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Impact of process variables on effective moisture diffusivity during convective drying of Osmotically dehydrated mushroom samples

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Abstract
The drying characteristics of osmosed mushroom slices were investigated in an experimental axial flow dryer at various air temperatures of 45, 55, 65, 75 and 85°C and velocity of air such as 1.0, 1.5 and 2.0 m/s. The entire drying process took place in the falling rate period. Effective moisture diffusivity (D_{eff}) was determined for examined temperatures and velocities using Fick's second law of diffusion adapted to slab geometry. The calculated effective moisture diffusivity of osmo-convectively dried mushroom samples varied considerably with moisture content and air drying temperature from 1.39 x 10^{-9} to 4.67 x 10^{-9}, 1.44 x 10^{-9} to 4.81 x 10^{-9} and 1.57 x 10^{-9} to 4.92 x 10^{-9} m^2/s for air velocity of 1.0, 1.5 and 2.0 m/s, respectively. Activation energy was also calculated and found to be 26.69, 27.91 and 29.26 kJ/mol for 1.0, 1.5 and 2.0 m/s air velocity respectively.

Keywords: Osmo-convective, Effective moisture diffusivity, Moisture ratio, Activation energy

Introduction
The button mushroom (*Agaricus bisporus*) is the most widely cultivated and consumed mushroom throughout the world and its global share is about 40 per cent. Presence of more than 90 per cent moisture content, mushrooms are extremely perishable and start deteriorating immediately just after harvest. It can not be stored for more than 24 hours at ambient conditions (Mehta *et al*. 2012) [5]. They develop brown colour on the surface of the cap due the enzymatic action of phenol oxidase, this results in shorter shelf life. In view of their high perishable nature, the fresh mushrooms have to be processed promptly to extend their shelf life for off season use.

Drying is an energy intensive operation and the main objective of any drying process is to produce a dried product of desired quality at a minimum cost and maximum throughput, and to optimize these factors consistently (Jain *et al*. 2011 and Mehta *et al*. 2013a) [6]. The challenge in fruits and vegetables drying are to reduce the moisture content of the product to a level where microbiological growth not occur and simultaneously keep the nutritive value high in final product. Hence, a new method i.e. osmotic treatment is often used for water removal, at low temperature with low energy consumption and improves the quality and stability of food products. Since this process cannot remove moisture to a level that will avoid microbial growth, it is a method suitable only for pre-treatment prior to drying (Pisalkar *et al*. 2011; Jain *et al*. 2011and Mehta *et al*. 2013b) [11, 7].

Many authors (Alam *et al.* 2010; Pisalkar *et al*. 2011; Jain *et al*. 2011and Mehta *et al*. 2017) [1, 11, 8] have investigated the effect of temperature and air velocity on the kinetics of convective drying of different food materials. Very few attempts have been made to study convective dehydration kinetics of button mushroom.

The work was aimed to analyse the convective drying of osmosed button mushroom (*Agaricus bisporus*) as a function of temperature and velocity and to determine moisture diffusivity as well as activation energy. The information so collected will be useful in predicting amount of moisture diffused during convective drying process. The activation energy data may be useful in estimation of energy requirement in drying process and thus help in functional design of dryers.

Materials and methods

Selection of raw materials: Freshly harvested, firm, dazzling white, mature button mushrooms of uniform size having about 87-91% moisture content (w.b.), were used as raw material for all the experiments. Common salt used as an osmotic agent, was procured from the local market.

Sample and solution preparation: Button mushrooms were thoroughly washed under tap water to remove adhering impurities and dried on a blotting paper, and then cut into 5±0.5 mm thick slices with the help of sharp stainless steel knife. The brine solution of desired concentration was prepared by dissolving the required quantity of salt (w/v) in tap water. Moisture content of fresh as well as osmotically dehydrated mushroom slices were determined.

Osmotic dehydration: Experiments were conducted of three concentration (10, 15 and 20%) three temperatures (35, 45 and 55ºC) and three duration of osmosis (30, 45 and 60 min) with respect to water loss (WL) and salt gain (SG) using Response Surface Method. The Box-Behnken design of three variables and three levels was used for optimizing input parameters at constant solution to sample ratio of 5/1 (w/w). The brine concentration of 17 per cent, temperature of 45ºC and 48 min duration of osmosis were found optimum for osmotic dehydration of mushroom samples. All the experiments were replicated thrice and results reported are from average value of three replications.

Convective Drying: The air drying behaviour was investigated for osmo-dehydrated mushroom samples, at air temperature of 45, 55, 65 75 and 85ºC with air velocity of 1.0, 1.5 and 2.0 m/s.

Moisture diffusivity during drying: Drying of moist food generally takes place in the falling rate-drying period, during which water migrates from the interior to the surface of the material by diffusion. Moisture diffusivity is, therefore, a transport property (an internal phenomenon) related to the food dehydration and essential for the calculation and modelling of various unit operations in food processing. Fick's second law has been adopted for evaluation of moisture transport mechanism of the falling rate regions and is mathematically expressed by classical mass balance equation (Crank, 1975) as

$$\frac{\partial M}{\partial \theta} = \frac{\partial}{\partial R}\left(D_d \frac{\partial M}{\partial R} \right) \qquad \ldots 1$$

Where,
M = moisture content, kg water per kg dry solids
θ = time, s
R = diffusion path or length, m
D_d = moisture dependent diffusivity, m^2/s

The diffusivity (D_d) varies considerably with moisture and can be estimated by an analysis of drying data applying the method of slopes. Several researchers have implemented this technique for estimating the effective moisture diffusivity (Patil and Kubde, 2011; Jain *et al*. 2011) [10].

Method of slope: The method of slopes is based on the solution of the Fick's law of unsteady state diffusion Eqn (1). It involves the comparison between slopes of experimental and theoretical diffusion curves.

The mushroom sample is assumed to be infinite slab (Rezagah *et al.*, 2010) [12] being dried from both the sides with the assumptions that (i) initially moisture is uniformly distributed throughout the mass of sample; (ii) resistance to mass transfer at the surface is negligible compared to the internal resistance of sample and (iii) mass transfer is by diffusion only. Following initial and boundary conditions have, therefore, been fixed for a solution to Eqn. (1) as

$M = M_0$ at $\theta = 0$ for all R
$M = M_s$ at $\theta > 0$, for $R = (+)\ell$ at the surface, and
$M = M_\infty$ at $\theta > 0$, for $R = (-)\ell$ at the surface

Where,
M_s = moisture content at the surface
M_∞ = equilibrium moisture content
ℓ = half the thickness of the sample, m

The mushroom slices were considered as infinite slab which were also suggested by Rezagah *et al*. (2010) [12]. Hence, the solution of Eqn (1) for constant diffusivity D in terms of infinite series, the following equation expresses the moisture content as a function of time in a slab

$$\frac{M - M_\infty}{M_0 - M_\infty} = \frac{8}{\pi^2}\left(e^{(-)\frac{D\pi^2\theta}{4L^2}} + \frac{1}{9} e^{(-9)\frac{D\pi^2\theta}{4L^2}} + \frac{1}{25} e^{(-25)\frac{D\pi^2\theta}{4L^2}} + \ldots \right) \qquad \ldots 2$$

When the time becomes large, limiting form of the Eqn (2) is as follows:

$$MR = \frac{M - M_\infty}{M_0 - M_\infty} = \frac{8}{\pi^2}\left(e^{(-)\frac{D\pi^2\theta}{4L^2}} \right) \qquad \ldots 3$$

$$= \frac{8}{\pi^2}\left(e^{(-)\frac{\pi^2}{4}F_o} \right)$$

Where,
MR = moisture ratio
M_o = initial moisture content, kg water per kg dry matter
M = moisture content at time θ, kg water per kg dry matter
M_∞ = equilibrium moisture content, kg water per kg dry matter
D = moisture diffusivity, m^2/s
L = thickness of the sample for drying from one side, m
F_o = Fourier number ($D\theta/L^2$)

Eqn (3) is evaluated numerically for Fourier number by rearranging and taking logarithm as

$$F_o = (-)\frac{4}{\pi^2}\ln\left(\frac{MR\,\pi^2}{8} \right)$$

$$F_o = (-)\frac{4}{\pi^2}\left(\ln MR + \ln \frac{\pi^2}{8} \right) \qquad \ldots 4$$

The Fourier number from Eqn (4) is used in evaluation of "effective moisture diffusivity", (D_{eff}). This established diffusion parameter (D_{eff}) is interpreted as an overall mass transfer property, wherein all possible contributory moisture transfer mechanism such as liquid diffusion, vapour diffusion, surface diffusion, capillary flow, hydrodynamic flow and the heterogeneity of food materials are recognized. The measurement of the effective diffusivity thus allowed a quantitative study of the drying characteristics in relation to controlled experimental variables.

The effective moisture diffusivity (D_{eff}) varied considerably with the moisture content (M) of mushroom sample during drying process, which resulted in nonlinear drying curves. For nonlinear drying curves the method of slope was adopted to estimate D_{eff} at various moisture contents. The theoretical moisture ratio MR, was evaluated numerically first for a range of Fourier number. The same ratio MR was evaluated using experimental drying data. Both curves of experimental and theoretical MR were plotted against time (t) and F_o, respectively, on a semi-log graph. By comparing the slopes of two curves Eqn (5), which could be determined by numerical differentiation at a specific MR, moisture diffusivity D_{eff} was evaluated from the following equation.

$$D_{eff} = \left(\frac{\left(\frac{dMR}{dt} \right)_{exp}}{\left(\frac{dMR}{dF_o} \right)_{the}} \right) \times L^2 \qquad \text{...5}$$

$$D_{eff} = \frac{(F_o)_{th}}{\left(\frac{t}{L^2} \right)} \qquad \text{...6}$$

Since moisture content (M) corresponded to the specific moisture ratio MR, D_{eff} could be found as a function of moisture content by repeatedly applying Eqn. (6).

Results and Discussions

Estimation of effective moisture diffusivity (D_{eff}): The drying data were used to compute moisture ratio (MR). The natural logarithms of moisture ratio (ln MR) were then plotted against average drying time (t) for different drying air temperatures, and are shown in Fig.1. It was observed from the figure that the relationship was non-linear in nature for all drying conditions. This non-linearity in the relationship might be due to reasons like shrinkage in the product,

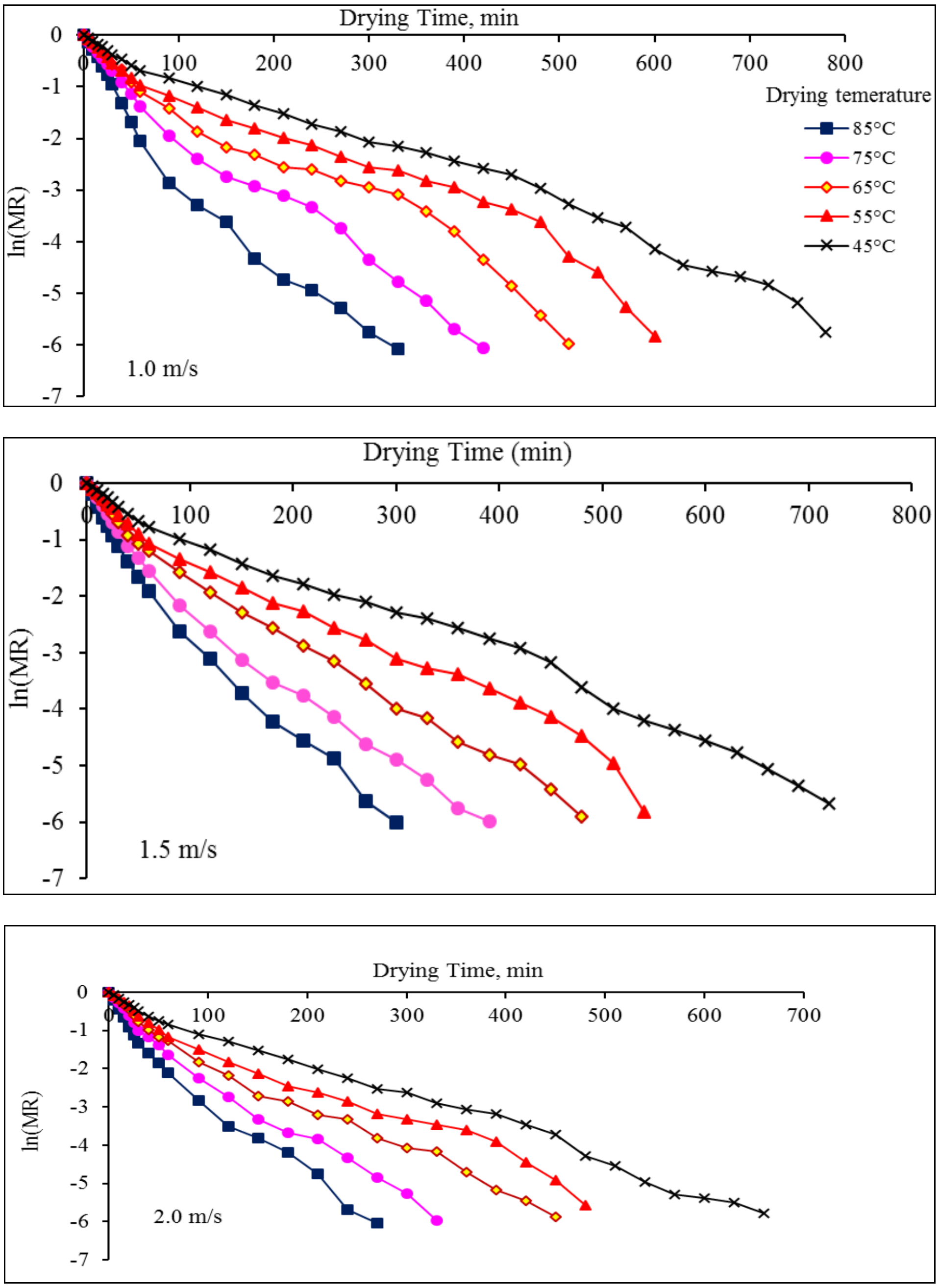

Fig 1: Variation in ln (MR) versus time for convective drying of osmotically dehydrated mushroom samples

Variation in moisture diffusivity with moisture content and change in product temperature during drying (Jain *et al*. 2011). The non-linearity of the curves, an indicative of the variation in moisture diffusivity with moisture content, was used to estimate effective moisture diffusivity of osmo-convectively dried mushroom samples at corresponding moisture content, under different drying conditions.

Effect of process variables on effective moisture diffusivity: The experimental D_{eff} values during convective drying of osmotically dehydrated mushroom samples were obtained by the modified method of slopes. The average effective moisture diffusivity $(D_{eff})_{avg}$ values of osmo-convectively dried mushroom samples varied considerably with moisture content and air drying temperature from 1.392 x 10^{-9} to 4.671 x 10^{-9}, 1.435 x 10^{-9} to 4.814 x 10^{-9} and 1.570 x 10^{-9} to 4.919 x 10^{-9} m^2/s for air velocity of 1.0, 1.5 and 2.0 m/s, respectively (Table 1). These values are within the general range of 10^{-8} to 10^{-12} m^2/s for drying of food materials (Murumkar, *et al.*, 2007; Patil *et al*., 2011 and Jain *et al*. 2011) [9, 10].

Table 1: Moisture diffusivity in air drying of osmotically dehydrated samples

S. No.	Temperature of drying (°C)	Air velocity, m/s	Diffusivity coefficient, $(D_{eff})_{avg}$ x 10^{-9}, m^2/s	Predicted diffusivity coefficient x 10^{-9}, m^2/s
1	45	1.0	1.392	1.251
2	45	1.5	1.435	1.352
3	45	2.0	1.570	1.428
4	55	1.0	1.613	1.871
5	55	1.5	1.682	2.022
6	55	2.0	1.837	2.136
7	65	1.0	2.793	2.616
8	65	1.5	2.870	2.827
9	65	2.0	3.161	2.986
10	75	1.0	3.391	3.486
11	75	1.5	3.966	3.767
12	75	2.0	4.339	3.979
13	85	1.0	4.671	4.481
14	85	1.5	4.814	4.842
15	85	2.0	4.919	5.115

It can be observed from the Table 1 that moisture diffusivity values increases with both parameters *i.e.* drying air temperature as expected and drying air velocity. Similar trends for moisture diffusivities have been reported by Jain *et al.*, 2006; Murumkar *et al.*, 2007 [9]; Pisalkar *et al.*, 2011 [11] and Patil *et al*., 2011 [10].

The ANOVA was carried out to study the effect of the process variables on $(D_{eff})_{avg}$ and the same is presented in Table 1. It was observed from F-values that drying air temperature, velocity and their interactions has significant effect on $(D_{eff})_{avg}$ at 1% level.

Table 2: ANOVA showing effect of process variables on average effective moisture diffusivity

Source	DF	SS	MSS	F_{cal}	SE (m) ±	CD at 5%	
T	4	72.59 x 10^{-9}	18.14 x 10^{-9}	6652575.22**	5.51 x 10^{-13}	1.59 x 10^{-12}	
V	2	1.16 x 10^{-9}	0.58 x 10^{-9}	212945.44**	4.26 x 10^{-13}	1.12 x 10^{-12}	
T x V	8	0.656 x 10^{-9}	0.08 x 10^{-9}	30077.49**	9.53 x 10^{-13}	2.75 x 10^{-12}	
Error	30	8.18 x 10^{-14}	2.72 x 10^{-15}				
Total	44						

**Significant at 1% level

Based on the diffusivity values presented in Table 1, the data were statistically analysed with SSPS software to develop a semi empirical equation demonstrating the relationship between moisture diffusivity and other related process parameters using the regression technique. The proposed mathematical relationship is as follows:

$(D_{eff})_{avg} = 6.0394 \times 10^{-13} \times T^{2.006} \times V^{0.191}$ …7

$R^2 = 0.96$

Where,

$(D_{eff})_{avg}$ = average effective moisture diffusivity, m^2/s

T = temperature, K

V = drying air velocity, m/s

The diffusivity values calculated by the Eqn (7) are also shown in Table 1 as predicted values. The above expression shows that the drying air temperature has a pronounced influence on the moisture diffusivity, whereas, the effect of air velocity was very limited as indicated by its predicted values Table (1). The average effective diffusivity during the convective drying of osmotically dehydrated mushroom samples at various air temperatures and velocities as determined experimentally (Table 1) and predicted by Eqn. (7) are shown in Fig. 2. It can be seen from the figure that there is a good co-relation between the observed and the predicted values of water diffusivities with $R^2 = 0.98$.

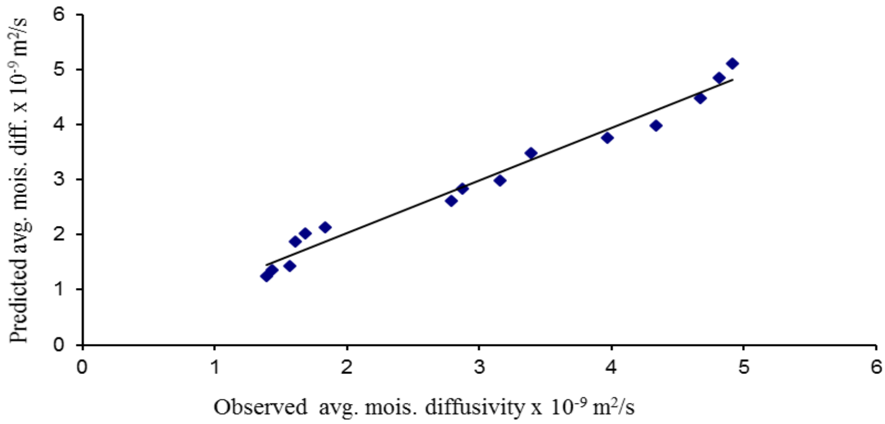

Fig 2: Experimental and predicted values of moisture diffusivities

Activation energy: It is universally accepted that temperature renders a dominant influence on moisture diffusivity. In general, this is manifested by a progressive increase in the effective moisture diffusivity with increasing temperature.

The temperature dependence of average effective moisture diffusivity $(D_{eff})_{avg}$ during convective drying can be expressed as Arrhenius type relationship. The activation energy for moisture diffusion were obtained from the slope of plot of ln $(D_{eff})_{avg}$ versus reciprocal of temperature in K^{-1} (Fig. 3) and found to be 26.697, 27.909 and 29.263 kJ/mol (Table 3) for 1.0, 1.5 and 2.0 m/s air velocities, respectively. It is implied from the figure that moisture diffusivity of mushroom sample decreased linearly with increase in 1/T. These values are closed to the E_a values reported by various researchers e.g.15-40 kJ/mol (Jain *et al.*, 2006 and Vega-Galvez *et al.*, 2007) [13] for various foods.

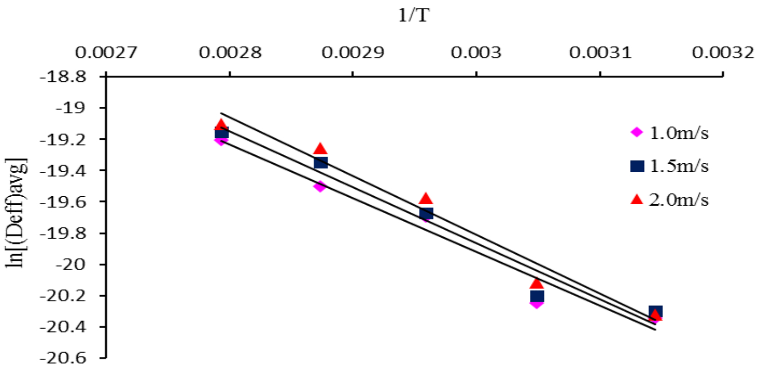

Fig 3: Relationship between moisture diffusivity with reciprocal of absolute temperature

Table 3: Activation energies for convective drying of osmo-dehydrated mushroom samples

Drying air velocity, m/s	Activation energy, kJ/mol
1.0	26.697
1.5	27.909
2.0	29.263

Conclusions

Air drying of osmotically dehydrated mushroom samples exhibited falling rate period of drying. Drying air velocity had little effect on the drying rate. There was a wide variation in drying time from 270 to 780 min for the range of drying temperatures (45 - 85°C) and air velocities (1.0 - 2.0 m/s) taken for study. Minimum drying time was observed for high temperature (85°C) and maximum time was recorded for low temperature (45°C) for all air velocities. The moisture diffusivity varied in the range of 1.392×10^{-9} to 4.919×10^{-9} m^2/s during air drying depending on the drying temperature and air velocity. The activation energy for moisture diffusion process was 26.697, 27.909 and 29.263 KJ/mol for 1.0, 1.5 and 2.0 m/s air velocity respectively.

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