Numerical simulation of an electro-cyclone for classification of micron-sized particles

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ABSTRACT

Cyclones are normally used to separate relatively larger particles from the aerosol. In this article, the feasibility of using cyclone to classify particles in specific mass range by applying an electric field between the outer cylinder and the vortex finder is studied. Moreover, the effect of cyclone geometry and electric field intensity on the cyclone efficiency and the classified particle diameter is quantified. FEM was used for the simulations of 3-D, steady and two-phase flow. It should be noted that the Reynolds number of inlet flow ranged between 4,000-10,000. The results reveal that the diameters of inner and outer cylinders have negligible effects on the cyclone efficiency. However, an increase in the length of the cyclone specifically the length of the vortex finder can significantly affect the cyclone performance which can be attributed to the higher particle residence time within the cyclone. For cyclones with twice larger cylinders, the classification efficiency is 6% - 17% higher based on the geometric standard deviation of the particle size distribution. It was also shown that different particle masses can be classified by adjusting the flow rate of the inlet aerosol or the magnitude of the electric field applied to the charged particles.

KEYWORDS

Electrocyclone, Micron-size particles, Soot, Particle classification, Mass

1. Introduction

Cyclones are used to remove relatively larger particles from an aerosol based on centrifugal force. Cyclones are numerically and experimentally studied in the literature in order to improve their performance and increase their collection efficiency. Avci et al. [1] investigated the effect of cyclone geometry on its performance. They showed that as the length of the vortex finder increases, the pressure drop across the cyclone decreases and the collection efficiency increases. Xiong et al. [2] experimentally compared six cyclones with different vortex finders and showed that conical vortex finder has higher collection efficiency compared to the cylindrical vortex finder. Shastri et al. [3] changed the length of the cylindrical section of the cyclone and the conical section to quantify the effect of the ratio of these two lengths on its performance. They studied eight different cyclones with the same total length but different cylindrical to conical length ratios and showed that cyclones with larger cylindrical section have lower pressure drop while the collection efficiency is higher in cyclones with larger conical section. Kim et al. [4] experimentally investigated the collection efficiency of three modified surface body cyclones. They compared the spiral guide body, circumferential groove body, and vertical groove body cyclones and showed that the guide does not play an important role in the collection efficiency of cyclone with high flow rates. They also showed that groove body cyclones are less efficient in comparison with conventional cyclones. Zhao et al. et al. [5] designed three cyclones with different inlet geometry including a conventional tangential single inlet, a direct symmetrical spiral inlet, and a converging symmetrical spiral inlet to study the effect of inlet geometry on the performance and efficiency of the cyclones. Their results reveal that the symmetrical spiral inlet geometry significantly increases the collection efficiency and slightly increases the pressure drop.

In some application, we need to classify particles with some specific size range, therefore, larger particles as well as smaller particles should be collected while particles in a specific size range are left in the aerosol. In this article, the feasibility of using the cyclone to classify particles in any specific size range is studied. A traditional cyclone is redesigned so an electric field is applied in the space between the inner and outer walls. Therefore, not only particles are affected by centrifugal force, but also there is an electric force applied to particles due to the electric field within the cyclone. These two forces are in the opposite directions so centrifugal force moves particles toward the outer wall while electric force moves them toward the inner wall. Since larger particles have higher mass, they are more affected by centrifugal force so they are then collected by the outer wall. On the other hand, smaller particles are

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more affected by the electric force so they are collected by the inner wall.

2. Methodology

The schematics of the geometries evaluated in the current study and the specifications of the cyclones are shown in Figure 1 and Table 1, respectively.

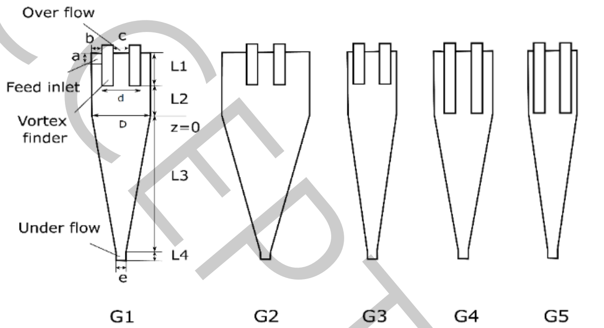

Figure 1. Schematic of the evaluated cyclones

Table 1. Spec. of the evaluated cyclones. Sizes are in mm.

Parameter	G1	G2	G3	G4	G5
A	12	12	12	12	12
B	8	20.5	4	8	4
C	15	15	15	15	15
D	34	34	34	34	34
D	50	75	42	50	42
E	8	8	8	8	8
L1	36	36	36	72	72
L2	36	36	36	0	0
L3	159.5	159.5	159.5	159.5	159.5
L4	10	10	10	10	10

An electric field with the magnitude of 20–30 kV/m is applied between the inner and the outer walls. Particles are injected in the center of the intake port. The assumptions are as follow:

- Particles and the gas are assumed to be soot and air, respectively
- Temperature does not have impact on the particles
- There is no interaction between particles
- Particles do not stick to each other after collision
- Particles are spherical
- Particles stick to the wall after collision with the wall
- The temperature of the cyclone and the aerosol is the same
- Particles are exposed to only gravity, centrifugal and electric forces

The boundary conditions for the simulations are summarized in Table 2.

Table 2. Boundary conditions

Surface	Boundary condition for the air	Boundary condition for the particles
Cyclone wall	Wall	Trap
Inlet surface	Velocity Inlet	Escape
The top outlet	Pressure outlet	Trap
The bottom outlet	Pressure outlet	Escape

In order to check the validity of the models, the results of the simulations are compared with the numerical and experimental results reported by Cui et al. [6] (See Fig. 2). Note that the volume flow rate is 60 l/min for the validation of the numerical simulations. It can be seen from Fig. 2 that the data estimated by simulations in the current study are in relatively good agreement with the results reported by Cui et al. [6] specifically with their CFD model results with less than 1% difference between the two data sets.

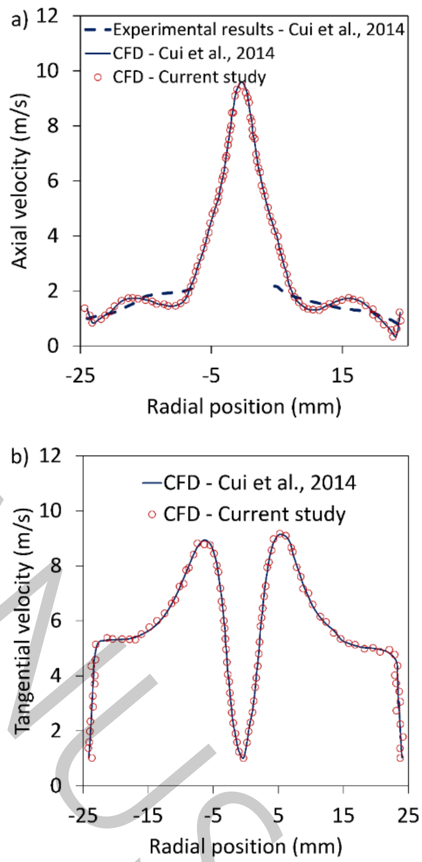

Figure 2. Axial and tangential velocities at z=+18 mm compared with the results reported by Cui et al.

3. Results

Fig. 3 shows particle size distributions at the inlet and outlet of the cyclone. It can be seen that the magnitude of electric field does not significantly change the count median diameter, however for G2 with larger cyclone diameter, CMD is more affected by electric field intensity. In other words, at 20 kV/m, the CMD for the outlet size distribution is lower than G1 while the opposite being the case at 30 kV/m. Figure 3 also shows that total concentration for G2 is greater than G1 which can be explained by noting that when the cyclone diameter increases in G2, particles should travel a longer distance to reach the walls. On the other hand, the length of the cyclone is not different in comparison with G1 meaning that particles have the same amount of time to get to the walls. Therefore, less particles are trapped inside the cyclone for G2 compared to G1.

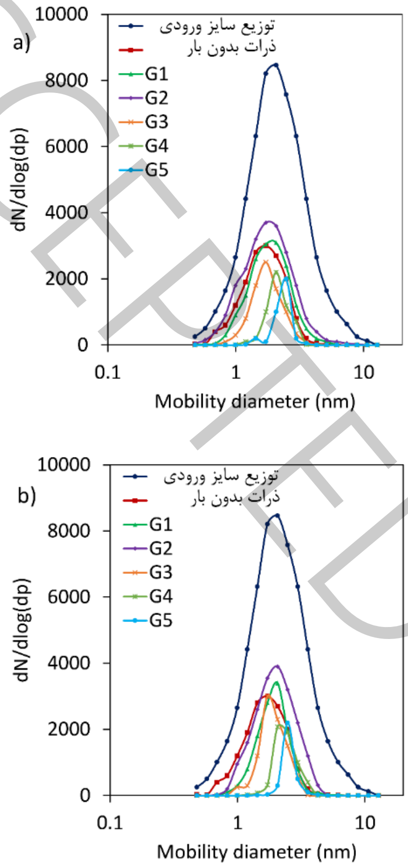

Figure 3. Particle size distributions for a) 20 kV/m and b) 30 kV/m

In G3, all cyclone dimensions are the same as G1 except for the cyclone diameter which in lower than G1. Therefore, as stated above, particle loss increases due to lower distance between cyclone inner and outer walls. Note that the diffusion loss is also higher for cyclone with lower diameter. Figure 3 shows that CMD is 1%–4% lower in G3 compared to G2 which means that there is no difference between these two geometries in terms of size classification.

The length of the vortex finder is larger in G4 and G5, therefore particles remain inside the cyclone for a longer time and consequently more particles attach to the walls. Figure 3 shows that the total concentration that find their way outside the cyclone is 52%–78 lower in G4 and G5 compared to G1. Note that for both G4 and G5, CMD is also greater than G1 which is due to higher loss for relatively smaller particles due to higher diffusion coefficient. It should be noted that the geometric standard deviation (GSD) for the outlet size distribution is also lower in G4 and G5 compared to G1 which shows that these two geometries can better classify particles. In other words, particles with a narrower size range are classified by the cyclone in G4 and G5.

4. Conclusion

In this study, the feasibility of using a cyclone to classify particles in a specific size range is studied. The results reveal that:

- Cyclone efficiency is significantly affected by the geometry of the cyclone specifically the length of the vortex finder.
- For cyclones with larger vortex finders, the total concentration is also lower, therefore, more work needs to be done to find the optimized length of the vortex finder for having a good classification efficiency as well as high concentration of particles.
- The inlet velocity affects the classification efficiency since it can increase the centrifugal force applied to particles. Therefore, using spiral inlet may improve the cyclone efficiency which needs to be studied in future.

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