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DEVELOPMENT OF A COMPUTATIONAL FLUID DYNAMICS MODEL FOR THE DESIGN OF PNEUMATIC DUST SAMPLING DEVICE

V. Duddempudi, Colorado School of Mines, Golden, CO
B. Goertz, Colorado School of Mines, Golden, CO
F. S. Barreto, Colorado School of Mines, Golden, CO
G. Bogin, Colorado School of Mines, Golden, CO
J. Brune, Colorado School of Mines, Golden, CO

INTRODUCTION

In designing a new pneumatic Dust Sampling Device (DSD) for coal mines, it was essential to analyze the air and particle flow inside the device in detail using Computational Fluid Dynamics (CFD) modeling. Several CFD models were developed to simulate the air and dust flow and sample collecting process of the DSD. These CFD models were developed to assist in the design of the DSD instrument prototypes for laboratory testing. Nozzle and injection parameters such as geometry, air velocity and pressure, were varied across a wide range to obtain the optimal settings to accurately simulate the fluid dynamics of the multi-phase flow within the DSD. Accordingly, these parameters were used as a guide for the design of the DSD and to verify the dust scouring dynamics, which is designed to represent the dust entrainment during an actual methane or coal dust explosion.

BACKGROUND

The 2010 explosion at the Upper Big Branch mine has demonstrated the destructive violence of a coal dust explosion. A major contributing factor for this disaster was that the mine operators did not have a reliable, direct-reading method to collect mine dust and determine inert content and combustibility. This led to the development of a new prototype handheld, pneumatic mine dust sampling device (DSD), which blows a puff of air and entrains the mine dust by mimicking the entrainment process during a mine explosion.

A computational Fluid Dynamics (CFD) model is used to analyze the air and dust flow inside the DSD. The objective of the CFD modeling effort is to find the optimum design of the DSD prototype, nozzle orientation, air pressure and pulse length by analyzing and varying these parameters so that the scouring action collects a valid, representative and repeatable mine dust sample.

CFD MODEL DESIGN

Figure 1 shows a wireframe image of the DSD which is utilized in the setup of the CFD model. The DSD has a triangular cross section and is 10 cm wide. Two nozzles with cross-sectional dimension of 2.8 cm by 0.25 cm act as inlets at the narrow end of the triangular cross section. The CFD model includes a reference plane 6 cm away from the nozzle to measure the quantity of dust collected. The geometry shown in Figure 1 was created for the model and it matches with the design of the actual device shown in the figure 2. Symmetry, along the plane X-Y through the center of the device, is used to reduce the number of computational cells in the CFD model. Figure 2 shows the prototype device used for experimental testing.

CFD MODEL SETUP

Figure 3 shows a hexahedral mesh with a cell size of 0.8 mm and the total number of cells is around 650,000. The ANSYS Fluent® pressure based solver with a transient case was used with a total duration of 40 ms. The 40 ms simulation time is based on experimental measurements to capture the injection of air and initial scouring of dust.

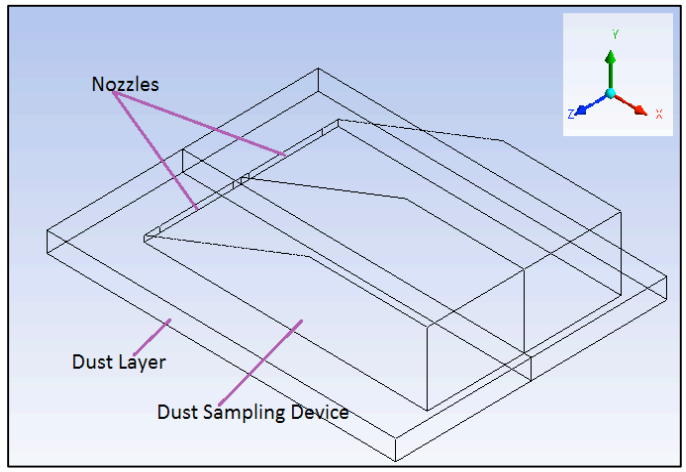

Figure 1. Geometry of the DSD used for the for the CFD model.

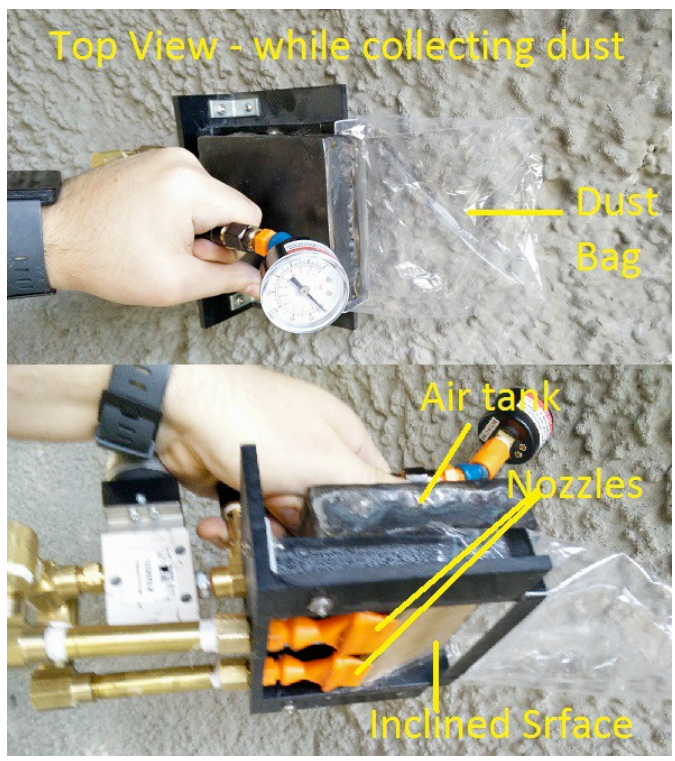

Figure 2. Prototype of the DSD used for experimental testing.

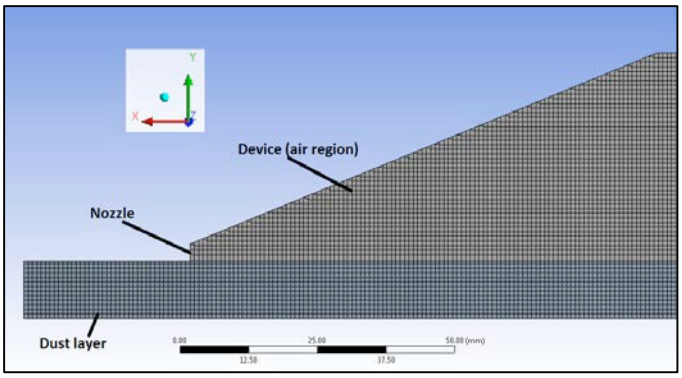

Figure 3. Uniform hexahedral mesh used for the CFD model.

The CFD model accounts for two material phases, air and rock dust, both treated as fluids. The density and viscosity used for air are 1.23 kg/m^3 and 1.79E-05 kg/ms; for rock dust, 2,140 kg/m^3 and 1.003E-03 kg/ms, respectively.

The fluid dynamics model within the DSD assumes a multi-phase flow with air as the primary and rock dust as the secondary phase. An Eulerian treatment was used, modelling both interacting phases separately. To solve the transient flow of air and dust particles, a viscous model with standard κ-epsilon parameters, standard wall treatment and dispersed turbulent multiphase flow have been used (Cokljat et al., 2000; Launder et al., 1972). Rock dust is considered as a fluid with an assumed granular diameter of 7 * 10^{-5} m.

Researchers defined a realistic velocity-time transient pulse for the injected air based on nozzle pressure measurements. This transient is shown in Figure 4 and was programmed into the model using a user defined function (UDF). The linear profile represented by red color in the figure 4 is used as reference for writing the UDF.

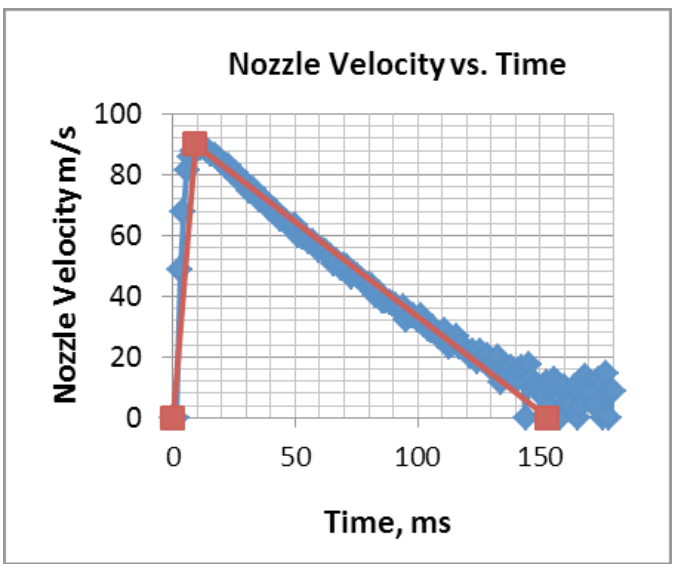

Figure 4: Velocity - time transient based on nozzle pressure measurements

CFD MODELING RESULTS

Figure 5 shows the reference planes used for visualization of the dust scouring results. The dust volume fraction is used as reference to measure the depth of the scour. Figure 6 shows the dust volume fraction at time = 40 ms along this reference plane. A reference line, represented in black, indicates the desired scour depth of 1/8th of an inch (3.2 mm).

The yellow line at 6 cm from the nozzle represents the reference plane for the measurement of the dust collected.

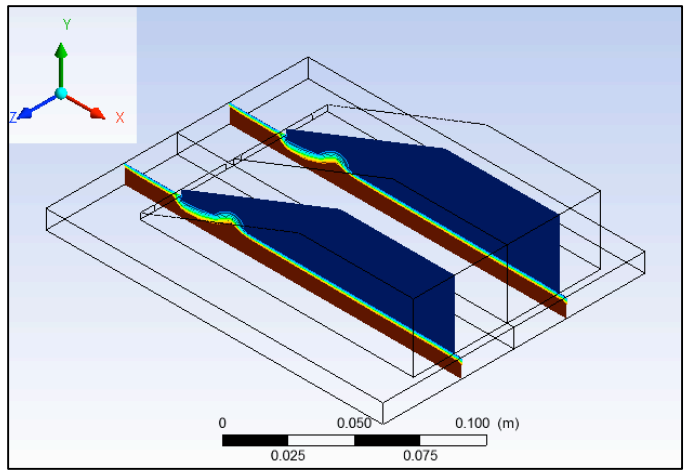

Figure 5. Location of the reference plane used for analysis of modeling results.

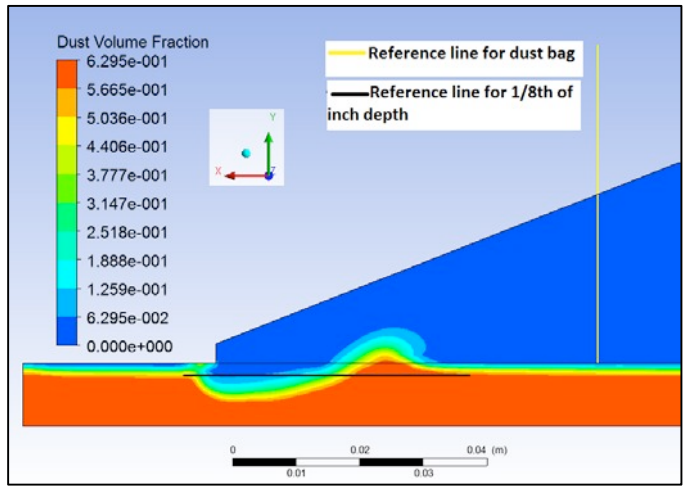

Figure 6. Scour profile along the reference plane at time 40 ms.

To measure the scour profile predicted in the model, reference lines are created along the Y-axis at 0.2cm from the nozzle at every 0.5cm along the Z-direction, as shown in Figure 7. Models show the depth of the scour profile ranging from 3mm to 4mm, which meets with the sampling depth of approximately 1/8 inch (3.2 mm) required by the MSHA (2013) dust sampling guidelines.

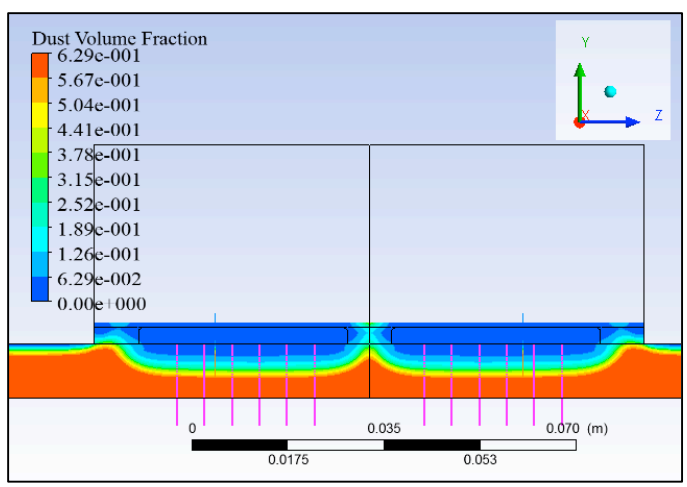

Figure 7. Reference lines along Y-axis to represent the actual depth of the scour profile.

In developing the DSD prototype, researchers aimed to avoid eddies and recirculation of air above the nozzles to minimize dust being suspended in the air and ensuring the maximum amount of dust being directed to the sampling bag. The tapered design shown in Figure 1 proved effective in avoiding recirculation and directed more dust into the collecting bag. The velocity vectors of the expanding air inside the device, as shown in Figure 8, demonstrate that that the inclined surface is effective in controlling the recirculation above the nozzles and the DSD generates a rather smooth, wrinkle-free air stream to scour up the mine dust.

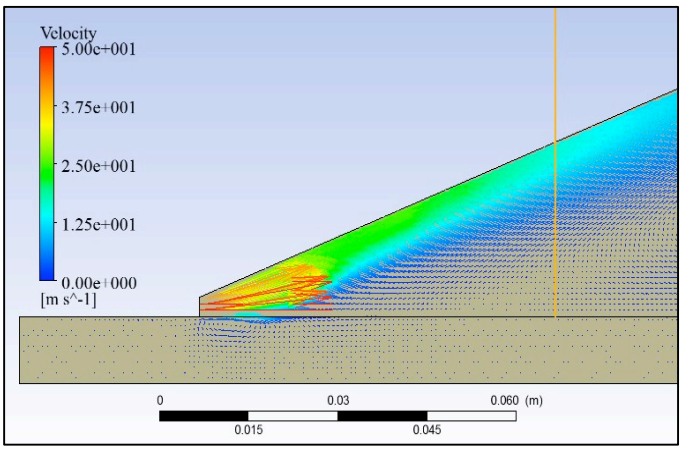

Figure 8. Velocity vectors of air in the XY plane.

The results presented above are calculated with a 0.8 mm hexahedral mesh. The cell size was later reduced to 0.4 mm and again to 0.2 mm to demonstrate that the solution is grid-size independent. The contour plots of dust volume fraction vs. scour depth for mesh cell sizes of 0.4 mm and 0.2 mm are shown in the Figures 9 and 10, respectively. In these figures, the pink line at a distance of 0.2 cm from the nozzle along the x-axis is used as a reference to compare the depth of the scour profiles. Comparison of calculated scour profiles is displayed in Figure 11 and confirms that the grid size does not cause significant differences in modeling results.

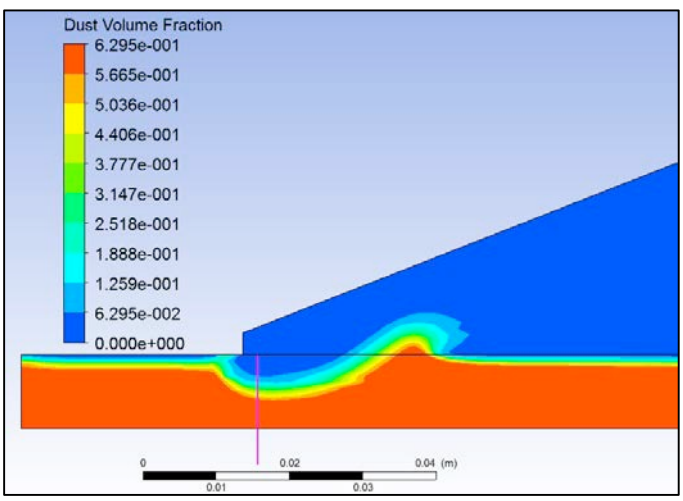

Figure 9. Scour profile along the reference plane at time 40 ms for 0.4mm cell size.

The model was tested at different air pressures to obtain the desired scour depth. The scour profiles at 15 and 20 psi pressure are shown in figures 12 and 13, respectively.

In both cases, the maximum scour depths are observed at a distance of 12mm from the nozzle. The relative change in depth for the two cases is determined at the pink reference line at a distance of 12mm from the nozzle along the x-axis, as shown in Figures 12 and 13.

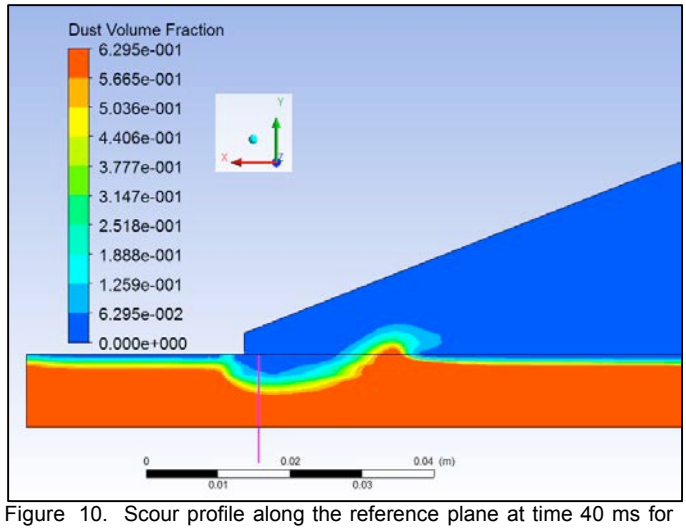

Figure 10. Scour profile along the reference plane at time 40 ms for 0.2mm cell size.

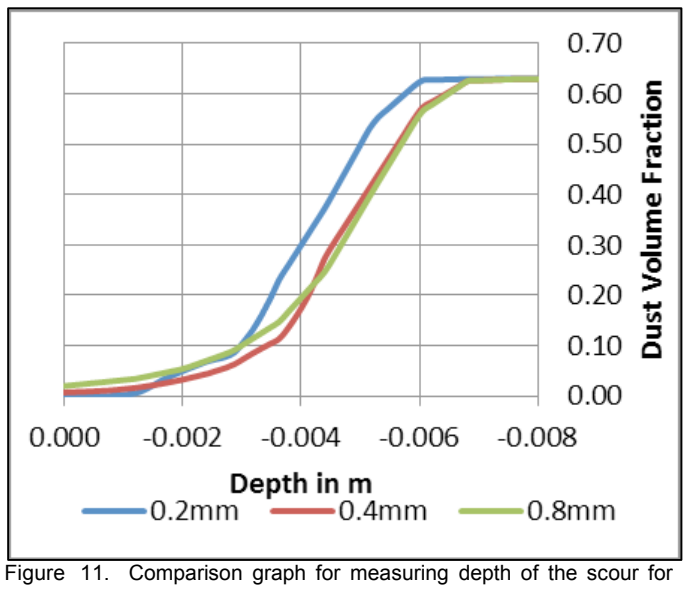

Figure 11. Comparison graph for measuring depth of the scour for different cell sizes.

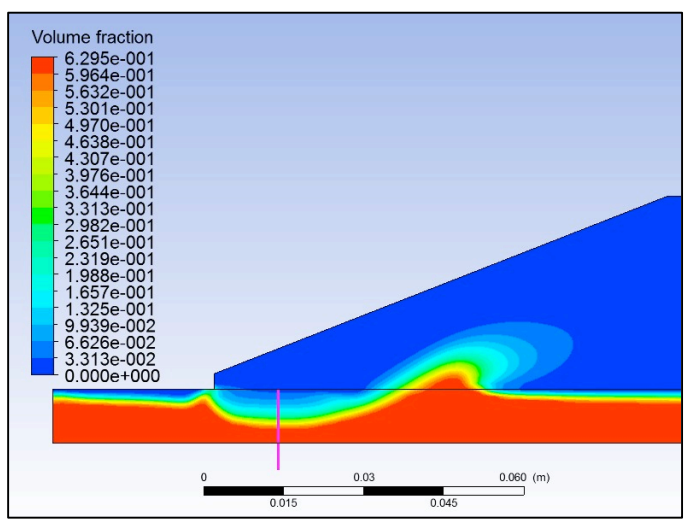

Figure 12. Scour profile along reference line at 80 ms using UDF at pressure 15 psi

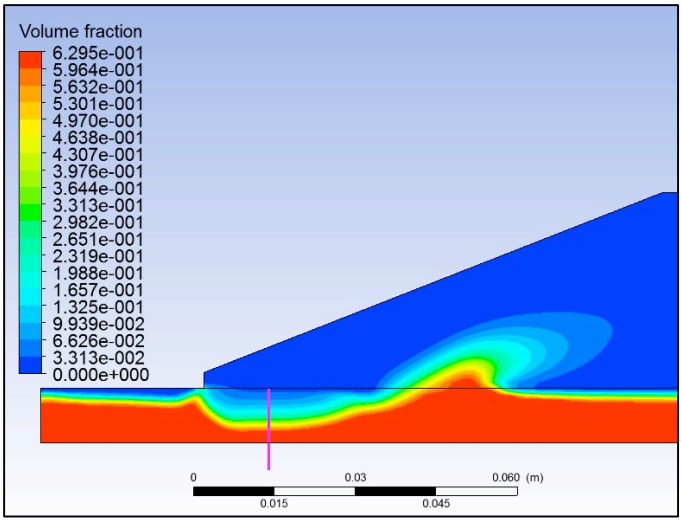

Figure 13. Scour profile along reference line at 80 ms using UDF at pressure 20 psi.

To validate the results, the CFD model is compared with experimental testing. Table 1 illustrates that increasing the line pressure from 15 to 20 psi leads to a slightly deeper scour. Experimental data indicate an increase of 6% in scour depth while models differed by 5%.

Table 1. Comparison of scour depth obtained from CFD model vs. experimental testing.

Pressure (psi)	Depth (mm)		
	CFD model	Testing (n=20)	
		mean	St. dev
15	3.2	3.1	0.40
20	3.3	3.3	0.80
Δ Depth	5%	6%	

The standard deviation and mean values of depth presented in table 1 are based on the results obtained from 20 tests performed at each pressure. Overall, the model shows excellent agreement with DSD prototype testing.

SUMMARY

Researchers at the Colorado School of Mines have developed a prototype mine Dust Sampling Device (DSD) to collect consistent and representative samples of mine dust. The DSD works by blowing a light puff of air onto the mine dust and entraining scoured dust into a sampling bag. These samples are then tested using the Coal Dust Explosibility Meter to determine inert content and to confirm that sufficient amounts of rock dust have been placed in order to prevent coal dust explosions. Numerical modeling using Computational Fluid Dynamics has helped refine the prototype design and has led researchers to determine optimum sampler geometry, air pressure and nozzle configuration.

REFERENCES

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2. B. E. Launder and D. B. Spalding [1972]: Lectures in Mathematical Models of Turbulence. Academic Press, London, England. 1972.

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