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# Effects of freeze dryer temperature on drying kinetics of tofu

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**Abstract**
In the present investigation tofu was dried in freeze dryer at -40°C temperature. Drying characteristics of tofu viz. drying rates, moisture diffusivity were evaluated and the drying data of tofu was used to calculate the effective diffusion coefficients by the Fick's law equation of diffusion. The moisture diffusivity of tofu was found $2\times10^{-8}$ m²/s. Also it was fitted to study the five models. Among the diffusion approach model was found most satisfactory to represent the thin-layer drying of tofu.

**Keywords:** soybean, tofu, freeze drying, drying characteristics, modeling

## Introduction
Soybean (*Glycine max.*), belongs to leguminous crop which is rich in proteins, used as health food, feed sources and industrial products (Anderson and Wolf, 1995) [2]. It contains about 38–40% protein, 18% fat and can therefore be used in combating protein calorie malnutrition in the poor strata (Penalvo *et al.*, 2004) [7]. Soypaneer (Tofu) is the most popular non-fermented nutritional products prepared from soybean. Tofu contains about 15% protein (Jha and Gandhi, 1987). It is highly perishable even under refrigeration because of its relatively high pH (5.86.2) and moisture content (80-88%) (Lim *et al.*, 1990; Shen *et al.*, 1991) [11, 22]. Drying is the most widespread method of preservation which also reduces weight and volumes of the product thereby, help in marketing. Various types of dryers are popular in industries used for drying purpose. Freeze drying is method of preservation and considered as the reference process for manufacturing high quality dehydrated products which are sensitive to heat. The method incorporates a low-temperature drying process during which most of the water is eliminated by sublimation (Sablani *et al.*, 2007) [20]. Freeze drying can be applied to circumvent heat damage and produce products with excellent structural retention. It is a costly process and is only suitable for high-value products.

## Materials and Methods
Soybean was procured in bulk from local market and sample of about 500 g cleaned soybean was soaked in cold water for 4-6h. The soaked sample was ground in domestic mixer grinder in hot water after removing outer layer from the soybean manually. The water extract of soybean henceforth called as soymilk was filtered with double layered muslin cloth and heated to 80°C and then coagulated with citric acid 0.2%. The curd was gently transferred and pressed, after removing whey, for about 15 min. The tofu block thus obtained was immediately kept in chilled water (Verma and Jain, 2002) [26]. Process flow chart for preparation of tofu is presented in Fig.1. The tofu samples were prepared in 2×2×1 cm size with the help of a sharp stainless steel knife for conducting dehydration experiments in Freeze dryer (Labconco) at -40°C. The initial moisture content of fresh tofu samples before drying was determined drying method for the drying experiment suggested by Ranganna, (2000) [19].

### Drying Kinetics
**Moisture content during drying:** Moisture content during freeze drying was calculated (Brooker *et al.*, 1974) [3] by determining the ratio of loss of moisture to sample weight.

**Drying rate:** The drying rate was calculated by estimation of loss of moisture per unit time per unit dry matter (Brooker *et al.*, 1974) [3].

**Moisture diffusivity:** Diffusivity is influenced by shrinkage, case hardening during drying, moisture content and temperature of material (Singh, 2001b; Karim and Hawaldar, 2005) [24, 10]. The falling rate period in drying of biological materials is best described by simplified mathematical Fick's second law diffusion (Crank, 1975) [5] as given below.

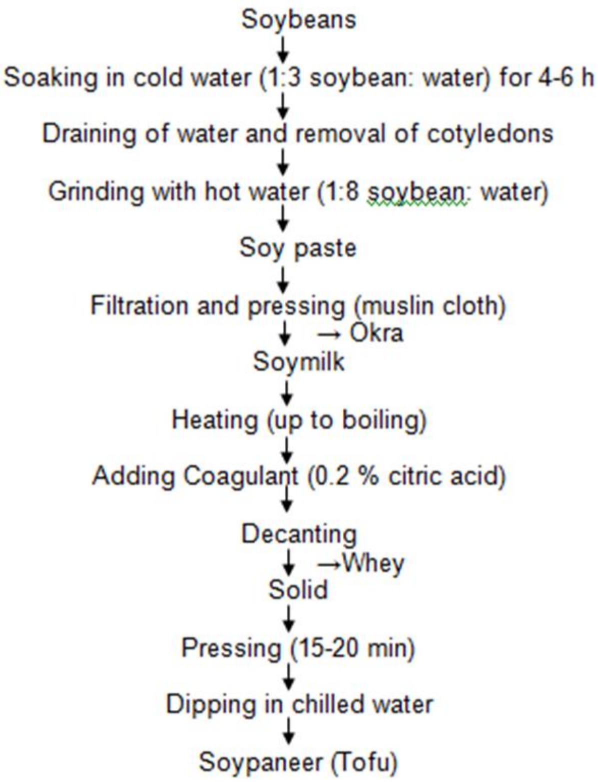


**Fig 1:** Process flow chart for the preparation of tofu

$$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta X^2} \qquad (1)$$

Where, D is diffusion coefficient, X is characteristic dimension i.e. distance from the center.

An experimental value of the effective diffusivity is typically calculated by plotting experimental drying data in terms of ln (*MR*) versus drying time t. It gives a straight line and the slope of the line would be used to measure the moisture diffusivity. This approach is a simplified one and shrinkage of the material is not taken into consideration, i.e. thickness of the material L is assumed constant throughout the drying process.

$$\text{Slope} = \pi^2 D_{eff}\left[\frac{1}{L_x^2} X \frac{1}{L_y^2} X \frac{1}{L_z^2}\right] \qquad (2)$$

**Mathematical models under study:** Modeling of the drying process is important for characterizing the process with different drying methods and conditions. Drying curves were obtained for the tofu sample under drying of freeze temperature (T) at constant pressure (P) and were fitted with five different moisture ratio models given in Table1. The moisture ratio (MR) was estimated from the ratio (M-Me)/($M_0$-Me), using the final moisture content of the dehydrated product as the equilibrium moisture content (Me). $M_0$ is initial moisture content and M is moisture content at any time t, expressed on a dry basis. The correlation coefficient ($R^2$) was one of the primary criteria used to select the best equation to account for the variation in the drying curves of the dehydrated samples (Ozdemir and Devres, 1999; Sarsavadia *et al.*, 1999) [16, 21]. The constants of the selected models were estimated by non-linear regression. The proposed models were fitted on the experimental data using linear regression. The statistical parameters, standard square error (SSE) and root mean square error (RMSE), were estimated by using MATLAB version7.0 software packages (Ramachandra and Rao, 2009) [18].

**Table 1:** Mathematical models used under drying study

| Model equation | Model name | Reference |
|---|---|---|
| $MR = a\exp(-kt^n) + bt$ | Midilli *et al.*, | Midilli *et al.*, (2002) |
| $MR = \exp(-kt^n)$ | Page | Zhang and Litchfield (1991) |
| $MR = a\exp(-kt)$ | Henderson and Pabis | Henderson and Pabis (1961) |
| $MR = a\exp(-kt) + (1-a)\exp(-kbt)$ | Diffusion approach model | Ertekin and Yaldiz (2004) |
| $MR = \exp(-kt)$ | Newton | Henderson (1974) |

Where, k is drying rate constant, t is drying time(min), n is dimensionless empirical coefficient, a, b, c are empirical constants in drying models.

## Results and Discussions

### Drying characteristics of tofu

The average initial moisture content of the tofu was 76% (wb) which was dried to final moisture content in the range of 10.19 to 12.57% (wb). The variations in moisture content with time during the drying period at freeze drying temperature is presented in Fig.2. The moisture content decreased exponentially with drying time at freeze drying temperature. The figure clearly shows that the maximum moisture loss was observed during first 900 min and decreases with the progress in the drying process. The drying followed a typical trend of drying behaviour for food materials as reported earlier (Singh, 2001a) [23]. The average drying time required to lower the moisture of tofu from initial (76%(wb)) to equilibrium moisture content (9.13%(wb)) was found to be 1800 min (30h).

The typical curves showing variation in drying rate with moisture content of tofu sample dried with drying temperature is shown in Fig.3 and clear that the drying of tofu occurred only in falling rate period throughout the drying process. A second order polynomial relationship was found to have fitted adequately to desirable variations in the drying rates with moisture content at experimental temperature and is presented by Eqn.(3) with their coefficient of determination values. It can be seen that the coefficient of determination is (more than 0.996) shows a good correlation between the drying rate Eqn.(3).

$$R = 7\times10^{-8}x^2 + 3\times10^{-5}x - 5\times10^{-5} \qquad (3)$$

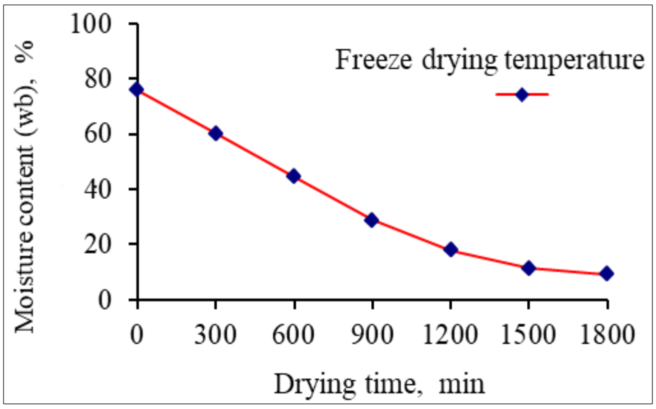


**Fig 2:** Variation in moisture content of tofu with drying time

**Moisture diffusivity of tofu**

Effective diffusivities are typically determined by plotting experimental drying data in terms of ln(MR) versus time (Lomauro *et al.*, 1985; Tutuncu and Labuza, 1996) [12, 25]. The effect of air temperatures on effective moisture diffusivity is generally described using Arrhenius type equation (Akpinar *et al.*, 2003) [1]. The moisture ratio (MR) was plotted with drying time in order to find out moisture diffusivity for tofu in Fig.4. The variation in ln (MR) with drying time for case was found to be linear with inverse slope. At the level, straight lines fitted well with coefficient of correlation (r) as 0.996. Moisture diffusivity was calculated using Eqn(7) from the slope of the straight line (Maskan *et al.*, 2002) [13] and is presented in Table2. The effective moisture diffusivity was $2\times10^{-8}$ m²/s during freeze drying of tofu. These value is within the general range of $10^{-08}$ to $10^{-12}$ m²/s for drying of food materials (McMinn and Magee, 1999) [14].

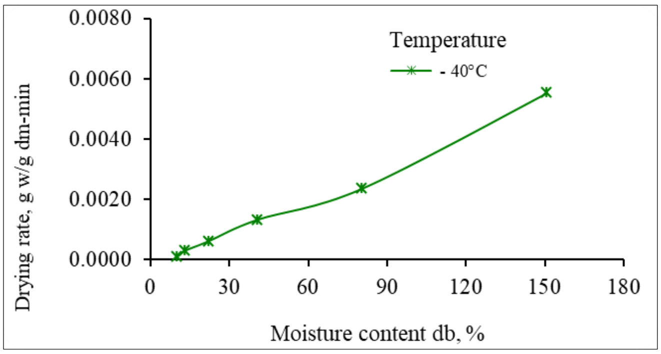


**Fig 3:** Variation in drying rate of tofu with moisture content

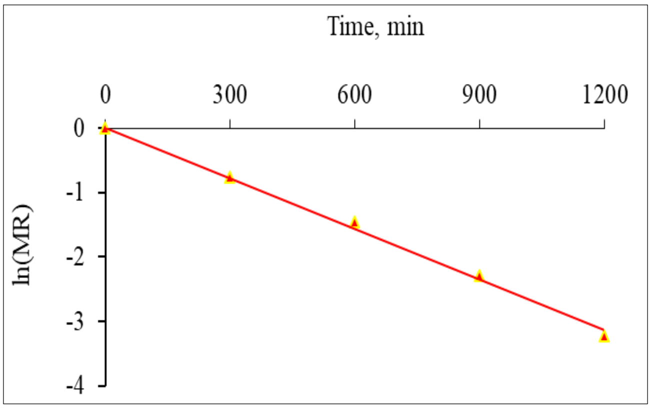


**Fig 4:** Variation in ln (MR) versus time for freeze drying of tofu at -40°C

**Table 2:** Average moisture diffusivity of tofu in freeze drying

| Temperature, °C | Equation of straight line y = mx + c | Diffusivity, m²/s | R |
|---|---|---|---|
| -40 | y = -0.002x | 2×10-8 | 0. 996 |

**Mathematical modeling of freeze drying of tofu**

Five drying models namely Page, Henderson and Pabis, Midilli *et al.*, Diffusion approach and Newton models were selected based on their ability to best fit the experimental data. The constants and parameters of all the models were estimated by using MATLAB7.0. Among these models, the best model suitable to fit the data was selected on the basis of highest value of coefficient of determination ($R^2$) and the lowest value of standard square error (*SSE*) and root mean square error (*RMSE*). The estimated values of statistical parameters *viz.*, standard square error (*SSE*), coefficient of determination ($R^2$) and root mean square error (*RMSE*) are shown in Table3. It was observed that the values of coefficient of determination ($R^2$) for Diffusion approach model at freeze drying temperature was about 0.96 higher and the values of standard square error (SSE) and root mean square error (RMSE) were 0.0367 and 0.0958 respectively which were lower than the rest of other. Hence, Diffusion approach model was found best fit than the other models to represent the freeze drying of tofu. The selected Diffusion approach model for freeze drying studies was validated by comparing the predicted and observed values of moisture ratio in drying experiment. The predicted and observed value of moisture ratio is shown in Fig.5.

**Table 3:** Values of coefficients for various models and their statistical parameters for freeze drying of tofu

| Name and equation of model | Drying model constant | | | | Statistical parameters | | |
|---|---|---|---|---|---|---|---|
| | k | n | a | b | SSE | R2 | RMSE |
| Newton model $\exp(-kt)$ | 0.7189 | - | - | - | 0.9725 | -0.107 | 0.4026 |
| Henderson and Pabis $a\ \exp(-kt)$ | 0.3383 | - | 1.000 | - | 0.9725 | -0.107 | 0.4410 |
| Midilli *et al.* model $a\exp(-kt^n)+bt$ | 70.31 | -2.8 | 0.938 | 0.0006 | 1.04 | -0.185 | 0.5888 |
| Page model $\exp(-kt^n)$ | 0.7130 | 1.0 | - | - | 0.9725 | -0.107 | 0.441 |
| Diffusion approach model $a\exp(-kt)+(1-a)\exp(-kbt)$ | 0.0014 | - | 1.780 | 0.9877 | 0.0367 | 0.958 | 0.0958 |

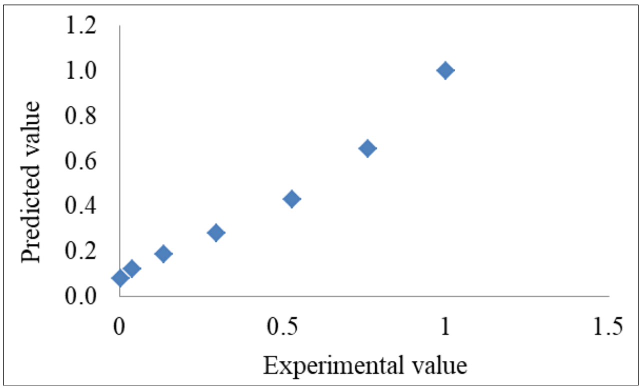


**Fig 5:** Experimental and predicted values of moisture ratio by Diffusion approach model for freeze drying of tofu

## Conclusion

The temperature -40°C used for drying of tofu, the drying time was found 1800 min at -40°C freeze drying temperature whereas the moisture diffusivity was $2\times10^{-08}$. No constant rate period was found during drying and whole drying process took place in the falling rate period only. Among the all model studied, Diffusion approach model gave better predictions and satisfactorily described the characteristics of tofu.

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