CFD Study on MR-deDuster As a Fine Particle Emission Control

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Abstract. Reynolds stress model (RSM) is known to demonstrate the closest approximation with experimental data and appraised as the most reliable turbulent model for the flow field in a cyclone simulation against other models. In this study, computational fluid dynamics (CFD) with RSM was used to simulate MR-deDuster, which is a newly developed multi-cyclone for fine particle emission control with axial inlet entry. The flow field characteristics of velocity contour and particle trajectories inside the cyclone were profiled while particle cut-diameter (dpc) of the unit was predicted based on fractional collection efficiency. Throughout the simulation, three different inlet velocities represented by their respective volumetric air flow rates (Q) ranging from 0.27 to 0.35 m³/s were applied and the results were plotted accordingly by referring to the value of these Qs. The velocity flows are almost identical for every unit of the cyclone in MR-deDuster system with the highest velocity of 33 m/s was found at the end of the vortex finder operated at 0.35 m³/s. This is crucial to ensure that each unit is operated in similar mode to get optimum performance of the system. Meanwhile, discrete phase model was used to estimate the particle trajectories in the flow. By releasing a certain number of inert particles at the cyclone’s inlet, fractional collection efficiency plot could be determined using the ratio of tracked particles trapped and released through the outlet. This study indicated that the predicted dpc of MR-deDuster was 1.85 and 2.05 µm for the highest and lowest Q respectively. The former represents the highest inlet velocity which is able to attract more of fine particle deep inside the bottom of the cyclone compared to the latter. Thus, the predicted fractional collection efficiency of 100% was achieved for particle larger and equal to 10 µm in size at the highest volumetric air flow rate or inlet velocity. The importance of inlet velocity in reducing the dpc which simultaneously increase the performance of a cyclone is illustrated in this study as successfully demonstrated by the CFD software.
1. Introduction
Cyclone has been utilized since late 1800s as a pre-cleaner to remove particles emitted from industrial gas streams. Typically, cyclone is effective in capturing particles larger than 10 μm, but higher collection efficiency cyclone can remove particles less than or equal to 2.5 μm [1]. This can be achieved by using multiple cyclones arranged in parallel or called as multi-cyclone and by continuously developing better performance of the equipment. Hence, to not just be settled as a pre-cleaner, a new multi-cyclone system known as MR-deDuster has been developed [2, 3] to control emission of fine particles from many industries. MR-deDuster has been designed with high efficiency which may improve the ability of multi-cyclone as one of the main air pollution control devices.

The configuration of the existing MR-deDuster unit had been modified in this study to increase the performance of the previous unit in acting as a practical particle collector. The modification involved the optimization of the system’s operating condition, decreasing the diameter of vortex finder and increasing the length of internal vanes accordingly to fit in the vortex finder into the cyclone body. In this paper, the prediction on performance of revised configuration MR-deDuster through modelling using computational fluid dynamics (CFD) with various inlet velocity is presented.

2. Methodology
MR-deDuster has been designed with four (4) units of miniature cyclones installed as one system. Solidwork software was used to draw geometry of MR-deDuster as shown in Figure 1. Five (5) specific parts were then assigned on the geometry drawing namely inlet, outlet, cyclone, cyclone trap and wall.

![Figure 1. Geometry drawing of MR-deDuster system](image1)

Next, the drawing was exported to Ansys Fluent software for simulation purposes using three-dimensional (3D) CFD approach. Figure 2 presents the symmetrical domain of MR-deDuster used in Fluent assuming uniform distribution of gas flow in all four units of cyclones aiming to shorten the simulation time.

![Figure 2. Symmetrical domain of MR-deDuster system](image2)
2.1. **Velocity profile**
The CFD study were then executed with three different values of volumetric air flow rates (Q) at 0.27, 0.31, and 0.35 m³/s which represented different values of effective inlet velocities. The model was computed using Reynolds stress model (RSM) with single precision and coupling of steady and unsteady state. The profiles for velocity axial streamlines, velocity axial contours, and also velocity contours were then plotted to monitor the flow gas pattern.

2.2. **Particle trajectories and collection efficiency**
The particle trajectories were demonstrated in this study by using Discrete phase model (DPM). Particles with various size fraction of PM₁₀, PM₅, PM₂.₅, and PM₁ were set to be released through the system’s inlet, captured in the cyclone trap section, and emitted over the outlet. Based on the results from CFD simulation, fractional collection efficiency and particle cut-diameter (dpc) were determined to predict the performance of MR-deDuster.

3. **Results and discussion**
RSM was used in this study as this approach has been considered as the most suitable turbulence model to investigate the flow of cyclone separators and said to offer the most precise estimation to the experimental results [4, 5, 6].

3.1. **Velocity profiles**
Figure 3 displays the streamline and contour of velocity axial for MR-deDuster system according to operating Q where (a, b), (c, d), and (e, f) are for 0.27, 0.31, and 0.35 m³/s respectively.

*Figure 3. Velocity axial streamline and contour at (a,b) 0.27, (c,d) 0.31, and (e,f) 0.35 m³/s flow rates*
As can be seen from Figure 3, negative velocity axial is observed at the right side of the vortex finder inner wall while higher velocity axial is spotted at the other side closer to the effective inlet area (i.e. between inner wall of cyclone body with vane and outer wall of vortex finder) for each cyclone unit. The velocity axial began to increase at the effective inlet area of the system and moved towards the outlet. This finding demonstrates that secondary flows occur due to the existing of vortex finder to carry the uncollected particle to be emitted at the outlet. Maximum axial velocity is said to be appeared at the end of the vortex finder due to the effects of the secondary flow [7].

Meanwhile, the velocity contour for MR-deDuster is depicted in Figure 4 (a, b, c) for Q equals to 0.27, 0.31, and 0.35 m³/s respectively. The highest velocity value of 33.02 m/s is discovered at the bottom of the vortex finder while the system is operating at 0.35 m³/s flow rate. In the meantime, the gas flow as portray in Figure 4 is almost equal for each unit of the cyclone. This identical flow within the system is crucial to achieve optimum performance of the system by ensuring that each cyclone is run in similar manner [8].

![Figure 4. Velocity contour at (a) 0.27, (b) 0.31, and (c) 0.35 m³/s flow rates](image)

3.2. Particle trajectories and collection efficiency

Any particles that enter a cyclone system will encounter centrifugal force and then migrate toward the cyclone wall [9].

3.2.1. Particle trajectories. Figure 5 illustrates PM10, PM5, PM2.5, and PM1 trajectories within MR-deDuster system for Q equals to (a) 0.27, (b) 0.31, and (c) 0.35 m³/s. It can be seen from the figure that the particle trajectories increase at finer particle diameter of 1 μm as the particle could not be collected inside the cyclone trap section of MR-deDuster. Besides, the system that simulated with 1 μm particles illustrates the path lines of finer particle flowing upward inside the vortex finder and escape the cyclone. Any particle which is able to be collected by the system will not be traced at the cyclone trap section.

Large particles mostly are separated by the action of centrifugal forces as they have relatively greater inertia [10]. The inertia of particles under influence of centrifugal forces (rotational movement) push the particles of the dispersed phase towards external wall which lead to the separation from gas streamline [11, 12]. Hence, larger particles will collide with cyclone wall while moving along the spiral outward to the bottom of cyclone and then being collected at cyclone trap.
Figure 5. PM$_{10}$, PM$_{5}$, PM$_{2.5}$, and PM$_{1}$ trajectories at (a) 0.27, (b) 0.31, and (c) 0.35 m$^3$/s flow rates

However, the fine particles escaped from the cyclone at the edge of vortex finder due to radially inward gas movement which caused by gas acceleration and pressure gradient. In addition, more
particle trajectories are visible as the volumetric air flow rates increase due to increasing of inlet velocities which affect the particle travel distance. Higher inlet velocity able to pull the particle deep inside the bottom of the cyclone compare to the lower inlet velocity operating condition. Thus, higher collection efficiency of the cyclone is predicted to happen with increasing of flow rates.

3.2.2. Collection efficiency. The performance of the system represented by collection efficiency plot is determined with feeding a number of particles at the cyclone inlet then calculated the ratio of particles which collected in cyclone trap and emitted through cyclone outlet. The more particles able to be tracked by the model, the more accurate efficiencies obtained [7]. Furthermore, it is safe to assume that the presence of the particle will not alter the flow field as the particle loaded in a cyclone separator is typically small [13].

Figure 6 shows the fractional collection efficiency of MR-deDuster at various Q which indicated that the fractional collection efficiency of particles increases as Q increases. 100% fractional collection efficiency is obtained with particle size equal and bigger than 10 µm except when operating at the lowest flow rate; which resulting 97.8% efficiency. Smaller particles escaped from the cyclone through the outlet as they have less centrifugal force and might be more strongly influenced by turbulence inside the system [14]. This predicted fractional collection efficiency is related to the dpc of the cyclone.

As shown in Figure 6, small dpc was relatively predicted for all simulated Q. Smaller dpc signifies the capability of the system to capture fine particle size fraction and generally, dpc decreases as the Q increases. The largest dpc is predicted at 2.05 µm at the lowest Q of 0.27 m³/s while the smallest dpc 1.85 µm is predicted by CFD at the highest Q of 0.35 m³/s. Smaller dpc also indicates higher collection efficiency of the system.

![Figure 6. CFD prediction of fractional collection efficiency and dpc for PM_{10}, PM_5, PM_{2,5}, and PM_1 at 0.27, 0.31, and 0.35 m³/s flow rates](image)

4. Conclusion
This study as predicted by CFD has shown that the modified configuration of MR-deDuster is able to enhance the ability of multi-cyclone in controlling fine particles emission. Hence, this optimized and
The high performance of multi-cyclone is believed to be a great contribution in reducing particle emission in many industries especially power generation, oil and gas, and waste incinerator. Higher volumetric air flow rate resulting smaller particulate cut-diameter which will increase the collection efficiency of multi-cyclone. However, it is important to run a device at its optimum operating condition to prevent any excessive additional operating cost.

**Acknowledgement**
The author gratefully acknowledged post-graduate research fellowship from Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur.

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