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Optimization of a Developed Multi-Cyclone Using Response Surface Methodology (RSM) to Control Fine Particulate Emission

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Abstract. The effects of increasing volumetric air flow rate and inlet particulate loading on overall collection efficiency of MR-deDuster; a developed multi-cyclone system was investigated using various segregated sizes of palm oil mill boiler fly ash. The operating conditions of the fabricated pilot plant scale of the unit were predicted theoretically and screened experimentally. Increasing volumetric air flow rate theoretically will increase the overall collection efficiency, yet the experimental results during screening stage demonstrated contradict finding when the increment of volumetric air flow rate caused the overall collection efficiency to be decreased for a constant particulate loading. Subsequently, the optimization work was done to determine the optimum operating conditions of the system using Response Surface Method (RSM) with Box-Behnken design. The parallel arrangement of multi-cyclone units proved the ability of the system to uniformly disseminate the gas flow with high volume of gas carrier. Nevertheless, excessive pressure drops between each unit of multi-cyclone due to high volumetric air flow rate should be avoided as such condition may lower the overall collection efficiency by allowing dust re-entrainment from the hopper to circulate between the cyclones. Through statistical analysis of variance (ANOVA), validation and verification studies, it is suggested that the developed pilot scale multi-cyclone unit would be able to meet the targeted limit of 150 mg/m³ for solid fuel burning equipment industry in Malaysia by operating with optimized volumetric air flow rate of 0.27 m³/s, and maximum inlet particulate loading rate and size of 2 g/m³ and 1000 µm respectively.

Introduction

As of 2019, there are a total of 452 palm oil mills which are in operation in Malaysia with 241 palm oil mills are located in Peninsular Malaysia and the rest are in East Malaysia. From the total of Malaysian oil palm planted areas, 2.77 million hectares are planted in Peninsular Malaysia which account to 46.9% of the total area with the remaining are in East Malaysia for another 3.13 million hectares of oil palm planted area [1]. Come with these large numbers, palm oil mill is one of the industries that need to fulfill Environmental Quality (Clean Air) Regulations 2014 with concentration limit of particulate matter (PM) using solid fuel that can be emitted is 150 mg/m^3 regardless the monitoring averaging time and frequency. Within the palm oil mills, boilers and incinerators are the main sources of PM emission. Hence, there are few existing technologies that have been implemented in order to comply with the regulation, including cyclone separators; cyclone and multi-cyclones. Cyclone separators are the most commonly applied in the mills as they are more robust to the high temperature exhaust flue gas, less maintenance required, and most importantly have high efficiency despite the function as a pre-cleaning device. However, in regard of controlling fine particulate emission, the cyclone efficiency is still fall apart compared to other subsequent technologies supplemented with typically below 70% [2].

Nevertheless, a separator with small multi-cyclones has better capability in removing particles than a large diameter cyclone [3]. Realizing the potential of cyclone advancement in capturing fine particulate matter, a prototype system of multi-cyclone namely MR-deDuster has been developed. This system has four miniature identical cyclone which arranged parallelly to optimize its performance by distributing the gas flow uniformly. Performance of a cyclone can be influenced by many factors including the design and dimension of the system itself, and also the operation parameters such as the system's air flow rate, particulate loading rate, and the size range of particulate loaded into the system. Fig. 1 illustrates a schematic diagram of MR-deDuster which showing the inlet, outlet, induced draft (ID) fan, and also emission sampling point. The speed of ID fan literally can be controlled to manipulate the volumetric air flow rate throughout the system.

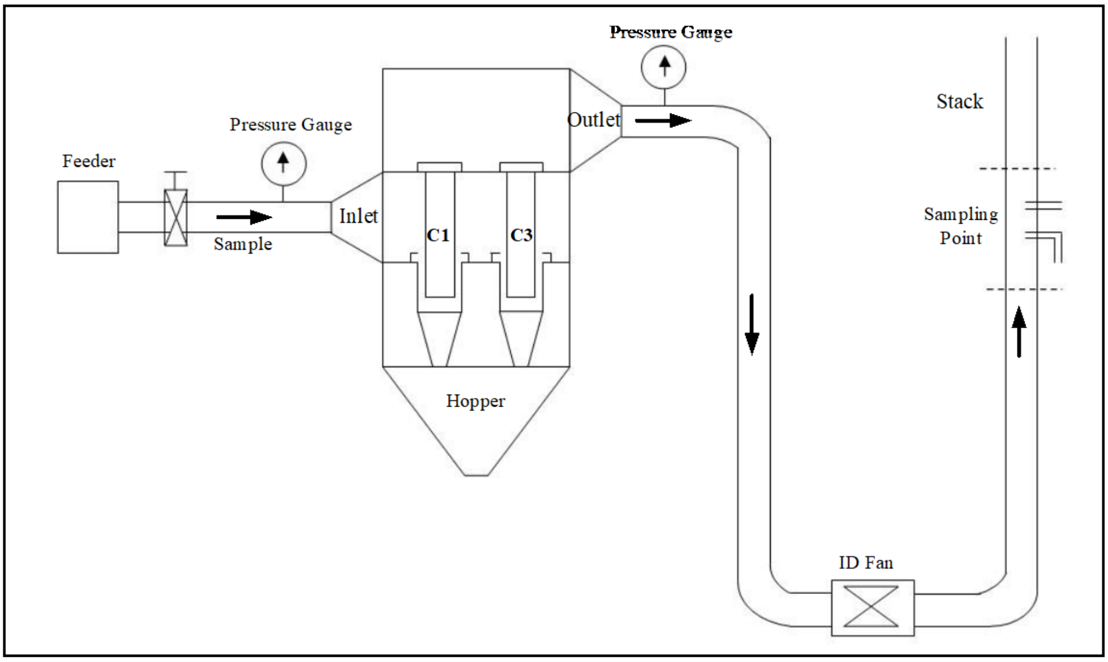

Fig. 1: Schematic diagram of MR-deDuster multi-cyclone system

Theoretically, increasing the volumetric air flow rate will increase the performance of a cyclone separator, for instance the overall collection efficiency [4, 5]. As such, this prototype multi-cyclone system has been theoretically predicted using modified [6] semi empirical model introduced by Lapple with volumetric air flow rate ranging from 0.19-0.35 m^3/s which resulting overall collection efficiency direct proportionally of 99.31-99.60%. This paper presents the experimental approach of the system tested using the same range of volumetric air flow rate. It is found that the experimental result did not satisfy the theoretical estimation which then lead to the optimization on the operating condition of the developed multi-cyclone system using Response Surface Method (RSM) with Box-Behnken design.

Material and Methodology

Sample. The sample used in this experimental study was palm oil mill boiler fly ash (POMBFA) which had been collected from various palm oil mills and thoroughly mixed to get a homogenous batch. POMBFA was then sieved using Endecotts Laboratory Test Sieve BS 410-1 to segregate the sample size into three categories; smaller than 100 µm, smaller than 500 µm, and smaller than 1000 µm. The same batch of sample was used throughout the study to ensure the accuracy and consistency of the results obtained.

Experimental Screening. The effect on increasing volumetric air flow rate ranging between 0.19-0.35 m^3/s was randomly examined experimentally using two segregated size POMBFA of smaller than 500 µm and smaller than 1000 µm with similar inlet particulate loading of 5 g/m^3. The sample was fed into the inlet through feeder and the particulate emission was monitored at the sampling point of the stack according to (simplified) USEPA Method 17: Determination of particulate emissions from stationary sources (in-stack filtration method) [7, 8]. The overall collection efficiency of the system was then calculated using Eq. 1 as follow:

$$\eta_o\ (\%) = \frac{\text{inlet dust loading}\left(\frac{g}{m^3}\right) - E\left(\frac{g}{m^3}\right)}{\text{inlet dust loading}\left(\frac{g}{m^3}\right)}\ x\ 100 \quad (1)$$

where η_o is overall collection efficiency and E is concentration of emitted particulate obtained from the stack sampling. The average data were obtained by repeating each run of the experiment and analyzed as based for the optimization study.

Optimization. Based on the results in experimental screening stage, the operating conditions of the system were optimized by using Design Expert® software for Box-Behnken Design of Response Surface Methodology (RSM) [9]. Table 1 indicates the three tested parameters represent by A for volumetric air flow rate, B for inlet particulate loading, and C for segregated particulate size in this optimization study. Seventeen combinations of experimental run were suggested by the software with responses on particulate emitted concentration (g/m³) and overall collection efficiency (%). The experimental result in this stage was then fit into the second order polynomial equation to represent the effect of changing the operating conditions. Eq. 2 indicates the general form of the model; where Y is the predicted response, b_0 is model constant, b_1, b_2, b_3 are linear coefficients, b_{12}, b_{13}, b_{23} are cross product coefficients, and b_{11}, b_{22}, and b_{33} are quadratic coefficients [10, 11]. The statistical model was then evaluated through F-test analysis if variance (ANOVA). Finally, one suggested combination of operating conditions with targeted particulate emission of 0.100 g/m^3 (equal to 100 mg/m^3 – within allowable emission limit) was verified during the validation stage of this optimization study.

Table 1: Tested parameters for optimization study

Operating Condition	Low Level	High Level
A- Volumetric air flow rate [m^3/s]	0.19	0.35
B- Inlet particulate loading [g/m^3]	1	10
C- Segregated particulate size (smaller than) [µm]	100	1000

$$Y = b_0 + b_1A + b_2B + b_3C + b_{12}AB + b_{13}AC + b_{23}BC + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 \quad (2)$$

Results and Discussion

Experimental Screening. Fig. 2 presents the overall collection efficiency of the system for two segregated sample sizes based on volumetric air flow rates ranging from 0.19-0.35 m^3/s. Contradict to the theoretical prediction, the result from experimental study shows that increased volumetric air flow rates would decrease the performance of the multi-cyclone separator. This similar relationship has been reported previously where the researchers found that the fine particulate emission of their cyclone increased with reducing inlet velocity [12] where inlet velocity is directly proportional to pressure drop [13] and so volumetric air flow rate. Besides, the larger sample size of smaller than 1000 µm gives higher performance compared to the smaller segregated size of smaller than 500 µm. This showing that increasing particulate size will increase the collection efficiency of a cyclone [14]. The collection efficiency can be influenced by many factors including flow interference at the inlet, particulate bounce and re-entrainment from the cyclone wall, effect of particulate loading and effect of surface roughness of cyclone [15].

Pressure drop of the system that is related to the volumetric air flow rate also need to be taken care of even though parallel arrangements of the multi-cyclone system can handle higher gas flows as excessive pressure drop can cause particulate re-entrainment from the hopper to be circulated back into the system hence reduce the multi-cyclone performance. Cyclone separator with lower pressure at the outlet will discharge more gas from the dust hopper than entering it. The gas which is in ascending vortex then will be higher, thus increased the velocity, but not in radial velocity [14]. This finding was then led to the optimization study of the system.

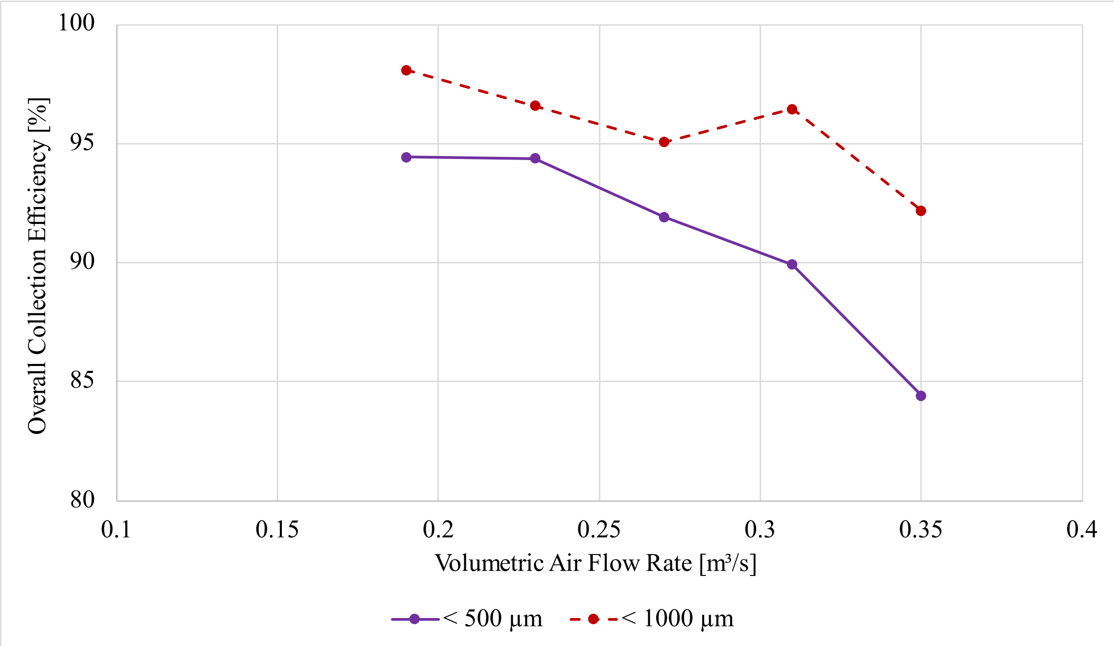

Fig. 2: Effect of volumetric air flow rate towards overall collection efficiency of MR-deDuster during experimental screening

Optimization. Table 2 presents the result of four out of seventeen total suggested combinations which meet the allowable limit of 0.150 g/Nm^3. Only combinations with lower volumetric air flow rate satisfy this condition. In this optimization experiment, it is found that the collection efficiency increased by decreasing the volumetric air flow rate at constant inlet particulate loading and segregated particulate size as depicted in Table 3.

Table 2: Results on suggested operating conditions using RSM which meet allowable emission limit

Run Order	A [m³/s]	B [g/m³]	C [µm]	Emission Concentration [g/m³]	Overall Collection Efficiency, η_o [%]
1	0.19	5.5	1000	0.1455	97.35
6	0.19	1.0	500	0.1300	87.00
13	0.27	1.0	1000	0.1146	88.54
8	0.27	1.0	100	0.0787	92.13

Meanwhile, the influence of inlet particulate loading can be observed from Fig. 3. At a constant volumetric air flow rate and segregated particulate size sample of smaller than 500 µm, increasing inlet particulate loading will increase the overall collection efficiency. This finding is in-line with other reported previous study [4, 16]. However, it is not the case with particulate size smaller than 100 µm where increasing inlet particulate loading will decrease the overall collection efficiency. Similar finding also has been reported in previous study [17, 18]. It is expected due to the sweeping effect of the coarser particulate, which will carry along the finer particulates to the cyclone wall surface and increase the agglomerates formation which then make it easier to be collected [18]. Besides, based on the results in this stage of study, it is realized that the inlet particulate loading should be remained constant in order to investigate the effect of volumetric air flow rate of a cyclone separator.

Table 3: Results on suggested operating conditions using RSM for effect of volumetric air flow rate

Run Order	A [m³/s]	B [g/m³]	C [μm]	Emission Concentration [g/m³]	Overall Collection Efficiency, η_o [%]
6	0.19	1	500	0.13	87
4	0.35	1	500	0.3148	68.52
9	0.19	5.5	100	0.2043	96.29
15	0.35	5.5	100	2.177	60.42
1	0.19	5.5	1000	0.1455	97.35
7	0.35	5.5	1000	0.8089	85.29
17	0.19	10	500	0.2879	97.12
2	0.35	10	500	1.6952	83.05

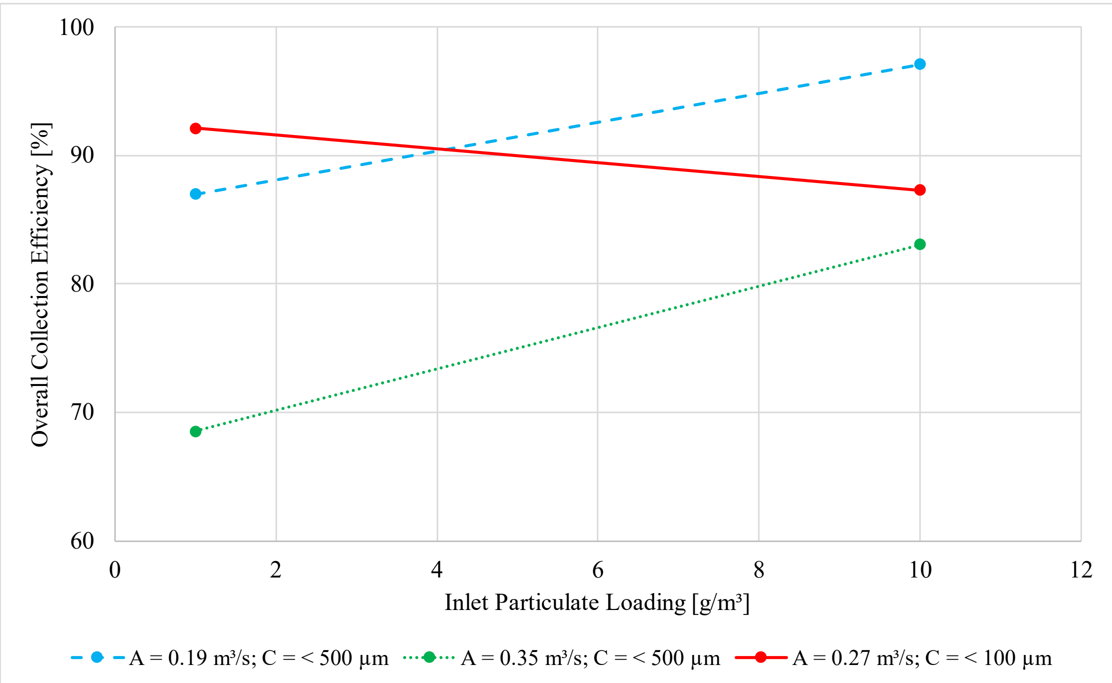

Fig. 3: Effect of inlet particulate loading towards overall collection efficiency of MR-deDuster during optimization study using RSM

The results from all seventeen runs included five replication experiments were then used to construct an empirical model and evaluated statistically. Table 4 presents the analysis of variance (ANOVA) on parameters for response surface reduced quadratic model of particulate emission concentration, while Eq. 3 shows the reduced quadratic model which has been generated to predict the particulate emission concentration, E from MR-deDuster.

The model's F-value of 18.72 implies that the model is significant with p value is less than 0.0001 which means that there is only 0.01% probability that this large Model F-value could occur due to noise. This model is also significant for the A, B, C, AB, and B^2 terms since the p-value is less than 0.05. The 'lack of fit F-value' is not significant reflecting a good condition as it means that the model is fit. The R-squared value of 0.9183 also expressed that the model is fit while the adequate precision that measures the signal to noise ratio with value of 14.85, which is greater than 4 shows that it is desirable [19, 20] and can be used to navigate the design space.

Table 4: ANOVA for particulate emission concentration response surface reduced quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remarks	Standard Deviation	R-Squared
Model	5.30	6	0.88	18.72	< 0.0001	Significant	0.22	0.9183
A	2.08	1	2.08	44.03	< 0.0001			
B	1.31	1	1.31	27.79	0.0004			
C	0.54	1	0.54	11.35	0.0071			
AB	0.37	1	0.37	7.92	0.0184			
AC	0.39	1	0.39	8.24	0.0166			
B^2	0.45	1	0.45	9.61	0.0113			
Lack of Fit	0.40	6	0.066	3.59	0.1184	Not significant		

$$E\ (g/m^3) = -1.5384 + 6.4713A + 0.0385B + 0.0019C + 0.8490AB - 0.0086AC - 0.0162B^2 \quad (3)$$

The response surface plots in Fig. 4 and Fig. 5 illustrate the particulate emission concentration response on the interaction between volumetric air flow rate and the inlet particulate loading, and the particulate emission concentration response on the interaction between volumetric air flow rate and segregated particulate size respectively. In order to obtain the lowest sampled particulate emission concentration, the optimum volumetric air flow rate is 0.19 m^3/s with 1.0 g/m^3 inlet particulate loading. However, it is observed during experimental study, that the MR-deDuster system is not recommended to be operated at volumetric air flow rate of 0.19 m^3/s since some of particulates were found to be remained on the unit and not completely drawn into the cyclones. Meanwhile, low particulate emission concentration was obtained by lowering the volumetric air flow rate and increase the particulate size samples fraction.

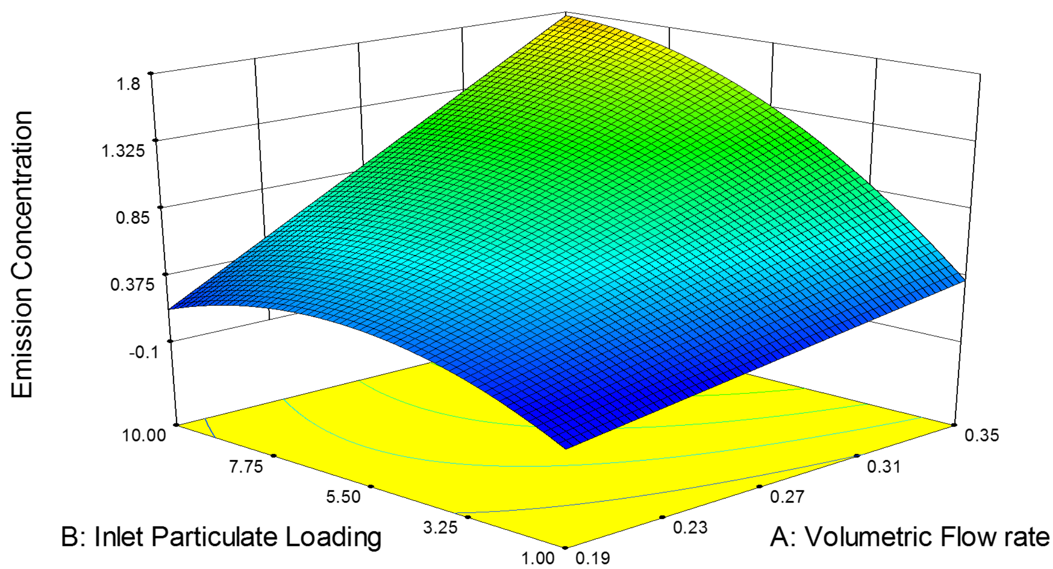

Fig. 4: 3D response surface plot showing the effect of volumetric air flow rate and inlet particulate loading towards particulate emission concentration

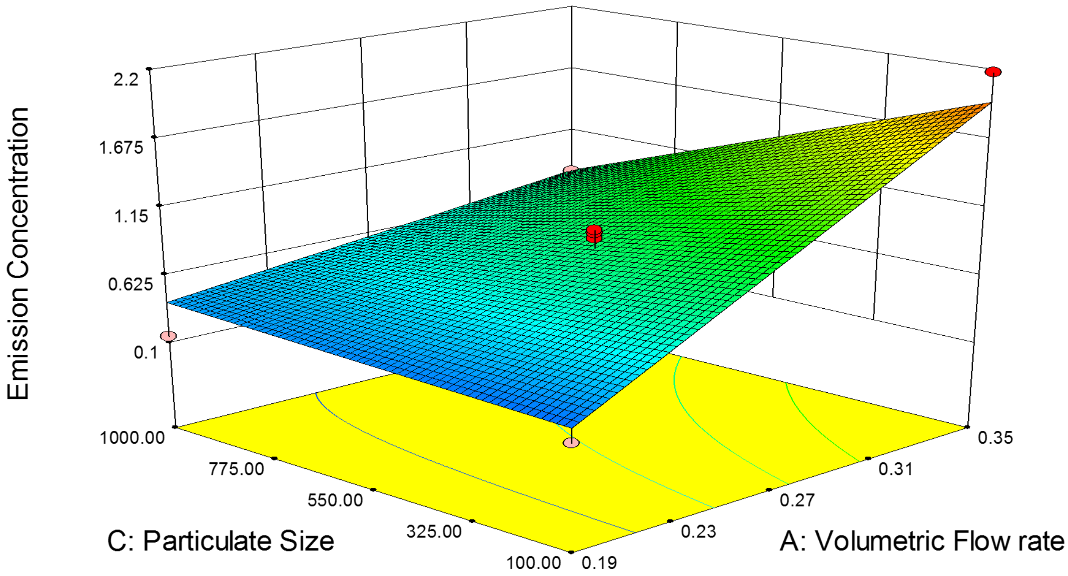

Fig. 5: 3D response surface plot showing the effect of volumetric air flow rate and particulate size towards particulate emission concentration

The second statistical analysis evaluated in this optimization stage is on the overall collection efficiency. Table 5 shows the results for response surface linear model of MR-deDuster's overall collection efficiency. It can be seen that the F-value 8.81 of the model is significant with p-value 0.0019. However, in this case, only the factor for volumetric air flow rate is significant with significant 'lack of fit'. Hence, this model is found to be not fit. Based on this result, only response on the particulate emission concentration was focused for the validation and verification of this optimization study.

Table 6 summarizes the prediction and results for validation and verification study on the particulate emission concentration of the multi-cyclone system. Out of forty-three suggested solutions, only the best combination was chosen to be verified experimentally. Based on the obtained results, the optimum operating conditions for this newly developed multi-cyclone system are volumetric air flow rate of 0.27 m^3/s with 2 g/m^3 inlet particulate loading and segregated particulate size of smaller than 1000 µm. Even with 15% difference between software predicted and experimentally verified particulate emission concentration, the response is still within allowable limit with only 1% discrepancy on the overall collection efficiency.

Table 5: ANOVA for overall collection efficiency response surface linear model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Remarks
Model	1005.48	3	335.16	8.81	0.0019	Significant
A	809.63	1	809.63	21.29	0.0005	
B	78.31	1	78.31	2.06	0.1749	
C	117.54	1	117.54	3.09	0.1022	
Lack of Fit	468.86	9	52.21	8.54	0.0269	Significant

Table 6: Verification on the suggested parameters for validation stage

A [m³/s]	B [g/m³]	C [µm]	Targeted Particulate Emission Concentration [g/m^3]	Predicted Overall Collection Efficiency [%]	Verified Particulate Emission Concentration [g/m^3]	Calculated Overall Collection Efficiency [%]
0.27	2	1000	0.1000	95	0.1146	94

Conclusion

This study concluded the optimum operating conditions for the pilot plant scale MR-deDuster multi-cyclone to control fine particulate emission with volumetric air flow rate 0.27 m^3/s, maximum inlet particulate loading of 2 g/m^3, and preferable particulate size of smaller than 1000 µm was able to meet the targeted limit 150 mg/m³ for solid fuel burning equipment. Even though higher volumetric air flow rate theoretically will result in higher cyclone performance, it is more favorable to maintain lower volumetric air flow rate as it is directly related to the pressure drop and subsequently the operating cost. Yet, through experimental activity, it was spotted that lower volumetric air flow rate will lead to small amount of particulate to be remained inside the cyclone structure rather than dropped into the hopper. When analyzing the influence of inlet particulate loading towards cyclone performance, it was found that the selection of the loading range was overestimated the capability of the pilot plant scale since the volumetric air flow rate in this plant was lower than in the actual industrial condition by tenfold. Besides, as this developed multi-cyclone separator aimed to control fine particulate matter, it was observed that with larger size particulate, it can be the driving force to assist in collecting particulate with finer sizes since it has more inertia and easier to hit the inside wall of the cyclone and drop down to the collecting hopper. The performance of this multi-cyclone system should be further verified by scaling down the inlet particulate loading based on the actual plant condition in industry towards this pilot plant scale.

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