

**COMPUTATIONAL FLUID DYNAMICS (CFD) MODELING OF FREE-SURFACES AND PARTICLE CAPTURE IN A VORTECONE SCRUBBER SYSTEM SCALED FOR INSTALLATION ON CONTINUOUS MINERS**

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**ABSTRACT**

Continuous miners are often equipped with a flooded-bed dust scrubber to clean the air from close to an active underground coal mining face. However, its impingement screen is prone to clogging due to an accumulation of dust, thereby lowering the scrubber's efficiency and potentially exposing the mine workers to higher levels of dust. Fans can compensate for the increased resistance by varying their operating parameters, but the scrubber screen needs significant maintenance which leads to downtime. The authors have proposed a suitably sized Vortecone as an alternative to the conventional flooded-bed dust scrubber system. Water is used as the filter medium, which is replaced and recycled continuously. Preliminary CFD investigations of Vortecone scrubbers have indicated higher cleaning efficacies, especially in the respirable range. This paper presents the results including the flow characteristics and capture efficacies of a full-scale Vortecone. Multi-phase flows, including free-surface modeling and particle tracking methods, have been adopted.

**Keywords:** Computational fluid dynamics, Vortecone, Free-surface modeling, Particle tracking, Scrubbing systems.

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**INTRODUCTION**

Continuous miners are the main production machines deployed in room and pillar mining operations. These miners extract coal by the shearing action of the wethead cutting drums. Strategically placed water sprays on the drum not only cool the bits extending their useful service life, they also suppress the dust at the point of generation itself. A flooded-bed dust-scrubber (Campbell, et al. 1983) is usually integrated onto the continuous miner to arrest dust from close to the active face. These fan-powered scrubbers have an impingement screen flooded with water, which also serves as the filter element. A demister downstream of the screen removes the excess water from the air cleaned. These conventional scrubbers have been found to be very effective in alleviation of respirable dust levels underground (Chao and De-sheng 2000) (Colinet, Reed and Potts 2013). However, the inefficiencies of the flooded-bed dust scrubbers arise out of their internal components. Depending on the mining conditions, the screen may be clogged by the accumulation of the trapped dust particles. The

resistance of the scrubber system is increased reducing the airflow. The flooded-bed dust-scrubber system would, therefore, require frequent maintenance of the screen and the demister (Listak 2010). Since any maintenance needs to be carried out under supported roof, this leads to loss of availability of the equipment as well. In addition to this, the continuous miner operators could be exposed to elevated levels of dust when satisfactory airflow at the face is not achieved.

The authors have proposed the application of a Vortecone scrubber as a substitute for the flooded-bed dust-scrubber used on continuous miners. The Vortecone, as shown in Figure 1 is a device that was invented at the Institute of Research for Technology Development at the University of Kentucky (Worley and Elkins 2005) (Salazar, et al. 2002). The dust-laden air brought into the system is accelerated by progressively decreasing area of cross section available to flow. Fast moving air is then released into a vortex chamber, where it undergoes a rapid swirling motion. The heavier dust particles are shed out of the air-stream differentially because they can not change directions rapidly unlike the streamlines of air. A thin film of water swirling swiftly at the periphery of the vortex chambers serves as the filter element and arrests the dust particles (Levy 2017). It is already being used on vehicle painting lines to arrest the over-sprayed paint particles. Painting via robotic arms is an inefficient process where only about 50-60% of all the sprayed paint particles stick to the surface of the vehicles. Over-sprayed particles generated through this process escape into the atmosphere of the assembly line. Deployment of Vortecone has not only enabled capture of over 99.9 % of paint particles, energy savings realized by this system has exceeded 30% (Tanigawa, et al. 2008). Water is recirculated and recycled continuously. The downtime for maintenance of scrubbers could be, therefore, reduced drastically. Further, the overall efficiency of a scrubbing system is a function of capture and cleaning efficiencies. The Vortecone could offer a flat profile of both these efficacies over prolonged periods. These Vortecones could replace the conventional flooded-bed dust scrubber systems on the continuous miners, particularly owing to their high particle cleaning efficacies and mechanical availability. This paper presents detailed computational fluid dynamics (CFD) models to exhibit the mechanism of dust capture through the Vortecone systems proposed to be installed on continuous miners.

**COMPUTATIONAL FLUID DYNAMICS MODELING**

Computational fluid dynamics (CFD) modeling has emerged as a powerful tool to model flows. CFD techniques have found numerous applications in the modeling of underground mining environments. Development of high-speed computing facilities and efficient algorithms have boosted the capabilities and hence, the application of CFD. The CFD solvers work by carrying out a numerical integration of Navier-Stokes equations of flow, which represent the continuity of flow and conservation of momentum and energy (NASA 2015). These equations are solved by numerically integrating these equations over millions of tiny control volumes using computer programs.

### STEADY STATE SIMULATIONS

Steady-state simulations were generated first to produce the operating pressure-quantity curve. Increasing flows through the inlet were imparted, whereas the outlet was assigned an outflow static pressure of 0 Pa. The convergence criterion was set at 0.0001 for the three components of velocity. Pressure, turbulent kinetic energy, and turbulence dissipation rate were also imparted the same criterion. All other surfaces were treated as impermeable walls. Since the maximum velocity in the Vortecone regularly approached compressible ranges, an additional set of steady-state simulations was developed to look at the changes in temperatures. The maximum change in temperature observed did not exceed 0.25°C, which is incapable of bringing about any phase changes in multi-phase systems. All further simulations considered air as an incompressible fluid to save on computing resources by eliminating the temperature variable. A preliminary examination of contours of pressure on a plane through the Vortecone, as shown in Figure 3 indicates that most of the pressure drops occur as the air passes through the constricted opening. Contours of velocity colored by their magnitude have been shown in Figure 4. Air incident at about 6 m/s is observed to get accelerated as it moves towards the vortex chamber, this also forces the particles to follow different trajectories based on their mass. Figure 5 shows the pressure-flow curve for the Vortecone. The curve is observed to follow the Atkinson's law, where pressure drop through the system varies proportionally to the second power of flows.

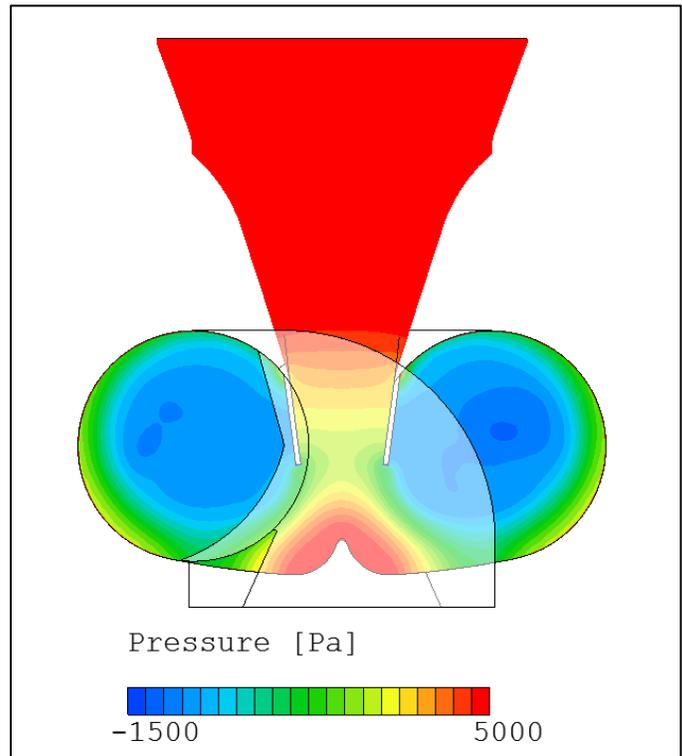


Figure 3. Contours of pressure on the plane.

To ensure the robustness of the computational grids, mesh independence studies were carried out. Richardson's method of establishing grid independence was chosen (Celik 2008). All relevant errors and approximate orders were calculated for grids. Three grids with increasing number of mesh elements were generated. The grids had about 0.94, 2.12 and 5.06 million polyhedral elements respectively. With the number of elements in each grid known, the representative size of the cell could be calculated. The decay ratio of the mean dimensions of the cells was kept at about 1.30.

Three points were chosen to monitor the variation of the magnitude of velocity over these meshes. A point has been chosen close to the flaps since air is accelerated rapidly in this zone. Points close to the first curve at the bottom and the outer periphery of the



Figure 1. One-eighth scale model of Vortecone developed at the Institute of Research for Technology Development, University of Kentucky (Source: Nippon Steel News July 2009).

The software SC/Flow was used to generate the CFD models for this research project. SC/Flow is built into independent modules dedicated to pre-processing, solving and post-processing respectively. For simulations, the structure of the Vortecone was first generated on a CAD platform. The volume and the relevant surfaces were demarcated and assigned unique names. An octree was then created with the elements refined in the zones of high gradients in physical parameters. Five prism layers were inserted to mimic the boundary layer phenomenon and a computational mesh was generated. The native tetrahedral and polyhedral elements enable generation of good quality meshes inside complex computational domains as well. Further, all the impermeable walls had over 99.5 % of the surface covered by the prism layers. Figure 2 shows the mesh on the surface of the Vortecone.

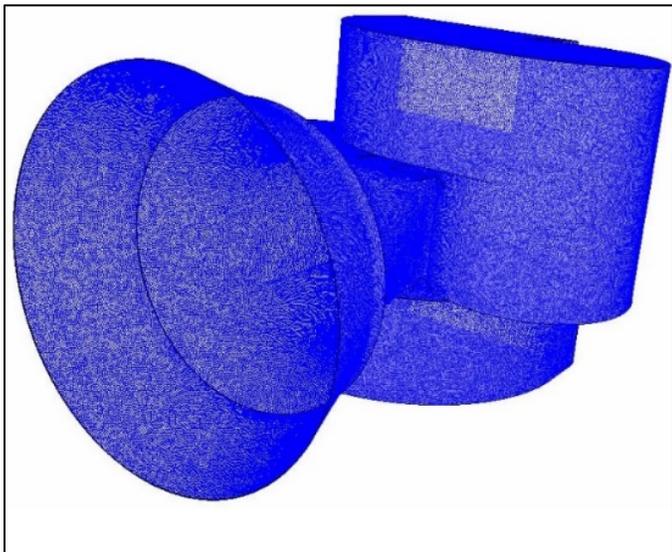
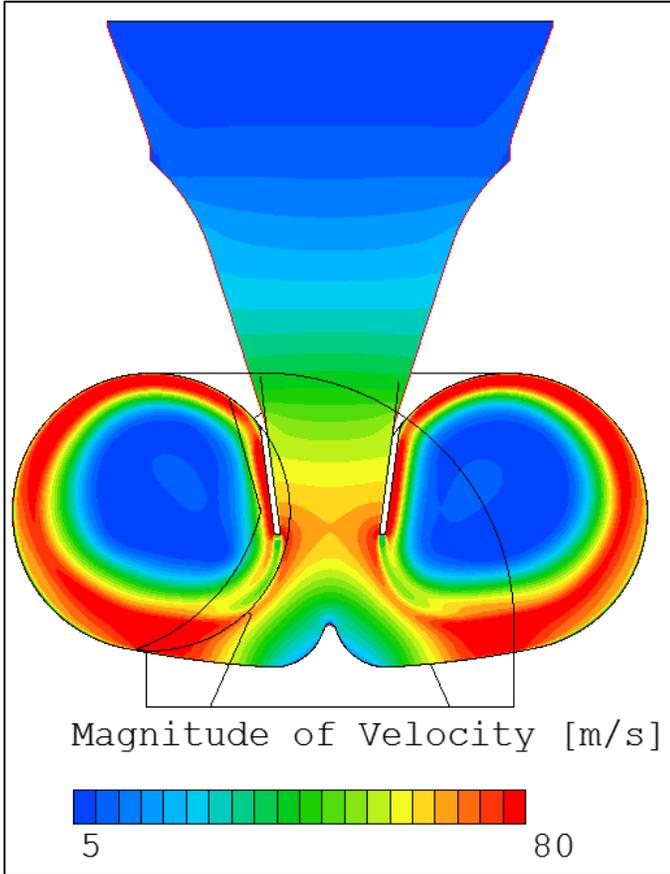


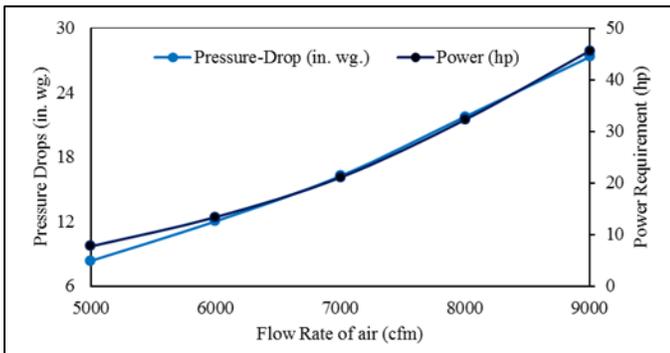
Figure 2. Polyhedral mesh on the surface of the Vortecone.

The software offers a wide range of turbulence models, which in integral form, could represent the dominant flow characteristics in a system. Since the flow in the Vortecone is expected to involve strong recirculation and separation, realizable  $k-\epsilon$  turbulence model was used. Application of this turbulence model to the Vortecone system is also encouraged by the steep pressure gradients along the surfaces accelerating the fluids.

vortex chamber have been chosen because these were near the areas where capture is most likely to occur as shown in Figure 6.



**Figure 4.** Contours of magnitude of velocity on a vertical plane, higher velocities are observed in the vortex chamber



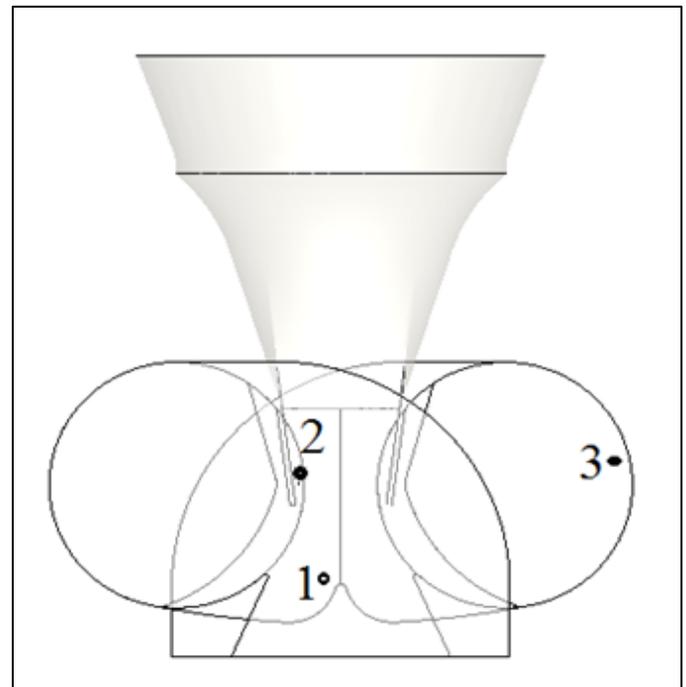
**Figure 5.** Trends of pressure drop and power requirement.

An apparent order was reported for all sets of calculations. Absolute errors, as well as relative errors in values, were calculated for all those parameters. A good mesh-independence could be readily inferred from these numbers. The mesh with about 2.12 million elements was used for generation of transient state models, including ones including free surfaces and particle tracking. All calculations have been performed at a velocity of 6 m/s, incident normally at the inlet. Table 1 and Table 2 show the calculations leading to grid independence.

**TRANSIENT STATE SIMULATIONS**

Transient state simulations were set-up to model the capture of dust particles on the rapidly circulating films of water. The volume of fraction (VOF) approach was used to simulate the interface between

air and water (Hirt and Nicholas 1981). Water was assigned a VOF value of 1, whereas dry air was imparted a VOF of 0. Air was introduced at the main inlet of the Vortecone, whereas water was released at the periphery. A time-step of the order of 0.25 milliseconds ensured that the average Courant number for flows do not exceed 1. Fluids moving into the Vortecone are forced to accelerate and move past each other resulting in a highly instable film of water on the internal surfaces of the Vortecone. Instabilities are enhanced particularly by the inherent design of the Vortecone, where air and water, having different physical and mechanical properties are forced to cross paths inside the system. The absence of steady values of parameters like maximum velocities at those chosen points in the Vortecone or mass flow rates at the outlets despite a constant air and water inflow at the inlet could be attributed to the presence of strong Rayleigh-Taylor and Kelvin-Helmholtz instabilities. Figure 7 shows the plot of the Courant number for first 2.50 s of flow for an airflow of 8,000 cfm and a water inflow of 45 gpm and shows a flat profile with time. Figure 8 shows the volumetric flow rate at the outlets. The unpredictability in these flow rates and allied parameters is expected to remain throughout and hence the shape of the films does not acquire a steady spatial shape, as shown in Figure 9. Table 3 shows the analysis conditions for transient state simulations.



**Figure 6.** Location of points chosen for grid-independence studies.

**Table 1.** Numerical values of parameters for grid independence studies.

Parameter	Unit	Mesh 1	Mesh 2	Mesh 3
Number of Elements, N	Count	943,076	2,116,058	5,067,392
Representative Cell, h	m	0.00244	0.00187	0.00139
Velocity, $\Phi_1$	m/s	24.56	23.21	23.00
Velocity, $\Phi_2$	m/s	64.40	63.93	64.00
Velocity, $\Phi_3$	m/s	82.20	82.94	80.90

**Table 2.** Important measures of grid independence.

Parameter	Symbol	$\Phi_1$	$\Phi_2$	$\Phi_3$
Approximate Relative Error (%)	$e_a^{21}$	0.91	0.11	2.52
	$e_a^{32}$	5.82	0.74	0.89
Extrapolated Values (m/s)	$\Phi_{ext}^{21}$	22.97	64.00	79.49
	$\Phi_{ext}^{32}$	22.97	63.85	83.51
Grid Convergence Index (%)	$GCI_{fine}^{21}$	0.17	0.02	2.17
	$GCI_{fine}^{32}$	1.30	0.13	0.86

PARTICLE TRACKING

Films were allowed to develop inside the Vortecone for a period of 1.50 s to ensure that the inflow and outflow of fluids attain an equilibrium. At this point, dust particles were introduced in the Vortecone system. The Lagrangian method of particle tracking was used to mimic the trajectory of the dust particles. Keystone Mineral Black, 325A has been prescribed for testing and has been incorporated in the CFD models since its characteristics are known, although any other dust sample could be used as well. A typical sample has a specific gravity of 1.22. A preliminary examination of the coal dust sample was carried out using a TSI optical particle sizer, OPC 3330. The particles were classified into a suitable number of class-intervals based on the diameter and a representative mean particle size was obtained for each of these class intervals. 10 particles of those diameters were released into the Vortecone at the inlet every 0.25 ms to represent a continuous inflow of dust into the system. The positions of these particles were tracked as they move under the effect of momentum, drag forces, and gravity. The particles were programmed to get destroyed at the outlet of the Vortecone system. Further, if the particles happened to fall into the zone enclosed by a pre-assigned iso-surface of the VOF, they were forced to be trapped by the fluid. This mimicked the capture by the film of water. The particles were counted at the outlet of the Vortecone, and therefore the number of particles caught inside the Vortecone was obtained. Figure 10 shows the spatial distribution of particles 1.0 s after they were released into the Vortecone when water was not present in the system. This was done for the ease of visualization and to keep the calculations simpler. The heavier particles tend to approach the solid periphery to get arrested by the film, whereas the smaller particles are more scattered and therefore exhibit a lower likelihood of getting captured. Figure 11 shows the particles colored by their diameters. The larger particles colored in red tend to move towards the periphery and are more prone to capture by the film of water.

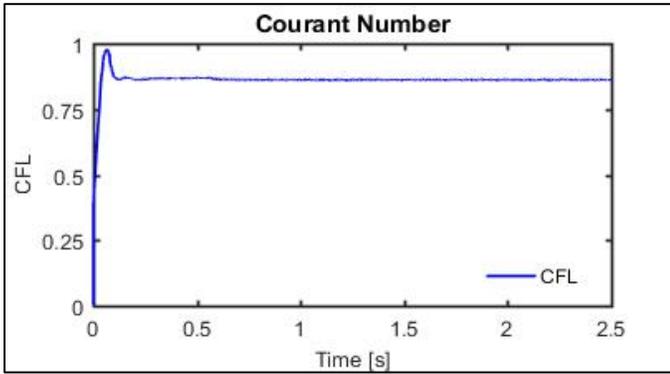


Figure 7. Courant number plotted with respect to time as the fluids move in.

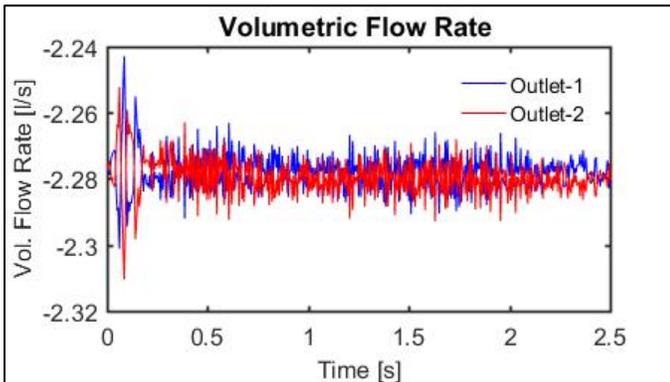


Figure 8. Volumetric flow rates through the outlets, the plot indicates strong instabilities in flow.

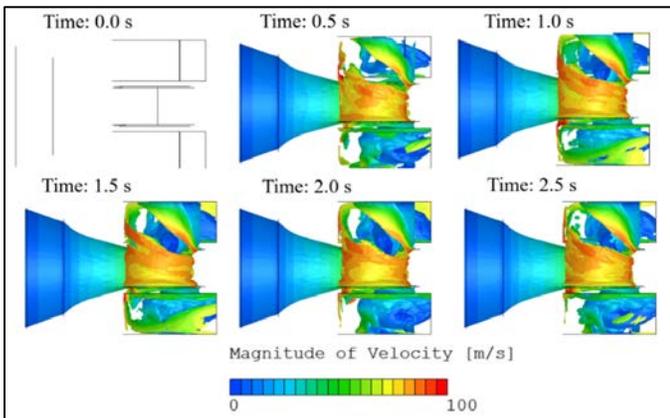


Figure 9. Iso-surface represented by a VOF of 0.05, the film has been colored by the magnitude of velocity.

Table 3. Analysis conditions for transient state simulations.

Parameter	Values
Flow type	Turbulent, Realizable $\kappa$ - $\epsilon$ turbulence model
Analysis type	Flow, Free-surface, Particle tracking
Basic settings	Transient state with time step of 0.25 ms for 2.50 s, Courant number under 1
Gravity	9.81 m/s <sup>2</sup> in -Z direction
Boundary conditions	Flux, Wall conditions, and static pressures
Free surface	Strict volume conservation implemented
Particle tracking	10 particles with specific gravity 1.22, released every cycle for a total of 2,000 cycles; Diameters ranged from 1.5 $\mu$ to 14.6 $\mu$ ; Particles destroyed at the outlet, trapped by a film of water
Log	Particle count and flows at surfaces

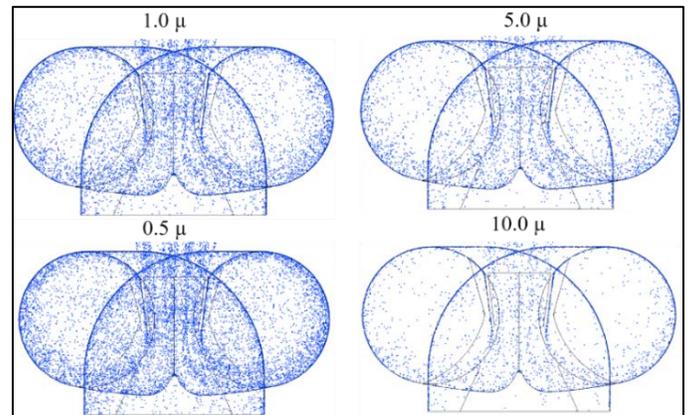


Figure 10. Position of particles of different diameters.

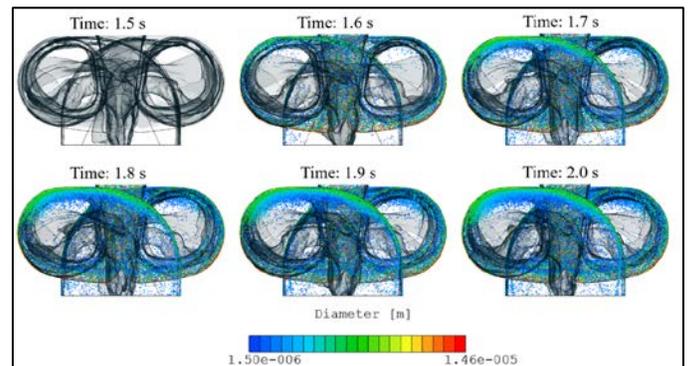
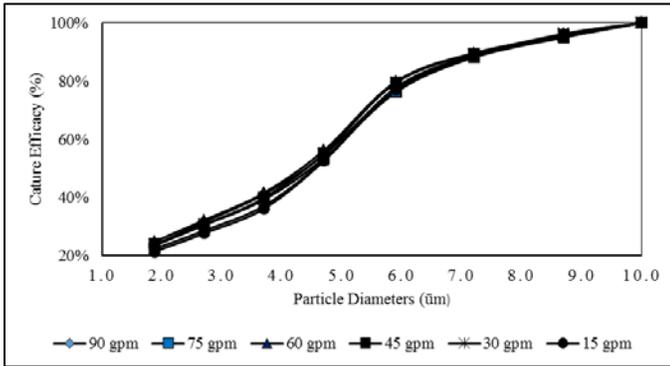


Figure 11. Position of particles as they travel inside the Vortecone, films of water have been shown as well.

The log file was analyzed for particles reporting to the outlet. Simulations were performed with a water inflow of 90 gpm and reduced

in steps of 15 gpm up to 15 gpm. The count of the particles indicated at the Vortecone was able to trap more than 50% of the particles of diameter exceeding 5.0 microns by count. The percent captured rose sharply with the diameter and about 90 % of the particles exceeding 7.2 microns were trapped. The Vortecone predominantly removed all the coal dust particles exceeding 10.0 microns in diameter. A substantial difference in cleaning efficiency was not observed, indicating that a much lower quantity of water might be as effective. Figure 12 shows the cleaning efficacies of the scrubber at a constant airflow of 8,000 cfm and different water influxes.



**Figure 12.** Trend of captures of particles indicated by the CFD models.

### CONCLUSIONS AND DISCUSSIONS

Clogging of impingement screen of the flooded-bed dust-scrubbers on the continuous miners results in a lowered operational efficiency and hence a reduced productivity of the machine. This research's goal resolves a maintenance task by utilizing a Vortecone scaled to a suitable size for installation on continuous miners. Preliminary CFD models were set-up to investigate the system curve for the scrubber, allowing for the system to be designed to the current scrubber specifications. CFD models also indicate high cleaning efficacies of the scrubber for the particles exceeding 5.0 microns in diameter. Since the Vortecone does not use a filter element like an impingement screen, the likelihood of this scrubber getting clogged is minimal. So, a steady performance curve over extended periods of operations could be expected for this system. Approximately, 15 gpm of water could be deemed sufficient to keep the internal surface wet and enable entrapment of dust particles. The water could be recycled and capture particles for a prolonged period of time before having to be replaced. Experiments could be planned for validation of these computer models.

### TASKS UNDERWAY

An underground dust gallery has been developed in a partner mine close to the University of Kentucky. The test gallery can recreate multiple extraction scenarios including 40 ft. deep cuts. This enables the authors to experiment with various cutting sequences underground on a full-scale scenario. An associated full functional full-scale mock of a continuous miner is also under construction at the university. It would have provisions to incorporate and test the conventional flooded-bed dust scrubber system as well as a Vortecone in addition to other dust alleviation provisions. The Vortecone will be modified to be installed on the machine to account for space constraints on the miner. Test procedures are also being devised for testing the efficacies of these systems. This work will be discussed in future papers.

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