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ORIGINAL ARTICLE

Drying kinetics and ANN modeling of paneer at low pressure superheated steam

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Abstract Drying characteristics, selection of analytical model and development of artificial neural network (ANN) models of 1 cm^3 paneer at low pressure superheated steam drying (LPSSD) were studied. Effects of steam temperature and pressure on drying rates were determined. Page's model was selected as the best predictive model. Second degree polynomial, non linear regression analysis resulted in a good agreement of defined model by changing the values of temperature and corresponding pressure. Optimized ANN models were developed for all data set. The correlation coefficient for all data set was >0.98 in all cases.

Keywords Paneer · Artificial neural network · Drying · Superheated steam drying

Superheated steam drying emerged as a viable new drying technology with immense potential only in the past decade or so. Low pressure superheated steam drying (LPSSD) is being explored for drying of food materials due to its numerous advantages such as less energy wastage, high heat transfer coefficient, no oxidative changes during drying, no resistance to mass transfer at the surface, higher porosity, recovery of latent heat of evaporation and higher mass transfer rates (Mujumdar 2006). Most foods or other temperature sensitive products melt, undergo glass transition or are damaged at the temperature of superheated steam corresponding to the atmospheric or higher pressure. One possible way to alleviate the above mentioned problems is to operate the dryer at reduced pressure. LPSSD has been applied to drying of shrimp banana, apples, potatoes, cassavas, and carrots (Elustondo et al. 2001; Mujumdar 2004a, b).

Elustondo et al. (2001, 2002) studied LPSSD of foodstuffs. Wood slabs, shrimps, bananas, apples, potatoes and cassavas were dried using steam pressures of 10–20 kPa and steam temperatures of 60–90 °C. Devahastin et al. (2004) studied the drying of carrot cubes in both LPSSD and vacuum dryers. Carrots were dried using 7–13 kPa pressure and temperature was 60, 70 and 80 °C. They observed that the difference between 2 sets of drying rate data were smaller at high drying temperatures. Leeratanarak et al. (2006) studied the drying of potato using both LPSSD and hot air drying. They found that LPSSD took shorter time to dry the product than hot air. Tatemoto et al. (2001, 2007) found that the sample temperature became lower as the pressure in the drying chamber decreased, since the boiling point of water decreased. Panyawong and Devahastin (2007) dried carrot cubes using LPSSD and vacuum drying and found that the shrinkage was not significantly different between the two processes.

Several attempts have been made to develop analytical and empirical models. Page's, generalized exponential and logarithmic model were used to select the best predictive model for LPSSD system. During last few years, interest in using artificial neural networks (ANN) as a modeling tool in food technology has increased. ANN have been successfully used in several food applications like model for prediction of drying rates, physical properties of dried carrot, prediction of dryer performance, extrusion processing of wheat and wheat-black soybean, energy requirements for size reduction of wheat, grain drying process, dough

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rheological properties among others (Huang and Mujumdar 1993; Ruan et al. 1995; Fang et al. 2000; Islam et al. 2003; Shihani et al. 2004; Kerdpiboon et al. 2006).

The present work, therefore, aimed at investigating the drying characteristics of paneer, selection of predictive model from the available analytical model namely Page's, generalized exponential and logarithmic model and to develop ANN models for drying of paneer using LPSSD.

Materials and methods

A schematic diagram of experimental setup of LPSSD is shown in Fig. 1. The drying chamber consisted of a box insulated properly with rock wool. Two electric heaters of 1.5 kW each was provided on opposite side walls of the drying chamber. The temperature of drying chamber was controlled by a temperature controller. The drying chamber was connected by a pipe from bottom to a chamber in which digital balance was kept. An autoclave was used as a steam generator and a steam reservoir. A steam trap was provided to reduce accumulation of steam condensate in the reservoir. Steam was transported to the drying chamber through a pipe insulated with glass wool. A heating tape, rated 1 kW was mounted on steam pipeline to increase the steam temperature to desired level of superheating. Sample holder was connected to a balance by a thin rod passing through a G.I. pipe. One side of the rod was attached to the sample holder and other side was rested on analytical digital balance. The balance had a weighing capacity of 320 g with a least count of 0.001 g. Electronic balance attached with computer through the serial cable allowed continuous weighing of the sample.

Chromel - Alumel (K type) thermocouples were installed to measure temperature of superheated steam at inlet of drying chamber, drying chamber itself and product chamber, instantaneously. These thermocouples were attached to the data logger (Model 1551 C12 of Digitech, Roorkee, India) Thermocouple signals multiplexed and transferred to the computer through Terminal Software, installed in PC. A vacuum pump was used to create the desired vacuum in the drying chamber. Paneer samples of 1 cm^3 size were used to study the drying kinetics. Experiments were performed at 10, 14 and 18 kPa absolute pressure and 62, 72 and 82 °C.

Materials and methods

Paneer with the brand name 'Anchal', prepared from standardized cow milk was procured from Anchal Dairy, Lalkuaon. It was kept at 4 °C in a refrigerator until use. The initial moisture content of paneer was about 50% (wb). Paneer was diced into 1 cm cubes using stainless steel

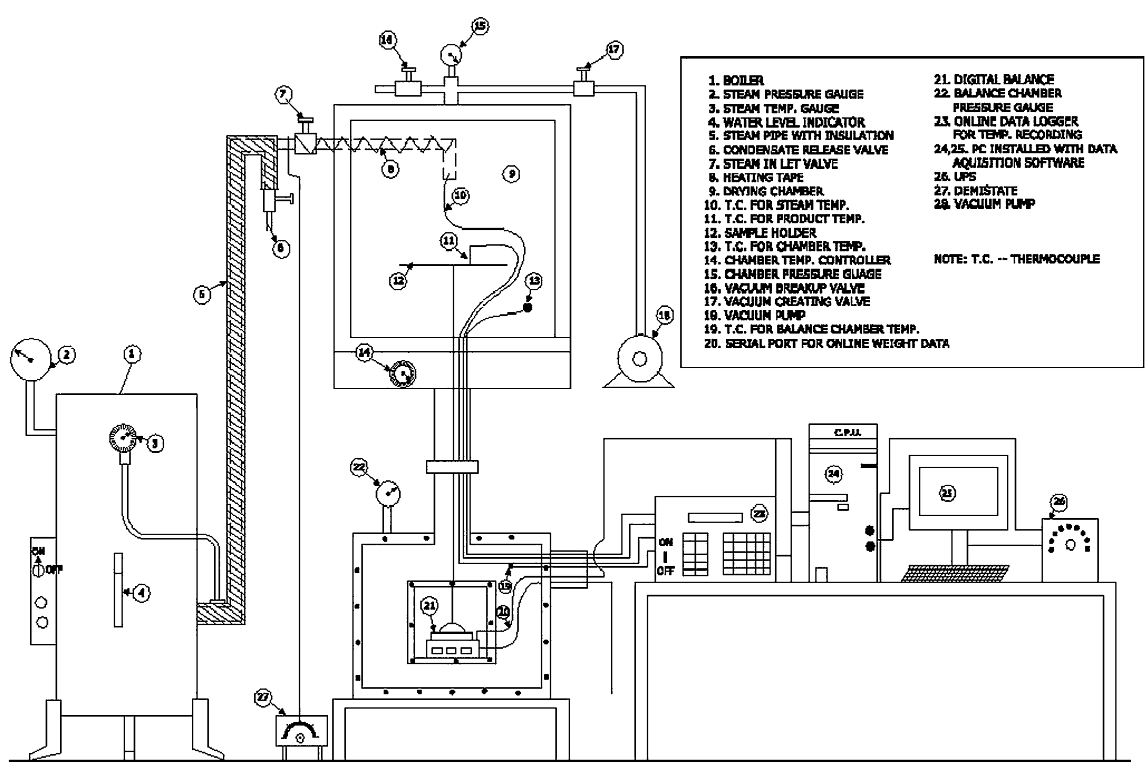

Fig. 1 Schematic diagram of the low pressure superheated steam dryer and associated units

knife. Prior to drying, cubes were pretreated with NaCl and potassium sorbate as suggested to prevent loss of fat and browning. A fixed volume of water (1/2 l) containing 2.5% NaCl and 0.5% potassium sorbate was heated to 50 °C in water bath. After pretreatment, 50 g of samples were dried. The samples were dried until the desired final moisture content of ~1% was obtained. The equilibrium moisture content of samples was also determined by drying the samples until no changes in their weight were observed. The drying chamber was then sealed tightly. Before that steam was generated till it reached to 150 kpa gauge pressure and it was maintained. A vacuum pump was then switched on to evacuate drying chamber to the desired operating pressure then steam inlet valve was opened slowly to flash the steam into the drying chamber. Because of the low pressure environment in the chamber, steam became superheated. Although the ratio of the steam pressure in the steam reservoir to that in the drying chamber was rather high, the effect of adiabatic expansion of steam introduced into the drying chamber on the steam temperature was rather small. This is because an electric heater was installed in the drying chamber to help stabilize the steam temperature. At the end of the drying, vacuum break up valve was opened to allow air into the drying chamber before opening the chamber door and removing the sample. The experiments were performed at 10, 14 and 18 kpa absolute pressure, 62, 72 and 82 °C steam temperature. All experiments were performed in triplicate.

Results and discussion

Moisture content of fresh paneer varied between 48.5 and 49.7% db while after drying between 1.002 and 1.892% db in LPSSD. Figure 2 shows that the moisture content of sample increased initially and then decreased continually. This apparent increase in moisture content was due to condensation of steam on the surface as the temperature of the sample was lower than the steam temperature. When the sample temperature increased to the saturation temperature, the moisture content thereafter started decreasing. This point is called reverse point. This typical phenomenon was also observed in all super heated steam drying studies (Devahastin et al. 2004; Pronyk et al. 2004). Moisture content decreased as the temperature increased. The difference in moisture content was less at lower pressure compared to that at higher pressure. This may be due to lower temperature gradient as the evaporation temperature increases with pressure. It can be seen from Fig. 3 that moisture ratio increased to greater than 1 initially due to increase in moisture content and then decreased. Similar trend has been reported by Tang et al. (2000), Devahastin et al. (2004) and Pronyk et al. 2004.

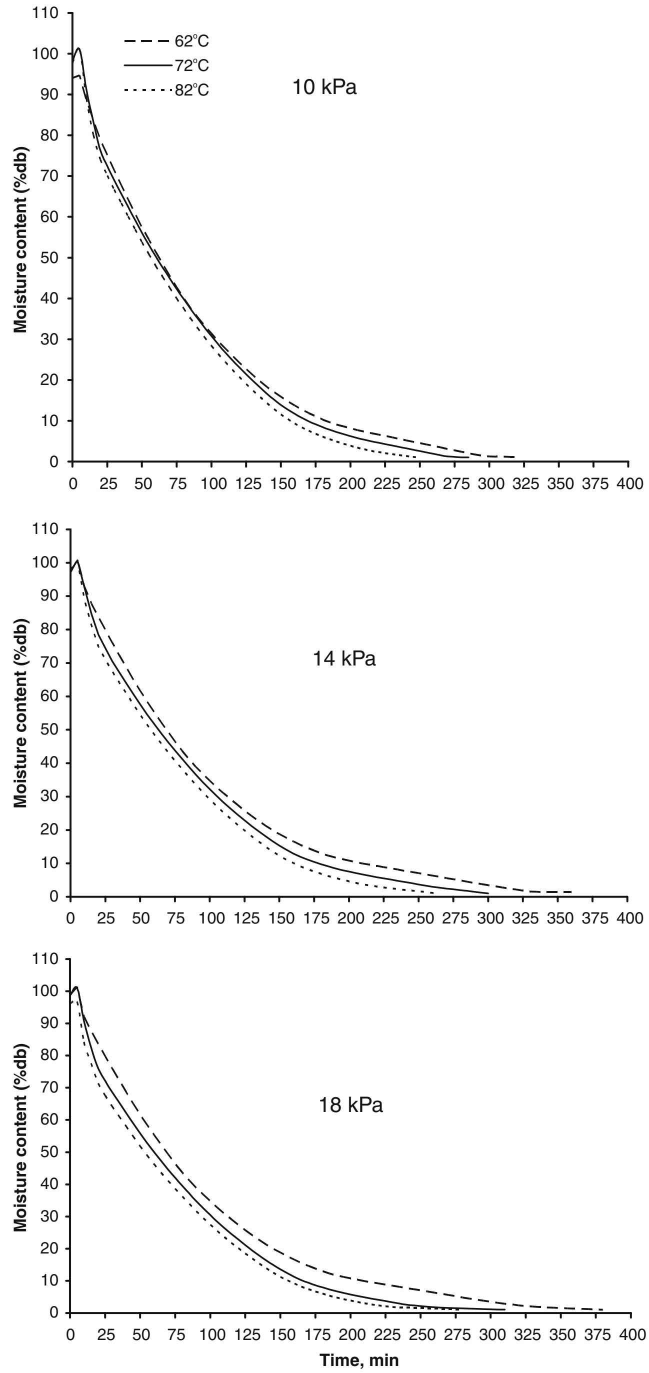

Fig. 2 Drying characteristics of paneer in low pressure superheated steam drying (LPSSD) at different steam pressures

Drying rates were calculated based on moisture loss data. As can be seen in Fig. 4, constant rate drying did not exist and drying of paneer took place in falling rate period. Falling rate drying curve could be divided into 3 periods. During first falling rate period, the rate of drying decreased vary rapidly up to about 80% db moisture content or 20 min time. In the second falling rate period, the drying rate decreased gradually and in the third it decreased very slowly. There was little variation in the drying rates.

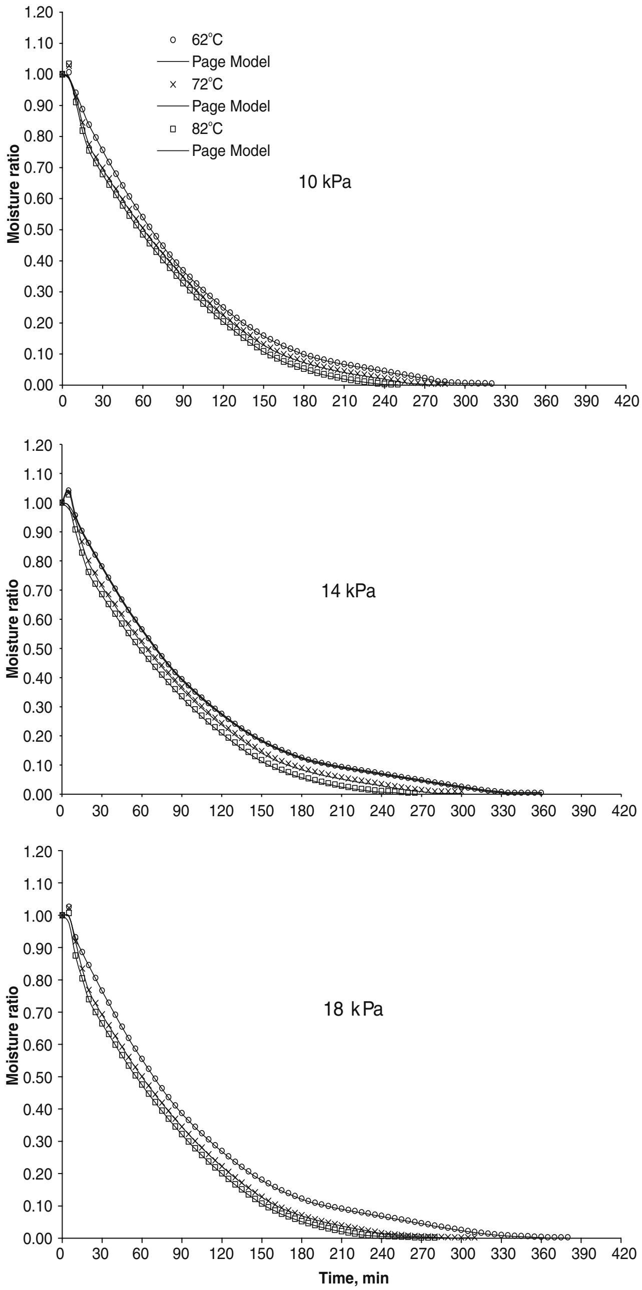

Fig. 3 Relationship between moisture ratio and drying time in LPSSD of paneer at different pressures (LPSSD: See Fig. 2)

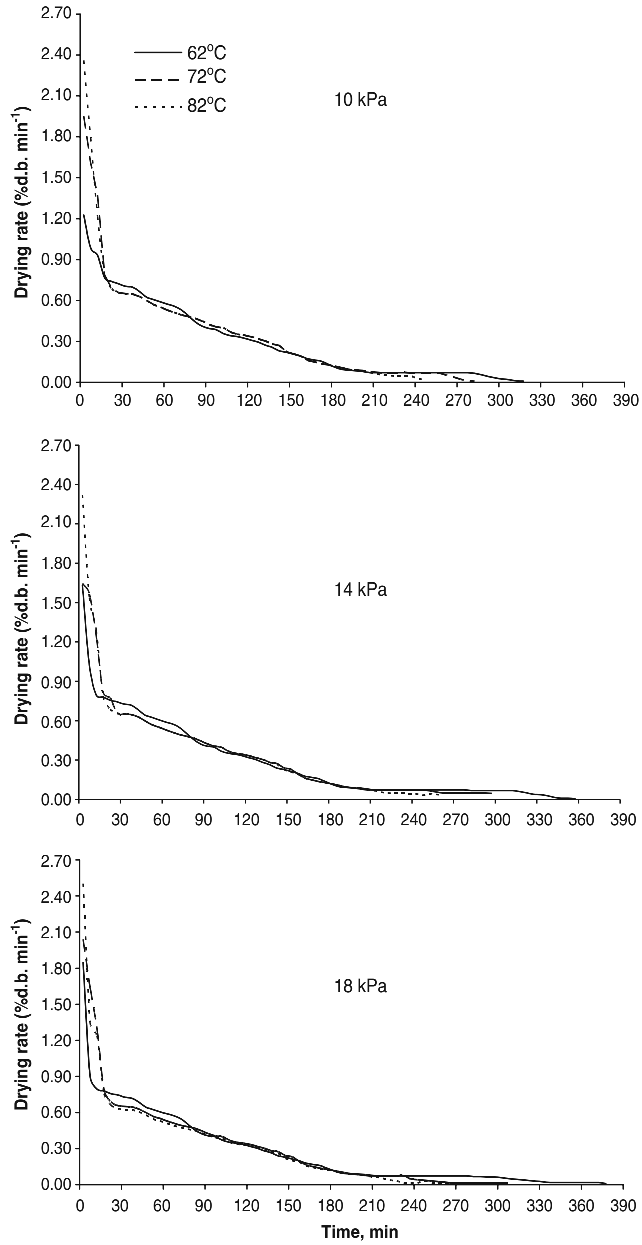

Fig. 4 Drying rate versus time in LPSSD of paneer at different steam pressure (LPSSD: Fig. 2)

Empirical modeling

It was found that Page's model had higher R^2 (0.9972) and lower standard deviation (0.0043) when compared with generalized exponential and logarithmic models for all the cases. Therefore, Page's model was chosen for detailed analysis.

Page's model is given below:

$$MR = \frac{M - M_o}{M_o - M_e} = Exp(-Kt^N) \quad (1)$$

where M=moisture content at any time (%db), M_e= equilibrium moisture content (%db), M_o=original moisture content (%db), K and N=drying constant (h^{-1}), MR= moisture ratio, t=drying time.

The average value of parameter K and N varied from 0.0041 to 0.0067 and 1.1552 to 1.2209 (Table 1), respectively in superheated steam drying. Predicted moisture ratio by Page's model is shown in Fig. 3.

For simulation it is generally not convenient to use individual value of Page's equation parameters K and N at selected experimental conditions. If condition changes, those parameters are not suitable for use in the equation.

Table 1 Coefficients for constants k′ and n′ of paneer dried with LPSSD

Coefficients	For K′	For N′
a_1	5.625E-06	−2.119E-03
a_2	−1.750E-06	3.754E-04
a_3	9.375E-08	−1.569E-05
b_1	−9.050E-04	3.099E-01
b_2	2.845E-04	−5.520E-02
b_3	−1.475E-05	2.308E-03
c_1	4.590E-02	−1.006E+01
c_2	−1.211E-02	2.018E+00
c_3	6.010E-04	−8.443E-02

LPSSD: See Fig. 2

Therefore, it was decided to develop a model relating the Page's equation parameters to temperature and pressure. Therefore K and N value were substituted by K′ and N′ which depended on temperature and pressure. A non linear regression analysis second degree polynomial was used to determine K′ and N′. The polynomial relation for K′ and N′ is given in Eq. 2. Detailed coefficients for drying constants K′ and N′ are given in Table 2 at different operating conditions. These models were developed in MATLAB-7 software.

$$K' \quad \text{or} \quad N' = A_1T^2 + B_1T + C_1 \tag{2}$$

$A_1 = a_1 + a_2P + a_3P^2; B_1 = b_1 + b_2P + b_3P^2;$
$C_1 = c_1 + c_2P + c_3P^2$
Where $A, B, C, a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2, c_3$
are constants $(LPSSD)$
$P = \text{Pressure}(kPa); T = \text{Temperature}\ (^\circ C)$

Table 2 shows that the generalized K′ and N′ in terms of temperature and pressure are in good agreement with K and N.

Table 2 Parameters of page's equation (LPSSD)

Temp °C	Pressure kPa	K	N	K′	N′
62	10	0.0041	1.2209	0.00412	1.2301
	14	0.0038	1.2152	0.00383	1.2266
	18	0.0050	1.1568	0.00504	1.1704
72	10	0.0054	1.1960	0.00542	1.2055
	14	0.0050	1.1917	0.00503	1.2035
	18	0.0054	1.2005	0.00540	1.2146
82	10	0.0062	1.1843	0.00623	1.1942
	14	0.0061	1.1805	0.00610	1.1927
	18	0.0067	1.1552	0.00673	1.1696

LPSSD: See Fig. 2

Artificial neural network (ANN) The input layer has two nodes, corresponding to two processing conditions: Time of drying and weight change with corresponding time. The output layer consisted of three neurons or dependent variables, representing the moisture content (%db), drying rate (dm/dt) and moisture ratio (MR). MATLAB-7 software was used for ANN modeling and evaluating the different training functions. The networks were simulated based on a multilayer feed forward neural network. This type of network is very powerful in function optimization modeling (Kerdpiboon et al. 2006). The input layer, hidden layers, and output layer structures are shown in Fig. 5. A back-propagation algorithm was used to implement supervised training of the network. A hyperbolic tangent was used as the transfer function in each hidden layer, and a linear transfer function was used in the output layer. Minimization of error was accomplished using the Levenberg – Marquardt (LM) algorithm. Training was completed after 5000 epochs. The number of hidden layers and number of neurons in each hidden layer were varied from 3 to 9 (3, 5, 7, or 9). The networks were simulated with the learning rate equal to 0.05.

The average mean square error (MAE), standard deviation of MAE (STDA), percentage of relative mean square error (%MRE), and standard deviation of %MRE (STDR) were used to compare the performances of various ANN models, and were calculated as (Kerdpiboon et al. 2006);

$$MAE = \frac{1}{N}\sum_{i=1}^{N} \Delta P_A \tag{3}$$

$$STD_A = \sqrt{\frac{\sum_{i=1}^{N} \left(\Delta P_A - \overline{\Delta P_A}\right)^2}{N-1}} \tag{4}$$

$$\%MRE = \left(\frac{1}{N}\sum_{i=1}^{N} \Delta P_R\right) \times 100 \tag{5}$$

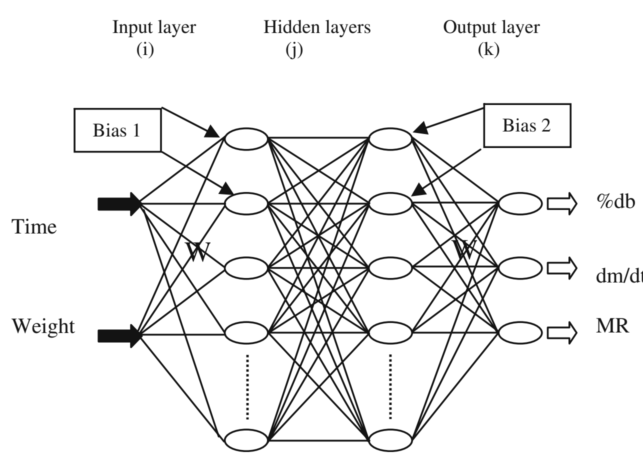

Fig. 5 Theoretical architecture of multilayer neural network for prediction of moisture content (dry basis), drying rate and moisture ratio

$$STD_R = \sqrt{\frac{\sum_{i=1}^{N} \left(\Delta P_R - \overline{\Delta P_R}\right)^2}{N-1}} \tag{6}$$

Where $\Delta P_A = |P_p - P_E|$; $\Delta P_R = |(P_p - P_E)/P_E|$;

P_p = Predicted output;

P_E = Experimantally measured output

A large number of hidden layers is not required to lower the error if there are enough number of neurons (Torrecilla et al. 2005). The results showed that the number of hidden layers, and neurons per hidden layer, that yielded minimum error was different for each drying technique. The best prediction for most of the data set contained two hidden layers. ANN developed for combined drying data had slightly higher error than individual conditions. The system equations, for example, representing the ANN for predicting drying rate are given in Appendix 1. The equation shows the input, transfer function, and relative weights of each node. Similarly, equations can be used in computer program to predict the moisture content, drying rate and moisture ratio of paneer cubes. Minimum and maximum error involved between actual and predicted values were 2.1657–3.929, 0.0555–0.0692 and 0.0207–0.0416 for moisture content, drying rate and moisture ratio, respectively.

Plots of experimentally determined moisture content, drying rate and moisture ratio versus ANN predicted values for all combined data are shown in Fig. 6. The correlation coefficients were greater than 0.98 in all cases. For all combined data set with superheated steam, the R^2 was found 0.998, 0.997 and 0.998 for moisture content, drying rate and moisture ratio, respectively. This shows that the ability of ANN to predict moisture content, drying rate and moisture ratio was very good.

Conclusion

Page's model had higher R^2 (0.9972) and lower SD (0.0043) in comparison with that of generalized exponential and logarithmic models for all the cases. Generalized K′ and N′ in terms of temperature and pressure are in good agreement with K and N. ANN can be used to predict the drying characteristics of paneer undergoing different drying techniques. The optimal models for combined drying can predict the moisture content, drying rate and moisture ratio with R^2 value greater than 0.98 offered better prediction than analytical model. For all combined data set with superheated steam, the R^2 was 0.998, 0.997 and 0.998 for moisture content, drying rate and moisture ratio, respectively.

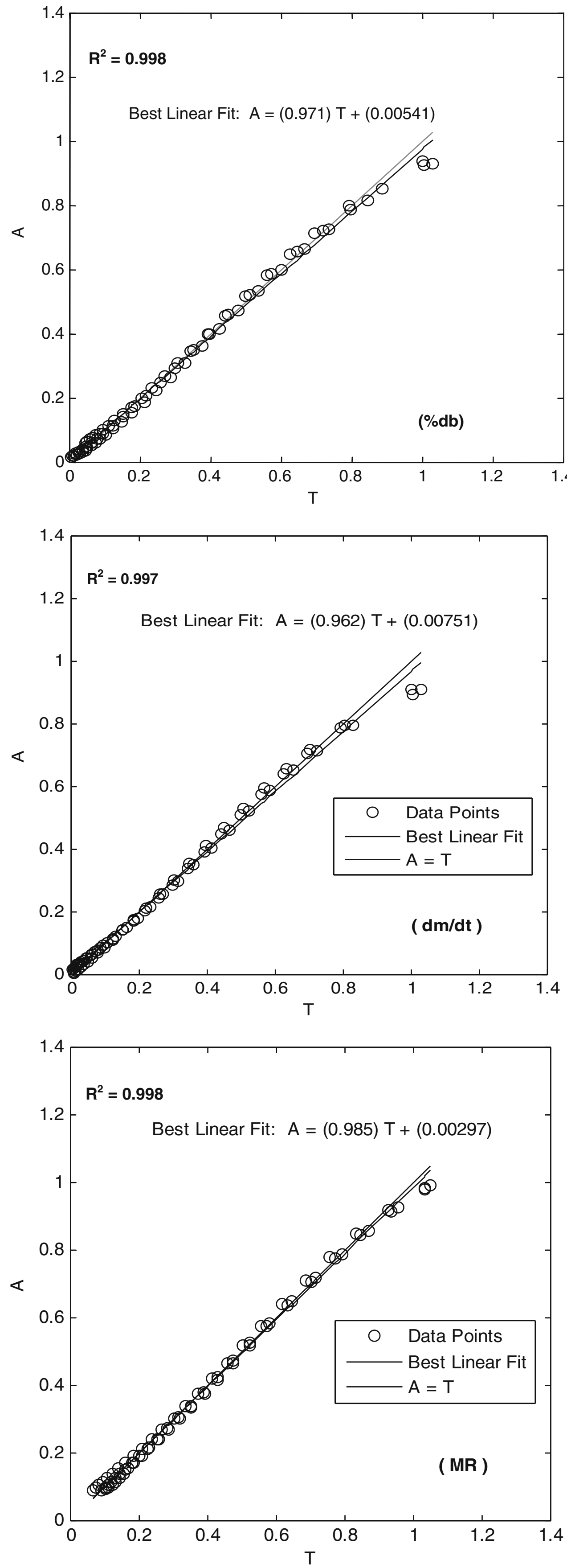

Fig. 6 Correlation between predicted and experimental values using the optimal ANN (LPSSD) ANN: Artificial Neural Networks, LPSSD: See Fig. 2

Appendix 1

System Equations

X = Moisture content

W = Weight of sample

$$X1 = \tanh\,[(-0.0233)^*X + (-0.1041)^*W + (10.2816)]$$
$$X2 = \tanh\,[(-0.3271)^*X + (1.2529)^*W + (-0.0695)]$$
$$X3 = \tanh\,[(0.0124)^*X + (-0.2476)^*W + (7.8621)]$$
$$X4 = \tanh\,[(-0.0182)^*X + (-0.1961)^*W + (8.4308)]$$
$$X5 = \tanh\,[(0.005)^*X + (-0.2789)^*W + (13.1905)]$$
$$X6 = \tanh\,[(0.8936)^*X1 + (1.6536)^*X2 + (-0.5165)^*X3 + (0.3501)^*X4 + (-0.3892)^*X5 + (-1.9825)]$$
$$X6 = \tanh\,[(-0.9668)^*X1 + (-0.7822)^*X2 + (-0.947)^*X3 + (-0.7253)^*X4 + (-0.7199)^*X5 + (1.0136)]$$
$$X7 = \tanh\,[(1.2624)^*X1 + (-0.989)^*X2 + (1.0186)^*X3 + (-0.3806)^*X4 + (-0.5801)^*X5 + (0.169)]$$
$$X8 = \tanh\,[(-0.513)^*X1 + (-0.7714)^*X2 + (1.0709)^*X3 + (-1.0464)^*X4 + (0.8953)^*X5 + (-1.1177)]$$
$$X9 = \tanh\,[(0.7447)^*X1 + (-1.6032)^*X2 + (-0.9085)^*X3 + (-0.603)^*X4 + (-0.1497)^*X5 + (2.0761)]$$
$$X10 = \mathrm{purelin}\,[(1.027)^*X1 + (-0.5584)^*X2 + (-1.2743)^*X3 + (-1.0635)^*X40.3642)^*X5 + (0.4652)]$$
$$dm/dt = ((0.67)^*X10 + (0.12))$$

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