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# Zingiber Roscoe (Ginger) Drying Kinetics and Statistical Examination

R Hasibuan[1], R Sundari[2*], R Anggraini[2], M Bairuni[1], J Hidayati[3]
[1]Department of Chemical Engineering, Universitas Sumatera Utara, Jalan Almamater, Kampus USU, Medan 20155, Indonesia
[2]Department of Mechanical Engineering, Universitas Mercu Buana, Jakarta 12650, Indonesia
[3]Department of Industrial Engineering, Universitas Sumatera Utara, Jalan Almamater, Kampus USU, Medan 20155, Indonesia

***Abstract—*** *This investigation has studied the drying kinetics of Zingiber Roscoe (ginger) with respect to moisture ratio vs. drying time and found that the temperature effect (33°C, 43°C, and 53°C) is more dominant than air velocity (1 m/s, 2 m/s, and 3 m/s). The drying rate of ginger has revealed substantial feature related to surface free water removal and bound water in material core. This study has also investigated the modeling of drying kinetics, i.e. the Newton, Page and Henderson-Pabis models. The results show that the Page modeling is the best fit model on the basis of statistical parameters, i.e. the* $R^2$ *(coefficient of determinant), RMSE (root mean square error), and* $\chi^2$ *(chi-square). The Page modeling shows* $R^2$ *value nearest to unity and lowest values of both RMSE and* $\chi^2$ *for all given temperatures (33°C, 43°C, and 53°C) and air velocities (1 m/s, 2 m/s, and 3 m/s).*

***Keywords—*** *Drying rate, Henderson-Pabis model, moisture ratio, Newton model, Page model.*

## I. INTRODUCTION

Drying process is applied to reduce moisture content of food and agricultural samples to impede microbial organism and deterioration, to preserve edible products, to minimize packing weight for reducing transportation problem. In drying operation, it is important to estimate moisture removal of edible samples especially herbals like ginger as the topic of this study in order to avoid material spoilage or deterioration. The study of drying kinetics is necessary to examine properties of food and agricultural materials particularly herbals since it is directly related to moisture removal. By studying the drying kinetics the drying operation can be controlled particularly in terms of temperature and air velocity, as well as relative humidity and sample size/thickness. According to Inyang et al. [1] the temperature and material size are the most influential factors in thin layer drying kinetics rather than air velocity and relative humidity. Moreover, a drying modeling is necessary for optimization of design process and therefore, the study of drying kinetics of agricultural, herbals, fruits and vegetables products is very substantial.

A lot of investigations on drying modeling applying statistical and mathematical approach for various food and agricultural products has been investigated [1 – 4]. Naderinezhad et al. [5] reported the Midilli-Kucuk equation is the best fit model for single layer drying of potato based on multiple regression analysis. While Fernando and Amarasinghe [3] investigated that Wang and Singh model was fit for hot air drying of coconut husk on the basis of coefficient of determinant, root mean square error and chi-square. Tzempelikos et al. [6] reported Weinbull equation as the best fit thin layer drying model for convective drying of quince slices at varied air temperatures (40°C – 60°C).

On account of that reason, this study attempts to use drying kinetics modeling for ginger based on experimental data at varied temperatures (33°C, 43°C and 53°C) and air velocities of (1 m/s, 2 m/s, and 3 m/s). This study has investigated the drying kinetics of ginger with respect to moisture content vs. drying time and drying rate under given drying conditions. The drying models (Newton, Page and Henderson-Pabis) are applied to assay which model is appropriate with experimental results obtained from drying kinetics of ginger. This study uses three statistic parameters, i.e. coefficient of determinant ($R^2$), root mean square error (RMSE) and chi-square ($\chi^2$).

## II. EXPERIMENTAL

The ginger drying modeling proposed three models (Newton, Page and Henderson-Pabis) based on experimental data of convective desiccant drying of ginger using silica gel. The drying conditions are varied at temperatures (33°C, 43°C, and 53°C) and air velocities of (1 m/s, 2 m/s, and 3 m/s). Part of the statistical examinations adopted from previous report [7].

The moisture ratio (MR) used for drying kinetics of ginger is defined as

$$MR = (Mt - Me) / (Mo - Me) \quad (1)$$

Where MR is the moisture ratio. Mt, Mo and Me are weights at given time, initial and equilibrium, respectively, and t is the given drying time. The equilibrium weight is usual defined as constant dry weight. The MR in Equation (1) was used for calculations of drying kinetics and the results are presented in Fig. 1 – 4. Furthermore, the results have used in three proposed drying models in order to examine which model is appropriate based on statistical parameters ($R^2$. RMSE, and $\chi^2$).

The convective desiccant drying of Zingiber Roscoe is considered as moisture transfer between air and product. Therefore, the drying behavior of Zingiber Roscoe can be described as thin layer drying model. On account of that reason, this study selected the Newton, Page and Henderson-Pabis models to examine the goodness fitness test with experimental data. The exponential and linear mathematical equations proposed for three models are given in Table 1 adopted the report of Rayaguru et al. [8].

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TABLE 1. Exponential and linear equations of proposed drying models as defined by Newton, Page and Henderson-Pabis [8].

| Drying model | Exponential equation | Linear equation |
|---|---|---|
| Newton | MR = exp (-kt) | ln MR = -kt |
| Page | MR = exp (-kt$^n$) | ln (-ln MR) = ln k + n ln t |
| Henderson-Pabis | MR = a exp (-kt) | ln MR = ln a – kt |

According to the understanding of thin layer drying, the drying constant involves with drying transport properties such as moisture diffusivity, thermal conductivity, density, specific heat, interface heat and mass coefficient [1]. With regard to linear modeling (Table 1), the Newton and Henderson-Pabis models are graphically plot as ln MR vs. t, while the Page model plot as ln (-ln MR) vs. ln t. Then the drying constants of each model are shown in Table 2 applying the experimental data of Fig. 1 and 2.

TABLE 2. Drying constant of models (Newton, Page and Henderson-Pabis) at temperatures (33$^o$C, 43$^o$C, and 53$^o$C) and air velocities (1 m/s, 2 m/s, and 3 m/s). Convective desiccant drying of ginger.

| Temp. ($^o$C) | Velocity (m/s) | Newton Model | Page Model | | Henderson-Pabis Model | |
|---|---|---|---|---|---|---|
| | | k | k | n | k | a |
| 53 | 3 | 0.3427 | 0.1846 | 1.3220 | 1.3623 | 0.3936 |
| | 2 | 0.2455 | 0.1286 | 1.3354 | 1.2602 | 0.2835 |
| | 1 | 0.2201 | 0.1059 | 1.3887 | 1.2350 | 0.2548 |
| 43 | 3 | 0.1671 | 0.1108 | 1.2287 | 1.0751 | 0.1790 |
| | 2 | 0.1349 | 0.0901 | 1.2224 | 1.0593 | 0.1444 |
| | 1 | 0.1220 | 0.0719 | 1.2923 | 1.0707 | 0.1332 |
| 33 | 3 | 0.0837 | 0.0817 | 1.0030 | 1.0164 | 0.0864 |
| | 2 | 0.0670 | 0.0610 | 1.0381 | 1.0216 | 0.0705 |
| | 1 | 0.0548 | 0.0368 | 1.1996 | 1,0390 | 0.0611 |

Thin layer drying models are examined by statistical parameters. This study applied three selected statistical parameters as already mentioned above, i.e. the coefficient of determinant ($R^2$), root mean square error (RMSE) and chi-square ($\chi^2$). The most fitted drying model is determined based on the highest value of $R^2$ and the lowest values of RMSE and $\chi^2$, respectively. The results are shown in Table 3.

## III. RESULTS AND DISCUSSION

This investigation applied a convection desiccant method for ginger drying. Dried air is used as drying media obtained by flowing hot air through silica gel desiccant to absorb water molecules from air. A heater provided at the bottom of a drying machine is used to yield hot air. A fan is applied to flow dried hot air through samples. The ginger was dried in a dried chamber with a size of 100 cm x 100 cm x 100 cm. The experimental moisture ratio (MR) was calculated applying eq. 1 and used to present drying kinetics of ginger at varied drying operations (Fig. 1 – 4).

TABLE 3. Statistical parameters for three drying models at given temperatures (33$^o$C, 43$^o$C and 53$^o$C) and air velocities (1 m/s, 2 m/s, and 3 m/s). Zingiber Roscoe convective desiccant drying.

| Temperature | Velocity | Model | $R^2$ | RMSE | $\chi 2$ |
|---|---|---|---|---|---|
| 53 ($^o$C) | 3 m/s | Newton | 0.9562 | 0.072047 | 0.005339 |
| | | Page | **0.9960** | **0.011940** | **0.000151** |
| | | Henderson-Pabis | 0.9783 | 0.069574 | 0.005125 |
| | 2 m/s | Newton | 0.9541 | 0.067660 | 0.004709 |
| | | Page | **0.9910** | **0.010244** | **0.000111** |
| | | Henderson-Pabis | 0.9778 | 0.055156 | 0.003221 |
| | 1 m/s | Newton | 0.9459 | 0.063839 | 0.004192 |
| | | Page | **0.9916** | **0.017356** | **0.000319** |
| | | Henderson-Pabis | 0.9703 | 0.051617 | 0.002821 |
| 43 ($^o$C) | 3 m/s | Newton | 0.9903 | 0.026557 | 0.000725 |
| | | Page | **0.9964** | **0.013042** | **0.000180** |
| | | Henderson-Pabis | 0.9962 | 0.013844 | 0.000203 |
| | 2 m/s | Newton | 0.9928 | 0.024611 | 0.000623 |
| | | Page | **0.9980** | **0.011110** | **0.000131** |
| | | Henderson-Pabis | 0.9978 | 0.011288 | 0.000135 |
| | 1 m/s | Newton | 0.9846 | 0.028835 | 0.000855 |
| | | Page | **0.9968** | **0.012320** | **0.000161** |
| | | Henderson-Pabis | 0.9941 | 0.015228 | 0.000246 |
| 33 ($^o$C) | 3 m/s | Newton | 0.9921 | 0.012381 | 0.000158 |
| | | Page | **0.9974** | **0.011876** | **0.000149** |
| | | Henderson-Pabis | 0.9934 | 0.012059 | 0.000154 |
| | 2 m/s | Newton | 0.9896 | 0.014255 | 0.000209 |
| | | Page | **0.9930** | **0.011724** | **0.000146** |
| | | Henderson-Pabis | 0.9929 | 0.012239 | 0.000159 |
| | 1 m/s | Newton | 0.9639 | 0.023387 | 0.000563 |
| | | Page | **0.9947** | **0.012706** | **0.000171** |
| | | Henderson-Pabis | 0.9779 | 0.017958 | 0.000341 |

Fig.1 and 2 are part of ginger drying kinetics presentations. Fig. 1 and 2 are selected because they reflected significant features useful for drying kinetics discussion. Fig. 1 shows the drying kinetics of ginger at varied temperatures (33$^o$C, 43$^o$C, and 53$^o$C) at constant air velocity (2 m/s). On the other hand, Fig. 2 shows the drying kinetics of ginger at varied air velocities (1 m/s, 2 m/s, and 3 m/s) at constant temperature (43$^o$C). By visual view on this two figures (Fig. 1 and 2), it can be deduced that the varied temperatures yielded more remarkable effect than that at varied air velocities.

On further examination, the discrepancy of the weight unit data (Fig. 1) between MR curves of "53$^o$C" and "43$^o$C" is about 73 unit and between "43$^o$c" and "33$^o$C" about 91 unit at 360 min. (6h) drying time. On the other hand, the discrepancy (Figures 2) between "3 m/s" and "2 m/s" is about 72 unit, and between '2 m/s" and "1 m/s" is only 19 unit at same duration time. At 480 min (8h) drying time, the discrepancy (Fig. 1) between "53$^o$C" and "43$^o$C" is about 91 unit and between "43$^o$C" and "33$^o$C" about 97 unit. While at the same duration time, Figure 2 shows a discrepancy of 33 unit between "3 m/s" and "2 m/s", and discrepancy of only 10 unit between "2 m/s" and "1 m/s". The weight unit data is linear proportional to MR data. In addition, the reduction of MR at varied temperatures (Fig. 1) looks more consistent with increasing temperature (33$^o$C → 43$^o$C → 53$^o$C). Fig. 2 shows that the change of MR reduction with increasing air velocities (1 m/s → 2 m/s → 3 m/s) is not consistent. The reduction of MR ratio (Figure 2) for "1 m/s" and "2 m/s" looks almost overlapping by each other.

Fig. 3 and 4 at different drying conditions show similar patterns as that one presented by Figures 1 and 2. Varied temperatures (33$^o$C, 43$^o$C, and 53$^o$C) at constant air velocity of

3 m/s (Fig. 3) yielded more remarkable effect on reduction of moisture content compared to that at varied air velocities (1 m/s, 2 m/s, and 3 m/s) at constant temperature of 53°C (Fig. 4). The temperature effect on reduction of moisture content is more significant at either constant air velocity of 2 m/s (Fig. 1) or 3 m/s (Fig. 3) rather than air velocity effect (Figures 2 and 4). Fig. 1 – 4 show similar downward exponential patterns that are a general drying kinetic pattern for all herbals drying [7].

Fig. 5 and 6 show the drying rate of ginger. Figures 5 and 6 are selected among some other ginger drying presentations on account of remarkable features giving valuable discuassion on drying rate of ginger. Regarding to Figure 5, for the first two hours the drying rate increased at all temperatures (33°C, 43°C, and 53°C) until gaining their maximum peak and looks consistent. Figure 6 also shows the similar trend as that of Fig. 5, however, Fig. 5 shows much less consistent and the maximum peak is achieved at different duration drying time. The “2 m/s” and “3 m/s” drying rate (Fig. 6) achieve a maximum peak less than 2 hours, however, the “1 m/s” drying rate (Fig. 6) achieves a maximum peak at a little bit after 2 hours. Therefore, the drying rate at varied air velocities looks less consistent.

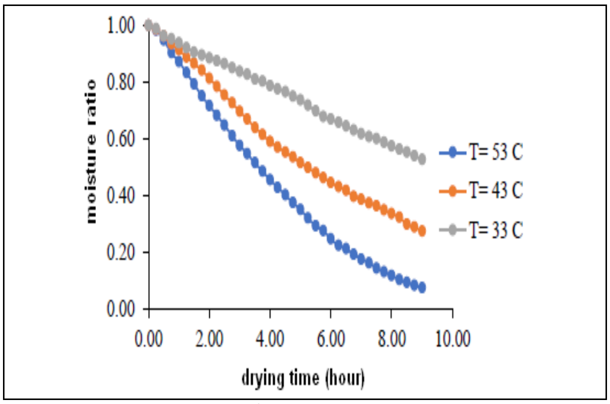

Fig. 1. Drying operation of ginger. Convective desiccant drying. Silica gel desiccant. Air velocity 2 m/s.

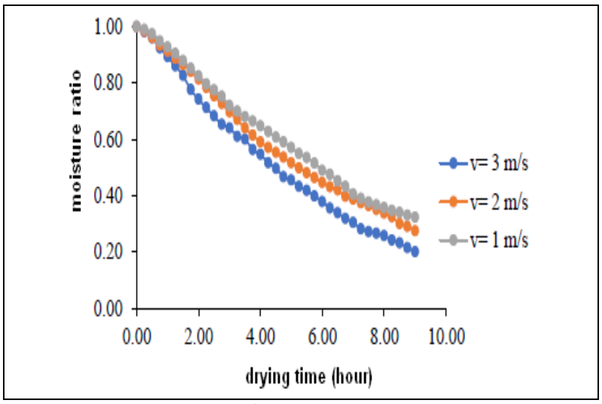

Fig. 2. Drying operation of ginger. Convective desiccant drying. Silica gel desiccant. Temp. 43°C

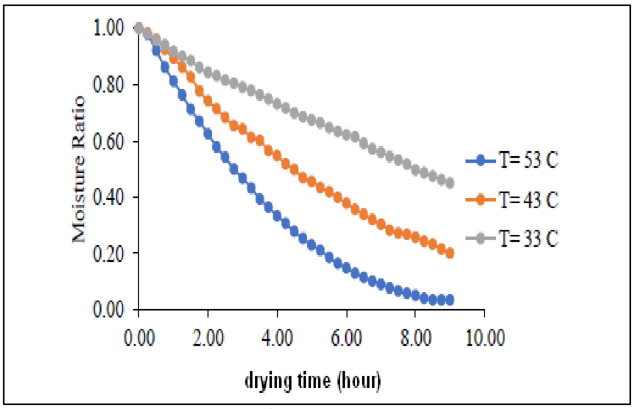

Fig. 3. Drying operation of ginger. Convective desiccant drying. Silica gel desiccant. Air velocity 3 m/s.

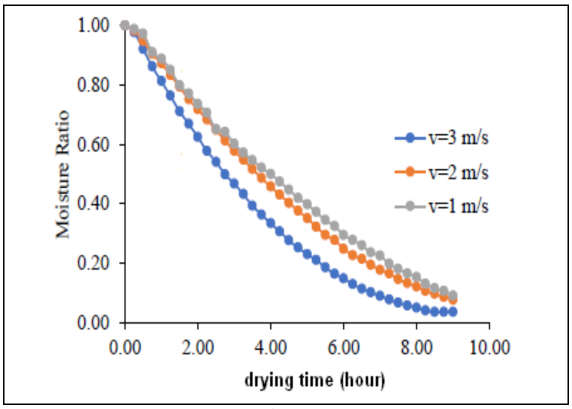

Fig. 4. Drying operation of ginger. Convective desiccant drying. Silica gel desiccant. Temp. 53°C.

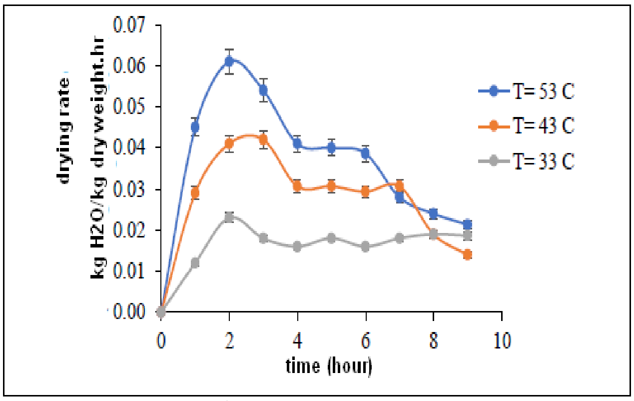

Fig. 5. Drying curve of ginger. Convective desiccant drying. Silica gel desiccant. Air velocity 1 m/s.

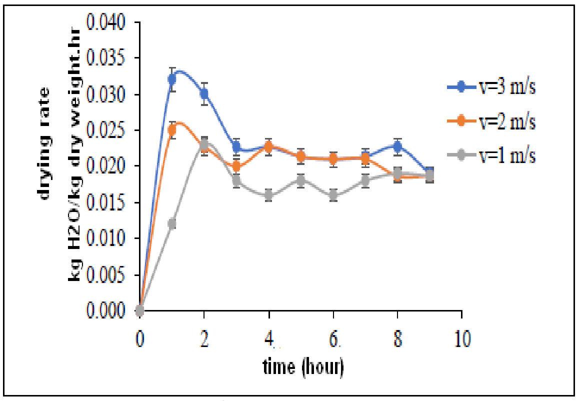

Fig. 6. Drying curve of ginger. Convective desiccant drying. Silica gel desiccant. Temp. 33°C.

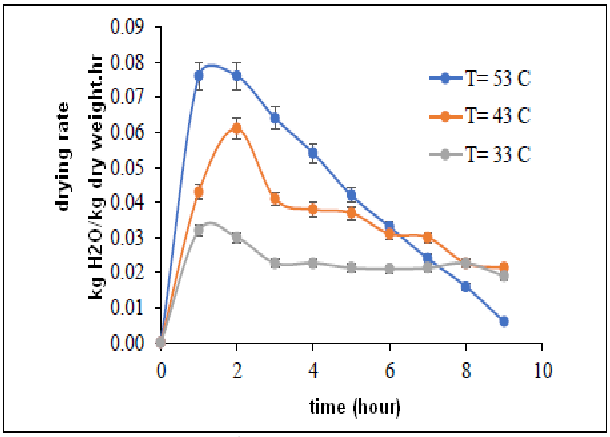

Fig. 7. Drying curve of ginger. Convective desiccant drying. Silica gel desiccant. Air velocity 3 m/s

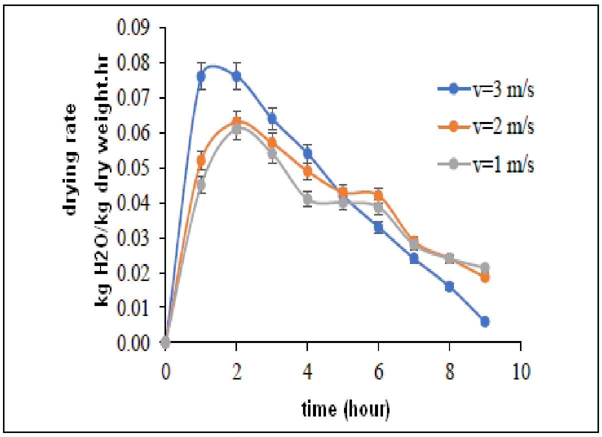

Fig. 8. Drying curve of ginger. Convective desiccant drying. Silica gel desiccant. Temp. 53$^{o}$C

On other occasions, Fig. 7 and 8 present another remarkable features in relation to varied temperatures (33$^{o}$C, 43$^{o}$C, and 53$^{o}$C) and varied air velocities (1 m/s, 2 m/s, and 3 m/s), respectively. Both Fig. 7 and 8 show a maximum peak of drying rate at early stage of drying operation ( < 2h ). The maximum drying rates at varied temperatures (33$^{o}$C, 43$^{o}$C, and 53$^{o}$C) as shown in Fig. 7 are significant distinctive. On the other hand, the maximum peaks at varied air velocities (1 m/s, 2 m/s, and 3 m/s) are not too distinctive especially for the drying curve of both 1 m/s and 2 m/s looks almost indifferent as shown by Fig. 8. This phenomenon clearly presented again the effect of temperature in this investigation is more influenced.

Generally, the drying rates of almost all herbals shows similar tendency, i.e. the drying curves show a maximum peak at earlier stage of drying process. In other words, the positive slope of drying curve is sharp at earlier drying time and then gaining its maximum. The general drying pattern is shown by all drying process particularly for herbal drying [9]. According to the drying theory, at the first stage the drying operation is related with evaporation process of free water on material surface. This evaporation process is fast because the adhesive force between water molecules and material surface is low due to weak physical interaction.

It is not surprising that the process of free water removal from material surface is rapid yielding sharply positive slope of drying curve. Liu and Lee [10] reported that half of the drying process occurred at the beginning stage since at early step the drying process involves with releasing free water surface. On further examination, the drying rate looks relative stable after 4h drying time and then after 6h drying time it fluctuated again (Fig. 5). On other occasion, the drying rates for all varied air velocities (1 m/s, 2 m/s, and 3 m/s) tend to fluctuate at certain range (0.015 – 0.025 unit) started after 3h drying time until experiment ending (Fig. 6). The relative constant drying rate in both figures (Fig. 5 and 6) involve with phase change from water liquid to water vapor at material surface in relation to change of cohesive forces. The fluctuated drying rate as seen remarkably in Fig. 4 involves with diffusion of water molecules in material core [9]. The drying rate of material is strongly related with hydrogen bonding of water molecule and any chemical interaction between bound water and ions/molecules in material through complex formation. Finally, the drying process is significant influenced by physical and chemical properties of material being dried in relation with density, solubility, internal forces and material structure whether amorphous or crystalline [9].

As already mentioned above, the drying kinetics obtained from experimental data referred to Figures 1 – 4 and other figures not shown here are assayed by three proposed drying models (Newton, Page, and Henderson-Pabis). Then the drying models are examined applying three statistical parameters, i.e. the coefficient of determinant ($R^2$), root mean square (RMSE) and chi-square ($\chi^2$). The results are shown in Table 3. As shown in Table 3, the coefficient of determinant belong to the Page model shows the highest value compared to the values of other two drying models (Newton and Hemderson-Pabis) at all given temperatures (33$^{o}$C, 43$^{o}$C and 53$^{o}$C) and air velocities (1 m/s, 2 m/s, and 4 m/s). At the meantime, both values of RMSE and chi-square of Page model show the lowest values among that values belong to other two drying models for all given temperatures and air velocities. The values of statistical parameters related to Page drying model are presented as bold printed values in Table 3. Table 4 shows the exponential Page model at given temperatures (33$^{o}$C, 43$^{o}$C, and 53$^{o}$C) and air velocities (1 m/s, 2 m/s, and 3 m/s) applying the drying constants from Table 2.

TABLE 4. Page exponential equations at given temperatures (33$^{o}$C, 43$^{o}$C, and 53$^{o}$C) and air velocities (1 m/s, 2 m/s, and 3 m/s). Zingiber Roscoe convective desiccant drying.

| Temperature ($^{o}$C) | Air velocity (m/s) | Page exponential equation |
|---|---|---|
| 53 | 3 | MR= exp (-0.1846 $t^{1.3220}$) |
| | 2 | MR= exp (-0.1286 $t^{1.3354}$) |
| | 1 | MR= exp (-0.1059 $t^{1.3887}$) |
| 43 | 3 | MR= exp (-0.1108 $t^{1.2287}$) |
| | 2 | MR= exp (-0.0901 $t^{1.2224}$) |
| | 1 | MR= exp (-0.0719 $t^{1.2923}$) |
| 33 | 3 | MR= exp (-0.0817 $t^{1.0030}$) |
| | 2 | MR= exp (-0.0610 $t^{1.0381}$) |
| | 1 | MR= exp (-0.0368 $t^{1.1996}$) |

The thin layer drying modeling is useful for optimization of drying operation and efficient drying process estimation that is necessary for cost value and product quality. Selection of goodness fit drying model and drying conditions (air temperature, air velocity, relative humidity and material size) are being considered in simplified thin layer drying modeling. In the upcoming, the drying machine is planned to apply a recharging aluminum battery in remote are [11].

## IV. CONCLUSION

The drying kinetic study of Zingiber Roscoe (ginger) shows valuable information that the temperature effect shown more significant influence than velocity effect under given condition range. The statistical examination shows that Page drying model is the most fitted drying model for experimental data obtained from convective desiccant drying of ginger at given temperatures (33$^o$C, 43$^o$C and 53$^o$C) and air velocities (1 m/s, 2 m/s, and 3 m/s).

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