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MR-deDuster: A Dust Emission Separator in Air Pollution Control

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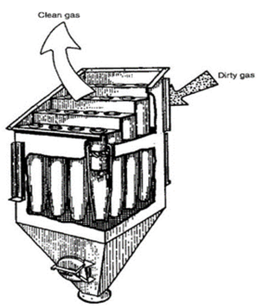
Graphical abstract



Abstract

There are many technologies developed to control dust emission in industry. A multi-cyclones separator is one of the commonly available technologies for dust emission control from a gas stream. However, it is usually used as a pre-cleaner unit installed prior to a more efficient air pollution control system such as fabric filters or baghouse. In this respect, a study has been carried out to investigate and theoretically predict the performance of a MR-deDuster, a newly developed multi-cyclones dust emission separator system. The MR-deDuster performance was measured by its collection efficiency based on the particle size distribution of two selected adsorbent material commonly used as flue gas cleaning agent, i.e., lime and activated carbon, as a representative of dust particles. The study illustrates that the unit manages to capture dust sized 2.4µm at 50% collection efficiency with reasonably low pressure drop. The unit also capable of achieving more than 95% total dust collection efficiency for all dust tested.

Keywords: Air pollution; MR-deDuster; dust emission; efficiency prediction; multi-cyclones; pressure drop prediction

1.0 INTRODUCTION

Cyclone is an air pollution control unit without any moving parts which separates dust emission from a gas stream by altering the inlet gas stream into a confined vortex. The unit is one of the most widely used separator in many industries and played important role in removing industrial dust from air or process gases. Compared to other air pollution control unit such as fabric filter, scrubber and electrostatic precipitator, cyclone is simpler to construct, require lower operating and maintenance cost and able to work in harsh operating conditions [1-2]. The centrifugal force, drag force and swirling motion are the mechanism involve in collecting dust in a cyclone unit [1, 3]. Basically, the gas-solid mixture enters the cyclone entry and the cylindrical body induces a spinning motion to the gas stream. Centrifugal force separates the dust from the gas stream and the gas spirals downward until certain depth before the gas spinning reversely inward and exit through the vortex finder (as shown in Figure 1)

The performance of a cyclone usually evaluated via its collection efficiency and pressure drop. The collection efficiency referred to the ability of the cyclone to separate the dust from the gas stream according to the dust size fraction. Meanwhile, the pressure drop defined as the differential pressure across the system. Many studies have been carried out to improve the cyclone performance. Madhumita *et al*. [5], used a new approach in increasing the cyclone collection efficiency by installing a unit called 'Post Cyclone' or PoC and manage to reduce the dust emission of 1-3 µm size range by approximately 30%. Jo *et al.* [6], also reported on the use of PoC in increasing the performance of cyclone and the authors found out that the installation of PoC able to increase the overall efficiency by 2-20%. Salcedo and Pinho [7] introduced a new geometry of reverse-flow gas cyclone with a partial recirculation system and able to reduce 75% dust emission without a significant increase in pressure drop. Dewika [8] improved the cyclone efficiency by attaching an external suction at the dust hopper. Chen *et al.* [9], studied on the effect of the bottom-contracted and edge-sloped vent-pipe on the cyclone performance. The study illustrated the efficiency and the pressure drop of the cyclone changed with the orientation of the slope edge. Meanwhile, Wang *et al.* [2], introduced a new type of cyclone known as circumfluent cyclone (CFC). The collection efficiency of CFC is higher by 8% than the conventional cyclone.

Even though, many researches has been conducted in improving the performance of cyclone, the unit often regarded as an air pre-cleaner device due to its low efficiency in capturing dust especially the finer size fraction. In order to overcome the problem, a number of small and high-efficiency cyclones which are installed in one unit known as multi-cyclone was introduced (as shown in Figure 2). Multi-cyclones is a type of cyclone which the miniature axial entry cyclones are installed in a parallel arrangement manner. The multi-cyclones is preferred compared to the other type of cyclone due to its ability to achieve higher collection efficiency and its capability to avoid the rapid increasing of pressure drop due to the use of small diameter cyclone [4, 10]. The use of axial entry also can minimise the eddy formation problem which commonly found in tangential entry cyclone [4]. Multi-cyclones unit generally provide higher efficiency and manage to attain as high as 90% collection efficiency for dust with 5-10 µm in size [11] The pressure drop of multi-cyclones commonly ranges from 2 - 6 inch H_2O [4, 11]. Although multi-cyclone is commonly used as air pollution control unit in industry, the study on the multi-cyclone is limited in the literatures. Therefore, this paper presents the performance of MR-deDuster ('MR' stands for Mohd Rashid), a newly developed multi-cyclone unit that is based on semi-empirical calculation. The study also introduced the new calculation approach to predict the performance of the unit. Its collection efficiency was evaluated based on two commonly used adsorbent materials i.e., activated carbon and lime which are usually applied as the flue gas cleaning agent. The collection efficiency were measured by percentage of adsorbents removed from flue gas.

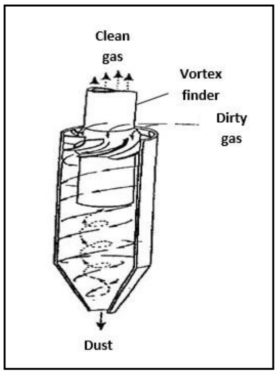


Figure 1 Cyclone with axial entry [4]

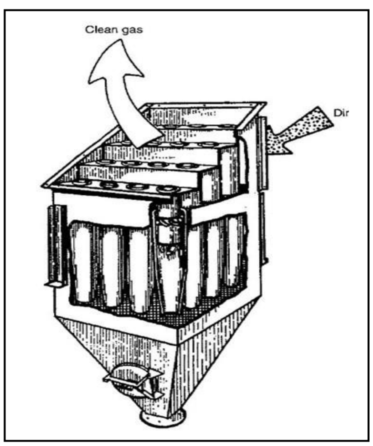


Figure 2 Multi-cyclones [4]

2.0 METHODOLOGY

2.1 Collection Efficiency of MR-deDuster

The cut diameter (d_{pc}) is a semi-empirical relationship developed by Lapple (1951) [12] which referred to the size (diameter) of dust collected at 50% efficiency. The d_{pc} is a convenient method in expressing the efficiency of a dust control device, which is shown Equation (1) as follows:

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

where 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). The value of W is difficult to obtain analytically and in this study, the W value is obtained using a modification of Stairmand cyclone dimension with tangential entry [13] based on same hydraulic diameter of axial and tangential entry [14]. Equations (2) and (3) are the tangential entry dimensions of a cyclone introduced by Stairmand [13],

$$D = \frac{W}{0.375} \tag{2}$$

$$D = \frac{H}{0.75} \tag{3}$$

where W is the width of tangential entry (m), H is the height of tangential entry (m) and D is the diameter of cyclone body (m). Substitution of Equation (2) into Equation (3), will produce Equation (4) as follows:

$$H = 2W \tag{4}$$

The hydraulic diameter (D_H) of tangential entry is referred to the W and H values as shown in Equation (5),

$$D_H = \frac{2HW}{H + W} \tag{5}$$

Meanwhile, the hydraulic diameter (D_H) of axial entry is referred to the D & D_e values as shown in Equation (6),

$$D_H = D - D_e \tag{6}$$

where D is the diameter of the body of the cyclone (m) and D_e is the diameter of the vortex finder (m) as shown in Figure 3.

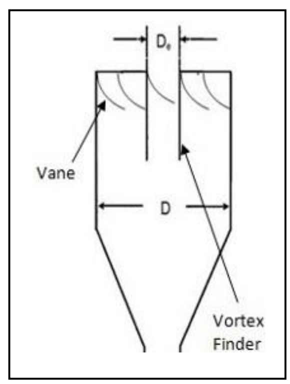


Figure 3 Schematic diagram of a miniature cyclone [15]

Substitution of Equations (4) and (5) into Equation (6) will produce Equation (7) as shown below,

$$W = \frac{3}{4}(D - D_e) \tag{7}$$

Finally, substitution of Equation (7) into Equation (1) will generate the equation of cut diameter for axial entry as shown in Equation (8),

$$d_{pc} = \left[\frac{27\mu(D - D_e)}{8\pi N_e V_i(\rho_p - \rho_g)}\right]^{1/2} \tag{8}$$

Table 1 presents the assumptions and operation conditions used in the calculation. The collection efficiency of MR-deDuster was predicted using the particle size distribution of adsorbent material commonly used as the flue gas cleaning agent i.e., lime and activated carbon

Table 1 Dimension of cyclone and operation conditions used in calculation prediction

Operating Condition	Value
Miniature cyclone diameter, D (m)	0.105
Vortex finder diameter, D_e (m)	0.089
Inlet velocity, V_i (m/s)	15
Temperature, T (K)	473
Pressure, P (atm)	1
Particle dust density, ρ_p (kg/m^3)	1000
Flue gas density, ρ_p (kg/m^3)	0.7448
Flue gas viscosity, μ (kg/hr.m)	0.093
Number of effective turns, N_e	5

The overall collection efficiency of MR-deDuster is predicted using Lapple approach [12] as shown below by Equations (9) and (10),

$$\eta_j = \frac{1}{1 + \left(d_{pc}/d_{pj}\right)^2} \tag{9}$$

$$\eta_o = \Sigma \eta_j m_j \tag{10}$$

where η_j is collection efficiency for the jth particle size range, d_{pj} is the characteristic diameter of jth particle size range, η_o is the overall collection efficiency and m_j is the mass fraction of particulate size range.

2.2 Pressure Drop of MR-deDuster

Benitez [10] approach was used in determining the pressure drop of MR-deDuster as shown in Equation (11),

$$\Delta P = \frac{N_H \rho_g Q^2}{2K_a^2 K_b^2 n^2 D^4} \tag{11}$$

where N_H is a constant which depends on cyclone configuration (N_H = 6.125) [16]. ρ_g is the density gas (kg/m^3), Q is the flow rate of gas (m^3/s), K_a and K_b are configuration ratio (for Stairmand cyclone dimension, K_a= 0.75 and K_b= 0.375), n is the number of miniature cyclones in multi-cyclones and D is the diameter of the cyclone body (m).

The determination of pressure drop using Benitez [10] approach strongly dependent on the relation of the number of miniature cyclones in a multi-cyclone, n and the volumetric flow rate of flue gas, Q (Equation (12)),

$$Q = nV_iA \tag{12}$$

where Q is the volumetric air flow rate (m^3/s), n is the number of miniature cyclones in multi-cyclones, V_i is the gas inlet velocity (m/s) and A is the effective area of gas entry for a miniature cyclone (m^2). The range of flow rate used in the study is based on a typical air volumetric flow rates from selected local industries (i.e., palm oil industry).

3.0 RESULTS AND DISCUSSION

3.1 Collection Efficiency of MR-deDuster

The cut diameter (d_{pc}) which is referring to the diameter of dust that will be removed from the swirling gas stream at 50% efficiency was used to define the collection efficiency of MR-deDuster. Dust larger than the d_{pc} will be removed with greater efficiency and smaller dust with lower efficiency. The higher the collection of the unit, the higher the ability of the unit to separate the dusts from the gas stream. The predicted d_{pc} of MR-deDuster from the study is 2.4 µm, which illustrated the ability of MR-deDuster in arresting fine dust particle, i.e., $PM_{2.5}$ (particulate matter with size 2.5 µm and smaller). The study also found out that the prediction of d_{pc} for MR-deDuster is smaller using Lapple approach with W value based on hydraulic diameter compared to the d_{pc} value obtained using Lapple approach with W value based on effective area of cyclone entry, (with the predicted d_{pc} = 3.8 µm) [15].

The collection of MR-deDuster was based on the dust particles size distribution of selected adsorbents materials (usually use as filter aids materials in filtering system), i.e., lime and activated carbon [17] which is shown in Figure 4. Since activated carbon is finer than lime, then the collection efficiency performance of the MR-deDuster was based on the former.

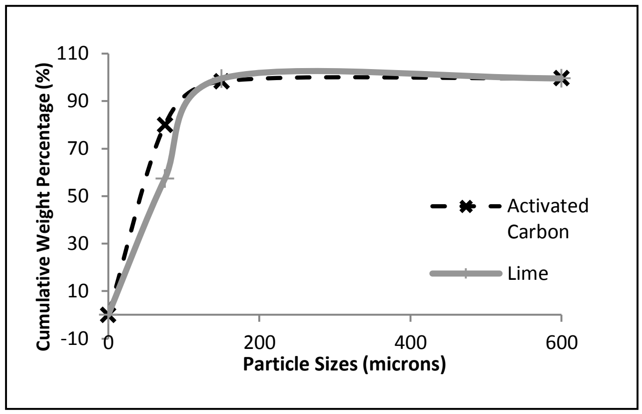


Figure 4 Particle size distribution of adsorbent materials [17]

Figure 5 presents the fractional collection efficiency (η_j) of MR-deDuster based on activated carbon particle size distribution which showed that MR-deDuster is able to collect 5µm size particles approximately at 80%. The plot also showed that the MR-deDuster able to collect as high as 94% of PM_{10} (particles with smaller or equal to 10µm in size) illustrating the ability of the unit as a dust arrestor system.

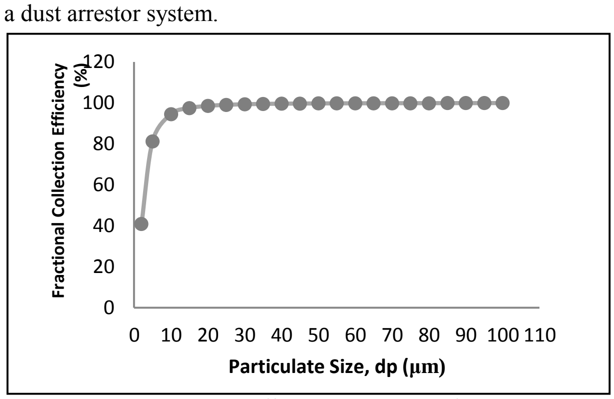


Figure 5 Fractional collection efficiency prediction of MR-deDuster on activated carbon dusts particles

The overall collection efficiency using Lapple [12] approach is strongly dependent on the mass fraction of the particles for each particular size range. The fractional efficiency in Lapple[12] approach is dependent on d_{pc} only and resulted in the same trend of fractional efficiency even using different particles size distribution. However, the overall collection efficiency of the unit is not the same for different particles size distribution due to dissimilarity of cumulative weight percentage of the particles. The finding shows that the overall collection efficiency of the unit was as high as the other air pollution control system [18]. Thus, MR-deDuster can be used as the main air cleaner without having to consider a more efficient air pollution control system for a selected industry.

3.2 Pressure Drop of MR-deDuster

Pressure drop is the other major consideration (besides efficiency) in determining the performance of air pollution control unit. High pressure drop will require high suction fan to drive the flue gas through the cyclone system, which eventually affects the operating cost. The Benitez [10] approach used in the prediction of the pressure drop of MR-deDuster is dependent on the number of miniature cyclones installed in the unit and the volumetric flow rates of the flue gas. Figure 6 shows the relationship between the number of miniature cyclones installed in MR-deDuster and the volumetric flow rates of the flue gas, which are linearly correlated.

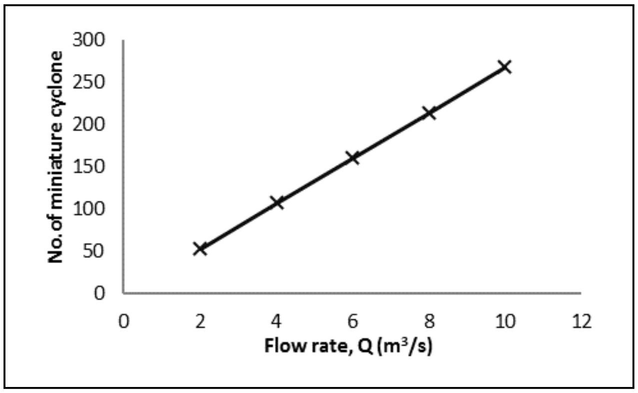


Figure 6 Number of miniature cyclones in MR-deDuster for different flue gas volumetric flow rates

Table 2 presents the pressure drop of MR-deDuster for different flue gas volumetric flow rates which shows the pressure drop can theoretically be maintained at 1.33 inch H_2O across the system. The differences in the flue gas volumetric flow rates will not affect the pressure drop of the unit since the number of miniature cyclone install in MR-deDuster is varied accordingly.

Table 2 Pressure drop prediction of MR-deDuster under various flue gas volumetric flow rates

Flue gas volumetric flow rate (m^3/s)	Number of miniature cyclone	Pressure drop (inch H_2O)
2	53	1.33
4	107	1.33
6	160	1.33
8	213	1.33
10	267	1.33

4.0 CONCLUSION

The study illustrates that MR-deDuster is capable to separate dust particles from the gas stream at high efficiency with low pressure drop. It is predicted that the cut diameter and the pressure drop of the unit was 2.4μm and 1.33 inch H_2O, respectively. The study also shows that MR-deDuster is capable of attaining more than 95% total dust collection efficiency, which depicts the ability of the unit as the main or primary air pollution control system.

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