data collected was done using MATLAB software programme. Well established drying models namely, Newton, Page, Modified Page, Henderson and Pabis, Logarithmic, Two term exponential, Wang and Singh (1978) and Verma and Singh (1985) were considered for modelling study. Result of the study at temperature of 60 ^{0}C and air velocity of 0.8 m/s is tabulated in Table 2. From the table it is evident that Logarithmic model recorded a maximum value R^2 value of 0.9989, minimum RMSE value of 0.0119 and the lowest Chi-square value of 0.000140574. The best fit Logarithmic model is as follows:

$$\mathbf{MR} = \frac{\mathbf{M - Me}}{\mathbf{Mo - Me}} = \mathbf{1.068e^{-0.008156t} - 0.07475} \qquad \text{......(4)}$$

Results of modelling studies (Regression analysis) of infrared assisted hot air drying of ginger at infrared temperature of 60 ^{0}C and air velocity of 1.4 m/s are presented in Table 3. The best fit Logarithmic model

Table 1 : Drying models considered for drying data collected

Model name	Equation	Reference
Newton	$MR = \frac{M - Me}{Mo - Me} = e^{-kt}$	Ayensu (1997)
Page	$MR = \frac{M - Me}{Mo - Me} = e^{-kt^{n}}$	Page (1949)
Modified page	$MR = \frac{M - Me}{Mo - Me} = e^{(-kt)^{n}}$	Yaldiz *et al.* (2001)
Henderson and Pabis	$MR = \frac{M - Me}{M0 - Me} = ae^{-kt}$	Henderson and Pabis (1969)
Logarithmic	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + c$	Akpinar *et al.* (2003)
Two-term exponential	$MR = \frac{M - Me}{Mo - Me} = ae^{-k1t} + A1e^{-k2t}$	Yaldiz *et al.* (2001)
Wang and Singh (1978)	$MR = \frac{M - Me}{Mo - Me} = 1 + at + bt^{2}$	Wang and Singh (1978)
Verma and Singh (1985)	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + (1 - a)e^{-gt}$	Verma and Singh (1985)

Table 2: Results of modeling study (T=60 ^{0}C, AV=0.8 m/s)

Model name	Equation	Parameter values	R^2	Adj. R2	RMSE	Chi-square
Newton	$MR = \frac{M - Me}{Mo - Me} = e^{-kt}$	k=0.009655	0.9948	0.9948	0.023	0.00053
Page	$MR = \frac{M - Me}{Mo - Me} = e^{-kt^{n}}$	k=0.006084 n=0.8567	0.997	0.9967	0.0184	0.000339
Modified Page	$MR = \frac{M - Me}{Mo - Me} = e^{(-kt)^{n}}$	k=0.01127 n=1.012	0.9948	0.9942	0.0243	0.000589
Henderson and Pabis	$MR = \frac{M - Me}{M0 - Me} = ae^{-kt}$	a=1.012 k=0.009768	0.995	0.9945	0.0238	0.000565
Logarithmic	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + c$	a=1.068 k=0.008156 c=-0.07475	0.9989	0.9986	0.0119	0.000140574
Two term exponential	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + (1 - a)e^{(-kat)}$	a=1.039 k=0.01002	0.9955	0.9935	0.0257	0.00152988
Wangh and Singh (1978)	$MR = \frac{M - Me}{Mo - Me} = 1 + at + bt^{2}$	a=-0.007121 b=0.00001323	0.9923	0.9914	0.0296	0.000876729
Verma and Singh (1985)	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + (1 - a)e^{-gt}$	a=-0.03897 k=0.988 g=0.01002	0.9955	0.9943	0.024	0.000578

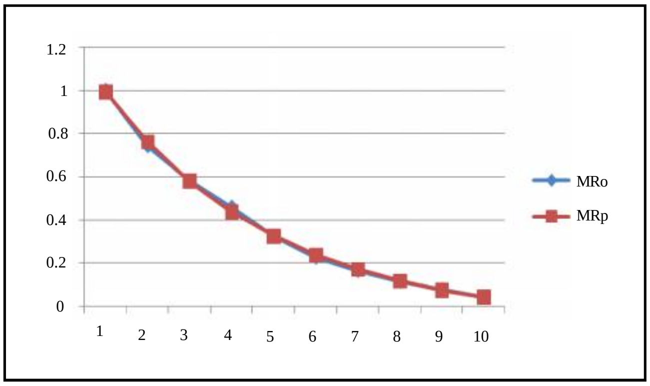

Fig. 3 : **Moisture ratio curve (T=60 ^{0}C, AV=0.8 m/s)**

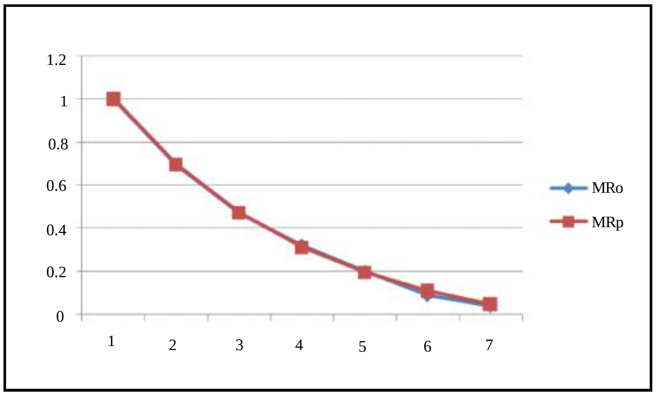

Fig. 4 : **Moisture ratio curve (T=60 ^{0}C, AV=1.4 m/s)**

shows $R^2 = 0.9991$, RMSE=0.0126 and λ^2=0.000159824. The model is represented by:

$$\mathbf{MR} = \frac{\mathbf{M - Me}}{\mathbf{Mo - Me}} = \mathbf{1.118e^{-0.01064t} - 0.1177} \qquad \text{......(5)}$$

Doymaz (2004) applied several thin layer models for air drying experiments of mulberry and found that Logarithmic model represents drying data batter than any other models with R^2=0.9990. in the present study, also Logarithmic model fitted into drying data very well with R^2= 0.9991. This confirms the findings reported in the present study.

The experimental and predicted values of moisture ratios at varying air velocity of 0.8 m/s and 1.4 m/s are presented in Fig. 3 and 4, respectively. It is evident from theses figures that minimum deviation exists between the experimental and predicted values. Hence, logarithmic model explains the drying characteristics satisfactorily.

Conclusion:

The study concluded that 30 per cent of reduction in drying time can be achieved when drying air velocity is increased from 0.8 to 1.4 m/s. the drying of ginger sliced occurs under falling rate period. Logarithmic model satisfactorily explains the drying process during whole range of drying temperature and drying air velocities.

Table 3 : Results of modeling study (T=60 ^{0}C, AV=1.4 m/s)

Model name	Equation	Parameter values	R^2	Adj. R^2	RMSE	Chi-square
Newton	$MR = \frac{M - Me}{Mo - Me} = e^{-kt}$	k=0.01356	0.9906	0.9906	0.0339	0.001147
Page	$MR = \frac{M - Me}{Mo - Me} = e^{-kt^n}$	k=0.006163 n=1.175	0.9964	0.9958	0.0225	0.000508
Modified Page	$MR = \frac{M - Me}{Mo - Me} = e^{(-kt)^n}$	k=0.1817 n=0.07464	0.9906	0.989	0.0366	0.001338
Henderson and Pabis	$MR = \frac{M - Me}{M0 - Me} = ae^{-kt}$	a=1.021 k=0.01383	0.9913	0.9898	0.0353	0.001245
Logarithmic	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + c$	a=1.118 k=0.01064 c=-0.1177	0.9991	0.9987	0.0126	0.000159824
Two term exponential	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + (1 - a)e^{(-kat)}$	a=-0.114 k=0.9841	0.994	0.9845	0.0358	0.001282937
Wangh and Singh (1978)	$MR = \frac{M - Me}{Mo - Me} = 1 + at + bt^2$	a=-0.009855 b=0.00002493	0.9966	0.9961	0.0219	0.000478657
Verma and Singh (1985)	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + (1 - a)e^{-gt}$	a=1.114 k=0.01498 g=0.9063	0.994	0.9916	0.032	0.001026

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