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# Energy Optimization of Fluidized Bed Drying of Orange Peel Using Taguchi Method

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**Abstract:** This paper presents the application of Taguchi method in optimizing the drying parameters of orange peels (Valencia orange or *Citrus sinensis*) in a fluidized bed dryer. The optimized drying parameters were operating temperature (60°C and 70 °C), air velocity (0.67 m/s, 0.85 m/s and 1.03 m/s) and orange peel to sand mass ratio (1:0, 1:10 and 1:20). Pareto ANOVA analysis method was used to determine the contribution factor of each parameter during the drying process. It was observed that orange peel to sand mass ratio factor contributed more to drying than air temperature and velocity. In order to bring the final moisture content to 0.1 g water/g dry solids, analysis using Taguchi method showed that the optimum parameters for minimizing the drying time were at air temperature of 70°C, air velocity of 1.03 m/s and orange peel to sand mass ratio of 1:10. The same result was obtained when using specific energy consumption method.

**Key words:** Citrus sinensis · Drying curves · Drying rate · Energy consumption · Pareto ANOVA

## INTRODUCTION

Orange juice industry produces large amount of orange peel during processing, which may create environmental problem [1, 2]. The utilization orange peel as by-product from orange juice industry could make substantial contribution, environmentally and economically to this industry. Orange peel was found to be rich in fibre, soluble sugars, protein, minerals and phenols [3]. This by-product can be used as animal feeds and source of dietary fibre [2]. Furthermore, orange peel is rich in vitamin C and could lower the cholesterol level in blood [4]. A study by Chen *et al.* [5] showed that orange peel has great potential to be used as natural biosorbent for polycyclic aromatic hydrocarbons removal in wastewater treatment. This plant residue could be a promising choice for organic pollutants treatment. Apart from that, previous study also has shown the applicability of orange peel as biosorbent for removing Cr(VI) in solution, making it a promising material for heavy metal bearing industrial wastewater [6]. Some other authors also reported the use of orange peel and their modifications for heavy metal removal [7-9].

Orange peel contains a high moisture content that reaches 2.97 kg water/kg db, therefore the reduction of its moisture content is necessary to increase its shelf life and assure its microbial and physico-chemical quality [3]. Drying has become a widely used way of food processing allowing the extension of shell-life of fruits and vegetables [2]. Several work have been conducted in the drying of orange peel. Slama and Combarnous [4] performed a study on the drying kinetics of orange peel in a solar dryer. The moisture sorption isotherm data of orange peel at 40, 50 and 60 °C has been established by Bejar *et al.* [3]. They found that Peleg model was the best model among thirteen equations studied for fitting the experimental data of desorption and adsorption isotherms of orange peel. Further work by Bejar *et al.* [10] investigated the effect of microwave drying on drying characteristics and functional properties of this by-product. Ortuno *et al.* [1] studied the

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convective drying kinetics of orange peel slabs (thickness 5.95 ± 0.41 mm) at 40 °C and 1 m/s with and without power ultrasound application. Results showed that drying kinetics of orange peel was significantly improved by the application of power ultrasound. A study by Garau *et al.* [2] concluded that orange peel was quite resistant to the different heat treatments applied within the range from 40 to 70 °C. The dietary fibre and antioxidant capacity of orange peel were degraded or modified either when extended drying periods and/or high drying temperatures are applied.

Fluidized bed dryers are widely used to dry food and agricultural materials. Among the applications of fluidized bed in the drying of food and agricultural materials are rice [11], carrot [12], green peas [13], chopped coconut [14] and lemon grass [15]. Fluidized bed dryers offer advantages such as good mixing of solids, high heat and mass transfer rates, ease of operation and maintenance and lower capital costs [16, 17]. Drying in fluidized bed dryer results in shorter drying time and produces excellent product quality compared to other drying methods due to the intensive heat and mass transfer between gas and solids [18]. A fluidized bed dryer with the presence of inert particles, whereby the inert particles serve as heat carrier, has been used to assist the drying of a variety of materials. Inert particles can improve the fluidization behavior of the materials and increase the convective heat and mass transfer rates [19, 20].

The conventional design of experiment is known as a very complicated and a highly disciplined process which required competent resources and will accrue high experimental cost. It is a complex and not easy to use, especially when large number of experiments has to be carried out when the number of the process parameters increases [21]. The time required to complete an experiment is extremely long especially for investigating and evaluating large quantity of factors that are affecting the desired quality characteristics. The difficulties are further encountered when experiment has to be repeated for several modeling and verification purpose until accurate and validated result is obtained. Therefore the Taguchi methodology in design of experiment has become the alternative in solving these phenomena and is chosen as the right solution to any industrial organization in improving their product and process design.

Taguchi design can determine the effect of factors on characteristic properties and the optimal conditions of factors. Orthogonal arrays and ANOVA are used as the tools of analysis. ANOVA can estimate the effect of a factor on the characteristic properties and experiment can be performed with the minimum replication using the orthogonal arrays. Conventional statistical experimental design can determine the optimal condition on the basis of the measured values of the characteristic properties while Taguchi method can determine the experimental condition having the least variability as the optimal condition. The variability is expressed by signal to noise (S/N) ratio. The experimental condition having the maximum S/N ratio is considered as the optimal condition as the variability characteristics is inversely proportional to the S/N ratio [22, 23].

A few articles have been published on the drying of orange peel, however, less work has been performed on the optimization of the design experiments for drying parameters. Therefore, this study attempts to optimize the drying of orange peel in a fluidized bed dryer with inert particles using Taguchi method. Effects of drying parameters such as operating temperature, air velocity and orange peel to sand mass ratio on quality parameters such as final moisture content and drying time are also investigated.

## MATERIALS AND METHODS

**Materials:** Fresh oranges (*Citrus sinensis*) were obtained from local market and their skins were cut into square slabs with side lengths of 0.5 cm. The peels were prepared on the day of the experiment and stored in a refrigerator until usage. In the drying experiment, sand was used as inert particles or heat carrier. Prior to use, the sand was dried in an oven at 105°C until the weight became constant.

**Drying Experimental Procedure:** A fluidized bed dryer (rapid bin dryer model TG 100, Retsch, Germany), as shown in Figure 1, was used to create conditions suitable for fluidized bed drying. The bin has a volume of 6 L, a voltage of 230 V and a frequency of 50 Hz. The air temperature used was 60 °C and 70 °C and air velocity of 0.67 m/s, 0.85 m/s and 1.03 m/s. A total of 50 g of orange peel and sand were prepared according to the required mass ratio between the orange sample and sand (1:0, 1:10 and 1:20). Sand was first placed into the bin and then the fluidized bed was turned on. Hot air was circulated for 10 min to ensure that the required experimental conditions were established. After wards,

Fig. 1: Fluidized bed dryer: Rapid bin dryer Model TG 100

Table 1: Factors and levels used in the drying experiments

| Factor / Level | 0 | 1 | 2 |
|---|---|---|---|
| A - Temperature (°C) | 60 | 70 | N/A |
| B - Hot air velocity (m/s) | 0.67 | 0.85 | 1.03 |
| C - Mass ratio of orange peel:sand (-) | 1:0 | 1:10 | 1:20 |

Table 2: Design of experiments using L18 array

| | Parameters | | |
|---|---|---|---|
| Set | Temperature (°C) | Velocity (m/s) | Mass ratio (-) |
| A1 | 60 | 0.67 | 1:0 |
| A2 | 60 | 0.67 | 1:10 |
| A3 | 60 | 0.67 | 1:20 |
| A4 | 60 | 0.85 | 1:0 |
| A5 | 60 | 0.85 | 1:10 |
| A6 | 60 | 0.85 | 1:20 |
| A7 | 60 | 1.03 | 1:0 |
| A8 | 60 | 1.03 | 1:10 |
| A9 | 60 | 1.03 | 1:20 |
| A10 | 70 | 0.67 | 1:0 |
| A11 | 70 | 0.67 | 1:10 |
| A12 | 70 | 0.67 | 1:20 |
| A13 | 70 | 0.85 | 1:0 |
| A14 | 70 | 0.85 | 1:10 |
| A15 | 70 | 0.85 | 1:20 |
| A16 | 70 | 1.03 | 1:0 |
| A17 | 70 | 1.03 | 1:10 |
| A18 | 70 | 1.03 | 1:20 |

the orange peel sample was placed into the bin and the drying experiment was immediately started. In addition to air temperature, air velocity and orange peel to sand mass ratio, another factor to be investigated was the drying time. The orange peel was dried for 10, 14, 20 and 24 min respectively.

The investigated parameters in the drying experiments were hot air temperature, hot air velocity and orange peel to sand mass ratio. The factors and levels for the experimental design used in this study are given in Table 1.

By using the L18 orthogonal array from Taguchi method, a total of 18 sets of experiments were obtained as presented in Table 2.

**Analysis of Results:** For Taguchi analysis, "the smaller the better" criterion was used as the criterion for final moisture content. The SN ratio for this criterion can be determined using the following equation:

$$SN = -10\log_{10}\left(\frac{\sum y_i^2}{n}\right) \quad (1)$$

where $y_i$ is the measured data and $n$ is the quantity of measured data.

In contrast, "the bigger the better" criterion was applied as a criterion for the drying rate as the highest rate of drying is desired. The SN ratio for this criterion can be determined using Eqn. (2).

$$SN = -10\log_{10}\left(\frac{\sum\left(\frac{1}{y_i^2}\right)}{n}\right) \quad (2)$$

The total energy requirement for drying of one charge of the dryer and the energy needed for the drying of 1 kg of wet product were determined by using Eqns. (3) and (4), respectively. The energy consumption for a convective dryer was determined using Eqn. (3) from Aghbashlo *et al.* [24] and Koyuncu *et al.* [25].

$$E_t = Au\rho_a C_a \Delta T\, D_t \quad (3)$$

where $E_t$ is the total energy consumption in each drying trial, $A$ is the cross section area of the drying column, $u$ is the air velocity, $\rho_a$ is the air density, $C_a$ is the specific air heat, $\Delta T$ is the temperature difference and $D_t$ is the total drying time required to reach a moisture content of 0.1 g/g db.

The energy consumed in drying a kilogram of orange peel was calculated using Eqn. (4) as follows:

$$E_{kg} = \frac{E_t}{W_0} \quad (4)$$

where $E_{kg}$ is the specific energy required and $W_o$ is the initial weight of the sample.

## RESULTS AND DISCUSSION

**Moisture Content:** Table 3 shows the experimental results and the computed SN ratio. The response variable is the final product moisture content after drying for 20 minutes. The larger SN ratio is desirable as it represents the smaller moisture content. Thus, according to the SN ratio analysis

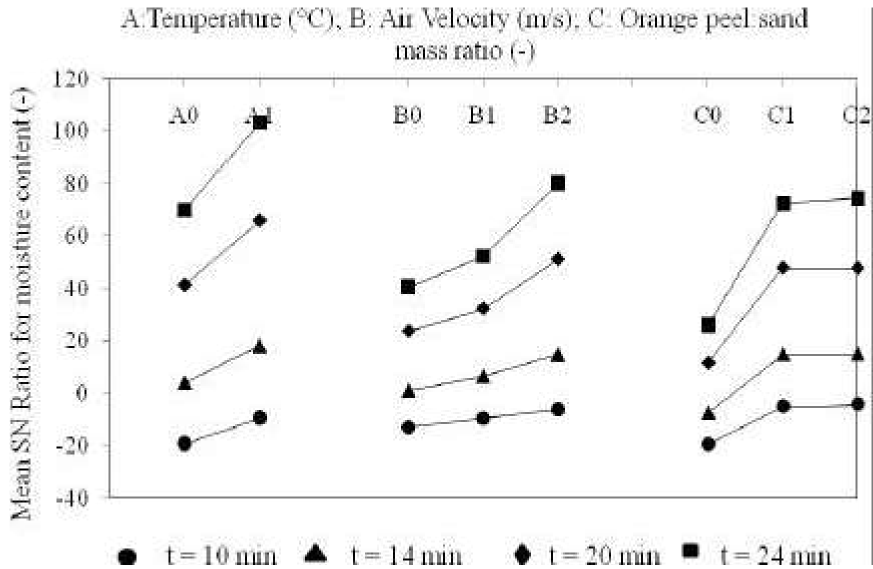


Fig. 2: SN ratios for final moisture content for orange peel drying at different drying times

Table 3: Final product moisture content and the computed SN ratio for orange peel drying process at time $t$ = 20 minutes

| Set number | Designaton | Moisture content (g/g db) | SN ratio (-) |
|---|---|---|---|
| 1 | A0B0C0 | 0.9324 | 0.61 |
| 2 | A0B0C1 | 0.6034 | 4.39 |
| 3 | A0B0C2 | 0.6139 | 4.24 |
| 4 | A0B1C0 | 1.0968 | -0.80 |
| 5 | A0B1C1 | 0.4723 | 6.52 |
| 6 | A0B1C2 | 0.4532 | 6.87 |
| 7 | A0B2C0 | 0.9054 | 0.86 |
| 8 | A0B2C1 | 0.4325 | 7.28 |
| 9 | A0B2C2 | 0.2753 | 11.20 |
| 10 | A1B0C0 | 0.7832 | 2.12 |
| 11 | A1B0C1 | 0.4760 | 6.45 |
| 12 | A1B0C2 | 0.5085 | 5.87 |
| 13 | A1B1C0 | 0.6853 | 3.28 |
| 14 | A1B1C1 | 0.3612 | 8.85 |
| 15 | A1B1C2 | 0.4188 | 7.56 |
| 16 | A1B2C0 | 0.5308 | 5.50 |
| 17 | A1B2C1 | 0.1928 | 14.30 |
| 18 | A1B2C2 | 0.2537 | 11.91 |

shown in Table 3, the lowest final product moisture content (i.e. the highest value of SN ratio) was achieved when the drying process was carried out at temperature of 70°C, velocity of 1.03 m/s and orange peel to sand mass ratio of 1:10.

Figure 2 shows the general trend of the stiffness of each line plotted at different drying times. It can be observed that the trend is somewhat similar over the duration of the drying process, namely up to $t$ = 24 min. The highest air velocity ($u$ = 1.03 m/s) and air temperature ($T$ = 70 °C) yield to the smallest value of moisture content in the drying product. This finding is in accordance with the findings of other researchers in the drying of different fruits and vegetables [17, 26-29]; more specifically, with a higher temperature and air velocity, more water vapors are removed to result in a lower moisture content in the material. The increase of the temperature would increase the diffusion coefficient during the moisture transport process [30, 31].

Mulet *et al.* [32] proposed the concept of a 'critical velocity', whereupon moisture movement was insensitive to any further increase and, hence, internal mass transfer controlled. In our case, the positive dependency of the moisture content reduction would suggest that external mass transfer is significant. Meanwhile, for the orange peel to sand mass ratio, the highest ratio of 1:20 gives the optimum moisture content minimization even though the difference between the ratios of 1:10 and 1:20 is seemingly very small. The addition of inert materials clearly seems to help in greatly reducing the moisture content, as shown in the large difference in the mean SN ratio values between the mass ratios of 1:0 and 1:10.

Pareto ANOVA analysis, which uses the Pareto principles, is a simplified ANOVA method. Pareto ANOVA analysis was used to determine the contribution factor of each drying parameter in the drying process. Table 4 presents the Pareto ANOVA analysis. From Table 4, it could be observed that the orange peel to sand mass ratio contributes 72.1% to moisture content, followed by temperature and hot-air velocity at 16.41% and 11.49%, respectively, for the orange peel drying

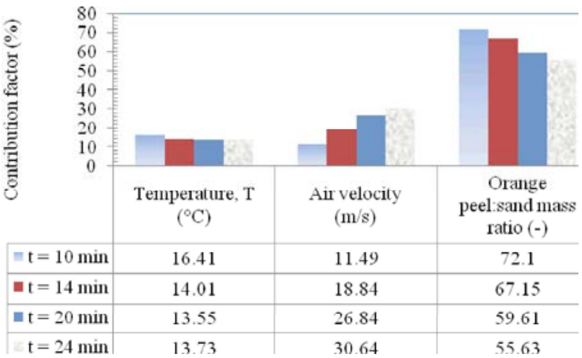


Fig. 3: Contribution factor of drying parameters on moisture content in orange peel drying at different drying times

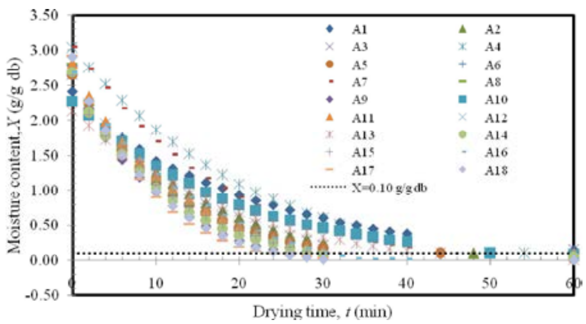


Fig. 4: Variation of moisture content with drying time for all experimental sets

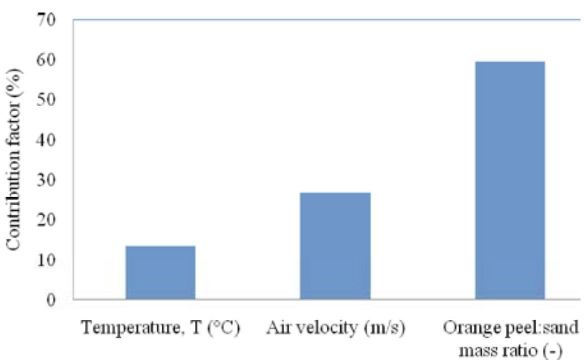


Fig. 5: Contribution factor of drying parameters on drying time in orange peel drying to reach a final moisture content of 0.1 g/g db

process when the drying process progressed until time $t$ = 10 minutes. Figure 3 shows that orange peel to sand mass ratio contributes the highest percentage when compared to both the gas velocity and the temperature over different drying times. The contributions of the gas velocity and the temperature are almost equal over the drying period, but when the period was prolonged, the gas velocity contributed more than the operating temperature.

Table 4: Pareto ANOVA analysis for moisture content in orange peel drying at time $t$ = 10 minutes

| Factor | | A | B | C |
|---|---|---|---|---|
| Sum at factor level | 0 | -19.45 | -13.01 | -19.42 |
| | 1 | -9.58 | -9.75 | -5.15 |
| | 2 | | -6.27 | -4.46 |
| Sum of squares of differences (S) | | 97.42 | 68.17 | 427.91 |
| Contribution factor (%) | | 16.41 | 11.49 | 72.10 |

Table 5: Drying time and the computed SN ratio for the orange peel drying process

| Set number | Designation | Drying time $t$ (min) | SN ratio (-) |
|---|---|---|---|
| 1 | A0B0C0 | 65 | -36.26 |
| 2 | A0B0C1 | 48 | -33.62 |
| 3 | A0B0C2 | 65 | -36.26 |
| 4 | A0B1C0 | 54 | -34.65 |
| 5 | A0B1C1 | 44 | -32.87 |
| 6 | A0B1C2 | 40 | -32.04 |
| 7 | A0B2C0 | 50 | -33.98 |
| 8 | A0B2C1 | 30 | -29.54 |
| 9 | A0B2C2 | 29 | -29.25 |
| 10 | A1B0C0 | 50 | -33.98 |
| 11 | A1B0C1 | 54 | -34.65 |
| 12 | A1B0C2 | 60 | -35.56 |
| 13 | A1B1C0 | 44 | -32.87 |
| 14 | A1B1C1 | 29 | -29.25 |
| 15 | A1B1C2 | 29 | -29.25 |
| 16 | A1B2C0 | 40 | -32.04 |
| 17 | A1B2C1 | 23 | -27.23 |
| 18 | A1B2C2 | 25 | -27.96 |

**Drying Time:** The variations in moisture content for all experimental sets over the whole drying period are shown in Figure 4. The initial moisture content of orange peel was in the range of 2.15 - 3.10 g water/g dry solids on dry basis. It was observed from Figure 4 that moisture loss of dried orange peel increased as the drying time increased. Table 5 shows the results for drying time and the computed SN ratio for the orange peel drying process. In this case, the drying time presented is the drying time necessary to achieve a moisture content of 0.1g/g db for each experimental run. Table 5 shows that the lowest drying time (i.e. the highest SN ratio) is at level 1 (70°C) for temperature, level 2 (1.03 m/s) for hot-air velocity and level 1 (1:10) for orange peel to sand mass ratio. This result is shown in the A17 set.

For the drying time to reach final product's moisture content of 0.1 g/g db, the Pareto ANOVA analysis presented in Figure 5 shows that the orange peel to sand mass ratio contributed 59.61% to the drying time, followed by the hot air velocity and the temperature, which contributed 26.84% and 13.55%, respectively. This supports the postulation that, in this case, the external

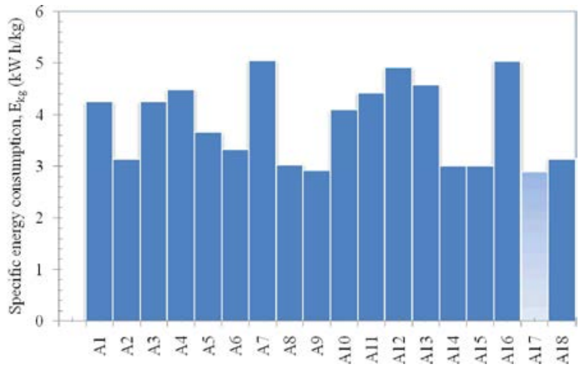


Fig. 6: Specific energy consumption for different sets of parameters

mass transfer resistance is significant, as pointed out by Senadeera *et al.* [27], because if only the internal resistance were important, the air temperature would be the more dominant contributing factor. The high solids circulation rate resulting from the addition of fluidizing sand particles in the dryer helped induce the mass transfer between the water vapors from the sample to the hot fluidizing air and vice versa. Sand also acts as a heat carrier to improve drying conditions, specifically by creating more uniform temperature conditions in the dryer; this in turn helps to increase the drying rate of the material [29].

**Optimization of Process Parameters Based on Energy Consumption:** The total energy requirement for a charge of the dryer and the energy needed for drying 1 kg of orange peel can be observed in Figure 6. It can be observed that the energy consumption decreases significantly with the addition of sand as a heat carrier, as observed in the plots of sets A2, A6, A8, A9, A14, A15, A17 and A18. Although the difference in $E_{kg}$ values for sets A17 and A9 appears to be very small, set A17 was found to give the minimum value of specific energy consumption (2.90 kW h/kg) for the drying of 1 kg orange peel at a temperature of 70°C, air velocity of 1.03 m/s and sample to sand mass ratio of 1:10. This confirms the finding obtained from the Taguchi method presented in previous section.

## CONCLUSION

The optimization of the drying of orange peel in a fluidized bed dryer with inert particles was performed using Taguchi method. From Taguchi analysis, it was shown that the optimum operating condition to achieve the lowest product moisture content and the shortest drying time was at the highest air velocity and air temperature. The addition of inert materials was shown to help in greatly reducing the moisture content. Pareto ANOVA analysis indicated that the orange peel to sand mass ratio was the dominant contribution factor for moisture content, followed by air velocity and temperature. This finding suggests that the external resistance of mass transfer is important in the drying of orange peel. The optimum condition predicted using Taguchi method was the same with the prediction based on energy consumption calculation. Taguchi method was thus proven as a suitable approach for application in the optimization of a drying process.

**Nomenclature:**

| | | |
|---|---|---|
| 1A | = | Cross section area of column ($m^2$) |
| $C_a$ | = | Specific air heat (kJ/kg ºC) |
| $D_t$ | = | kotal drying time to reach a certain moisture content (hr) |
| $E_{kg}$- | = | Specific energy required (kW h/kg) |
| $E_t$ | = | Total energy consumption in each drying trial (kW h) |
| n | = | Quantity of measured data |
| SN | = | SN ratio |
| T | = | Air temperature (ºC) |
| $u$ | = | Air velocity (m/s) |
| $W_o$ | = | Initial weight of the sample (kg) |
| $y_i$ | = | Measured data (-) |
| $\rho_a$ | = | Air density (kg/$m^3$) |
| ΔT | = | Temperature difference (ºC) |

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