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# Effect of pulsation period and microwave power on paddy drying

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## Abstract

In this study, the influence of different microwave powers (90, 270, and 450 W) and pulsation periods, i.e., On/Off times (30/60 and 30/120 $ss^{-1}$) on drying rate and seed breakage of “Nemat” and “Hashemi” paddy varieties” was investigated. According to the results, the Midilli et al.'s model showed the best prediction accuracy for drying rate of the "Nemat" variety in the pulsation period of 30/60. Furthermore, the two-term model was found as the best model for "Hashemi" variety in the pulsation periods of 30/60 and 30/120 and for "Nemat" variety in the pulsation period of 30/120.The 270 W microwave power and 30/120 pulsation period can be recommended as a final conclusion of this study for drying “Hashemi” paddy variety. The breakage percentage at this condition was 19.1%. Breakage percent of the Nemat variety was more than 40% at all of the conducted measurements, indicating that this variety is not suitable for microwave drying. The final concluding massage of this study is that a pre-test should be conducted before applying the microwave for paddy drying.

**Keywords:** Microwave drying, breakage percent, Moisture ratio, thin layer, drying models.

## Introduction

Rice (*Oryza sativa L.*) is a valuable source of energy and nurtents, which is consumed by almost half of the world population. It has been producing in tropical and sub-tropical countries such as India, Thailand, the Philippines and several other countries. The latest data shows that world paddy production in 2016 was745.5 million tons (495.2 million tons milled rice), FAO (2016).

In Iran, rice is an ancient crop which is widely grown on areas of about 615000 ha with an annual production of about 3 million tons. Main areas of rice cultivation in Iran are located in the Northern provinces, Guilan and Mazandaran, producing 75% of the total cultivated rice crop in this country (Alizade et al. 2006).

Agricultural crops commonly contain a high level of moisture and microorganisms at the harvest time. After harvesting, the moisture content of rice paddy is in the range of 25% - 28% (wet basis) and even higher during the rainy season. For this reason, immediate drying is a requirement in postharvest processing to avoid quality losses of these perishable agricultural products (Balbay *et al.* 2012, Al-Harahsheh et al. 2009, Soysal 2004*)*. Drying is one of the most widespread methods for post-harvest protection of agricultural products such as paddies for allowing quick preservation (Dadali *et al.* 2008, Doymaz and Kocaygit 2011, Discala *et al*. 2013). Rice paddy is typically dried to reduce the moisture content to 11% or lower for a safe storage before a milling process. However, if the moisture content in paddy is too low, the grain will be brittle in the milling process. This can lead to a higher fraction of broken kernels. Keeping the rice paddy at optimized moisture content can prolong storage time and prevent mould growth (Cheenkachorn 2007).

Several drying approaches are used in the drying of foodstuff. The use of microwave technique in the drying of products has recently become common due to the quick and effective heat distribution in the product (Li *et al*. 2009, Alibas 2010, Dong *et al*. 2011). In this regard, many mathematical models have

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been formulated in order to describe the thin layer drying process (Kardum *et al.* 2011). Thin layer models can be categorized as theoretical, semi-empirical and empirical models (McMinn 2006, Alibas 2014).

The aims of this study were: I) to investigate the kinetics of thin layer microwave drying of two more conventional paddy varieties in Iran, i.e., Nemat and Hashemi, II) derivation of the semi-empirical models for the moisture ratio and seed breakage percentage as a function of drying power and time, III) evaluation of the conventional thin layer drying models in application of the microwave drying conditions, which have not been examined before.

**Materials and Methods**

The paddy grain used in this study was obtained from Rice Research Institute located in the Sari Agricultural Sciences and Natural Resources University, Iran. The evaluated paddy varieties (Nemat and Hashemi) are common varieties of paddy in the north of Iran (Zareiforoush *et al.* 2009). Initial moisture content (MC) of the paddy was determined by drying the samples in a laboratory oven at 103°C for 48 hr (Sacilik *et al.* 2003). Initial moisture content of "Nemat" and "Hashemi" were 20.48% and 24.5% w.b, respectively. Microwave drying experiments were performed in a domestic digital microwave oven (MW-F304ADY-S.Media, China). The microwave oven had 5 different microwave generation power stages between 90 and 900 W. The inside area of the device was 520mm× 467mm× 335mm with a rotation plate of a 300mm in diameter at the base of the oven. Microwave drying tests were carried out at three different microwave generation powers of 90, 270, and 450 W. The mass of each paddy sample was 30 g. Moisture loss was determined by weighting the samples using a digital balance with 0.01 precision. For a pulsed mode, the magnetron was alternately turned on and off corresponding to the specified pulsation periods. Paddy was hulled with a laboratory husker. Rice kernels with lengths smaller than 75% of that of whole kernels were chosen as broken rice (Kalantari and Eshtevad, 2013). The whole experimental period including several 30/60 or 30/120 $ss^{-1}$ On/Off pulsation periods was 450 s in all of the conducted experiments in this study.

**Mathematical formulation**

Moisture ratio of the samples after drying was calculated using the following equation (Manikantun et al. 2012):

$$MR = \frac{(M - M_e)}{(M_o - M_e)} \quad (1)$$

where MR is dimensionless moisture ratio, M is moisture content at time t, $M_o$ is initial moisture content, and $M_e$ is equilibrium moisture content on the wet basis.

In this study, the regression coefficient ($R^2$) was considered as the main criterion for choosing the most appropriate model for describing the microwave drying curves. This correlation factor can be used to examine the linear relationship between the measured and the estimated values, which can be calculated using the following expression (Alibas 2014):

$$R^2 = \frac{\sum_{i=1}^{N}(M_{R_{exp,i}} - M_{R_{expmean,i}})^2 - (M_{R_{pre,i}} - M_{R_{exp,i}})^2}{\sum_{i=1}^{N}(M_{R_{exp,i}} - M_{R_{expmean,i}})^2} \quad (2)$$

where $R^2$ is the coefficient of correlation, $M_{R_{exp,i}}$ is experimental moisture ratio obtained by the measurements, $M_{R_{pre,i}}$ is estimated moisture ratio, and N is total number of observations.

The standard error of estimate (SEE) indicates information on the long-term performance of the actual deviation between predicted and measured values term by term. The ideal value of SSE is "zero". The SEE is given as Equation 3 (Alibas 2014):

$$SEE = \sqrt{\frac{\sum_{i=1}^{N}\left(M_{R_{exp,i}} - M_{R_{pre,i}}\right)^2}{N - n_i}} \quad (3)$$

Where $n_i$ is the number of constants.

Root mean square error (RMSE) provides information on the short-term performance which can be computed from the following equation (Alibas 2014):

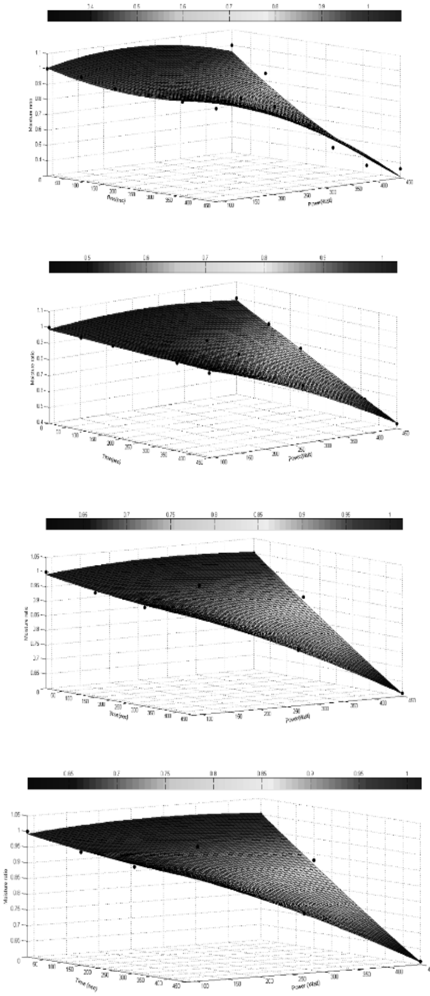
$$\mathrm{RMSE} = \sqrt{\frac{\left[\sum_{i=1}^{N}\left(M_{R_{exp,i}}\right) - \sum_{i=1}^{N}\left(M_{R_{pre,i}}\right)\right]^2}{N}} \quad (4)$$

To choose an appropriate model for describing the drying kinetics of the examined paddies, ten empirical and semi-empirical thin-layer drying models were evaluated (Table 1). However, some of the proposed models presented in this table have been constructed based on the previous models with some minor modifications .In this research, MATLAB 2013 has been used for model analyzing.

**Result and Discussion**

**Effect of different powers and drying time on moisture ratio**

The simultaneous influence of different powers and drying time on the moisture ratio (MR) in two verities of "Nemat" and "Hashemi" and two pulsation periods of 30/60 and 30/120 are shown in Fig.1 (a) to (d). According to the results presented in Fig.1 (a) to (d), the moisture ratio was decreased simultaneously with the power increment and drying time. Initially, moisture ratio was decreased with a high rate due to the high moisture content of the paddy. Meanwhile, moisture ratio in the 30/60 pulsation period was decreased with a larger slope in comparison with that of 30/120 pulsation period. A prior investigation conducted by Cheepsathit and Pattala (2005) indicated that the product temperature at the pulsation period of 30/60 was higher than that of 30/120. Higher microwave powers led to higher temperature gradients inside the grain allowing water to faster evaporate during the power-on time, also increasing diffusion of water during the power-off time. In contrast, longer off times resulted in temperature decrease due to evaporative cooling, convection and radiation heat losses from paddy external surfaces. These latter results obtained in this study were similar to the previous observations on paddy drying (Yongsawasdigul and Gunasekaran 1996, Cheenkachorn 2007).



(a) (b) (c) (d)

**Fig.1. Effect of different powers and drying time on moisture ratio in “Nemat” and “Hashemi” variety at 30/60(ss$^{-1}$) and 30/120(ss$^{-1}$) pulsation periods, (a); (b); (c); (d), respectively.**

**Evaluating the existing drying models**

Evaluation of the 10 different well-known thin-layer drying models (summarized in Table 1) is presented in Table 2and 3 for “Nemat” and “Hashemi” varieties respectively at three different microwave powers. In these tables, the values of the standard error of estimate (SEE), coefficient of correlation ($R^2$), and root mean square error (RMSE) are presented for two examined thin-layer drying models (i.e., Midili et al.'s model and two-term model). The best drying model was selected in this study based on the $R^2$, RMSE and SEE values for the microwave drying powers of 90, 270, and 450 W and for the 30/60 and 30/120pulsation periods (Doungporn *et al.*, 2012).

**Table 1. The most conventional mathematical thin-layer drying models.**

| Model No. | Model name | Model equation | Eq No. |
|---|---|---|---|
| 1 | Lewis (Doymaz and Ismail 2011) | $MR = \exp(-kt)$ | (5) |
| 2 | Page (Jangam *et al.* 2008) | $MR = \exp(-kt^{n})$ | (6) |
| 3 | Henderson and Pabis (Pehlivan and Toğrul 2004) | $MR = a\exp(-kt)$ | (7) |
| 4 | Logarithmic (Kingsly *et al.* 2007) | $MR = \exp(-kt)+c$ | (8) |
| 5 | Two-term (Demirhan and Ozbek 2011) | $MR = a\exp(-k_0 t) + b\exp(-k_1 t)$ | (9) |
| 6 | Wang and Singh (Demirhan and Ozbek 2011) | $MR = 1 + at + bt^2$ | (10) |
| 7 | Midilli et al. (Midilli *et al.* 2002) | $MR = a\exp(-kt^{n})+bt$ | (11) |
| 8 | Weibull distribution (Babalis 2006) | $MR = a - b\exp[-(kt^{n})]$ | (12) |
| 9 | Aghlasho et al. (Aghlasho *et al*. 2009) | $MR = \exp\left(\frac{-k_1 t}{1+k_2 t}\right)$ | (13) |
| 10 | Logistic (Alibas 2014) | $MR = \frac{a_0}{(1 + a\exp(kt))}$ | (14) |

MR is moisture ratio, $k$, $k_0$, $k_1$, $k_2$, $a$, $a_0$, $b$, $c$ are drying constant and t is drying time.

Regarding the results summarized in Table 2 for ($R^2$), (RMSE) and (SEE) values, the model proposed by Midilli et al had a better prediction for the Nemat variety at 30/60 pulsation period, whereas the two-term model indicated a better estimation at 30/120 pulsation period. The average of the standard error of estimate (SEE), the coefficient of correlation ($R^2$), and root mean square error (RMSE) for the model of Midilli et al at 30/60 pulsation period were equal to 0.00053854, 0.9840, and 0.013130667, respectively. For two-term model at 30/120 pulsation period, the average of the standard error of estimate (SEE), the coefficient of correlation ($R^2$), and root mean square error (RMSE) were equal to 0.000940283, 0.9783, and 0.03847, respectively.

Table 2. Statistical results obtained from thin-layer drying model for different microwave power and pulsation period "Nemat"

| 270 Watt | 450 Watt | | |
|---|---|---|---|
| $R^2$ | SEE | RMSE | $R^2$ |
| 0.9672 | 0.01209 | 0.04918 | 0.9674 |
| 0.9028 | 0.01499 | 0.0707 | 0.888 |
| 0.9688 | 0.01199 | 0.05475 | 0.9677 |
| 0.9701 | 0.01099 | 0.07414 | 0.9179 |
| 0.968 | 0.01173 | 0.05416 | 0.9684 |
| 0.9123 | 0.01473 | 0.08581 | 0.89 |
| 0.968 | 0.01146 | 0.05354 | 0.9691 |
| 0.9119 | 0.01481 | 0.08605 | 0.8894 |
| 0.968 | 0.01173 | 0.06253 | 0.06253 |
| 0.8702 | 0.008108 | 0.09004 | 0.9394 |
| **0.9703** | **4.652e-05** | **0.004823** | **0.9999** |
| 0.8797 | 0.01079 | 0.005786 | 0.9194 |
| 0.9671 | 0.008025 | 0.04479 | 0.9784 |
| 0.9791 | 0.008005 | 0.06327 | 0.9402 |
| 0.9681 | 0.01068 | 0.07306 | 0.9713 |
| **0.999** | **0.002632** | **0.07974** | **0.9803** |
| 0.9716 | 0.0003397 | 0.01303 | 0.9991 |
| 0.7213 | 0.0348 | 0.02347 | 0.74 |
| 0.9679 | 0.01189 | 0.05452 | 0.968 |
| 0.002593 | 0.007155 | 0.05981 | 0.9466 |

Table 3. Statistical results obtained from different thin-layer drying model for different microwave power and pulsation

| 270 Watt | | 450 Watt | | | | 90 Watt | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $R^2$ | SEE | RMSE | $R^2$ | Model | Pulsation period ($ss^{-1}$) | SEE | RMSE | $R^2$ | SEE | RMSE |
| 0.9625 | 0.002926 | 0.02419 | 0.9872 | Lewis | 30/60 | 0.0005258 | 0.01025 | 0.917 | 0.001606 | 0.01792 |
| 0.9761 | 0.0008906 | 0.01723 | 0.99 | | 30/120 | 0.0001734 | 0.007602 | 0.9471 | 0.00413 | 0.0371 |
| 0.9701 | 0.0002675 | 0.008178 | 0.9988 | Page | 30/60 | 0.0002465 | 0.00785 | 0.9611 | 0.00153 | 0.01956 |
| 0.9883 | 0.000249 | 0.01116 | 0.9972 | | 30/120 | 9.314e-05 | 0.006824 | 0.9716 | 0.00127 | 0.0252 |
| 0.965 | 0.002255 | 0.02374 | 0.9901 | Henderson and Pabis | 30/60 | 0.0004428 | 0.01052 | 0.9301 | 0.00157 | 0.01981 |
| 0.9805 | 0.0007251 | 0.01904 | 0.9918 | | 30/120 | 0.0001438 | 0.008479 | 0.9561 | 0.003726 | 0.04316 |
| 0.9649 | 0.002404 | 0.02451 | 0.9895 | Logarithmic | 30/60 | 0.0004431 | 0.01052 | 0.93 | 0.00157 | 0.01981 |
| 0.9804 | 0.0007367 | 0.01919 | 0.9917 | | 30/120 | 0.0001438 | 0.00848 | 0.9561 | 0.003744 | 0.04326 |
| 0.9566 | 0.0001252 | 0.006459 | 0.9995 | Logistic | 30/60 | 0.0002834 | 0.00972 | 0.9552 | 0.00157 | 0.01981 |
| 0.5174 | 0.000353 | 0.01879 | 0.996 | | 30/120 | 0.0001438 | 0.01199 | 0.9561 | 0.005515 | 0.07426 |
| 0.9683 | 0.0001214 | 0.00636 | 0.9995 | **Midilli et al** | **30/60** | **0.0001161** | **0.007619** | **0.9817** | **0.001453** | **0.02695** |
| 0.9899 | 0.0001263 | 0.00674 | 0.9999 | | 30/120 | 0.0001231 | 0.01109 | 0.9624 | 0.005109 | 0.03784 |
| 0.9689 | 0.0001335 | 0.005778 | 0.9994 | Wang and Singh | 30/60 | 0.0001455 | 0.00603 | 0.977 | 0.00161 | 0.02006 |
| 0.9843 | 0.0004263 | 0.0146 | 0.9952 | | 30/120 | 0.0001316 | 0.008111 | 0.9598 | 0.0008895 | 0.02109 |
| **0.9706** | **0.0001331** | **0.008157** | **0.9994** | **Two Term** | 30/60 | 0.0001387 | 0.008327 | 0.9781 | 0.001565 | 0.02797 |
| **0.9935** | **0.0001046** | **0.008153** | **0.9988** | | **30/120** | **0.0001454** | **0.01206** | **0.9556** | **4.345e-05** | **0.02234** |
| 0.971 | 0.0002291 | 0.0107 | 0.999 | Weibull distribution | 30/60 | 0.0005748 | 0.01695 | 0.9092 | 0.001393 | 0.02639 |
| 0.9999 | 0.002435 | 0.0124 | 0.9726 | | 30/120 | 0.0004971 | 0.01789 | 0.8482 | 0.01184 | 0.02879 |
| 0.9689 | 0.0001221 | 0.005524 | 0.9995 | Aghlasho et al | 30/60 | 0.000175 | 0.006614 | 0.9724 | 0.001573 | 0.01983 |
| 0.984 | 0.0004099 | 0.01432 | 0.9954 | | 30/120 | 0.0001169 | 0.007646 | 0.9643 | 0.002593 | 0.0294 |

| | | 90 Watt | | | | |
|---|---|---|---|---|---|---|
| Model | Pulsation period($ss^{-1}$) | SEE | RMSE | $R^2$ | SEE | RMSE |
| Lewis | 30/60 | 0.0001775 | 0.005958 | 0.9395 | 0.00175 | 0.01871 |
| | 30/120 | 0.0005103 | 0.01304 | 0.7874 | 0.0006481 | 0.0147 |
| Page | 30/60 | 0.0001774 | 0.006659 | 0.9395 | 0.001398 | 0.0187 |
| | 30/120 | 4.54e-05 | 0.004764 | 0.9811 | 0.0003167 | 0.01258 |
| Henderson and Pabis | 30/60 | 0.0001722 | 0.006561 | 0.9413 | 0.001637 | 0.02023 |
| | 30/120 | 0.0003834 | 0.01385 | 0.8403 | 0.0005284 | 0.01625 |
| Logarithmic | 30/60 | 0.0001722 | 0.00656 | 0.9413 | 0.001639 | 0.02024 |
| | 30/120 | 0.0003835 | 0.01385 | 0.8402 | 0.0005299 | 0.01628 |
| Logistic | 30/60 | 0.0001953 | 0.008068 | 0.9334 | 0.002026 | 0.02599 |
| | 30/120 | 0.0002667 | 0.01633 | 0.8889 | 0.01307 | 0.1143 |
| Midilli et al | 30/60 | 0.0001786 | 0.007716 | 0.9391 | 0.001484 | 0.02224 |
| | 30/120 | 0.0001786 | 0.007751 | 0.9999 | 0.0002746 | 0.02238 |
| Wang and Singh | 30/60 | 0.0001709 | 0.006537 | 0.9417 | 0.001454 | 0.01907 |
| | 30/120 | 0.00011 | 0.006547 | 0.9999 | 0.0004263 | 0.0146 |
| **Two Term** | **30/60** | **0.0001536** | **0.008762** | **0.9477** | **0.001373** | **0.02621** |
| | **30/120** | **0.0001547** | **0.008774** | **0.9999** | **0.0001764** | **0.0261** |
| Weibull distribution | 30/60 | 0.0001706 | 0.009236 | 0.9418 | 0.001354 | 0.02602 |
| | 30/120 | 0.0003553 | 0.009365 | 0.852 | 1.27E-08 | 0.02453 |
| Aghlasho et al | 30/60 | 0.0001698 | 0.006514 | 0.9421 | 0.001453 | 0.01906 |
| | 30/120 | 0.0002637 | 0.01148 | 0.8901 | 0.0004337 | 0.01473 |

In the meantime by considering the information given in Table 3, the average of standard error of estimate (SEE), coefficient of correlation ($R^2$), and root mean square error (RMSE) for the " Two-term model" at 30/60 pulsation period were equal to 0.000553233, 0.9726, and 0.014376333, respectively. For two-term model at 30/120pulsation period, the average of the standard error of estimate (SEE), the coefficient of correlation ($R^2$), and root mean square error (RMSE) were equal to 0.000145233, 0.9974, and 0.014342333, respectively.

Drying constant and coefficient values for the Midili et al.'s and "Two-term model" have been computed using the Matlab software. The obtained data for the parameters existing in their models including k, $k_0$, $k_1$, n, a, and b are given in Table 4 for the Nemat and Hashemi varieties.

Variation of the moisture ratio (MR) as a function of time (t) was given in Fig.2 (a) to (d) for two examined paddy grains. Prediction of the Midili et al.'s model for "Nemat" variety at 30/60($ss^{-1}$) pulsation periods is presented in Fig 2(a). The results presented in this figure indicate a good prediction of this model at the lower power-off time, whereas the "Two-term model" proposed by Demirhan and Ozbek (2011) had a better prediction for the longer off-times, i.e., 120 s off-time. It is interesting that the "Tow-term model" showed the best prediction at 120 s off-time for all of the microwave powers for both "Nemat" and "Hashemi" verities. The latter results can be observed in Fig.2 (b) to (d). The average coefficient of correlation ($R^2$) for the “Two-term model” was the highest amount within the 10 examined models, (Table 2). For “Two-term model”, the value of the coefficient of correlation ($R^2$) was very close to "1", meaning that the estimated data corresponded well with the experimental data.

Considering the results presented in Fig.2(a) to (d), moisture ratio decreased with increasing the power and drying time. This result has a good agreement with the previous observations on drying of paddy, (Yongsawasdigul and Gunasekaran 1996, Cheenkachorn 2007,Cheepsathit and Pattala 2005,Zarein *et al.*, 2013 and Chungcharoen *et al.*, 2015).

Based on the results obtained in this study, moisture ratio in the 30/60 pulsation period was decreased with a higher rate in comparison with the 30/120 pulsation period only at higher power rates, i.e., 450 W. At lower powers rate (90 and 270 W), influence of the 30/60 and 30/120 pulsation periods was not significant, (Table 5). This result is also presented in Fig 3(a) to (d), indicating that moisture transfer inside the paddy occurs faster at the higher microwave powers and lower microwave power off-times. This phenomenon can be explained by the more continuously heat generation within the paddy at higher microwave powers, yielding a larger vapor pressure difference between the center and surface of the grain.

**Table 4. Statistical results and coefficients obtained from thin-layer drying models for the different microwave power and pulsation period for “Nemat” and “Hashemi” varieties.**

| | Model | Pulsation period (s/s) | Power (Watt) | SEE | RMSE | $R^2$ | a | b | K | n | $K_0$ | $K_1$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nemat variety | Midili et al | 30/60 | 90 | 0.0001161 | 0.007619 | 0.9817 | 1.001 | 0.0007988 | 0.0007667 | 1.089 | - | - |
| | | 30/120 | | - | - | - | - | - | - | - | - | - |
| | | 30/60 | 270 | 0.001453 | 0.02695 | 0.9703 | 1 | -0.0004766 | 0.003973 | 0.4201 | - | - |
| | | 30/120 | | - | - | - | - | - | - | - | - | - |
| | | 30/60 | 450 | 4.652e-05 | 0.004823 | 0.9999 | 0.9998 | 0.000719 | 0.0001509 | 1.639 | - | - |
| | | 30/120 | | - | - | - | - | - | - | - | - | - |
| | Two-Term | 30/60 | 90 | - | - | - | - | - | - | - | - | - |
| | | 30/120 | | 0.0001454 | 0.0001454 | 0.9556 | 0.0161 | 0.9839 | - | - | 0.1186 | 0.0001408 |
| | | 30/60 | 270 | - | - | - | - | - | - | - | - | - |
| | | 30/120 | | 4.345e-05 | 0.02234 | 0.999 | -1.081e-16 | 0.9975 | - | - | 0.07664 | 0.0004286 |
| | | 30/60 | 450 | - | - | - | - | - | - | - | - | - |
| | | 30/120 | | 0.002632 | 0.07974 | 0.9803 | -5.729e-17 | 0.9817 | - | - | 0.07922 | 0.0008697 |
| Hashemi variety | Two-Term | 30/60 | 90 | 0.0001536 | 0.008762 | 0.9477 | -1.484 | 2.48 | - | - | 0.0006935 | 0.0004564 |
| | | 30/120 | | 0.0001547 | 0.008774 | 0.9999 | 0.7071 | 0.2929 | - | - | 0.0009077 | 0.001051 |
| | | 30/60 | 270 | 0.001373 | 0.02621 | 0.9706 | -0.05872 | 1.057 | - | - | 0.007436 | 0.0007637 |
| | | 30/120 | | 0.0001764 | 0.0261 | 0.9935 | 1.038 | -0.03759 | - | - | 0.0006226 | 0.1161 |
| | | 30/60 | 450 | 0.0001331 | 0.008157 | 0.9994 | -3.372 | 4.373 | - | - | 1.447e-07 | 0.0003113 |
| | | 30/120 | | 0.0001046 | 0.008153 | 0.9988 | 1.055 | -0.05509 | - | - | 0.001236 | 0.112 |

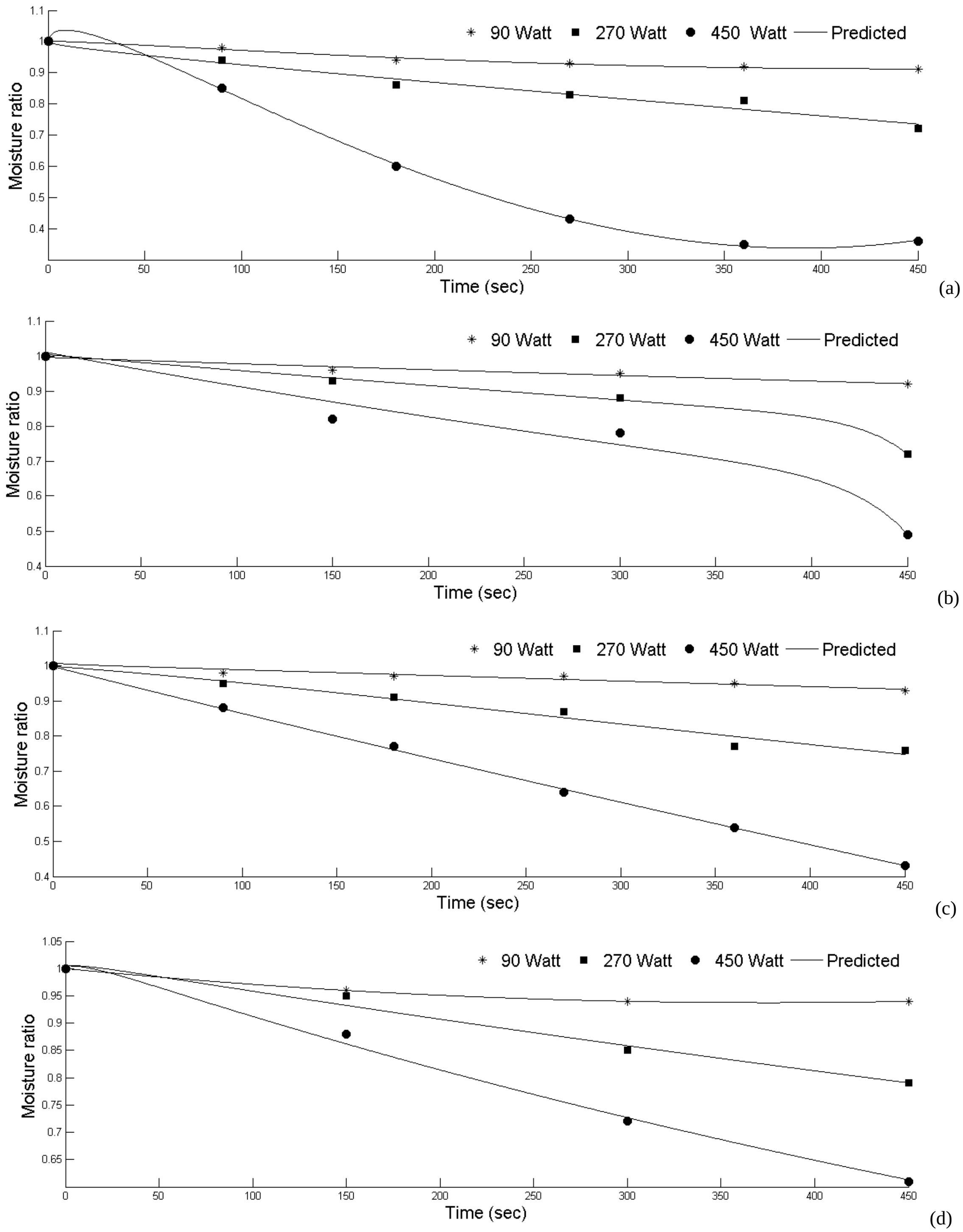



**Fig.2. Moisture ratio versus drying time, comparing prediction curves (—) with the experimental data ( single points): a) Model of Midilli et al for the "Nemat" variety and 30/60($ss^{-1}$) pulsation periods; b) Two-term model for the "Nemat" variety and 30/120($ss^{-1}$) pulsation periods; c) Two-term model for the "Hashemi" variety and 30/60($ss^{-1}$) pulsation periods; and d) Two-term model for the "Hashemi" variety and 30/120($ss^{-1}$) pulsation periods.**

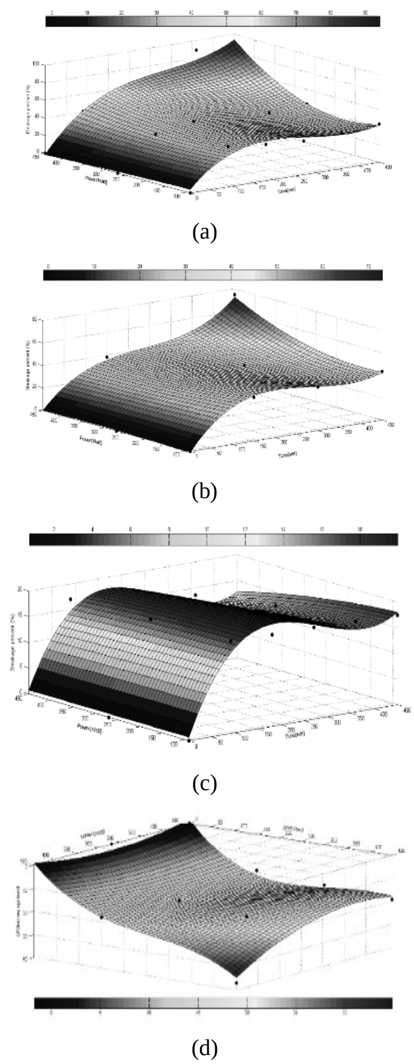
**Table 5. Moisture ratio at the end of drying time for all powers and variety**

| Variety | Pulsation period ($s\ s^{-1}$) | Power (Watt) | | |
|---|---|---|---|---|
| | | 90 | 270 | 450 |
| Nemat | 30/60 | 0.91 | 0.72 | 0.36 |
| | 30/120 | 0.92 | 0.72 | 0.49 |
| Hashemi | 30/60 | 0.93 | 0.76 | 0.73 |
| | 30/120 | 0.94 | 0.79 | 0.61 |

**Effect of different powers and drying time on seed breakage percentage**

Simultaneous influence of different powers and drying time on the seed breakage in two "Nemat" and "Hashemi" varieties and two pulsation periods of 30/60 and 30/120 are shown in Fig.3 (a) to (d).

According to Fig.3 (a) to (d), the seed breakage was increased simultaneously with increasing the microwave power and drying time. The experimental data showed that both microwave power and pulsation period affect the broken fractions. For the pulsation period of 30/60, the higher broken fraction was observed at higher microwave powers, e.g., 450 W. These results might due to the higher energy absorption of the paddy grains which led to a rapid increase in the grain temperature. However, a rapid increase of grain temperature resulted in the higher rate of water removal. Excessively high moisture content removal most likely causes a high fraction of broken kernels. The results were similar to those of previous studies conducted by Soponronarit et al. (1996), Taweerattanpanich et al. (1999) and Cheenkachorn (2007). The obtained empirical expressions for the seed breakage percentage (SB %) as a function of microwave power and drying time together with the moisture ratio (MR) are given in Table 6. These expressions have been derived using MATLAB software



(a) (b) (c) (d)

**Fig.3.Effect of different powers and drying time on seed breakage percent in "Nemat" variety and "Hashemi" variety at 30/60($ss^{-1}$) and 30/120($ss^{-1}$) pulsation periods, (a); (b); (c); (d), respectively.**

**Conclusion**

In this investigation, the influence of different microwave powers and pulsation periods on the moisture ratio and seed breakage of two paddy varieties was investigated. According to the obtained results in this study, the following conclusions can be summarized.

**Table 6. Fitted equation for moisture ratio and seed breakage according to power and drying time in different variety and pulsation period**

| $R^2$ | SEE | RMSE |
|---|---|---|
| 0.9621 | 0.03114 | 0.05094 |
| 0.9572 | 0.01065 | 0.04214 |
| 0.9923 | 0.00371 | 0.01758 |
| 0.9931 | 0.00116 | 0.01395 |
| 0.9655 | 0.03688 | 0.06402 |
| 0.9872 | 0.00699 | 0.0483 |
| 0.9449 | 0.00391 | 0.02086 |
| 0.9453 | 0.00707 | 0.04857 |

- The minimum moisture ratio and the maximum seed breakage percentage were observed at the microwave power of 450 W and pulsation period of 30/60. This can be explained by the higher heat generation inside the grain and consequently higher evaporation rate at the grain surfaces, yielding larger pressures and thermal gradients inside the grain.
- The maximum moisture ratio and the minimum seed breakage percentage were obtained at the microwave power of 90 W and pulsation period of 30/120.
- At all of the examined microwave powers (90, 270 and 450 W), the “Midilli et al.'s model” and “Two-term model” have been found to be the best model for the "Nemat" variety in the 30/60 and 30/120 pulsation periods, respectively.
- For all of the examined microwave powers, the “Two-term model” has been found to be the best model for the "Hashemi" variety in the 30/60 and 30/120 pulsation periods. This model has been selected using the statistical information including $R^2$, SEE, and RMSE and simultaneously comparing with the experimental data.
- Moisture ratio in the 30/60 pulsation period was decreased with a higher rate in comparison with 30/120 pulsation period at higher microwave power, i.e., 450 W for both examined varieties. This result is in agreement with the prior investigation carried out by Cheepsathit and Pattala (2005).
- The Nemat variety is not recommended for a microwave drying based on the results obtained in this study for all of the examined microwave powers and test conditions. The minimum breakage percentage was obtained about 40% at 90 W and 270 W microwave powers and 30/120 pulsation period.
- For the Hashemi variety, the minimum breakage percentage was obtained equal to 17.6% at 90 W and 30/120 pulsation period. The breakage percentage at 270 W and 30/60 and 30/120 pulsation periods were obtained equal to 20% and 19.1%, respectively. Therefore overall and simultaneously considering the breakage percentage and the drying rate (Figs.3 (a) to (d),the 270 W microwave power and 30/120 pulsation period can be recommended as a final concluding results of this study. The 270 W microwave power with 30/60 pulsation period is not recommended due to the larger energy consumption and no significant drying rate increment and breakage percenaget decrement in comparison with 270 W and 30/120 pulsation period.

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# اثر دوره تابش و توان مایکروویو در خشک کردن برنج

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## چکیده

در این تحقیق اثر توان‌های مختلف (90، 270 و 450 وات) و دوره تابش یعنی زمان های روشن– خاموش (30/60 و 30/120 ثانیه/ ثانیه) بر روی نسبت خشک شدن و صدمه دانه در خشک کردن به روش مایکروویو در دو رقم نعمت و هاشمی مورد بررسی قرار گرفت. طبق نتایج به‌دست آمده، مدل میدیلی و همکاران بهترین پیش بینی را برای خشک کردن رقم نعمت در دوره 30/60 نشان داد. علاوه براین مدل Two-term برای رقم هاشمی در دوره‌های 30/60 و 30/120 و برای رقم نعمت در دوره 30/120 بهترین پیش‌بینی را داشت. طبق نتایج این تحقیق برای رقم هاشمی توان 270 وات و دوره 30/120 توصیه می‌شود. در این شرایط شکست دانه 19/1 درصد بود. در تمام حالات درصد شکست در رقم نعمت بالای 40 درصد بود و این نشان می‌دهد این رقم مناسب خشک کردن با مایکروویو نیست. توصیه می‌شود یک پیش آزمایش قبل از انجام آزمایش های مایکروویو انجام شود.

**واژه‌های کلیدی**: خشک کن مایکروویو، درصد شکست، نسبت رطوبت، لایه نازک، مدل خشک‌کنی

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