Experimental, Computational Fluid Dynamics and Theoretical Study of Cyclone Performance Based on Inlet Velocity and Particle Loading Rate

Sakura G. Bogodage, Andrew Y. T. Leung

Abstract**—**This paper describes experimental, Computational Fluid Dynamics (CFD) and theoretical analysis of a cyclone performance, operated 1.0 g/m^3 solid loading rate, at two different inlet velocities (5 m/s and 10 m/s). Comparing experimental results with theoretical and CFD simulation results, it is pronounced that the influence of solid in processing flow is more significant than expected. Experimental studies based on gas-solid flows of cyclone separators are complicated as they required advanced sensitive measuring techniques, especially flow characteristics. Thus, CFD modeling and theoretical analysis are economical in analyzing cyclone separator performance but detailed clarifications of the application of these in cyclone separator performance evaluation is not yet discussed. The present study shows the limitations of influencing parameters of CFD and theoretical considerations, comparing experimental results and flow characteristics from CFD modeling.

Keywords**—**Cyclone performance, inlet velocity, pressure drop, solid loading rate.

I. INTRODUCTION

THE popularity of cyclone separators in the field of particle separation is mainly due to their simple and high efficiency operational principle which uses the double-vortex flow combined with simple design, low maintenance cost and easy operation at wide ranges of operational and environmental conditions. The performance of cyclone separators depend on operating parameters and geometric configurations, while the inlet velocity and the particle solid loading rate are identified as significant operational parameters for any type of cyclone geometric design.

Experimental studies conducted by Stern, Caplan and Bush [1] (as quoted by Ji, Xiong, Wu, Chen and Wu [2]), Mori, Suganuma and Tanaka [3], Patterson and Munz [4], Zenz [5], Tawari and Zenz [6] (as reported by Fassani and Goldstein Jr. [7]), Hoffmann, Arends and Sie [8], Hoffmann, Van Santen, Allen and Clift [9], Zenz [5] and Tawari and Zenz [6] (as reported by Fassani and Goldstein Jr. [7]) and Ji, Xiong, Wu, Chen and Wu [2] observed a trend of an increasing collection efficiency with the increase of particle loading rate. Contradicted results were reported by Tuzla and Chen [10] (as reported by Fassani and Goldstein Jr. [7]) and Fassani and Goldstein Jr. [7] under higher solid loading conditions, expressed by the effect of the dramatic reduction of turbulence kinetic energy at high solid loading conditions. Increase of particle separation efficiency with the increase of inlet velocity is also reported by Mori, Suganuma and Tanaka [3], Patterson and Munz [4], Kim and Lee [11] and Xian, Park and Lee [12]. CFD studies based on particle loading rates, particle agglomeration and particle-particle and particle-wall collisions were conducted by few resent studies; Derksen [13], Derksen, Sundaresan, and Van Den Akker [14], Qian, Huang, Chen and Zhang [15] and Wan, Sun, Xue and Shi [16], but many of the results are not validated by practical experimental investigations. But all of these studies stated the influence of solids in the flow, which change the flow characteristics. Wan, Sun, Xue and Shi [16] and Chu, Wang, Xu, Chen and Yu [17] also proved the dramatic reduction of swirl in the cyclone flow due to presence of solid particles.

It has proven by many experimental investigations; Dirgo and Leith [18], Patterson and Munz [4], Kim and Lee [11], Zhou and Soo [19], Bohnet [20], Zhu and Lee [21] and Fassani and Goldstein Jr. [7] that cyclone pressure drop increases dramatically with the inlet velocity regardless of the geometric and operational parameters due to increase of turbulence kinetic energy of the swirling flow. On the other hand, the presence of particles in the cyclone flow field has been experimentally investigated by several studies, Shepherd and Lapple [22], Briggs [23], Kang, Kwon and Kim [24], Baskakov Dolgov and Goldobin [25], Hoffmann, Van Santen, Allen and Clift [9], Fassani and Goldstein Jr. [7], Gil, Romeo and Cortés [26] and Kharoua, and Khezzar and Nemouchi [27], have observed the increase of particle loading influence the decrease of pressure drop. Reduction of pressure drop with the presence of solids in the flow is also proven by Derksen, Sundaresan, and Van Den Akker [14], Qian, Huang, Chen and Zhang [15] and Xue, Sun, Wan and Shi [28] using CFD modeling applications and stated that this reduction is due to reduction of turbulence energy of the flow field. Griffiths and Boysan [29] conducted CFD analysis to show the increase of pressure drop with the inlet velocity, due to increase of turbulence kinetic energy with the inlet velocity.

A number of theoretical models for predicting cyclone separator performance were derived in the literature (e.g., Lapple [30], Barth [31], Smolik [32] and Muschelknautz [33]), but based on different assumptions of the gas-solid flow field of the cyclone separators. However, the validity of these theories is still questionable, as in their comparison, many of have ignored at least one parameter of the cyclone flow, which is considered as significant in performance. For example, theories derived by Lapple [30] and Barth [31] are have not considered the solid loading rates and though the theory by Smolik [32] considered this parameter, the developed theory is fully empirical. Only the cyclone

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performance theory developed by Muschelknautz [33] (as quoted by Muschelknautz and Greif [34]) has considered many relevant cyclone operational and geometric parameters.

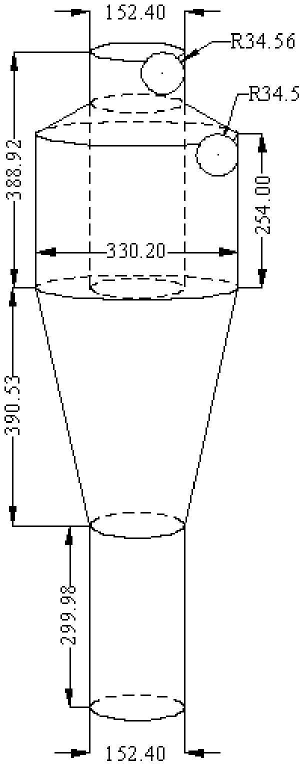


Fig. 1 Geometry of the cyclone separator

In point of fact, CFD modeling and theoretical analyses are important in cyclone separator performance analysis as they are economical and convenient than handling practical experiments. However, comparisons of experimental, CFD modeling and theoretical knowledge based studies on gas-solid flow and inlet velocity of cyclone separators is still basic and partial for a general conclusion. Hence, the behavior of cyclone performance at 1.0 g/m^3 solid loading rate at two different inlet velocities was studied in this study. Experimental collection efficiency and pressure drop results were compared with CFD and theoretical results to understand the accuracy of CFD and theoretical predictions. Also, flow characteristic from CFD modeling analysis were also analyzed to understand the changes in flow characteristics at two different inlet velocity conditions.

II. EXPERIMENTAL PROCEDURE

Geometric dimensions of the studied cyclone separator are shown in Fig. 1. Experimental conditions are given in the Table I.

TABLE I
EXPERIMENTAL CONDITIONS

Parameter	Value/ condition
Inlet velocity	Case A: 10 m/s Case B: 5 m/s
Solid loading rate	1.0 g/m^3
Solid type	Arizona Test dust (Powder Technology, INC; Size range: 0.742 to 18 µm, Standard deviation: 1.762 µm and Density: 2650 kg/m^3)

A schematic diagram of the experimental setup is shown in Fig. 2. Two isokinematic flow volumes were extracted from the inlet and outlet by using sampling probes connected to suction tubes (VRL 50-080108, Nihon Pisco) and the extracted flows were diluted by supplying additional air using air blowers (Fig. 2). Weight of the collected solid mass at the bottom of cyclone separator was measured by using a sensitive balance. Fluke particle counter (Fluke 983, FLUKE Inc.) was used to obtain fractional efficiencies of particles.

Air Flow Meter (TSI PVM620) was used to measure the pressure drops, considering mean pressure difference between inlet and outlet.

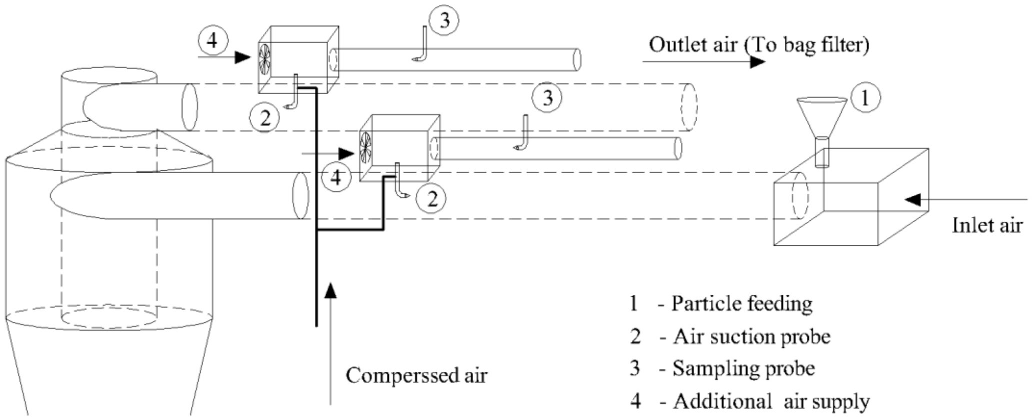


Fig. 2 Schematic diagram of the experimental setup

III. CFD MODELING

CFD modeling was conducted by using CFD commercial software, ANSYS CFX 14.0. Gas-solid flow field was defined by accounting the air at 25°C as the continuous phase and the particles (with similar characteristics in experiments), as the dispersed phase. Simulations were conducted at considered inlet velocities, while randomly distributed particles were injected from the inlet surface with same velocity defined to the continuous phase. Gas-solid flow in cyclone separator was modeled by using 10000 of poly-dispersed particle samples which represent 1.0 g/m^3 of inlet flow rate. Atmospheric pressure (101.325 kPa) was the specified reference pressure. Pressure specified opening boundary condition was selected at outlet. Particles were identified as collected when those touched the cyclone hopper base by setting zero restitution factors at the wall boundary. All other walls were considered as free slip, smooth boundaries and perfectly elastic to particle-wall collisions.

Large Eddy Simulation (LES) turbulence model combined with Smagorinsky–Lilly SGS model was used in simulations. Superiority of this model in cyclone flow field simulation was reported by many studies find in the literature (e.g., Derksen [13], Derksen [14] and Schmidt, Blackburn, Rudman and Sutalo [35]). Dispersed phase was simulated by Eulerian–Lagrangian method. One-way coupling method was safely assumed for considered solid volume fractions [36], [37]. Detailed descriptions of LES model and Eulerian–Lagrangian method are available in ANSYS CFX Solver Theory Guide [38].

IV. RESULTS AND DISCUSSION

The experimental, CFD and theoretical results for the cyclone collection efficiency and pressure drop at two velocity conditions under the solid loading rate of 1.0 g/m^3 are were considered. The collection efficiencies were measured by considering overall collection efficiency, grade efficiencies and cut-size diameter d_{50}. d_{50} provides direct information about the particle grade efficiency by means of the smallest particle size with 50% separation efficiency. For the theoretical comparison, Muschelknautz theory (see more details in Muschelknautz [33]) was used, as the theory incorporates with many parameters such as, solid loading rate, inlet velocity and geometric parameters of cyclone separator, which were unconsidered in other theories.

A. Overall Collection Efficiency

Overall collection efficiencies of experimental, CFD and Muschelknautz theory are shown in Table 2. The overall collection efficiencies are greater at higher velocity condition which was proved in the literature (e.g., Kim and Lee [11] and Xian, Park and Lee [12]). However, CFD and Muschelknautz theory provides closer and higher results than the experiments. This reveals the importance of contemplation of particle back- mixing, agglomeration, losses of swirling flow due to presence of particles and wall friction into CFD modeling and theories as the influence of these are significant in real particle laden flows.

TABLE II
THE THEORETICAL, EXPERIMENTAL AND MUSCHELKNAUTZ THEORY OVERALL COLLECTION EFFICIENCIES

	Overall Collection Efficiency at,	
	10m/s	**5m/s**
Experimental	0.8847	0.8185
CFD	0.9571	0.8735
Muschelknautz	0.9534	0.8788

B. Grade Efficiency Curves

Fig. 3 shows the grade efficiency curves resulted from experimental, CFD and Muschelknautz theory at 1.0 g/m^3 solid loading rate.

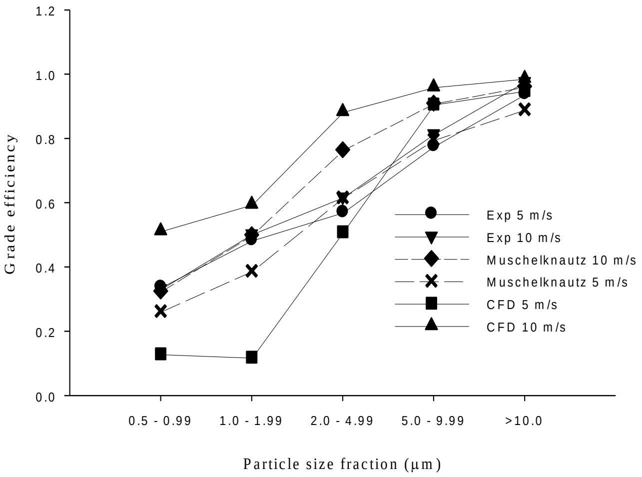


Fig. 3 Experimental, CFD and theoretical grade efficiency curves at 1.0 g/m^3 solid loading rate at two velocity conditions

Considering the grade efficiency curves from experiments, the differences in fine particle collection were smaller at the two velocity conditions, but larger for coarse particle collection. This observation shows the pronouncement of fine particle back-mixing at high velocities inside cyclone separators. Conversely, with the long residence time at low velocity conditions, particle agglomeration is higher at 5 m/s velocity than at 10 m/s velocity. Thus, the fine particle separation is closer at two velocities, which is well shown at low mass loading situations.

In CFD results, at 10 m/s, the numerical grade efficiency curve was over-predicted by the experimental values. It was under-predicted at 5 m/s for particle fractions of 0.5- 4.99 μm and over-predicted for diameters larger than 5.0 μm. The results were inconsistent as the particle agglomeration effect and particle re-entrainment were not considered in the modeling.

Comparing experimental and CFD data with theoretical findings by Muschelknautz theory, matched data from the theory were obtained by selecting the modification factor (d_{fact}) in as 0.27 and 0.18 for 5 m/s and 10 m/s inlet velocity conditions, respectively, which differed from the range specified by Muschelknautz (0.9 to 1.4). Also to compute grade efficiencies, m was set to 1.1237 and 1.426 for 5 m/s and 10 m/s in this study, while Muschelknautz specified m values of 2 to 7. The reason for this contradiction may due to assumed high collection efficiency ranges by Muschelknautz at low solid loading rates, which was higher than the present study results.

C. Cut-Size Diameter

Table 3 displays the theoretical, experimental and Muschelknautz d_{50} values at the solid loading rate considered. With the limitations of measurements in Fluke 983, only particle fractions were considered in experiments, thus in CFD results. The decrease of d_{50} value with the increase of inlet velocity is well shown in all three studies.

TABLE III
THE THEORETICAL, EXPERIMENTAL AND MUSCHELKNAUTZ THEORY CUT SIZE DIAMETERS

	Cut size diameters (d_{50}) at,	
	10m/s	**5m/s**
Experimental	1.00- 1.99	2.00- 4.99
CFD	0.50- 1.00	2.00- 3.00
Muschelknautz	1.41	2.11

Theoretical d_{50} values from Muschelknautz's theory are in the experimental d_{50} particle fraction ranges with the assumed values stated before. CFD results show lower d_{50} at 10 m/s velocity condition. The discrepancy may due to the inconsideration of particle agglomeration and back-mixing, which are higher in finer particle ranges, in the present CFD modeling.

D. Cyclone Pressure Drop

The pressure drops at the 5 m/s and 10 m/s velocities at 1.0 g/m^3 solid loading rate relevant to experimental, CFD and Muschelknautz's theory are shown in Table 4. The pressure drop dramatically reduces at 5 m/s velocity than at 10 m/s velocity in all three cases, similar to those of previous studies by Fassani and Jr [7], Allen and Clift [9] and Gil, Romeo and Cortés [26]. This reduction of pressure drop at low velocity is due to the decrease in swirling energy at low velocity conditions.

TABLE IV
THE THEORETICAL, EXPERIMENTAL AND MUSCHELKNAUTZ THEORY OVERALL PRESSURE DROPS

	Pressure drops at,	
	10m/s	**5m/s**
Experimental	157.05 Pa	37.30 Pa
CFD	198.74 Pa	43.8 Pa
Muschelknautz	308.28 Pa	88.08 Pa

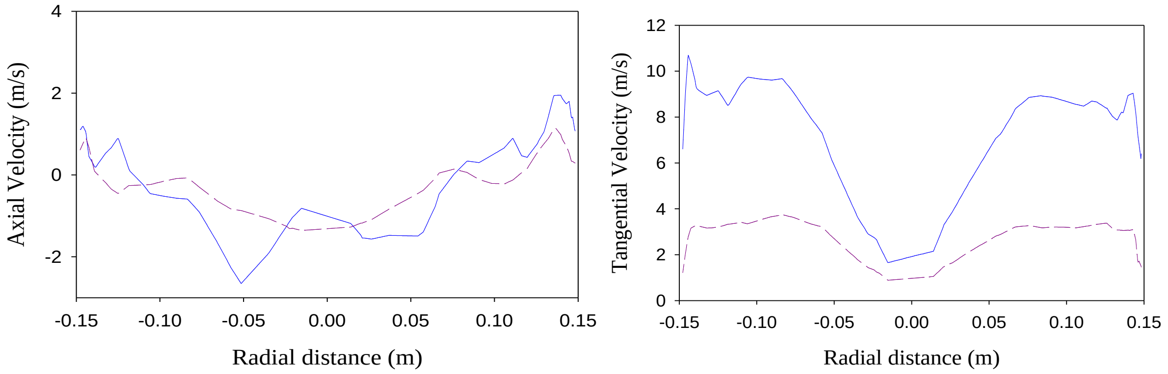
However, over-predicted results from CFD studies may be due to the one-way coupling assumption, which ignored the effects from the particle phase on the fluid flow and ignores the wall friction in modeling, the highest shows from the Muschelknautz theory, though the theory considered many operational and geometric parameters. The reason may due to variations of fluid velocities and wall frictions inside the cyclone separator with the solid deposition, which was not incorporated into the theory.

E. Flow Field Pattern at Two Velocity Conditions

Fig. 4 shows the simulation results for the axial and tangential velocity components at horizontal sections located at 0.075 m, 0.2 m and 0.3 m down from the vortex finder inlet. In general, the flow inside the cyclone separator was not axi-symmetric. Inside the cyclone body, the axial velocity was higher on the right side (opposite the inlet location) and the tangential velocity was higher on the left side (under the cyclone inlet), which is greater at high velocity.

The axial velocity is responsible for the transportation of particles down to the collection hopper. Thus, near the walls, a higher axial velocity contributes more to particle separation than the gravitational effect. Fig. 4 shows the unchanged behavior of the axial velocity profiles with the velocity in the cyclone body and an insignificant variation along the vertical axis. At 10 m/s, the shape of the axial velocity is W-shaped, whereas at 5 m/s it is more flat. This result indicates the significance of the attenuation effect on swirling flow by friction losses on vortex finder walls at higher velocity conditions [39]. The sharpness of the W-shape increased in a downward direction; similar flow patterns have been investigated numerically by Chuah, Gimbun and Choong [40], El-Batsh and Haselbacher [41], Zhao, Su and Zhang [42] and Luqman, Jolius and Thomas [43]. At the dust collection hopper, the increase in the axial velocity at the quasi-forced vortex is due to recirculation, which may have worsened the collection efficiency.

When the axial and tangential velocity profiles at different axial positions are compared in Fig. 4, the tangential velocity at the cyclone body is found to be higher, which confirmed that it is the major velocity component of cyclonic flow. However, the strength of this velocity component is reduced approximately 2.5 times when the inlet velocity is decreased by half. Similar to the axial velocity, the change in the tangential velocity is insignificant along the cyclone axis.



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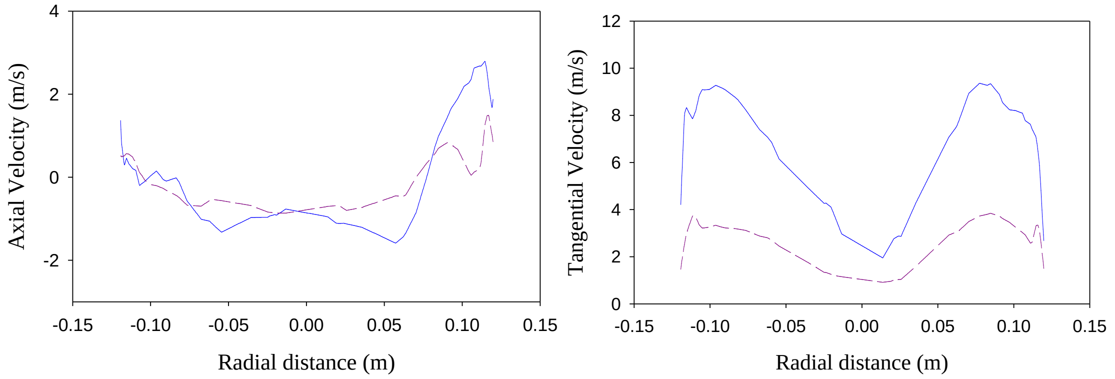

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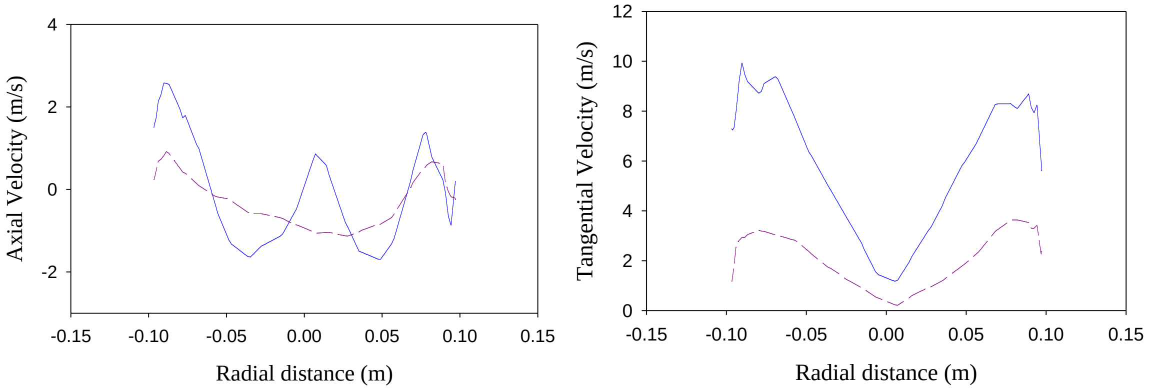

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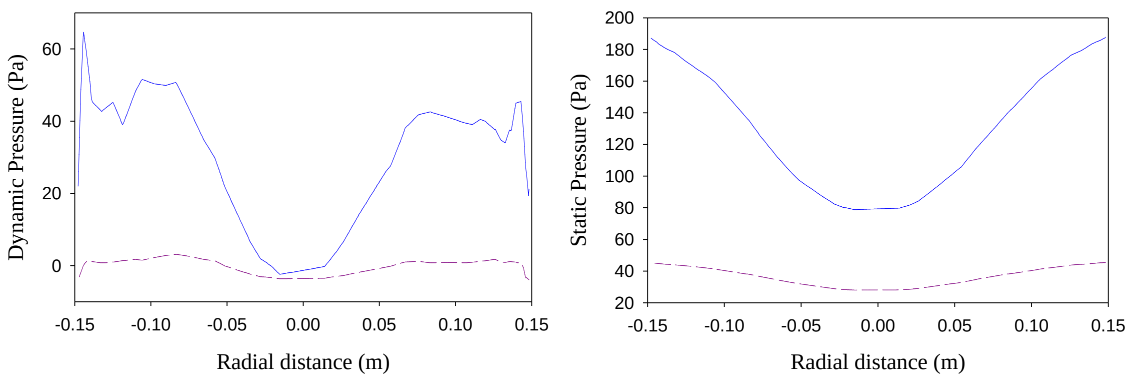
Fig. 4 Axial (Left) and Tangential (Right) velocity profiles at three horizontal locations down from the vortex finder inlet at 10 m/s (Straight lines) and 5 m/s (Dash lines), (a) at 0.075 m, (b) at 2.0 m and (c) at 3.0 m

The unchanged tangential flow patterns along the vertical axis of the cyclone body have also been investigated in previous studies performed by Chuah, Gimbun and Choong [40], Zhao, Su and Zhang [42], Wang, Xu, Chu and Yu [44] and Elsayed and Lacor [45]. However, due to the presence of particles in the flow, the magnitude of the flow may have changed, especially in zones with a higher particle concentration, due to a reduction in the swirling capacity of the flow [17], [46].

Fig. 5 shows the static and dynamic pressure profiles at the same axial cross sections. The pressure drop represents the energy consumption of the cyclone separator, which may be directly related to the operation cost. However, comparing the dynamic pressures and static pressures at 10 m/s and 5 m/s, the maximum dynamic pressure at the cyclone core is reduced by nearly 50 times and the maximum static pressure near the wall is reduced approximately six times when the inlet velocity is reduced by half.

The dynamic pressure in the pressure field consisted of the swirling kinetic energy of the cyclonic flow. This pressure increases towards the cyclone body and reaches a maximum; it then decreases at the cyclone center.



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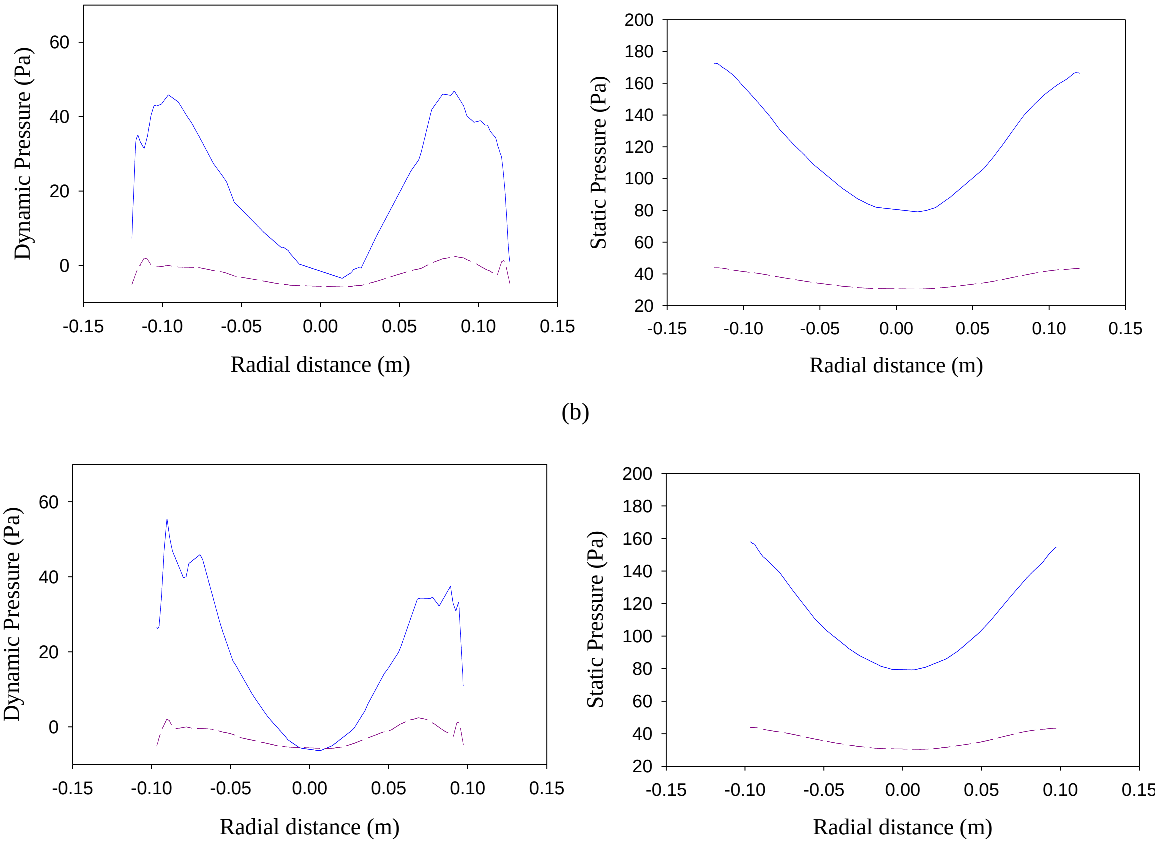

(b)

(c)

Fig. 5 Dynamic (Left) and Static (Right) pressure profiles at three horizontal locations down from the vortex finder inlet at 10 m/s (Straight lines) and 5 m/s (Dash lines), (a) at 0.075 m, (b) at 2.0 m and (c) at 3.0 m

At both 5 m/s and 10 m/s, the minimum dynamic pressure at the cyclone's center axis is nearly zero. The static pressure is reduced radially from the wall to the cyclone center, combined with a reduction in the tangential velocity near the walls. The increase in the quasi-forced vortex at the center is mainly governed by the axial velocity.

V. CONCLUSION

In this study, the performance of a cyclone separator at 0 g/m^3 to 1.0 g/m^3 particle loading rates was investigated at two inlet velocities. The investigation was conducted by comparing performance results from experiments, CFD modeling and theoretical methods. The common increasing behavior of the collection efficiency at the considered solid loading range was seen when increasing the inlet velocity. Discrepancies of CFD and theoretical results compared to experimental findings may due to less consideration of operational and geometric parameters in the previous two cases.

However, the study shows the significance of the effects of solid loading in cyclone flow, which is different than expected, especially in CFD modeling and theoretical predictions and therefore more investigation is required to analyze the effects of solid loading on particle performance. Experimental studies of gas-solid flow in cyclone separators required control systems and sensitive measuring equipment. Then, CFD modeling and theoretical analysis are more economical in cyclone separator analysis. However, in both applications many of the affecting operational and geometric parameters of cyclone separator gas- solid flows have been ignored. Particle back-mixing, particle agglomeration, wall frictional effects, losses of swirling flow with the presence of particles and effects from particle accumulation zones are significant in cyclonic flows and thus studies are required first to understand and derive accurate theories and modeling parameters.

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