Preprint 13-137

PRESSURE AND FLOW INVESTIGATION OF AN AXIAL BOOSTER FAN WITH VARIABLE BLADE SETTINGS – EXPERIMENTAL AND CFD APPROACH

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ABSTRACT

A study has been undertaken on two 1.12 m diameter industrial booster fans operating under different blade settings powered by a 1200 rpm motor at the Missouri University of Science and Technology. The fans total pressure varies up to 1kPa forcingup to 25 m^3/s through the workings. A pressure-quantity survey has been conducted inby and outby the booster fans with different blade settings. The study uses a variable speed drive (VFD) to determine the effect of rotational frequency on the system. The pressure drop across the bulkheads has been monitored during the experiments. The fans were operated with various blade settings to determine the optimal scenario that maintains the maximum airflow quantity and the lowest power demand at a particular ventilation station. Five scenarios were conducted with different blade setting and mostly with two different speeds. The experimental results show that alteration of fans' speeds by use of a VFD unit can reduce power consumption while maintaining airflow requirements. With the flow rate forced through the mine by the surface fan the blade settings 4 and 5 were determined as possible alternative for the mine ventilation system. In scenario 4, the airflow at the particular ventilation station for a number of speeds is over 20m^3/s. The power consumption at 1080 rpm was measured to be 20.1 kW compared to 25.5 kW at 1200 rpm. The operating cost would be significantly less at lower speeds. Scenario 5 is the alternative making use of both booster fans and the main fan in series that meets the minimum airflow requirement at the particular ventilation station along with minimum power consumption. Reducing both booster fans speeds to 1054 rpm results in power consumption of both together dropping to 11.8 kW. Therefore blade setting 5 using two booster fans was determined to be the optimal setting. Separately it was determined that the combination with use of only one booster fan, the West booster fan, running in series with the main fan is the overall optimal scenario. The power consumption of the West booster fan was calculated to be 8.8 kW at 860 rpm with the minimum airflow requirement being met.

Computational fluid dynamics is used for analyzing three dimensional flow structures in time domain and calculating the corresponding unsteady pressure fluctuations. The sliding and dynamic mesh techniques were used to study the unsteady flow interaction arising due to the rotation of the fan blades. The numerical predictions of the variables in the form of velocity vectors and contour plots detailing the flow characteristics are then analyzed according to the known physical situation and existing experimental data.

INTRODUCTION

The Missouri S&T Experimental Mine is an underground dolomite mine located in Rolla, Missouri. The mine is accessed by two adits and has three raises to the surface along with the primary ventilation shaft. The two mine portals both have ventilation doors as indicated. Two booster fans with VFDshave been installed in bulkheads in a flexible manner so locations can be varied during research. Airflow that leak through stoppings depend on various factors including the type of materials and maintenance. A poor quality stopping construction leads to increased leakage and will significantly raise power consumption (Gillies, 2010). Air leakage in underground mines commonly varies between 25 and 90 percent of total (McPherson, 1993).

A study has been conducted to build a ventilation model of the Missouri S&T Experimental Mine with Ventsim ventilation software (Figure 1). The booster fans increase available pressure to overcome mine resistance. Additional pressure increases stopping leakage flow.

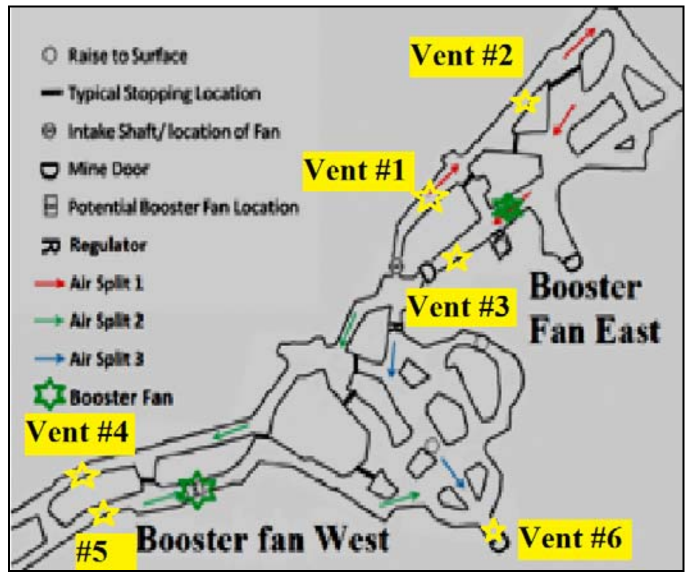

Figure 1. Missouri Experimental Mine and Booster fans location.

Computational Fluid Dynamics (CFD) approach has been used to simulate pressure drops across the booster fans. The additional pressures imparted by the booster fans will increase network airflow but lead to additional recirculation. The developed CFD model has been calibrated by comparison with experimental results.

MISSOURI S&T BOOSTER FANS

The booster fans have been installed in bulkheads underground. Site preparation started by blasting to widen the selected locations (Figure 2). Bulkheads consist of 150 x 150 mm timbers and plywood sheet panels filling areas surrounding the fans and a galvanized steel door. Cementitious mixtures and expanded foam sprays have been used to seal cracks and leakage paths in bulkheads and stoppings to reduce the leakage. Booster fans have been mounted on skids to facilitate transportation. The skids have been bolted to the ground to reduce vibrations generated by the booster fans.

Each booster fan is driven by a 12kW three phase 460V motor that loads the circuit by approximately 20A. Safety issues mean a requirement of a total of 60A including 1.5 safety factor. Safety switches have been installed underground.

The electrical components have been installed next to the fans. The power cable enters the main switch box which contains fuses, circuit breakers, contactors and starter. A VFD has been installed for each fan. The VFDs have been mounted in separate boxes next to the switch boxes (Figure 3).

Figure 2. Bulkhead schematic view, East Booster fan.

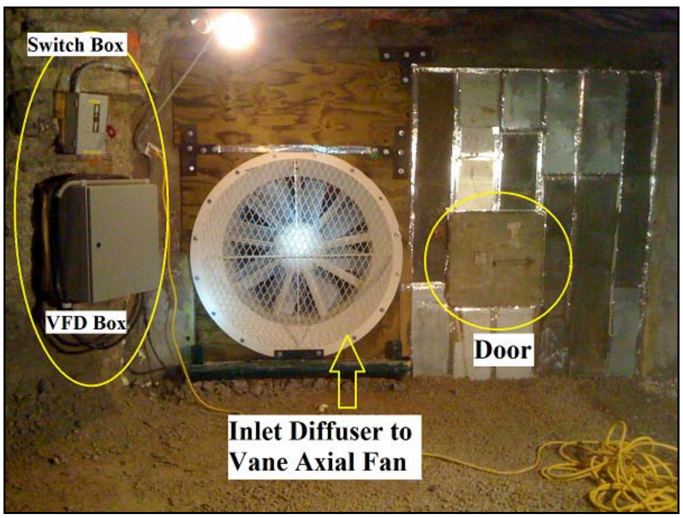

Figure 3. Electrical components at the West booster fan.

VENTILATION SURVEY

Six ventilation stations have been selected as shown in Figure 1. Ventilation station 4 is the particular ventilation station under study and has been determined as the working face. The goal is to maintain a specified flow rate for this target point.

A ventilation survey is an organized procedure for acquiring data that quantifies the distributions of airflow, pressure and air quality parameters throughout the main flow paths of a ventilation system. Mine pressure and quantity surveys are undertaken to gain an understanding of mine characteristics in total and in particular airflow characteristics through sections of a mine.

The single-base method was used for the ventilation survey, where one precision recording pressure transducer is used underground while the second one remains at a base point underground. Readings at both are taken simultaneously. Three corrections to altimeter data (atmospheric pressure changes, velocity differences, and elevation differences) are necessary to calculate the pressure (SME Handbook, 1992).

Two velocity readings have been taken at each ventilation station and evaluated for consistency. Readings deviating more than 5 percent from each other have been repeated. At junctions and splits, readings have been taken to ensure the fulfillment of Kirchhoff's First Law (the sum of the airflow entering a junction equals the sum of the airflow exiting a junction). In order to calculate the airway resistance accurately, pressure readings have been taken at the same time as airflow readings.

The measured readings have been analyzed and later inputted into a program. The total intake and exhaust air quantity balance has been compared. The error between intake and exhaust airflows is principally due to turbulence around the base of the intake shaft and leakage through the surface elbow.

Differential air pressures have been measured across key stoppings and bulkheads. Flow quantities have been determined through mine airways. This data has been used to determine optimal placement of booster fans within the ventilation circuit. Results have been used to calibrate Ventsim and CFD models.

Figure 4. Pressure Measurements across the Bulkhead.

The digital pressure transducers (Paroscientific 765-16B) have been used to measure the absolute pressure at every station. Digital instruments have also been used to measure air thermal properties. The Davis anemometers were used to measure air velocities.

The psychrometric properties (pressure, wet and dry bulb temperatures) have been measured using sling psychrometers.

FAN CURVE AND BLADE SETTINGS

The manufacturer's fan characteristic curves have been used for simulation purposes (Figure 5). Both booster fans are set to operate on identical blade settings at the same time. All blades' leading and trailing edges have been inspected.

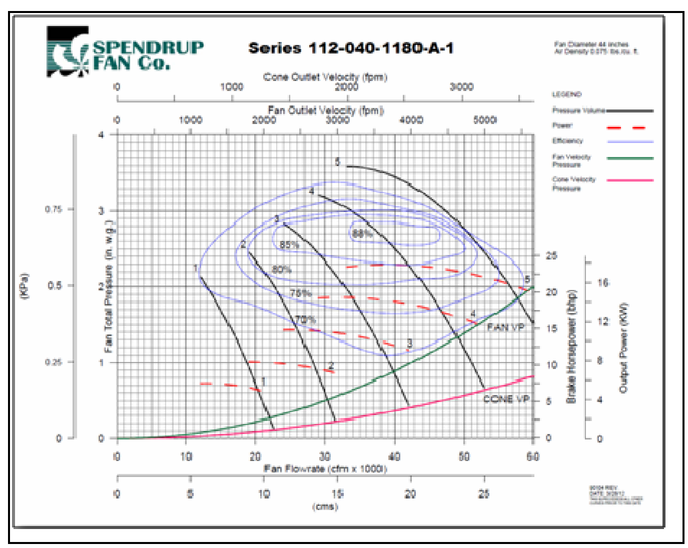

Figure 5. Booster Fan Characteristics Curve.

Experiments were conducted to investigate a range of operating point against motors current draw, bulkheads pressure drops, air flow rates at different blade settings and different fan speeds. The optimal scenario is the one that maintains adequate volume flow rate at station 4 with the lowest operating cost. Figures 6 and 7 show the different blade settings.

Figure 6. Adjusting blade settings.

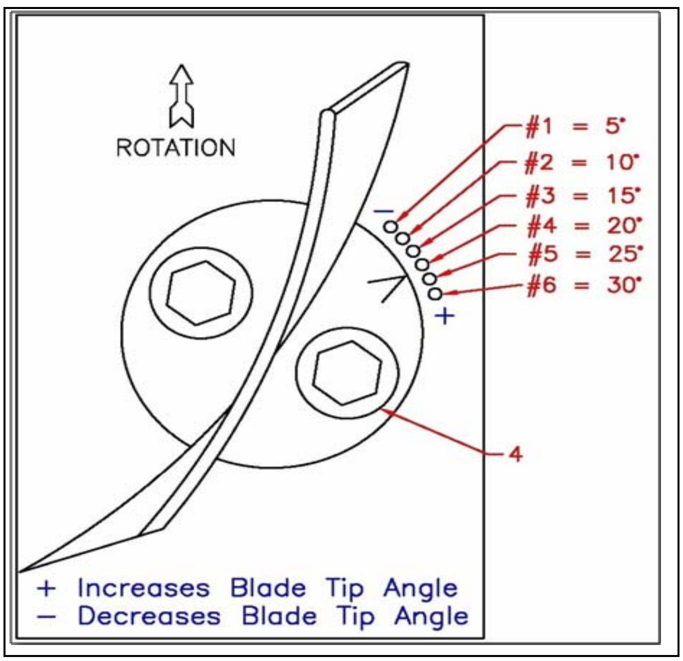

Figure 7. Manufacturer's drawing of various blade settings.

DATA ANALYSIS

All survey data have been inputted into a spreadsheet. The pressure losses, air density, and K frictional value and resistance for every airway have been determined. The psychrometric properties (such as humidity, vapor pressure, dew point, saturation vapor pressure and wet and dry bulb temperature) have been calculated. The results were then used to calculate the average corrected density with respect to local elevation, temperature and atmospheric pressure. If the airflow is restricted the flow around the impeller blades breaks away at the hub. This leads to a drop in pressure and a substantial increase in the noise level caused by turbulence.

EXPERIMENT SCENARIOS

Several scenarios have been conducted with five different blade setting parameters and two different speeds (full speed, 1200 rpm, and 90 percent of full speed,1080 rpm).The study investigated the practicality of reducing operating cost by using a VFD units on the surface-based fan main. Currently, the mine surface fan is operating at 100percent rpm of 1740 rpm, at 60 Hz). There are advantages realized with installation and utilizing of VFDs on booster fans:

1. Reducing the fan speed by adjusting the frequency lowers wear on fan parts.
2. An ability to over speed the motors.
3. Increases safety by being flexible in case of emergencies. For example increase East booster speed to ventilate the target station in case of losing West booster fan.
4. An ability to set the blades on high settings and for slow speeds to reduce the operating cost. In this case the fan is capable of pushing more air by increasing the VFD frequency at any time.
5. The power consumption has been calculated for each scenario. The power factor has been assumed to be 0.9 for the booster fans motors in these calculations.

Scenario 1.Booster Fan Blade Setting #1

In scenario 1 both fans' sets of blades were adjusted to setting #1. According to the manufacturer's fan characteristic curves the fan can move up to 12m^3/s at 500 Pa. The surface fan blows 20m^3/s of air into the mine. A pressure drop of 235 Pa was measured across the East booster fan. The booster fan was reducing the pressure drop through the mine as it acted as an impedance. This scenario shows that blade setting #1 is not the appropriate and efficient setting to match with the surface fan.

In altering the booster fans to blade setting #1 it was determined that this setting does not have sufficient capacity to provide airflow to match that being blown into the mine by the surface fan.

Scenario 2. Booster fan Blade Setting #2

The Pressure Quantity survey for all six ventilation stations was conducted while the blade settings were set on #2, or 10˚.

Table 1. Scenario 2, Quantity Experimental Results.

Station	Area (m^2)	Q(m^3/s)	
		1198 rpm	**1080 rpm**
#1	5.4	18.6	18.1
#2	5.0	19.5	17.5
#3	5.8	21.7	18.6
#4	4.0	15.2	14.1
#5	3.9	16.0	14.9
#6	4.0	16.3	15.6

From manufacturer's curve each booster fan can blow up to 15m^3/s at up to 550 Pa of total pressure. The survey was conducted at two different speeds. Table 1 shows the Quantity results at speeds of 1200 and 1080 rpm. The VFD motor features have been monitored for given speeds. Table 2 shows the measurement results at 1200 rpm vs. 1080 rpm.

Table 2. Scenario 2, Booster Fan Motor Parameters.

Motor Results				
	East Booster		**West Booster**	
Speed, rpm	1198	1080	1198	1080
Frequency, Hz	63.1	56.9	63.1	56.9
Current (Amp)	9.5	9.4	10.6	9.9
Motor Load %	39.5	39.1	44	40.8
Voltage	428	430	430	432
Calc.Power (kW)	6.3	6.3	7.1	6.7

The results show the airflow quantity at target vent #4 station at both speeds is similar. The West booster fan is working harder. A pressure difference of 50 Pa across the West booster fan unit was measured. The number shows that the operating point for both booster fans, specifically for the West booster fan is barely on the fan characteristic curve. In other words an insufficient amount of air enters into and passes through the West Booster fan. The conclusion for this scenario is that this blade setting is not the optimal one. The VFD reduces the operating cost by reducing the motor load while maintaining the airflow requirements.

Scenario 3. Booster fan Blade Setting #3

Both booster fans blades were set on #3, or 15˚. As before a Pressure Quantity survey was conducted for six ventilation stations at two speeds. A pressure drop of 180 Pa was measured across the East booster fan while that across the West booster was less than 50 Pa. This highlights that the West booster fan is not adding any pressure to the system and is not operating efficiently. Tables 3 and 4 show the experimental results of relevant quantity, survey and booster fans motors.

Table 3. Scenario 2, Quantity Experimental Results.

Station	Area (m^2)	Q(m^3/s)	
		1198 rpm	1080 rpm
#1	5.4	18.3	17.9
#2	5.0	19.2	19.3
#3	5.8	0.0	23.5
#4	4.0	20.2	17.8
#5	3.9	20.5	19.5
#6	4.0	21.1	18.0

The Quantity results show the airflow at station #4 is slightly more at 1200 rpm compared to the lower speed. Table 4 shows the power consumption is significantly higher as well. The motor load has increased comparing to #2 blade setting.

Table 4. Scenario 3, Booster Fan Motor Parameters.

Motor Results				
	East		West	
rpm	1198	1080	1198	1080
f (Hz)	63.1	56.9	63.1	56.9
Output Current, I (Amp)	13.3	11.3	13.8	12.2
Motor Load %	55.4	47	58	50.8
V (Volt)	401.7	401.1	415	401
Calculated Power (kW)	8.3	7.1	8.9	7.6

Scenario 4. Booster fan Blade Setting #4

Blade setting #4 or 20˚ was set for both booster fans. The booster fan can blow up to 25m^3/s air at 750Pa at this blade setting. The Pressure Quantity survey was conducted at the two different speeds of 1200 and 1080 rpm. Tables 5 and 6 show the experimental results for this scenario.

Table 5. Scenario 4, Quantity Experimental Results.

Station	Area (m^2)	Q(m^3/s)	
		1198 rpm	1080 rpm
#1	5.4	19.2	18.9
#2	5.0	20.5	20.5
#3	5.8	28.7	27.0
#4	4.0	23.2	21.9
#5	3.9	24.4	22.5
#6	4.0	22.1	21.9

Table 6. Scenario 4, Booster Fan Motor Parameters.

Motor Results				
	East		West	
rpm	1198	1080	1198	1080
f(Hz)	63.1	56.9	63.2	56.9
Output Current I (Amp)	19	14.4	20.6	16.9
Motor Load %	79.1	60	85	70.8
V (Volt)	392.9	399.7	452.4	422.8
Calculated Power (kW)	11.6	9.0	14.5	11.1

Scenario 5. Booster fan Blade Setting #5

The blade setting in both booster fans was set to the highest blade setting #5, or 25˚. The experiment could not be completed at 1200 and 1080 rpm. It was determined that the maximum amount of current being pulled by motors was exceeding 20 Amp. Therefore the motors were in overload, were overheating and were shut down by the VFD units.

Due to this overloading situation the control panels on the VFD were used and the speed was adjusted manually on both booster fans to 1052 rpm. This speed kept the corresponding current being pulled by the motors under 20 Amp. Therefore the test for blade setting #5 was conducted for this speed and the results are as shown in Table 7 and 8.

Table 7. Scenario 5, Booster Fan Motor Parameters.

Blade setting 5, Rpm 1200			
Station	A	V	Q
#1	5.4	3.4	18.2
#2	5.0	4.1	20.7
#3	5.8	4.5	26.4
#4	4.0	5.3	21.6
#5	3.9	5.8	22.3
#6	4.0	5.8	23.0

Table 8. Scenario 5, Booster Fan Motor Parameters.

Motor Results		
	East	West
rpm	1054	1054
f(Hz)	56	47.1
Output Current I (Amp)	19.5	19.8
Motor Load %	81	82.5
V (Volt)	388.6	305.2
Power (kW)	11.8	9.4

Single Booster

A single booster fan scenario was considered at blade setting #5, or 25˚,. Each booster fan was run alternatively in series alone with the surface fan. The results show that the combination of West booster fan with main fan would increase the airflow quantity in all ventilation stations. The Motor load was measured as 80 percent. The fan speed was set to 860 rpm. The pressure quantity survey result for the combination of East and main fan showed that the power consumption is higher than the previous scenario.

It can be concluded that the motor load and the power consumption rate increase by setting the blade to higher angles. Figure 9 shows the correlation of blade settings vs. motor load, power consumption and current being pulled by the motor for East booster fan with different blade settings rotating at full speed 1200 rpm.

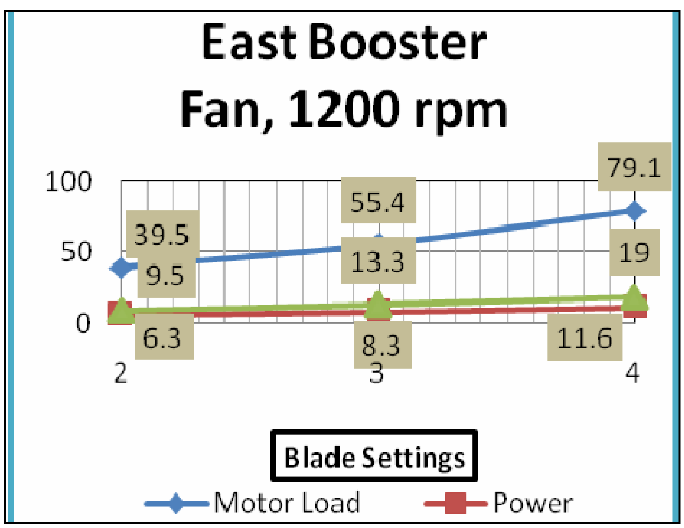

Figure 9. Correlation of various blade setting vs. power, current and motor load.

Meeting the Objectives

It was found that the blade setting 1, 2 and 3 were not suitable options. With the flow rate forced through the mine by the surface fan the blade settings #4 and #5 were determined as possible alternative for the mine ventilation system. In scenario 4, the airflow at ventilation station for both speeds is over 20m^3/s. The power consumption at 1080 rpm was measured to be 20.1 kW compared to 25.5 kW at 1200 rpm. The operating cost would be significantly less at lower speeds. Scenario #5 is the alternative making use of both booster fans and the main fan in series that meets the minimum airflow requirement at ventilation station #4 along with minimum power consumption. Reducing both booster fans speeds to 1054 rpm results in power consumption of both together dropping to 11.8 kW. Therefore blade setting #5 using two booster fans was determined to be the optimal setting. Separately it was determined that the combination of only the West booster fan running in series with the main fan is the overall optimal scenario. The power consumption of the West booster fan was calculated to be 8.8 kW at 860 rpm with the minimum airflow requirement met.

CFD STUDY

CFD is an approach in fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flow. The FLUENT software code is based on finite element methods and is capable of modeling many characteristics of fluid flow such as compressible and incompressible, viscous and non-viscous, steady and unsteady, laminar and turbulent, transient and so on (Ansys, 2010).

"Solidworks" is a preprocessor for engineering analysis with advanced geometry and meshing tools. An Experimental Mine booster geometric CFD model has been built using this software. The geometric model has been simplified to facilitate flow simulation. Figure 10 shows the simplified geometric model built in "Solidworks". The geometric model for blade setting #2, 3 and 4 was created.

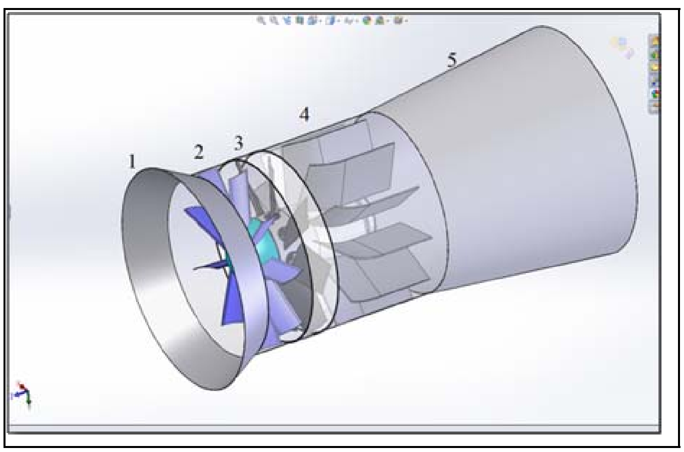

Figure 10. The geometric model of MS&T Booster fan.

The geometry model has been imported to Ansys workbench. An attempt is made to simulate the airflow distribution inside the booster fan and compare the predicted pressure drop across the fan with the measured results. The computation domain for the booster fan with 10 degree rotor blade angle setting is shown in the Figure11. Air enters into the domain in the axial direction as shown in Figure 11. The total length of the computational domain measures 2.62 m. The diameters of rotor and stator are fixed at 1.11 m and the diameter at the inlet and at the exit measures 1.42 m. There are two sets of stator and one set of rotor blades as shown in the figure. The first stator blades turns the flow in the direction of rotor blades and the second stator blades turns air exiting the rotor back to the axial direction. During this flow the total pressure of the air increases depending on the air flow rate and the rotor blade settings.

The computational domain is meshed using GAMBIT and the grid generated with approximately 1.16 million cells for 10 degree blade angle is shown in Figure 12. The three dimensional time averaged Navier-Stokes and continuity equations along with the boundary conditions are solved using finite volume method.

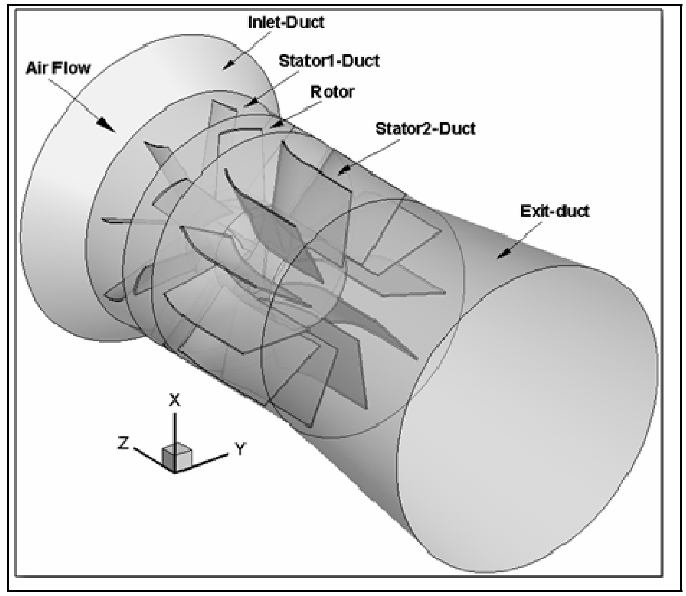

Figure 11. Fan physical model imported to Ansys Fluent.

The turbulence in the flow is resolved using standard k-ε model with wall functions for near wall treatment. The physical properties of air are treated as constants and obtained for the inlet air temperature of 27°C. Air entering the inlet duct is fully developed with Re = 796,900. The air flow rate at this Reynolds number is 13m^3/s. No slip boundary conditions are applied to all the wall boundaries and outflow flow boundary condition is imposed at the fan outlet. The rotor blade speed is set at 1200 rpm.

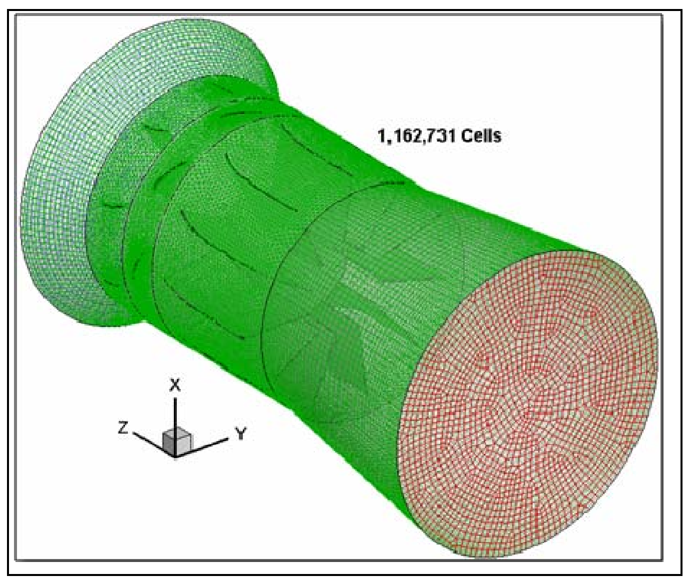

Figure 12. Mesh Generation.

Numerical simulation is carried out using commercially available CFD code ANSYS FLUENT. The SIMPLE algorithm is used for the pressure velocity coupling. The momentum and scalar turbulence equations are discretized using second order. The moving mesh technique available in FLUENT is used to model the rotor rotation. The convergence criterion is set at 10^{-6} for continuity, momentum and turbulent scalar equations. More details on the solution procedure can be found in FLUENT manual.

RESULTS AND DISCUSSION

Simulated results for the total pressure distributions are shown in Figure 13 for the rotor blade angle of 10° and air flow rate of 13m^3/s. The total pressure and velocity distributions for two-dimensional cross-sectional planes inside the calculation domain are also shown in Figure 14 and 15.

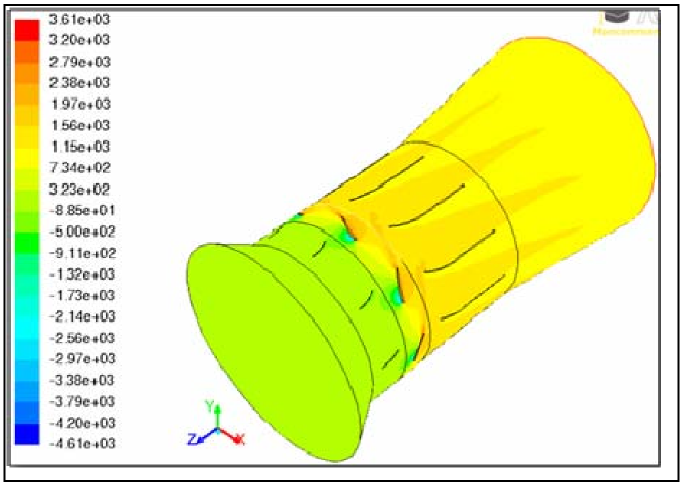

Figure 13. Total Pressure distributions in Pascals.

It can be seen that the total pressure increases as the air flows through the booster fan. The comparison of simulation results with the measurement is made by comparing the total pressure drop across the booster fan inlet and outlet with the measured pressure drop.

It can be seen that the simulated pressure increase across the booster fan is more than the value for the air flow rate of 13m^3/sat 1200 rpm. This large deviation of predicted value from the measured value could be due to (i) excessively coarse mesh used for the simulation (ii) turbulence model used for the present study and (iii) experimental error. Further studies are being carried out to determine the reasons for this behavior.

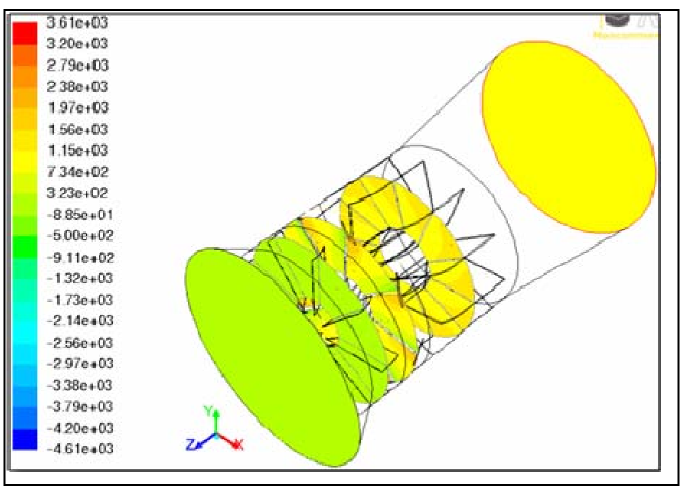

Figure 14. Total Pressure distributions (Pa) at various cross-sectional planes.

CONCLUSION

The study was conducted using VFD units installed on booster fans. The fans were operated with various blade settings to determine the optimal scenario that maintains the maximum airflow quantity at ventilation station #4 with the lowest power demand. Five scenarios were conducted with different blade setting. Most scenarios examined the mine system at two speeds. The experimental results show that use of the VFD unit can reduce power consumption while maintaining the airflow requirements.

The pressure drop across the bulkheads was measured in each scenario to determine the pressure added by the booster fans into the system. It was found that the blade setting #1, #2 and #3 were not suitable options. With the flow rate forced through the mine by the surface fan the blade settings #4 and #5 were determined as the best alternative for the mine ventilation system.

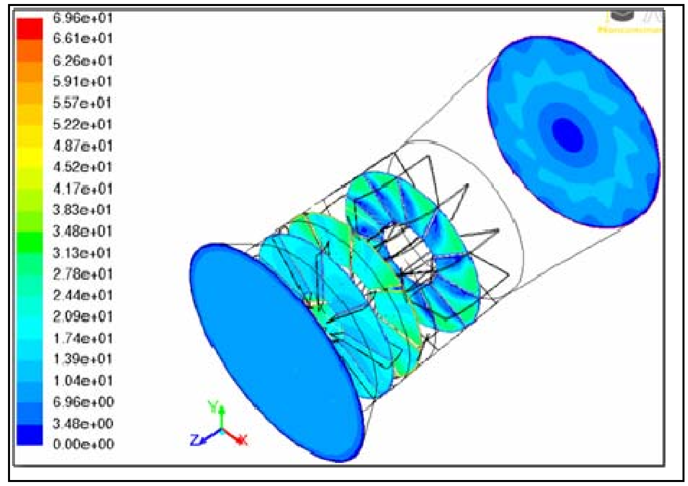

Figure 15. Velocity magnitude (m/s) distributionsat various cross-sectional planes.

In scenario 4, the airflow at ventilation station for both speeds is over 20m^3/s. The power consumption at 1080 rpm was measured to be 20.1 kW compared to 25.5 kW at 1200 rpm. The operating cost would be significantly less at lower speeds. Scenario #5 is the alternative making use of both booster fans and the main fan in series that meets the minimum airflow requirement at ventilation station #4 along with minimum power consumption. Reducing both booster fans speeds to 1054 rpm results in power consumption of both together dropping to 11.8 kW. Therefore blade setting #5 using two booster fans was determined to be the optimal setting.

Separately it was determined that the combination of only the West booster fan running in series with the main fan is the overall optimal scenario. The power consumption of the West booster fan was calculated to be 8.8 kW at 860 rpm with the minimum airflow requirement being met.

CFD was used to simulate the airflow behavior and pressure drop across the booster fan. A geometric model of blade setting #2 was built and numerical simulation was carried out. The predicted simulation result is more than the experimental measurement for the given airflow. Further studies will be carried out to calibrate the model with finer mesh on blade setting #2, 3 and 4.

ACKNOWLEDGEMENT

This paper was prepared with financial support from NIOSH. This assistance is gratefully acknowledged as is the support efforts of Missouri S&T Rock Mechanics and Explosive Research Center and Experimental Mine personnel. The Spendrup fan company collaboration is highly appreciated for the advice and using the model.

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