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Scale and numerical modeling to determine operating points of a non-clogging Vortecone filter in mining operation

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Category

Research Article

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Keywords

Vortecone, Froude number scaling, Filter resistance, Aerosol capture, CFD

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Scale and numerical modeling to determine operating points of a non-clogging Vortecone filter in mining operation

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Abstract

Numerical and scale modeling studies of Vortecone, a pressure-driven wet-scrubber device for the efficient capture of over-sprayed paint in the automobile industry, are presented. In this manuscript, Vortecone was tested for removing dust particles from underground mining operations. The pressures required to operate Vortecone and the airflow rates through the Vortecone are the two most important factors for mine ventilation systems. This study used dry, no-particle conditions to obtain relationship between these two parameters and then designed a Vortecone filter ventilation system for mining operations. Commercial software, SC/Flow, was used to generate the CFD model with unstructured meshes and a series of numerical calculations were accomplished. Included in these were calculation of a 1/3rd scale model of Vortecone along with experimentation that was accomplished to validate the numerical predictions. The experiments were conducted to measure pressure drops for known airflow velocities at critical points within Vortecone. The scale model experimental results agreed very well with the CFD numerical calculations. For scaling the performance of the 1/3rd scale model to full scale, the scaling laws were developed using the law approach; they are discussed along with the feasibility of the Vortecone filter system for underground mining operations.

Keywords: Vortecone; Froude number scaling; Filter resistance; Aerosol capture; CFD

Nomenclature

R, S	radius/perimeter of a large Vortecone
L	length of a large Vortecone
D	hydraulic diameter of a large Vortecone
A	cross-section area of a large Vortecone inlet
X	resistance of a large Vortecone
$H, \Delta P$	head loss/pressure drops for a large Vortecone
Q	volumetric flow rate through a large model
V	air velocity at a large Vortecone inlet
W	power required for a large Vortecone
ρ	air density
r, s	radius, perimeter of a small Vortecone
l	length of a small Vortecone
d	hydraulic diameter of a small Vortecone
a	cross-section are of a small Vortecone inlet
x	resistance of the a small Vortecone
$h, \Delta p$	head loss and pressure drops through a small Vortecone
q	volumetric flow rate through a small model
v	air velocity in a small Vortecone inlet
w	power required for a small Vortecone
f	coefficient of surface friction

Introduction

The mining industry predominantly uses finely woven fibrous filters to capture dust particles in underground environments. If not decreased to safe limits, respirable dust particles are detrimental to the health of mineworkers causing coal workers' pneumoconiosis and progressive massive fibrosis.

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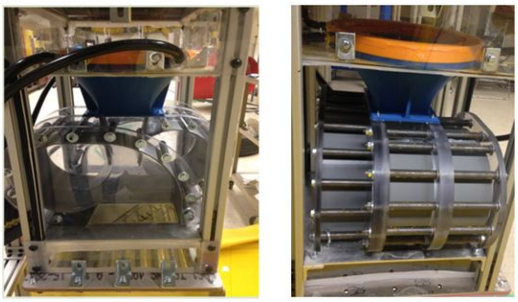

Fig. 1. A reduced scale model of the Vortecone.

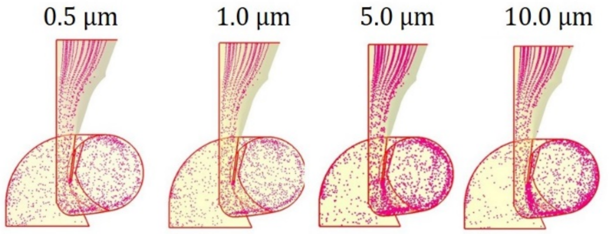

Fig. 2. The trajectory of aerosol particles of different sizes inside the Vortecone.

Prolonged exposure is likely fatal to workers [1–3]. Also, coal dust accumulated above critical concentrations is explosive, and could detonate [4]; for example, an explosion in the Upper Big Branch mine in the United States was tied to excess coal dust within the mine that led to 29 fatalities [5].

Currently, mining operations use a variety of remedial measures to combat dust. These include mechanical ventilation to dilute aerosols to safe levels with water-sprays and fan-powered dust-scrubbers to remove particulate from miners' environments [6].

The Mine Health and Safety Administration (MSHA) in the US promulgates regulations to improve the work-place environment of mining operations [7,8]. One device approved by MSHA is called a flooded-bed dust scrubber; it captures dust particles on finely-woven fibrous filters [9,10]. Comprised of 10–30 fiber layers with a capacity to operate at airflow rates near 2.83 m^3/s or higher as required by a mine's ventilation plan, some of these devices contain more fiber layers and are more efficient in capturing aerosol particles but also have a much higher resistance to airflow.

The MSHA mandates continuous operations of these dust filters which leads to filter clogging if the filters are not maintained properly. A clogged filter has a higher resistance to air flow than a newly installed filter [11–13] which decreases the extent to which dust is removed and increases miners' exposures to unhealthy airborne concentrations of coal dust. Hence, vigilant attention has to be paid to proper filter maintenance but, during this maintenance, the airflow through the filter has to be stopped and operations within mines have to be halted. The downtime during maintenance is not desirable for maintaining high productivity within a mine, leading to a distain for flooded bed dust scrubbers. Vortecone, a wet scrubber device that does not use filters, could be a suitable and efficient alternative to these filters.

Vortecone is a patented non-clogging wet filter technology jointly developed by the University of Kentucky and Toyota [14–17]. It has been installed in more than fifteen automobile assembly lines worldwide as of 2010, and effectively and energy efficiently captures over-sprayed paint particles that do not adhere to automobile surfaces during painting. Particle separation and capture is accomplished by smoothly accelerating airflows towards a progressively lower cross-section area. As the airflow continues to move at higher speeds, it is rapidly transitioned into a vortex chamber where the flow quickly becomes one of rapid circulation. Such circulatory motion of particle-laden fluids is used in mineral separation and other processing industries to differentially separate particles by cyclonic action. Fig. 1 shows the reduced scale prototype of the Vortecone device used in this study.

Shedding of particles which are heavier entities in the flow region is carried out by rapid swirling streamlines. Particles in the airstreams of the cyclone within Vortecone, because of their mass, are unable to follow the airflow streamlines and concentrate toward the outer edges of the cyclonic flow. Particles and air flows can be followed by computational fluid dynamics (CFD), enabling accurate visualizations of particle positions and trajectories in the flow volumes. In this study, a transient-state fluid dynamic model was used to calculate particles in air flows at a volume rate of 0.38 m^3/s, as depicted in Fig. 2. In it, inertia is a dominant factor determining particle motion with larger and heavier particles more prone to impact by the action of flows within Vortecone.

Besides air, water is also injected into the flow within a Vortecone and provides a continuous dust removing medium. Since water also follows the walls of the Vortecone under cyclonic action, the particles have a high probability of being retained within a water underflow region in the flow scheme.

Past experience with Vortecone in automobile painting has shown paint particulate removals of 99.9% and overall energy usage near 30–55% less than other scrubbers. The use of Vortecone for cleansing large amounts air being sent underground to ventilate sub-surface mines and facilities where workers are prone to particulate inhalation if the air has excess dust levels may be a suitable and effective application. Scale modeling could be useful in sizing Vortecone for higher particulate captures at lower energy consumption.

Scale modeling is a powerful numerical tool to replicate processes, natural phenomena or events that are usually in large length scales [18]. In fact, laboratory-scale prototypes are often used for experiments or numerical models instead of expensive full-scale setups, and scale modeling examines trends in the behavior of important parameters under study. Therefore, an accurate hypothesis leading to the identification of underlying phenomena in large scale forms the crux of the scale modeling procedure.

Emori [19] developed a unique method for deriving scaling laws known as the law approach that and was further developed by Saito. This method of reduced scale modeling has helped engineers understand science and operations more precisely and has been valuable for avoiding mistakes in the design phase of experimentation and application [20]. This manuscript summarizes the scaling of important parameters of a reduced scale model to a larger scaled-up model, and CFD simulations.

Scaling analysis

Scaling power requirements

Vortecone is designed to accelerate the air to high speeds through narrow passages; typically, such operation is energy-intensive. Vortices are generated and sustained in a vortex chamber causing the dissipation of a significant amount of input energy. This energy usage accompanied by a relatively high-pressure drop could be attributed to the inertial forces of the fluids. Pressure forces also arise due to the fluids moving in constricted spaces; in addition, gravity acts on the water flow and solid particles in the system.

Darcy's law defines the total pressure drop for fluid flow through a pipe, while the Darcy–Weisbach equation defines loss in the pressure for flow through a round pipe as:

$$H = f\frac{L}{D}\frac{V^2}{2g} \tag{1}$$

The substitution of the diameter term, D, by the hydraulic diameter will enable an equation usable for a wide range of cross-sections; this substitution also yields the Atkinson equation:

$$P = \rho f\frac{L}{D}\frac{V^2}{2} \tag{2}$$

$$P = \rho f L\frac{S}{4A}\frac{V^2}{2} \tag{3a}$$

$$P = \rho f L\frac{S}{4A^3}\frac{Q^2}{2}\text{, where } Q = AV \tag{3b}$$

Eq. (3b) could also be expressed as $P = XQ^2$ where

$$X = \rho f L\frac{S}{8A^3}, \tag{3c}$$

and X = resistance of the Vortecone to airflow.

Hence, the resistance of the Vortecone to flow depends on its geometrical dimensions. Since the area or cross-section is $A \propto L^2$, and perimeter is $S \propto L$, thereby:

$$X \propto \frac{1}{L^4}\text{; Ratio of resistances, } \frac{X}{x} \propto \frac{l^4}{L^4} \tag{3d}$$

Scaling pressure drop

Most filters are required to be operational throughout the duration of people working within a dusty environment like a mine. Pressure drops through a filter are critical pressure is directly related to power requirements.

Pressure drop, $P = XQ^2$,

where $X = \rho f L\frac{S}{8A^3}$ represents the resistance of the Vortecone to airflow.

$$\frac{P}{p} = \frac{X}{x}\frac{Q^2}{q^2} \tag{4a}$$

$$\frac{P}{p} = \frac{X}{x}\frac{A^2V^2}{a^2v^2} \tag{4b}$$

$$\frac{P}{p} = \frac{l^4}{L^4}\frac{A^2V^2}{a^2v^2} \tag{4c}$$

$$\frac{P}{p} = \frac{V^2}{v^2} \tag{4d}$$

Scaling power requirements

The power required is critical for sizing a suitable fan to generate the airflow needed during Vortecone operation. The power required, W, is given by:

$$W = \frac{1}{\eta}PQ = \frac{1}{\eta}XQ^2Q = \frac{1}{\eta}XQ^3 \tag{5a}$$

A fan for continuous operation of Vortecone was assumed to have a ratio of unity for its efficiency in both small and large scale system. Then:

$$\frac{W}{w} = \frac{X}{x}\frac{Q^3}{q^3} \tag{5b}$$

$$\frac{W}{w} = \frac{l^4}{L^4}\frac{A^3V^3}{a^3v^3} \tag{5c}$$

$$\frac{W}{w} = \frac{l^4}{L^4}\frac{(L^2)^3\,V^3}{(l^2)^3v^3} \tag{5d}$$

$$\frac{W}{w} = \frac{L^2}{l^2}\frac{V^3}{v^3};\ W \propto L^2V^3; \quad W \propto L^{7/2} \tag{5e}$$

where Froude's number scaling is applied.

These relationships show dynamic scaling and are dependent on the characteristic lengths and velocities at the inlet, and other dimensions and velocities throughout a Vortecone scrubber. Because Vortecone would process maximal volumetric airflow rates driven by a fan, velocities would not scale with characteristic length. Rather, dynamic scaling relationships would be required [18, 19].

Scaling Laws

The law approach was used to develop the scaling laws. The inertial forces of the air and particulate, the gravity forces acting on the particulate, the viscous forces of air acting on particulate, and the external pressure forces of the Vortecone system were considered to be the most significant. These four forces are described in the following parameters and Eqs. (6a) – (6d):

i. The inertial force, F_i

$$Fi = \rho l^2 v^2 \tag{6a}$$

ii. The gravitational force, F_g

$$Fg = \rho l^3 g \tag{6b}$$

iii. The viscous force, F_μ

$$F\mu = \rho \frac{lv}{\mu} \tag{6c}$$

iv. The pressure force, F_p

$$Fp = \Delta P l^2 \tag{6d}$$

where μ is the coefficient of viscosity of air, ρ is the air density, l is the characteristic length of the Vortecone, v is the characteristic air velocity at a representative point inside the Vortecone, and ΔP is the pressure drop across the Vortecone at a given airflow rate. These four forces yield the following three independent pi-numbers.

$$\pi 1 = \frac{Fi}{F\mu} = \frac{\rho l v}{\mu} \tag{6e}$$

$$\pi 2 = \frac{Fi}{Fg} = \frac{v^2}{lg} \tag{6f}$$

$$\pi 3 = \frac{Fp}{Fi} = \frac{\Delta P}{\rho v^2} \tag{6g}$$

where $\pi 1$ is the Reynolds number, the square root of $\pi 2$ is the Froude number, and $\pi 3$ is the Euler number.

It is well known that Reynolds and the Froude numbers cannot be satisfied without changing physical properties of ρ and μ. As a consequence, a relaxation method [19] was applied to maintain the Fr number and eliminate the Re number by assuming the viscous force of air would be small compared to the inertial force of air due to a relatively high-speed airflow rate. However, caution must be taken with this assumption because it may not apply in local regions within the Vortecone where the airflow may circulate at a very low speed. Therefore, Eqs. (6f) and (6g), respectively, yield the following equations:

$$v \propto \sqrt{l} \tag{6h}$$

$$\Delta P \propto v^2 \tag{6i}$$

Combining Eqs (6h) and (6i) and applying (5e), the following is obtained.

$$W = \Delta P l^2 v \propto l^{7/2} \tag{6j}$$

Eqs (6h), (6i) and (6j) can be used for the design criteria of the scale model and then help scale-up from the reduced scale to a full-scale model.

Computational fluid dynamics modeling

The software used during the CFD calculations was SC/Flow. The geometry of the reduced scale Vortecone measured 0.45 m in height, and was chosen to satisfy scaling laws (6f) and (6g) because if the size was too small the Reynold's number (6e) could not be avoided.

The presence of symmetry in Vortecone was utilized to choose a virtual plane that would split the Vortecone into two geometrically identical entities. This choice resulted in a reduced computational domain. All surfaces, including those at the inlet, were demarcated and given unique names. Flux, wall functions and static pressures were chosen to provide appropriate analyses conditions. An octree was generated to control the insertion of mesh elements. Five prism layers were inserted to capture boundary layer phenomena and a computational mesh was generated.

Preliminary analysis favored s realizable k-é, Spallart-Allmart and RNG-k-EPS models, and a realizable k-é model was finally chosen for further analyses for recirculating and separating flows. Air was first assumed as a compressible and later as an incompressible fluid; a maximum difference of 3.7% in pressure was observed when the compressibility of the air was considered. Therefore, it was decided to generate all the models with incompressible air to avoid excess computations and save on computing resources. The system curve obtained is shown later in this article.

A grid independent study was carried out for examining mesh quality and confirming the objectivity of results for a preferred mesh. Six points were chosen along the path at air ingress and enabled examination of velocity magnitudes. Of these, the first two points were located close to the inlet, the third point located at the first curve at the bottom of Vortecone (see Fig. 3), and a fourth point was chosen to be near to the mechanical flaps that guides the fluid into Vortecone. The other two points were located inside the vortex chamber and near the outlet in a region experiencing recirculation.

Meshes were generated with 0.96, 1.44 and 2.14 million elements. The CFD models were generated for a

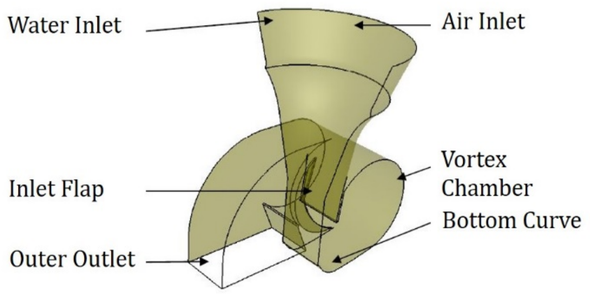

Fig. 3. Points used for mesh independence studies.

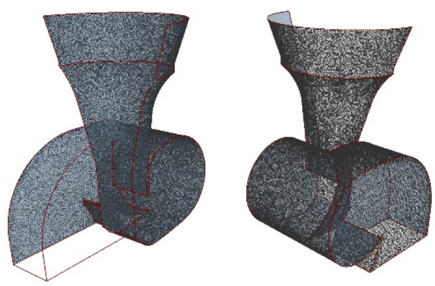

Fig. 4. Polyhedral mesh on the Vortecone surface.

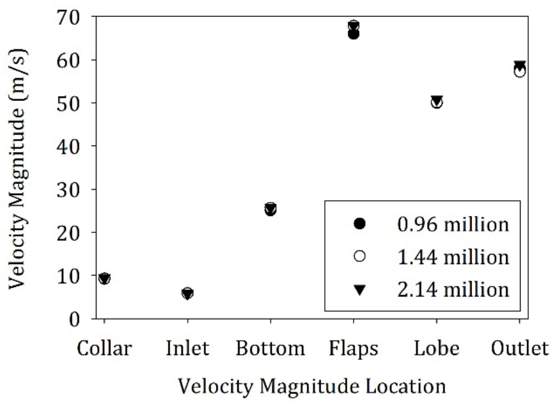

Fig. 5. Plots of velocity magnitudes using three different meshes at the selected points.

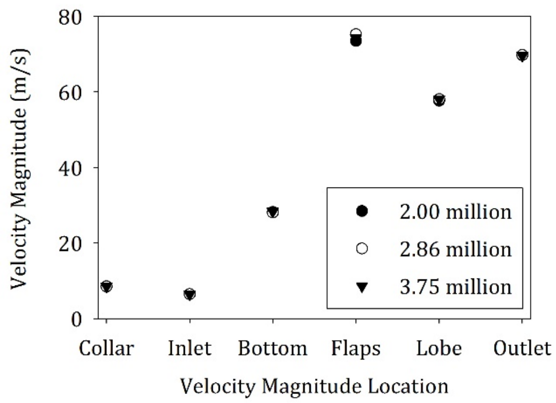

Fig. 6. Velocity magnitudes at the six points full scale Vortecone.

Fig. 7. The experimental set-up to generate the flow-pressure drop curve.

flow of 0.38 m^3/s for the reduced scale model and deviations of the magnitude of velocities from their mean values were calculated. The meshes were considered accurate and replicated the expected physics of the flow if the deviation was low. The standard deviations in velocity magnitudes over the mean velocity magnitude were observed to range between 0.00–1.59 %. Finally, a mesh with about 1.44 million elements was chosen, as shown in Fig. 4, for further simulations because a higher number of mesh elements would outweigh the computational resources without significant improvements in accuracy.

Identical steps were repeated for a full-scale CFD model of Vortecone; meshes with 2.00, 2.86, and 3.75 million elements were examined and the velocity magnitudes were calculated for a flow of 3.77 m^3/s. The deviations in the full scale ranged between 0.1–1.19% and were considered acceptable. The mesh with 2.86 million elements was also chosen for further simulations. Figs. 5 and 6 show plots of the variation of the velocity magnitudes at the six chosen points when different grid resolutions were used for the reduced and full-scale models.

Pressure drops for a range of flows were obtained from the CFD models of the reduced and full-scale Vortecone, and a system curve that shows the pressure drops for specific airflows was obtained for both scales. Figs. 7 and 8 show the curves for the reduced scale and full-scale models, respectively, with incompressible air as the working fluid. A physical prototype of Vortecone was then chosen that was 0.45 m in height. This prototype was used during experimental trials.

Laboratory experiments

Laboratory experiments were designed and performed to validate the findings of the CFD models; agreement between the experimental data and CFD calculations was taken as confirmation and affirmation of the scaling laws. The laboratory prototype was constructed using 3D printing. Figs. 1 and 7 show components of the laboratory prototype.

A wind-tunnel attached to a centrifugal fan was built to handle the air flow with turning vanes affixed to assist the air to have a smooth transition into the inlet of Vortecone because it was set at right angles to the wind tunnel due to space limitations. A sensitive pressure measurement station was installed upstream of Vortecone in the tunnel; Fig. 7 shows the laboratory set up. Total and static pressures were measured for the system with a frequency of 10 Hz and flows were calculated from the pressures. Fig. 8 shows a plot of system curves obtained on two separate trials and compared with the CFD models with compressible air and incompressible air as the working fluid.

As displayed in Fig. 8, results from both CFD simulations and laboratory experiments were in excellent agreement. Hence, the CFD model was considered to be sufficiently accurate in predicting the pressure drops for known airflow rates.

Results

Figs. 9 and 10 show the CFD calculated pressure drops and power requirements for reduced-scale and full-scale Vortecone.

Fig. 11 shows the streamlines of airflow for the reduced as well as full-scale models, both of which display excellent similarity. Fig. 12 shows iso-surface static pressures inside the vortex chamber in which the emergence of zones of low static pressure indicated swirling flow patterns.

Scaling laws could be used to predict flow parameters for any other known scale of a Vortecone using results from experiments and CFD models. A frequency of 43.0 Hz was chosen for the vortex forced draft van and a flow of 0.38 m^3/s for the reduced scale model.

The flow parameters observed with this fan setting could be readily obtained from the graphs shown in the preceding and were used to approximate operational parameters for different-sized models. The pressures and power requirements from the CFD calculations obtained with a flow of 3.77 m^3/s through a full-scale model are compiled in Table 1, and values obtained using scaling laws are also displayed.

Effort towards generating accurate numerical models that examined the motion of water to capture dust particles with free-surface capabilities were also generated. In this, a volume fraction approach to representing the two immiscible fluids was used. Preliminary CFD results indicated good agreement between the models and the experiments performed in the laboratory. For example, Fig. 13 compares the films obtained from the CFD models with the laboratory experiments in which the water film was observed to follow the Vortecone surface in both models and the experiments.

Conclusions

The scaling laws for flows and pressure inside of the Vortecone technology using basic flow equations were

Table 1. Comparison of analytical and CFD modeling results.

Parameter	CFD	Scaling Laws	Error (%)
Pressure drop	20.33	20.98	+3.20
Power required	25.00	25.81	+3.24

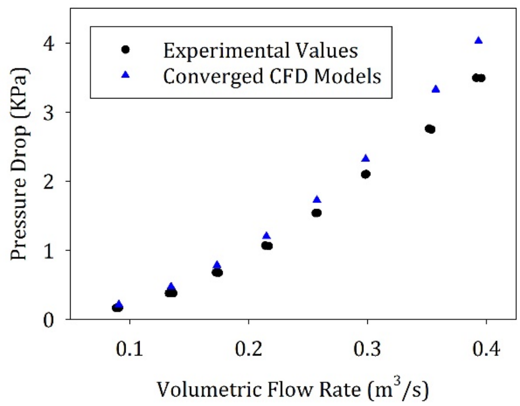

Fig. 8. Pressure drop comparison between CFD models and experimental results.

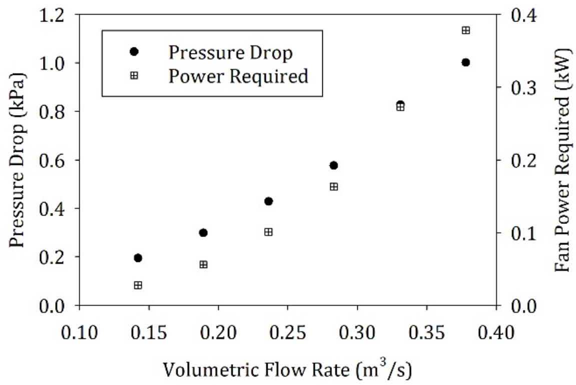

Fig. 9. Projected pressure drop and fan power requirement for the smaller Vortecone.

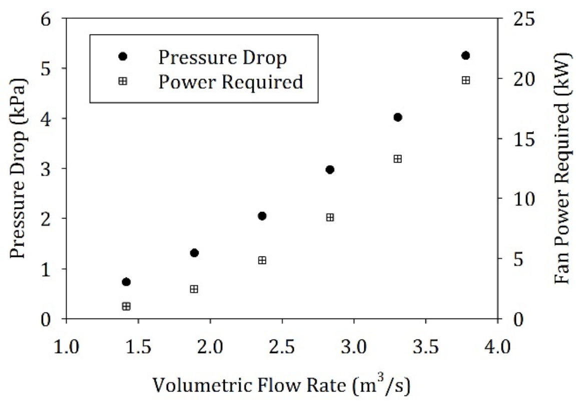

Fig. 10. Projected pressure drop and fan power requirement for a large Vortecone.

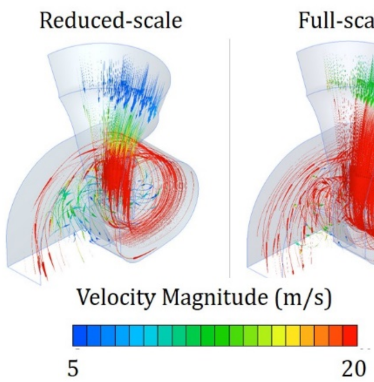

Fig. 11. Streamlines of airflow in the reduced and full-scale model.

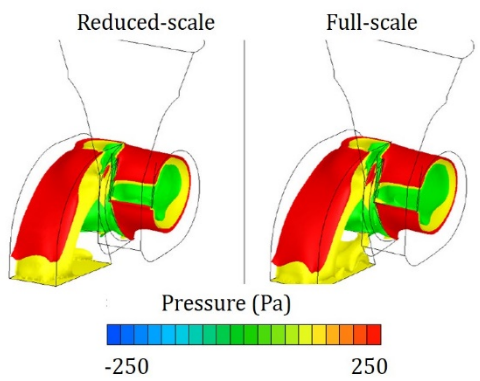

Fig. 12. Iso-surfaces of pressure in the reduced and full-scale model.

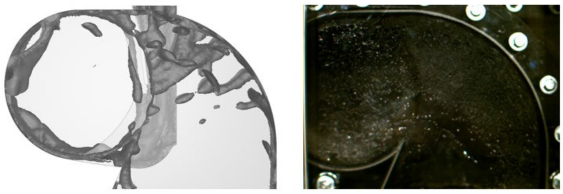

Fig. 13. Comparison of multi-phase CFD model and an image from a high-speed camera during experiments.

established. The results obtained from detailed CFD modeling and laboratory experiments were used to validate these scaling relations. Pressure drops across the Vortecone was found to scale to the second power of air velocity at the inlet. Furthermore, power requirements were determined to scale to the product of third power of velocity at the inlet and square of characteristic length. These scaling laws could be used to predict and optimize operations of Vortecone technology at different sizes, even for turbulent flows. This capability would enable design engineers and researchers to devise new applications using even larger Vortecones as opposed to a bank of smaller Vortecones for particulate removal from air streams.

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References

[1] Arnold, C., "A scourge returns: black lung in Appalachia," Environ. Health Perspect. 124: A13–A18, 2016.

[2] Blackley, D. J., Halldin, C. N., Laney, A. S., "Continued increase in prevalence of coal workers' pneumoconiosis in the United States, 1970-2017.," Am. J. Public Health. 108: 1220–1222, 2018.

[3] Joy, G. J., Colinet, J. F., Landen, D. D., "Coal workers' pneumoconiosis prevalence disparity between Australia and the United States," Min. Eng. 64(7): 65–71, 2012.

[4] U.S. Department of Labor, Report of Investigation, Fatal Underground Coal Mine Explosions, September 23, 2001, No. 5 Mine, Jim Walter Resources, Brookwood, Tuscaloosa County, Alabama, ID No. 01-01322, 2001.

[5] U.S. Department of Labor, Report of Investigation, Fatal Underground Mine Explosion, April 5, 2010, Upper Big Branch Mine-South, Performance Coal Company, Montcoal, Raleigh County, West Virginia, ID No. 46-08436, 2011.

[6] Beck, T. W., Seaman, C. E., Shahan, M. R., Mischler, S. E., "Open-air sprays for capturing and controlling airborne float coal dust on longwall faces," Min. Eng. 70: 42–48, 2018.

[7] Campbell, J. A. L., Moynihan, D. J., Roper, W.D., Willis, C., "Dust control system and method of operation," US 4380353 A, 1983.

[8] Colinet, J. F., Reed, W., Potts, J.D., Report of Investigations 9693; Impact on Respirable Dust Levels When Operating a Flooded-bed Scrubber in 20-ft Cuts, Pittsburgh, PA, 2013.

[9] Mine Safety and Health Administration (MSHA), Federal Mine Safety and Health Act of 1969 (Mine Act, Public Law 91-173), 1969.

[10] Mine Safety and Health Administration (MSHA), Federal Mine Safety and Health Act of 1977 (Mine Act, Public Law 95-164), 1977.

[11] Callé, S., Bémer, D., Thomas, D., Contal, P., Leclerc, D., "Changes in the performances of filter media during clogging and cleaning cycles," Ann. Occup. Hyg. 45: 115–121, 2001.

[12] Kanaoka, C., Hiragi, S., "Pressure drop of air filter with dust load," J. Aerosol Sci. 21: 127–137, 1990.

[13] Agranovski, I. E., Shapiro, M., "Clogging of wet filters by dust particles," J. Aerosol Sci. 32: 1009–

1020, 2001.
[14] Salazar, A. J., Saito, K., Alloo, R. P., Tanaka, N., "Wet scrubber and paint spray booth including the wet scrubber," US Patent 6,024,796, 2000.
[15] Salazar, A. J., Saito, K., Alloo, R. P., Tanaka, N., "Wet scrubber and paint spray booth including the wet scrubber," US Patent 6,093,250, 2000.
[16] Tanigawa, Y., Alloo, R., Tanaka, N., Yamazaki, M., Ohmori, T., Yano, H., Salazar, A. J., Saito, K., "Development of a new paint over-spray eliminator," in: Saito, K. (Ed.), Progress in Scale Modeling: Summary of the First International Symposium on Scale Modeling (ISSM I in 1988) and Selected Papers from Subsequent Symposia (ISSM II in 1997 through ISSM V in 2006), Springer Netherlands, Dordrecht, 2008, pp. 325–341.
[17] Toda, K., Salazar, A., Saito, K., Automotive Painting Technology: A Monozukuri-Hitozukuri Perspective, 2014.
[18] Saito, K., Ito, A., Nakamura, Y., Kuwana, K., Progress in Scale Modeling, Volume II: Selections from the International Symposia on Scale Modeling, ISSM VI (2009) and ISSM VII (2013), Springer International Publishing, 2014.
[19] Emori, R. I., Schuring, D. J., Scale Models in Engineering: Fundamentals and Applications, Pergamon Press, 1977.
[20] Kumar, A. R., Arya, S., Wedding, W.C., Novak, T., "Examination of capture Efficacies of a shearer mounted flood ed bed dust scrubber using experiments and computational fluid dynamics (CFD) modeling on a reduced scaled model," in: Brune, J. F. (Ed.), Proc. 16th North Am. Mine Vent. Symp., Golden, CO, USA, 2017, pp. 20/1–20/8.