Process Optimization of Pneumatic Separator Machine Using Response Surface Methodology

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ABSTRACT
Pneumatic separator machine is one of the alternative methods used for the grain cleaning process. To obtain the efficient grain cleaning process, the design of a pneumatic separator should consider aerodynamic properties of the material such as terminal velocity value. Form of material, material density, water content are factors to determine the value of aerodynamic properties of material. This study attempts to design and optimize the process parameter of a pneumatic separation machine on cleaning paddy seeds from light impurities contaminants to achieve the optimal separation efficiency. A numerical approach was used to predict the minimum and maximum value of the air velocity required to optimally separate the impurities contaminant from grain product. An experimental design based on Response Surface Methodology (RSM) was used to evaluate the effect of variables, including air velocity, material feed rate and material moisture content on separation efficiency. Quadratic polynomial models were adjusted to the data to predict the behavior of the selected factors on the separation efficiency. The experiment confirmed that air velocity, water content and feeding rate are significant on separation efficiency while the interaction between factors were found to be insignificant. The statistical results confirmed that R2 of quadratic polynomial models was 0.83 for the separation efficiency. The increase in air velocity increased the separation efficiency, while there was curvature in the material feed rate factor. According to the response optimizer, the optimum separation efficiency was found at 5.39 m/s of air velocity, 2.18 kg/min of material feed rate and 10% of material moisture content. This approach enabled us to design and optimize the performance of pneumatic separator machine for different conditions of grain material.

Keywords: *Grain Cleaning Process, Pneumatic Separator, Process Optimization, RSM, Aerodynamic Properties*

1. INTRODUCTION

Obviously, after harvesting and threshing processes, the crop contains various undesired materials other than grain (MOG) such as debris, sand, stone pebbles, chaff, and straw which can significantly increase both density of materials and its dockage level. Cleaning and separating process then required to remove MOG in order to upgrade the grain quality. Separation of grain from its contaminant will help improve its storage, increase market value and ease the further processing. One of the frequently used methods for cleaning the grain mixture from the impurities contaminants is a pneumatic separation machine. This machine utilizes the air flow to separate the undesired materials from grain based on its different physical and mechanical properties. The development of a pneumatic separator machine for cleaning purpose is conditioned by a number of parameters, including physical properties of grain material, cleaning accuracy, cleaning efficiency, the flexibility of adjusting the machine for the range of parameter value [1]. Different types of grain material have different physical and mechanical properties, therefore, a different setup of pneumatic process for separation is required to clean and separate a specific type of impurities from grain product. In the process of pneumatic separation, aerodynamic properties of particles are used as the machine setup determination, while the characteristic measure is their terminal velocity [2]. A proper setup of the air velocity in the pneumatic separator then required to optimally separate the undesired contaminants from grain product with high separation efficiency and low level of grain losses.

Many factors influence the precision and effectiveness of separation of certain grain products from contaminants such as the characteristic of contaminants, the different value of terminal velocity between grain and contaminant, feeding rate of the input material, setup of the air velocity and water content of the basic product [3]. Different type of contaminants result in different terminal velocity required to drag and seperate it from the basic grain product. The higher the difference between the critical velocity value of the contaminant and basic product, the easier to select the setup air velocity in terms of increasing separating efficiency and reducing product losses. The setup of feed rate of the input material may significantly determine the required airflow in the suction channel of the pneumatic separator. Higher feed rate requires higher volume of airflow to be added in the suction channel. While adding moisture content of material increases the terminal velocity of the material; thus it increase the force to drag the material in terms of separating process [4].

Some studies attempt to adequately model the separating process of contaminants from basic products using a pneumatic separator machine [5-7]. Afolabi, et al. [8] designed a pneumatic separator machine to clean a maize grain material from impurities contaminant. They analyzed the influence of setup parameters namely air velocity and feed opening gate on separation efficiency and product losses. They found that air velocity and feed opening gate factors were significant on separation losses. However, the influence of grain moisture content of the basic material on the separation efficiency is not considered in this study. Panasiewicz, et al. [3] found that an increase in the moisture content of crushed lupine seeds significantly decrease the separation effectiveness, while an increase in air velocity increase the separation effectiveness. However, this study did not consider both the feed rate and air velocity on the product losses. Choszcz, et al. [9] analyzed the effect of selected factors such as air velocity, moisture content and type of grain material on the separation efficiency of the Pneumatic Conical Separator. They found that there were significant effects of moisture content and air velocity on the separation efficiency for different seed mixtures. In terms of increasing the test weight and reducing impurities from types of grain product, Crepon and Duyme [10] tested the efficiency of three different types of grain cleaner machine using different grain flow and aspiration rate. They found that the highest test weight increase was obtained with low grain flow rate while an increase in aspiration rate has no major impact on the test weight gain.

According to the literature review, it is found that there are still limited works investigating the influence of factors such as air velocity, material feed rate and material moisture content on separation efficiency. This study attempts to design and optimize the process parameter of a pneumatic separation machine on cleaning paddy seeds from light impurities contaminants to achieve the optimal separation efficiency. The main contribution of this paper is on the consideration of both setup parameters of the pneumatic separator machine and the aerodynamic properties of the basic material in terms of optimizing the performance of the pneumatic separator machine.

1.1. Determining the air velocity of the pneumatic separator

The proper air velocity can be set according to the different between the aerodynamic properties of grain materials and the undesired impurities contaminant such as terminal velocity and drag coefficient. According to Khoshtaghaza and Mehdizadeh [11], when the material is freely dropped from a sufficient preference height, the force of gravity will be accelerated until the drag force exerted by the air on the chamber, and then balanced the gravitational force. It will then drops at a constant velocity named the terminal velocity, which can estimated using the following equation:

M.g = 1/2 ρ.Vt 2.Cd.A (1)

Where, M refers to mass of the material (kg), g refers to gravitation accelerating (m/s2), Cd refers to drag force coefficient, ρ refers to air density in the suction channel (kg/m3), A refers to the area of the object interacts with air in the suction channel (m2), while Vt refers to terminal velocity (m/s). From this equation, the drag coefficient of an object can be found from its terminal velocity :

$$C_d = \frac{M.g}{\frac{1}{2}.V_t{}^2 A} \quad (2)$$

A horizontal wind tunnel construction can be used to calculate and estimated the value of drag coefficient of any large objects. The drag force coefficient of the material can be calculated using a Reynold number approach. However, for the small particles (like grain seeds and impurity contaminant), the drag force cannot be estimated and calculated directly using this method. So the drag force coefficient of grain materials is estimated from their terminal velocity (Eq.2) throughout experimental study. Thus, the air velocity (V_air) at the suction channel of this pneumatic separation machine should be set as follow:

$$Vt_c < V_{air} < Vt_p \quad (3)$$

Where, Vt_c is the terminal velocity of the contaminant, V_{air} is the setup air velocity at the suction channel, and Vt_p is the terminal velocity of the basic grain product. The terminal velocity of each material differs according to the moisture content and the form of the material [12]. In this study, the range of terminal velocity of the contaminant and basic product were determined through preliminary experiment.

1.2. Design of Proposed Pneumatic Separator

Fig. 1 showed the design of the proposed pneumatic separation machine. It is consisted of a hopper, suction channel, sieve and output channel. The hopper was designed to enable user determines the feed rate of the material through an opening gate. The suction channel also equipped with an electric motor (3 phase electric motor of 1 HP) and a frequential regulator that enable user to set the air velocity in the suction channel. The sieve is equipped with a heigh adjuster and vibrator motor to create a vibration on the sieve screen. The output channel was devided into 3 level, first level for material or contaminant whose diameter size is larger than the basic product, the second level screen for the basic product output, while the third level screen for the contaminant whose diameter size lower than the basic product.

2. MATERIAL AND METHODS

2.1. Sample Preparation

The sample used in this study was a Situ Bagendit variety of paddy seed from Department of Agricultural Service, Yogyakarta Province. In each run, the sample contain the mixture of paddy seed of 4.500 g and light impurity material as the contaminant of 500 g. To get the paddy in 3 different moisture content, the first sample is the paddy seed with the normal moisture content (10% wb), the second sample is the paddy that has been dried using cabinet dryer at 45 ^oC for 3 hours (to get lower moisture content, 8% wb), and the third sample is the paddy that has been sprayed with water and dried for 30 minutes at room temperature to obtain a sample with higher moisture content (12% wb).

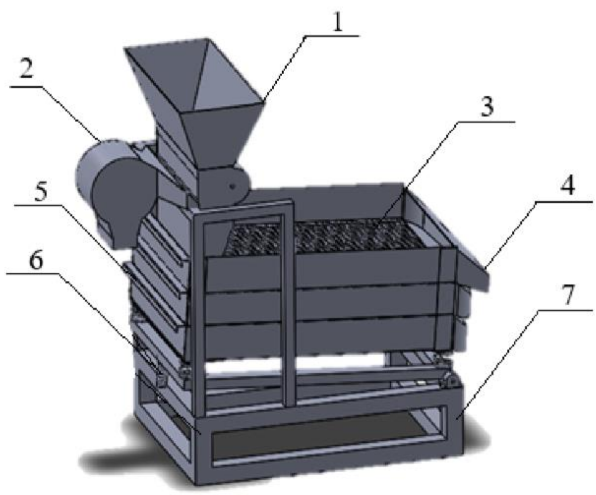

Figure 1 Scheme of grain separator : 1 - hooper, 2 - pneumatic suction, 3 – sieve, 4 – output, 5 – sieve substitute, 6 – height adjuster, 7 – machine frame.

2.2. Design of Experiment

This study was based on Response Surface Method (RSM) to analyze the influence of the selected factors on the separation efficiency and to determine the optimum setup parameters of the separation machine. The selected factors and its level can be found at table 1. The experiment was conducted based on Box-benkhen design with 3 factors and 3 reflications. Separation efficiency of the pneumatic machine was calculated using the following equation:

$$\text{Separation Efficiency (\%)} = \frac{M_1 - M_2}{M_1} \times 100\% \quad (4)$$

Where, M_1 is the weight of impurities contaminant (500), M_2 is the weight of the impurities passed the suction channel after separating process.

Table 1. Selected factors and levels.

Selected Factors	Low Level	Medium Level	High Level
Air Velocity (m/s)	4	5	6
Material Feed rate (kg/min)	1.7	2.5	2.7
Material Moisture Content (%)	8	10	12

The effect of air velocity, feed rate and moisture content on the response was assessed and analyzed. A second-order polynomial regression model was used to model the dependent variables in this case separation efficiency as follow:

$$yi = a_0 + \sum_{i=1}^{b} a_i\, x_i + \sum_{i=1}^{b} a_{ii}\, x_{ii} + \sum_{i=1}^{b} a_{ij}\, x_i\, x_{ij} \quad (5)$$

Where, yi is the response (separation efficiency), x_i is the selected factors (including air velocity , feed rate and moisture content) and a0, ai , aii and aij are coefficient for intercept, linear, quadratic and interactive effect, respectively. The statistical data of each term was assessed using analysis of variance (ANOVA) for the separation efficiency. The adequacy of the model was then checked by using correlation coefficient R2 and the p-value of the term.

3. RESULTS AND DISCUSSION

3.1. Statistical Analysis

The results provided in table 2 and 3 showed the experimental results data and the model statistics and their significance, respectively. The regression models for separation efficiency was found significant ($p<0.05$) with correlation coefficients $R^2 = 0.83$. The air velocity, material feed rate and material moisture content are significant ($p<0.05$) on the separation efficiency value. However, the interaction term are found to be insignificant on the separation efficiency that can be excluded from the model.

Table 2. Experimental results.

RunOrder	Air Velocity (m/s)	Material feed rate (kg/min)	Material moisture content (%)	SE (%)
1	4	2.5	8	90.6
2	4	2.5	12	94.8
3	4	1.7	10	83.2
4	5	2.5	10	97.4
5	5	2.7	12	96.6
6	4	2.5	8	87.2
7	6	2.5	12	98
8	5	1.7	12	96
9	5	1.7	8	93.4
10	4	1.7	10	86.2
11	6	2.7	10	94.2
12	4	2.7	10	88
13	4	2.7	10	81.6
14	5	2.5	10	95
15	5	2.7	8	93.6
16	5	2.7	12	95.4
17	6	2.5	8	96.6
18	5	2.5	10	96.4
19	5	1.7	8	94.2
20	6	2.5	12	98.6
21	6	2.5	8	96
22	5	1.7	8	95
23	6	2.5	12	97.6
24	5	1.7	12	96.4
25	6	1.7	10	93.4
26	6	1.7	10	96.2
27	5	2.5	10	98.2
28	4	2.7	10	85.8
29	6	2.7	10	95
30	5	2.5	10	97.2
31	5	1.7	12	96.4
32	4	2.5	12	93.6
33	6	2.5	8	92.2
34	6	1.7	10	91.6
35	5	2.5	10	97.4
36	5	2.7	8	93
37	5	2.5	10	96.6
38	5	2.7	8	92.6
39	5	2.5	10	93.8
40	4	1.7	10	89
41	6	2.7	10	90.6

42	4	2.5	8	86.2
43	5	2.5	10	97.8
44	5	2.7	12	96.8
45	4	2.5	12	94.8

Table 2. Analysis of variance for separation efficiency of the developed pneumatic separation machine.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	645.90	107.649	31.90	0.000
Linear	3	395.96	131.988	39.11.00	0.000
Air Velocity (m/s)	1	260.04.00	260.042	77.06.00	0.000
Material feed rate (kg/min)	1	53.78	53.783	0,69027	0.000
Material moisture content (%)	1	82.14.00	82.140	24.34.00	0.000
Square	3	299.44.00	99.814	29.58.00	0.000
Kecepatan Udara (m/s)*Kecepatan Udara (m/s)	1	185.20.00	185.195	54.88	0.000
Laju Pengumpanan (Kg/min)*Laju Pengumpanan (Kg/min)	1	96.29.00	96.290	28.53.00	0.000
Kadar Air (%)*Kadar Air (%)	1	18.56	18.560	05.50	0.024
Error	38	128.23.00	3.375		
Lack-of-Fit	6	25.93	4.322	01.35	0,183333
Pure Error	32	102.30.00	3.197		
Total	44	774.13.00			

The polynomial regression model for this experiment to estimate the separation efficiency can be found at the following equation:

SE (%) = 91.8 + 44.18 Air velocity (m/s)
+ 86.9 Material feed rate (kg/min)
*- 5.55 Material moisture content (%) - 4.089 Air velocity * Air velocity (m/s)*
*- 19.90 Material feed rate (kg/min) * Material feed rate (kg/min)*
*+ 0.324 Material moisture content (%) * Material moisture content (%).*

3.2. Effect of selected factors on separation efficiency

According to fig. 2, the increase in the air velocity increases the separation efficiency value, this indicated that at the higher air velocity more impurities can be drag out from the mixture materials. This results also fit with experimental study that have been conducted [3, 8, 12] earlier. While, there was a curvature found on the material feed rate, the highest separation efficiency has been obtained at feed rate of 2.18 kg/min. The increase in moisture content also increase the separation efficiency. However, this phenomena happened because of the light impurities used in this experiment as the contaminant were sticked on the paddy seed (at higher moisture content) during the mixing process. So that, the higher the moisture, the more contaminant will be sticked on the paddy seed surface.

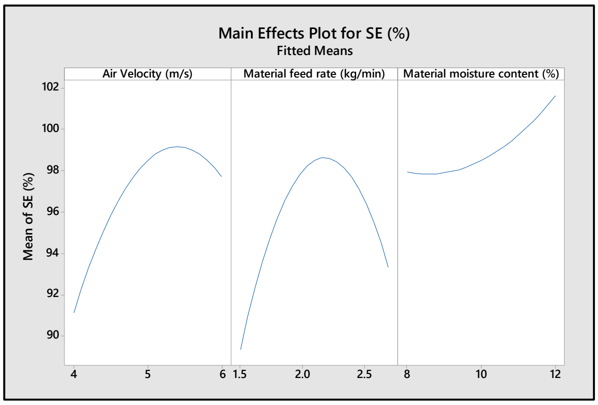

Figure 2 The effect of the selected factors on Separation efficiency.

The response surface plot for the separation efficiency with the two independent variables at material feed rate as the holding value illustrated that the two variables have to be enhanced to diminish the separation efficiency as shown in fig. 3.

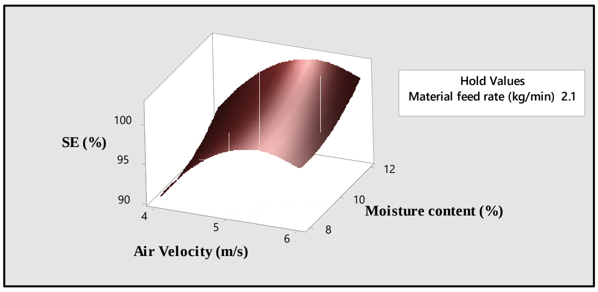

Figure 3 The effect of air velocity and moisture content of separation efficiency.

According to response optimizer (fig. 4), the optimum separation efficiency can be obtained at 5.39 m/s air velocity, 2.18 kg/min of material feed rate and 12% of material moisture content. The maximum separation efficieny obtained in this experiment using the proposed pneumatic separator machined design was 98.6%. it revealed that the proposed design was qualified to use as grain cleaning machine.

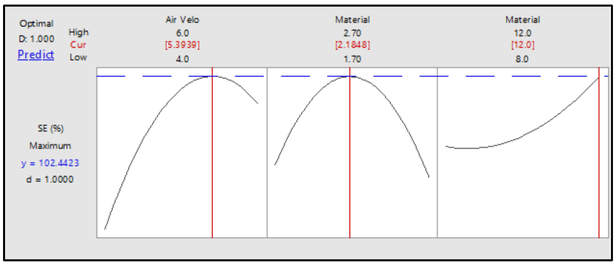

Figure 4 Response surface optimizer to enhance the separation efficiency.

4. CONCLUSION

According to the statistical analysis, it can be concluded that the effect of the selected factors namely air velocity, material feed rate and material moisture content are significant on the separation efficiency of the proposed pneumatic separator machine design. The proposed design can give up to 98.6% to clean the grain product from the light impurities contaminants. This approach enabled us to design and optimize the performance of pneumatic separator machine for different conditions of grain material.

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