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Theoretical Performance of a Multi-Cyclone Fine Particulate Emission Control System

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Abstract. The study involves the development of theoretical performance background of a newly developed multi-cyclones fine particulate emission control system named as MR-deDuster. The theoretical background of the unit was developed based on the modifications of established design equations available in literatures. The Leith & Licht model and modified Lapple model with different definitions of maximum radial distance travelled by a particulate (W) were used to predict the performance of the unit under various volumetric gas flow rate ranging from 0.13 to 0.21 m³/s. The result reveals significant differences among predictions, but yet all the predictions approve the capability of the unit to capture the particulate matter, especially the fine size fraction.

1. Introduction

Cyclone is one of the oldest types of particulate control equipment developed for removing or separating industrial dust from air or process gas [1-3]. Extensive studies involving experimental work on such unit started since the last decade of 19th century [4]. The data gathered from these studies was used to develop theoretical models as a simple method to predict the performance of a cyclone and many of which were based on semi-empirical ground.

Lapple (1951) introduced the first model on the prediction of the collection efficiency of a cyclone [5]. The model is based on time flight particulate approach, which is similar to the method applied in sedimentation chambers, which assumed particulate travel from the entry half width to the wall [4,6]. The time for a particulate to reach the wall is considered as gas residence time for particulate to be separated at 50% collection efficiency. This model also assumed that the particulate distribution is uniform across the entry section. The number of effective turns, N_e is fixed at average value of 5 and the tangential velocity used is assumed at constant rate. Leith & Licht (1972) introduced another model based on time flight particulate approach as well [7]. However, their model considered a continuous flux of particulate instead of single particulate applied in Lapple model. The collection efficiency equation of Leith & Licht model considered turbulent diffusion within the cyclone and the equation was derived by material balance of centrifugal force and inertia [4].



There are many other models developed to predict the collection efficiency of cyclone, such as Dietz model (1981), Iozza & Leith model (1989), and Mothes & Löffler model (1988) [8-10]. However, the Lapple model and Leith & Licht model are the only models discussed in this study. The Lapple method is preferable due to its simplicity and it is acceptable for many situations according to Cooper and Alley (2011) [11]. Meanwhile, the Leith & Licht model is an elaborate model using the same principle of Lapple model and one of the popular models used in predicting the collection efficiency of cyclone [4].

In this paper, the theoretical prediction on the collection efficiency of a newly developed multi-cyclones using modified Lapple model, and Leith & Licht model for different volumetric gas flow rates is presented. The comparative collection efficiency between these two models was performed to highlight the capability of the unit in capturing dust, especially in the fine size fraction.

2. Methodology

The theoretical collection efficiency of MR-deDuster was predicted based on modified Lapple model, and Leith & Licht model. The existing Lapple model, as shown in equation (1), was developed based on tangential entry cyclone with the assumption of W as the width of cyclone entry, which is not as in axial entry cyclone of MR-deDuster. In this case, the W value for axial entry cyclone was assumed with different assumption from tangential entry cyclone. Three different assumptions were made to define the W value for axial entry cyclone in this study: i) W based on distance from vortex finder wall to cyclone wall, $W=D-D_e/2$, ii) W based on inlet area of cyclone entry, $W=A/0.75D$, and iii) W based on hydraulic diameter, $W=3(D-D_e)/4$.

$$d_{pc} = \left[\frac{9\mu W}{2\pi N_e v_i (\rho_p - \rho_g)} \right]^{1/2} \quad (1)$$

where, d_{pc} is the cut diameter, μ is the gas viscosity (kg/m^3), W is the maximum radial distance of particulate (m), N_e is the number of effective turns, V_i is the gas inlet velocity (m/s), ρ_g is the density of gas (kg/m^3), and ρ_p is the density of dust (kg/m^3).

Leith & Licht model was also used to predict the collection efficiency of MR-deDuster. The Leith & Licht model used in this study is the model that has been re-arranged by Benitez (1993) for multi-cyclone unit collection efficiency prediction, as shown in equation (2) [12].

$$\eta_j = 1 - \exp \left\{ -2 \left[\frac{kQ\tau}{MND^3} \right]^2 \right\} \quad (2)$$

where, η_j is the collection efficiency, Q is the volumetric gas flow rate, k is a dimensionless geometric configuration parameter, N is the number of miniature cyclones installed in the multi-cyclones, D is a diameter of single miniature cyclone, whereas M and τ are described coefficient related to cyclone configuration, temperature, pressure, and velocity of gas flow.

The performance prediction was based on four units of MR-deDuster arranged as a multicyclone system. The performance prediction of the unit was studied under four different volumetric air flow rates of 0.13, 0.16, 0.19, and 0.21 m^3/s with respective inlet velocity of 13, 16, 19, and 21 m/s.

3. Results and Discussions

3.1. Theoretical Collection Efficiency

Table 1 shows the cut diameter prediction of MR-deDuster for different models at various volumetric gas flow rates of 0.13, 0.16, 0.19, and 0.21 m^3/s , which depicted that the cut diameter reduces as the volumetric gas flow rate increases and the trend was applied to all models tested. The smallest cut diameter for all models is obtained at volumetric gas flow rate of 0.21 m^3/s , while figure 1 depicts the fractional collection efficiency prediction of the unit based on the different theoretical models for various

volumetric gas flow rates, which showed that the fractional collection efficiency increases with the increasing of volumetric gas flow rate. The highest fractional collection efficiency of each particulate size fraction was obtained at the highest volumetric gas flow rate of 0.21 m³/s. The overall collection efficiency of all models tested is shown in table 2. The overall collection efficiency of the unit showed similar trend as fractional collection efficiency, which indicates that the overall collection efficiency increases with the increasing of volumetric gas flow rate.

Table 1. Cut diameter prediction of MR-deDuster for different models at various volumetric gas flow rates

Volumetric Flow Rate (Q), m ³ /s	Cut Diameter (d_{pc}), μm			
	Lapple: $W = D - D_e/2$	Lapple: $W = A/0.75D$	Lapple: $W = 3(D - D_e)/4$	Leith & Licht
0.13	1.8	3.6	2.2	2.5
0.16	1.7	3.2	2.0	2.2
0.19	1.5	3.0	1.8	1.9
0.21	1.4	2.8	1.7	1.7

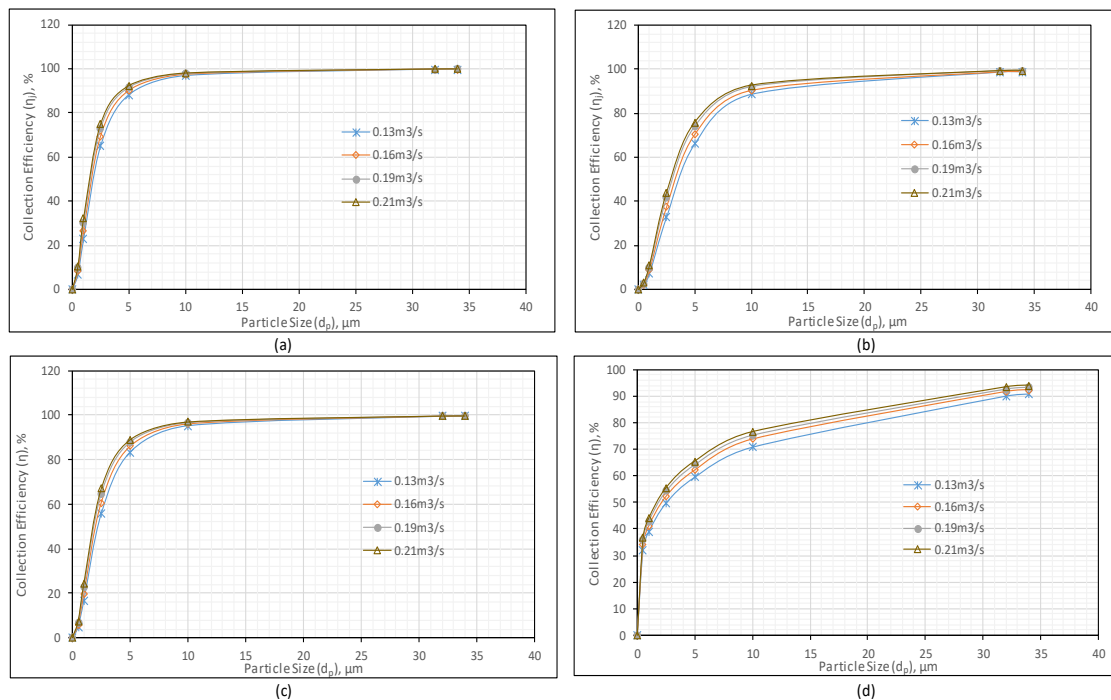


Figure 1. The fractional collection efficiency prediction of MR-deDuster for different models (a) Lapple model: $W = D - D_e/2$ (b) Lapple model: $W = A/0.75D$ (c) Lapple model: $W = 3(D - D_e)/4$ (d) Leith & Licht model

Table 2. Overall collection efficiency prediction of MR-deDuster for different models at various volumetric gas flow rates

Volumetric Flow Rate (Q), m^3/s	Overall Collection Efficiency (η_o), %			
	Lapple: $W = D - D_e/2$	Lapple: $W = A/0.75D$	Lapple: $W = 3(D - D_e)/4$	Leith & Licht
0.13	96.90	92.92	96.02	84.79
0.16	97.30	93.73	96.51	86.49
0.19	97.60	94.34	96.88	87.81
0.21	97.75	94.67	97.08	88.53

Figure 2 (a-d) presents a comparison between fractional collection efficiency predictions of MR-deDuster based on different theoretical models for volumetric gas flow rates of 0.13, 0.16, 0.19, and 0.21 m^3/s . As can be observed from the figures, the fractional collection efficiency predictions differ widely, especially for fine size fraction particulate. Consequently, the choice of model significantly affects the predicted PM_{10} and, especially, $\text{PM}_{2.5}$ efficiencies. For example, the predicted $\text{PM}_{2.5}$ efficiency of cyclone operating at volumetric gas flow rate of 0.13 m^3/s can be higher than 60%, according to Lapple: $W = D - D_e/2$, and lower than 35%, according to Lapple: $W = A/0.75D$.

The model of Leith & Licht yields exponential type curve with high fractional collection efficiency for fine size fraction particulate (i.e., more than 50% of collection efficiency for particulate is smaller and equals to $1\mu\text{m}$ in size for all volumetric gas flow rates tested). However, the collection efficiency of Leith & Licht model was increased slower compared to other models as the particulate coarser. Meanwhile, the three modified Lapple models produced sigmoid type of curve. Among all models, Lapple: $W = D - D_e/2$ and Lapple: $W = 3(D - D_e)/4$ indicate yield curves with fast fractional collection efficiency transient from low values to high values.

The model of Lapple: $W = D - D_e/2$, yields higher fractional collection efficiency for most of particulate size fractions for all volumetric gas flow rates tested. This is due to the small cut diameter value of the model compared to other models. As for fine particulates size fractions ($d_p < 1\mu\text{m}$), the Leith & Licht model yields higher fractional collection efficiency compared to the other models for all volumetric gas flow rates tested. On the other hand, the model produced lowest fractional collection efficiency for all volumetric gas flow rates tested for coarser particulates ($d_p > 5\mu\text{m}$), which later affects the overall collection efficiency.

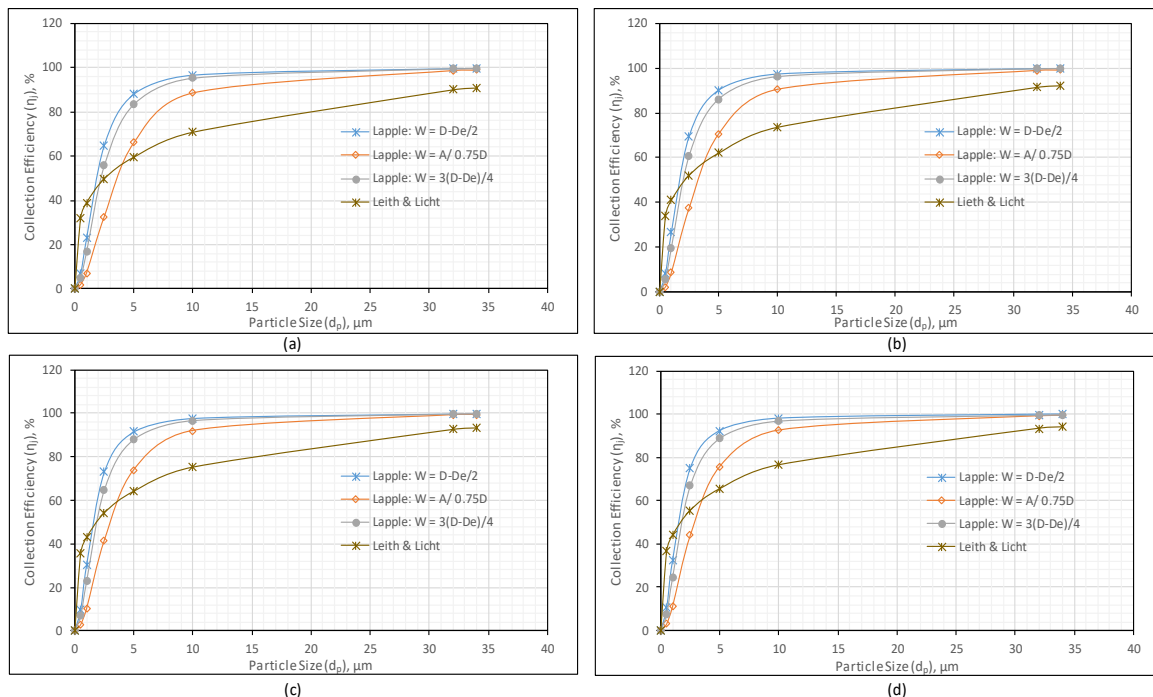


Figure 2. Comparison of fractional collection efficiency prediction models of MR-deDuster for different volumetric gas flow rates (a) $0.13\text{m}^3/\text{s}$ (b) $0.16\text{m}^3/\text{s}$ (c) $0.19\text{m}^3/\text{s}$ (d) $0.21\text{m}^3/\text{s}$

4. Conclusion

The study predicted that the increasing of volumetric gas flow rate results in a reduction of cut diameter, and an increase of fractional collection efficiency, and overall collection efficiency. These trends are applied to all theoretical models used in this study. Even all tested models show similar trends, the results show that the collection efficiency predictions differ significantly, especially for fine size fraction particulate. Consequently, the choice of model significantly affects the predicted PM_{10} and, especially, $\text{PM}_{2.5}$ efficiencies. The study indicated that the Lapple model: $W=D-D_e/2$ exhibits the smallest cut diameter and the highest overall collection efficiency, while Lapple model: $W=A/0.75D$ displays the largest cut diameter and low overall collection efficiency. However, Leith & Licht model exhibits the lowest overall collection efficiency despite of having small cut diameter and high sensitivity towards volumetric gas flow rate changes. This is due to lower fractional collection efficiency of coarse particulate, which represents most mass percentage of overall mass fraction. The findings illustrate that the overall collection efficiency not only depend on cut diameter, but also depends on the fractional collection efficiency of each size fraction.

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