Mining, Metallurgy & Exploration (2022) 39:887–895
https://doi.org/10.1007/s42461-022-00574-4

Experimental Study of Improving a Mine Ventilation Network Model Using Continuously Monitored Airflow

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Received: 1 November 2021 / Accepted: 10 February 2022 / Published online: 7 March 2022

Abstract
A calibrated and well-tuned ventilation network model plays a critical role in mine ventilation planning, optimization, and ventilation control. Moreover, it is critical to the mine fire simulation program as well since the fire simulation is built upon the mine ventilation model. The contaminants generated from a fire are transported by airflows throughout the mine ventilation system. The accuracy of the fire simulation results not only depends on the fire source model itself but also on the ventilation network model. With the increasing use of atmospheric monitoring systems in underground mines, airflow is continuously monitored using airflow sensors in the key areas of mines to ensure a steady and reliable ventilation. Experimental studies have been conducted at an experimental mine, the Safety Research Coal Mine (SRCM), to gain a better understanding on how to use the continuously monitored airflow data to improve the calibration of the mine ventilation network model. This paper introduces an improved method to calibrate a ventilation network using continuous airflow monitoring and addresses the practical problems encountered while calibrating and tuning the ventilation network of the SRCM using continuously monitored airflow data. In this study, the fluctuation of the air velocity sensor readings is analyzed, and the sensor location correction factors are applied to obtain a more accurate average air velocity for the ventilation network calibration.

Keywords Mine ventilation · Airflow monitoring · Ventilation network · Atmospheric monitoring system · Barometric pressure

1 INTRODUCTION

Since the first viable electrical analog computers to simulate ventilation networks were developed in the 1950s, mine ventilation network analysis techniques have seen a significant advancement because of the availability of digital computers. Nowadays, mine ventilation simulation software, a computer program for mine ventilation network analysis, has become an essential tool for the mining industry to design and manage mine ventilation operations. Furthermore, mine ventilation simulation is the foundation of a mine fire simulation program, which simulates ventilation disturbances, smoke and toxic gas spread, and air temperature changes caused by fires. The current available mine fire simulation software, such as MFIRE [7], VentSim™ [4], and VentGraph™ [9], all require a well-calibrated mine ventilation model to ensure the accuracy of simulations.

In recent years, researchers from the National Institute for Occupational Safety and Health (NIOSH) have conducted a number of studies involving mine fire modeling using a NIOSH-developed mine fire simulation software, MFIRE, and full-scale fire tests at the Safety Research Coal Mine (SRCM) at NIOSH's Bruceton Campus near Pittsburgh, PA. Zhou et al. [12] simulated the carbon monoxide (CO) spread in two fire tests (one diesel fire and one belt fire) conducted at the SRCM using MFIRE. The comparisons between the measured and simulated CO concentrations demonstrated that MFIRE can predict CO spread in underground diesel and belt fires accurately with a well-tuned mine ventilation network. Zhou et al. [13], Bahrami et al. [1], and Zhou et al. [14] developed a real-time method to determine a fire location and calculate the fire intensity through the integration of an atmospheric monitoring system and MFIRE. In those studies, the accuracy of the MFIRE simulation heavily relies on the accuracy of the airflow results calculated from the mine ventilation network as the contaminants and the heat

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generated from a fire are transported by the ventilation airflow. Therefore, how to build and maintain a reliable ventilation network at the SRCM is the first critical step of the fire research mentioned above.

Building a well-calibrated mine ventilation network is very time consuming and requires great efforts in airflow and pressure surveys, fan performance measurement, and comprehensive data analysis. Frequent network recalibration is also necessary since changes can always occur during the lifetime of a mine. To make a mine ventilation network model truly functional in routine mine ventilation management, mine ventilation engineers will need to update and re-tune the ventilation model, as frequently as needed, throughout the life of the mine. In the last several decades, the mining industry has seen a steady increase in the use of air velocity sensors to monitor airflow and detect unexpected abnormal airflow in some key locations in underground mines [2]. Besides ensuring a safety mine ventilation system, whether and how the continuously monitored airflow data can be used to calibrate and update the ventilation network becomes a question. To answer this question, a month-long ventilation experimental study has been conducted at the SRCM employing a mine-wide AMS monitoring. The objectives of this paper are as follows: (a) to report the practices and efforts we have taken in our research to build a reliable mine ventilation network at the SRCM using a conventional method such as airflow surveys to construct the base ventilation network model and (b) to calibrate the ventilation network using atmospheric monitoring systems (AMS) data on a routine and ongoing basis. The work in this study has been presented at the 18th North American Mine Ventilation Symposium [15]. The current paper also addresses the relevant feedbacks and comments received during the conference.

2 Building the Base Network Using Ventilation Surveys

The SRCM is one of the two experimental mines at the Bruceton campus of the NIOSH. The SRCM is a room-and-pillar mine, approximately the size of a working section, with one main intake entry and one main return entry. The entries have an average height of 6.5 ft and an average width of 14 ft. The main fan, installed at the surface above the return shaft, exhausts air from the mine. Stoppings, doors, regulators, and brattices are used in the mine to direct the airflow to the desired routes. The quantity of airflow getting into the mine is controlled by the main fan and a door at the main return entry.

As of now, three thorough ventilation surveys have been performed in 2014, 2016, and 2018 to construct and tune the ventilation model for the SRCM. The first ventilation survey was initiated to build the first ventilation network model of the SRCM with joint efforts from the University of Pittsburgh [5]. In 2016, some major renovation in the mine took place to remove debris and re-support the ribs and roofs. Therefore, the second and the third surveys (2016 and 2018) were conducted to evaluate the resistance changes after the renovation. Air velocity was measured at key stations along the main airflow pathways by performing full-section vane anemometer traverse measurements, and then the average airflow rate was obtained by multiplying the measured cross-sectional area. The pressure losses of the selected airways were measured using the gauge and tube method due to its higher accuracy as compared to the barometer and altimeter methods. * MERGEFORMAT Fig. 1 shows the layout of the SRCM and the 21 airflow measuring stations established to take the measurements of airflow velocities, temperatures, and relative humidity, and the 13 measuring stations for the pressure differential measurements in the first ventilation survey conducted in 2014.

The ventilation survey provides direct access to the primary input parameters in building a ventilation network model. As the airways in the network are short, each pressure measurement segment typically spans several airway junctions. We calculated the total resistance using pressure drop and airflow rate for each pressure measurement segment and then proportionally prorated to each airway by its length. At the same time, the Atkinson frictional factor of each airway was calculated by applying it to those unmeasured airways with similar roughness conditions. The fan curve was generated using the measured operating airflow and pressure data obtained from the first survey [5].

With further calibrating and tuning, the simulation results from the ventilation network model of the SRCM using MFIRE were compared against the measured air velocities and pressure drops at each location showing a very good agreement. However, a mine ventilation survey is only a snapshot in time of the ventilation network. By the time the survey results are determined and the ventilation network model is built, the ventilation survey results are already outdated [8]. Ventilation planning is a continuous and routine process as any operating mine has new workings continually being developed and older ones coming to the end of their productive life [6]. Therefore, frequent mine ventilation network recalibration becomes an essential routine for mine ventilation engineers to manage and maintain the mine ventilation system.

Several attempts have been made to develop optimization algorithms to calibrate a mine ventilation network. Danko et al. [3] developed a least-square-fit numerical algorithm to optimally adjust the resistances of network airways until the simulated results of the ventilation network model best matched the in situ mine surveying airflow rates and pressure differences,whereas, Xu et al. [10] used the nonlinear

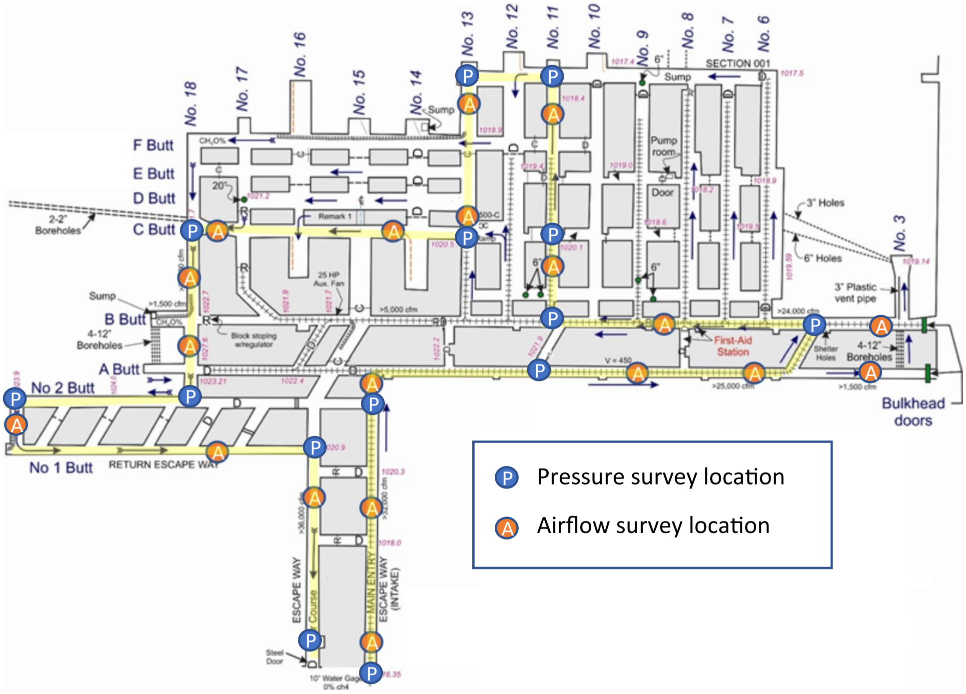


Fig. 1 The pressure and airflow measurement locations of the first survey

optimization algorithm to reach the same goal. These algorithms can tune the ventilation network by adjusting all or the selected airway resistances to minimize the difference between the measured and simulated results. However, a drawback of these approaches is that they may yield a false match by adjusting the resistances that are not supposed to change. For example, putting up a ventilation brattice in an entry will cause airflow changes not only in the entry itself but also in the adjacent airways. To update the ventilation network, it only needs to increase the resistance of the airway with installed brattice. However, using the above algorithm to calibrate the changed ventilation network, it may end up changing resistances in multiple airways instead of only the brattice airway. It will result in a false calibration even though the simulated airflows may match with the changed airflows. These two approaches are very efficient in calibrating a ventilation network with numerous ventilation survey data. The common approach to update and tune a ventilation model is to spot check the airflow and/or the pressure loss in the airways that have possible changes affecting the network. Besides the pressure and/or airflow spot check, we have explored the use of continuous mine-wide AMS monitoring data to improve updating and tuning the SCRM ventilation network. For this approach, accurately measured airflow rates are required as the targeting airflow rates to calibrate the ventilation network. The continuously monitored airflow and other atmospheric data can provide a more thorough picture on the change of airflows. However, the fluctuations in the readings and the influence of sensor location on the readings are two problems that need to be examined carefully prior to applying the AMS data to calibrate a ventilation network.

3 Fluctuations in the Monitored Ams Air Velocity Readings

The SRCM is equipped with a mine-wide AMS to continuously monitor the atmospheric condition of the mine. There are 8 AMS stations installed throughout the mine (as shown in Fig. 2 labeled in dark blue). Each AMS station consists of 8 AMS sensors to monitor air velocity, temperature, barometric pressure, carbon monoxide, carbon dioxide, smoke density, humidity, and oxygen. A second air velocity sensor is also installed in an entry adjacent to each AMS station to monitor air velocity accurately at the selected locations (marked in light blue in * MERGEFORMAT Fig. 2). In total, there are 16 airflow monitoring locations in the SRCM. The real-time measured data is sent to a server on the surface through cables, and the mine atmosphere can be remotely monitored.

The continuous monitoring of an underground mine atmosphere, especially the air velocity, is typically used to promptly detect unexpected changes in the ventilation network and identify potential ventilation problems within the mine. Besides the detection of abnormal airflow, a question was brought up about whether the monitored real-time airflow or pressure readings can be used to update the ventilation network model to replace the manual spot check. When we use the monitored airflow data as the targeting airflow for calibration, should we use an instantaneous reading or a time

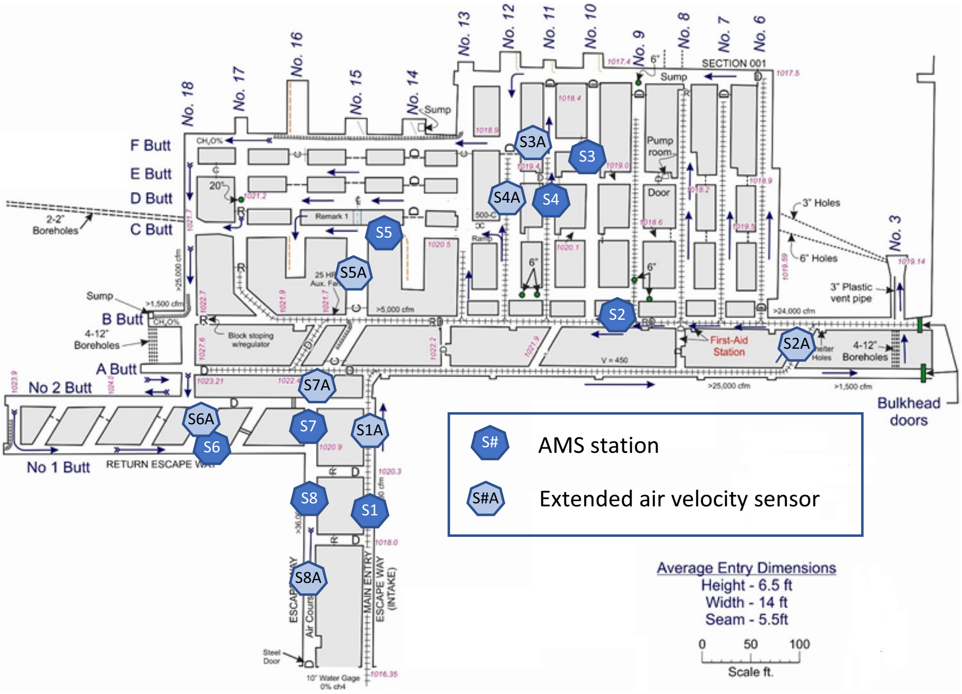


Fig. 2 Installation of AMS monitoring stations and air velocity sensors at the SRCM

averaged value? For this purpose, we closed the SRCM for 3 weeks to only allow personnel access for a routine safety check and prevent any unnecessary interruptions caused from any other mine activities, so that we could examine the monitored airflow and other atmospheric parameters without interruptions. It needs to be noted that it is impractical to close a production mine to study the sensor readings in the real world. The purpose of closing the mine in this study was to exclude any interferences to the AMS readings from mining activities.

The analysis of the maximum, minimum, mean, and standard deviation of the monitored air velocity during the testing period can be found in * MERGEFORMAT Fig. 3. The ranges of the measured air velocity at each sensor location are very diverse. Generally, the smaller the measured value, the smaller are the range and the standard deviation. At sensors S1, S1A, S2, and S8, the maximum reading is around two times the minimum reading, which indicates that the air velocity reading fluctuation is significant.

The fluctuation in the readings frequently impacts the interpretation of the survey results. Many factors can contribute to the fluctuation of the airflow within a mine, such as mining activities, mine fan operation, atmospheric conditions (barometric pressure, temperature, and humidity), and

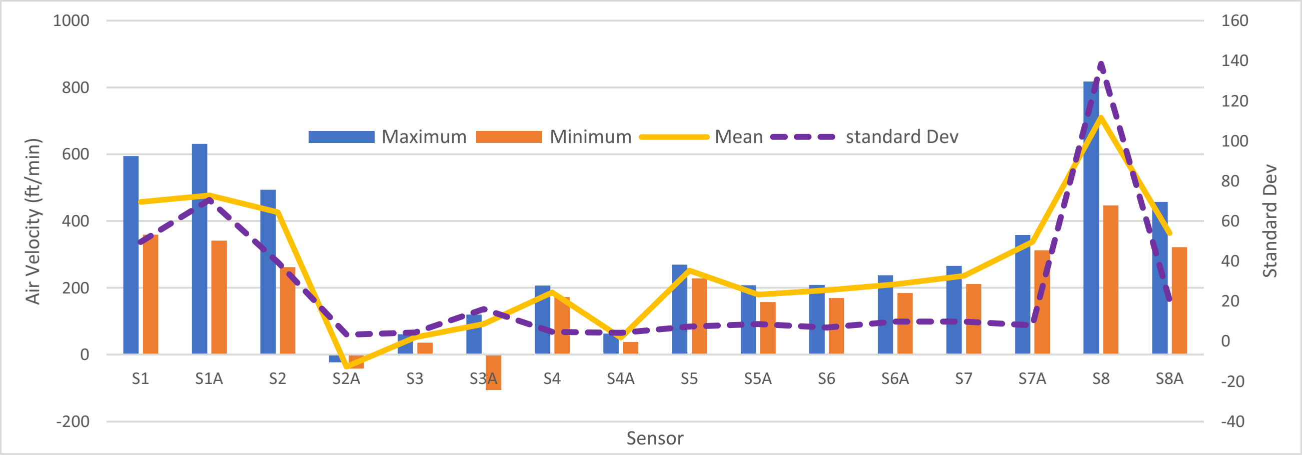
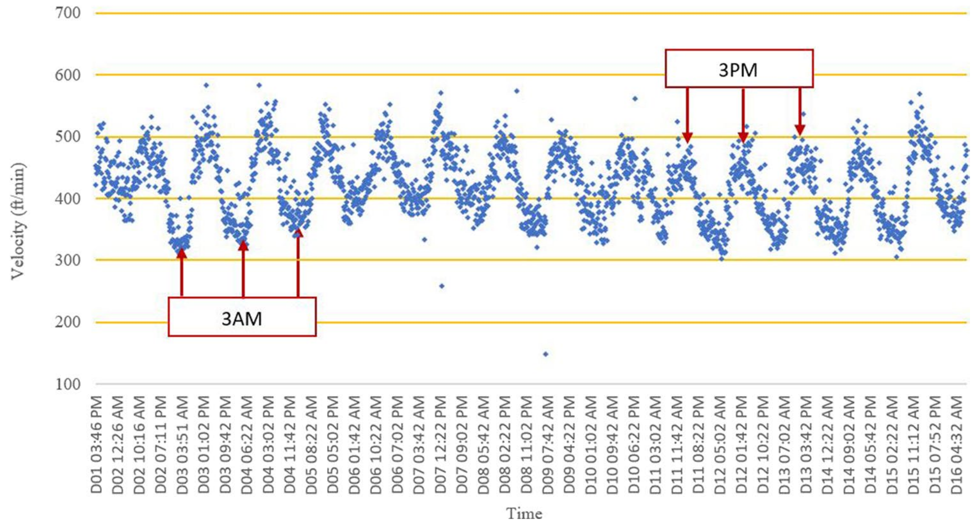


Fig. 3 Summaries of air velocities measured by each sensor

sensor performance. In the current study, we have limited the mine activities to the minimum level by reserving the mine only for atmospheric monitoring data collection. An example of the AMS measurement from August 21 (denoted as D01) to September 5 (denoted as D16), 2018 is used here to further investigate the variations in the air velocity monitoring. During this time period, the AMS recorded the instantaneous air velocity every 10 min. Figure 4 shows the monitored air velocity at the AMS station S1 during this time period. We can see a clearly repeated wave pattern in the monitored air velocity data. Interestingly, the frequency of the wave is about 24 h with the peak value occurring at around 2:00 pm and the minimum value appearing at around 2:00 to 3:00 am every day. The air velocity at S1 fluctuated in the range of 300 ft/min to 550 ft/min with an average of 436 ft/min. We can see that the variation of the air velocity at S1 during a day is significant with the peak value almost double the minimum value. The wave pattern displayed by the S1 reading is fading as the air velocity sensor is further away from the portal. As shown in * MERGEFORMAT Fig. 5, the air velocity readings at S3A still show an insignificant wave pattern, while those at the S5 station show no pattern at all.

As mentioned above, the fluctuation of the air velocity readings can be largely attributed to the atmospheric conditions such as temperature, barometric pressure, and

Fig. 4 Monitored air velocity at S1



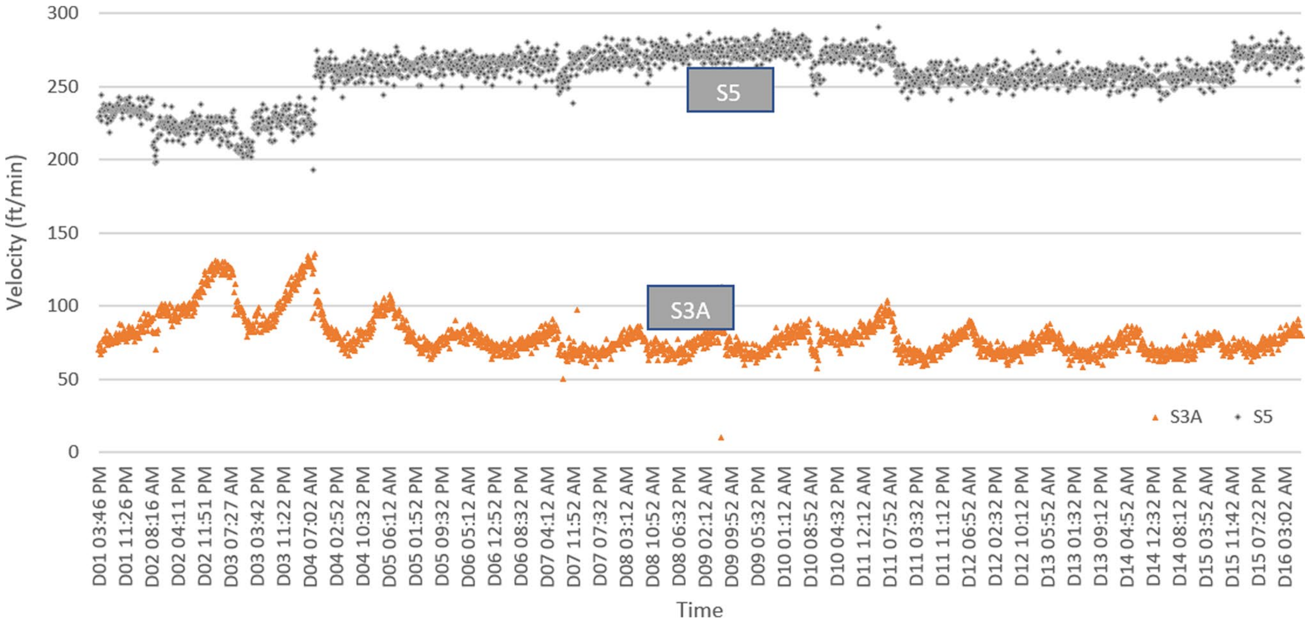


Fig. 5 Monitored air velocity at AMS stations S3A and S5

humidity. In this case, the AMS station S1 is very close to the portal opening to the outside, and the variations of temperature, atmospheric pressure, and humidity of the atmosphere affect the air velocity reading of S1. In contrast, the AMS stations further away in the mine, such as stations S3 and S5, are under less influence of the atmospheric variations. That is the reason why the fluctuations of the air velocity readings in the inner side of the mine are less than that of S1. * MERGEFORMAT Fig. 6 gives an example of how the temperature and air velocity are correlated at the AMS station S1. It can be seen very clearly that the temperature has the same wave pattern as the air velocity. Moreover, the measured temperatures at the AMS stations S1, S4, S5, and S7 shown in * MERGEFORMAT Fig. 7 indicate that the further into the mine, the less the temperature varies. Therefore, the airflow further inside the mine has less fluctuation than that closer to the surface. Due to the fluctuation in the air velocity readings, it is important to use the time averaged air velocity value for the ventilation network calibration to avoid the error of using a one-time reading from all sensors simultaneously. The impact of barometric pressure on the fluctuation of the airflow at S1 was inspected as well and found not as significant as the temperature.

4 Correction Factor for Each Sensor Location

Besides the fluctuation in the air velocity readings, the location of the air velocity sensor also plays a role in applying the AMS data to calibrate a ventilation network. The air velocity measured by an AMS velocity sensor is a point reading at where the sensor is mounted. The air velocity sensors used in the SRCM are typically installed at the upper section of the entry, close to the roof or ribs, to avoid interference from the moving equipment and miners. The point reading of the air velocity unlikely represents the average air velocity in the entry since air velocity is not uniformly distributed over the cross section of an entry. To obtain the average velocity for the calculation of airflow rate in an entry, the point sensor reading needs to be converted to the average air velocity using the sensor location correction factors [11]. The sensor location correction factor is site-specific and there is not a general correction factor that applies to all the cases.

To obtain the sensor location correction factor for each AMS velocity sensor at SRCM, the average velocity at each sensor plane was measured using the moving traverse method with handheld anemometer once per day for 8 days. At the same time, the velocity sensor reading at the time of the traverse measuring was recorded as well. The sensor location correction factor for each sensor can be calculated as the ratio of the average air velocity obtained from the moving traverse measurement and the time averaged sensor reading during the measuring period. Figure 8 shows an example of the measured average air velocity using the moving traverse method, the recorded air velocity sensor reading, and the calculated correction factor for each measuring day at sensor S1A. Furthermore, the correction factor at each sensor location was calculated, and the distribution of the correction factors for different sensor locations are displayed in Fig. 9. The correction factors for each sensor fall into a relatively large range; therefore, it is necessary to obtain the average correction factor at each sensor location. The average

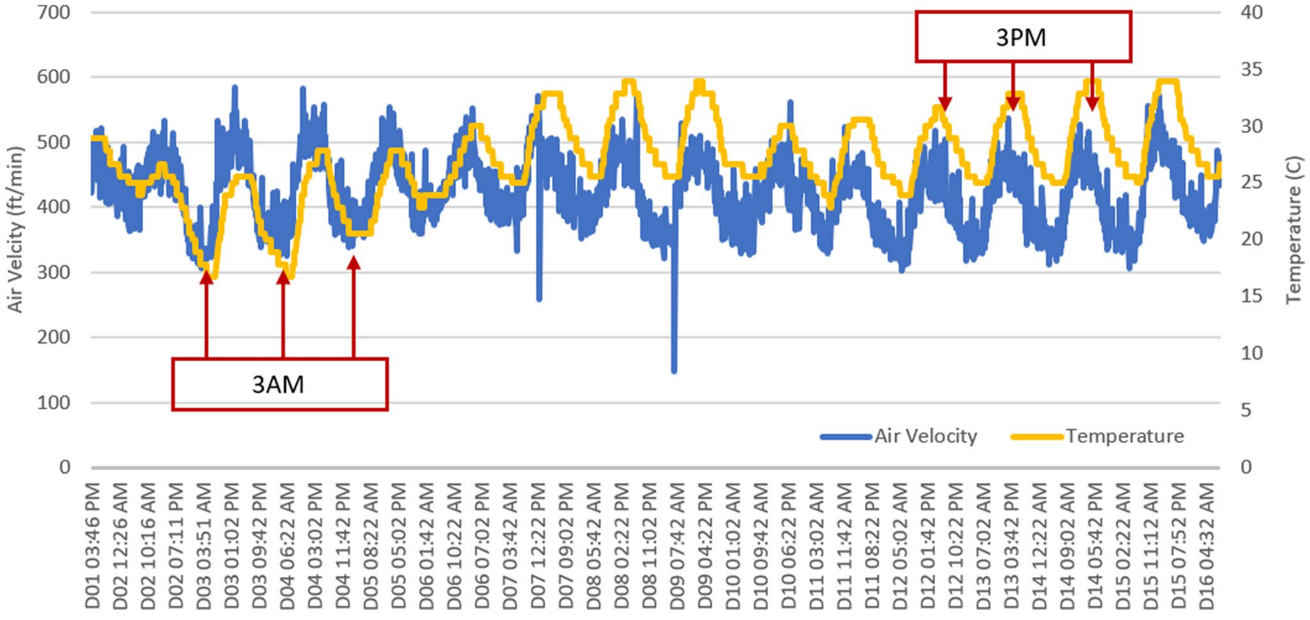


Fig. 6 Monitored air velocity and temperature at the AMS station S1

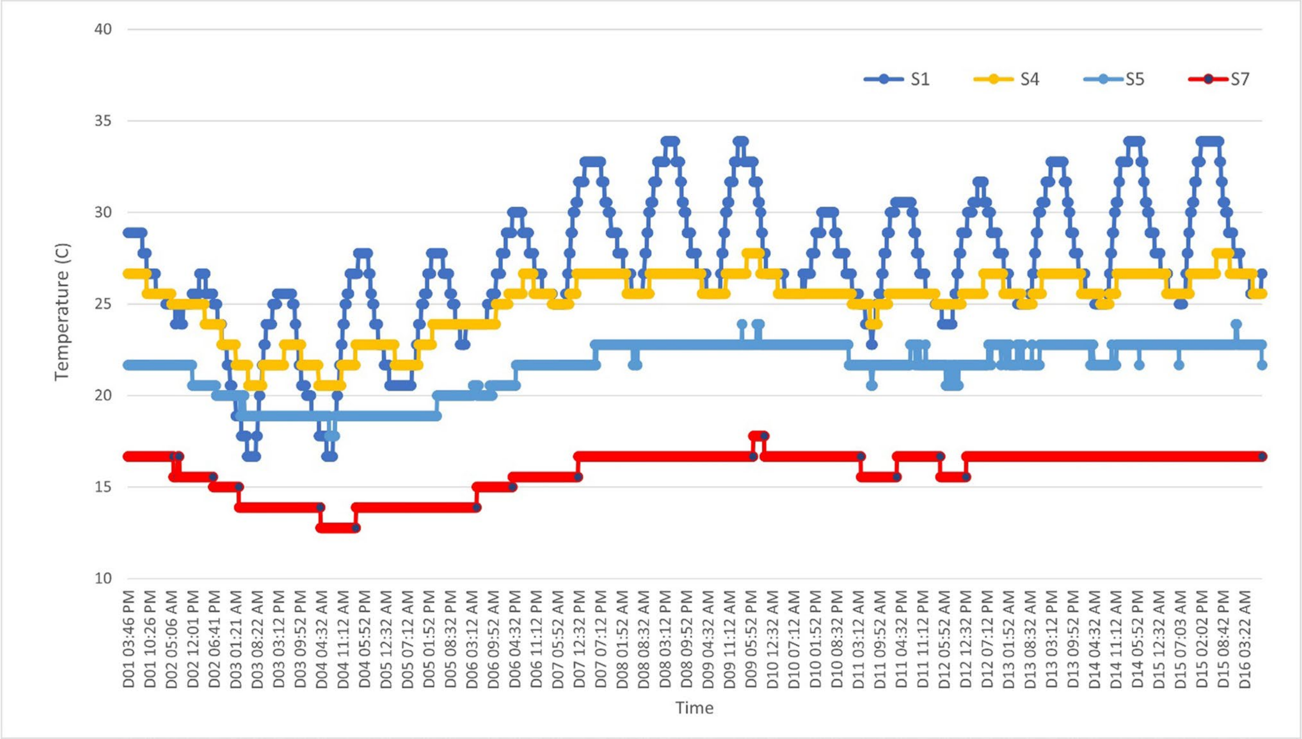
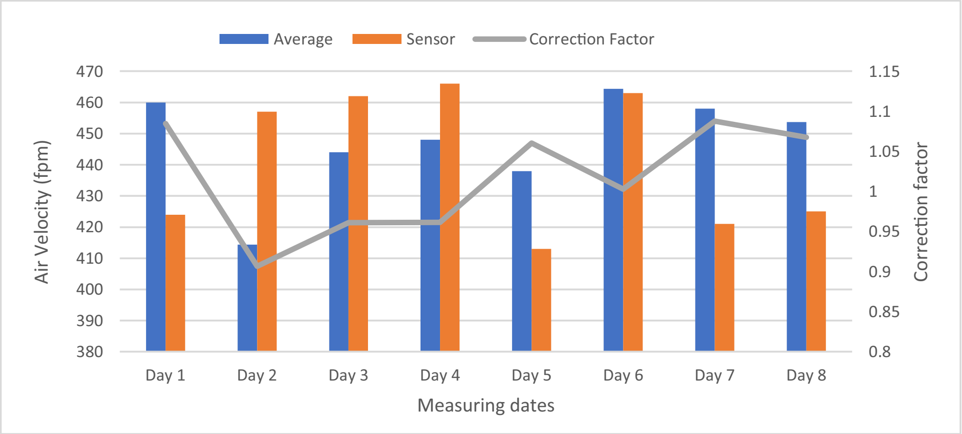


Fig. 7 Monitored temperature at the AMS stations S1, S4, S5, and S7

Fig. 8 The average air velocity, sensor reading, and correction factor at sensor S1A



correction factor ranges from 0.74 at sensor S4A to 1.31 at sensor S8. These results indicate that the air velocity measured directly from the sensor could be off by up to 30% from the average velocity over the cross section without applying the correction factor. A correction factor smaller than 1 indicates that the air velocity measured by the sensor is larger than the average air velocity and a correction factor larger than 1 means the air velocity measured by the sensor is smaller than the average air velocity. The average correction factor at each sensor location is applied to convert the sensor velocity reading to the average air velocity in this paper.

5 Calibrating The Srcm Ventilation Network

The purpose of ventilation network calibration is to adjust the airway resistances to allow the simulated airflow to match the measured airflow. Before a mine ventilation network can be calibrated or updated, the airways where the resistance changes occur need to be determined. The resistance changes could result from adjusting a regulator, putting up/down a curtain, opening/closing a door, or a new development, etc. As discussed above, we have generated a very reliable ventilation network model for SRCM from

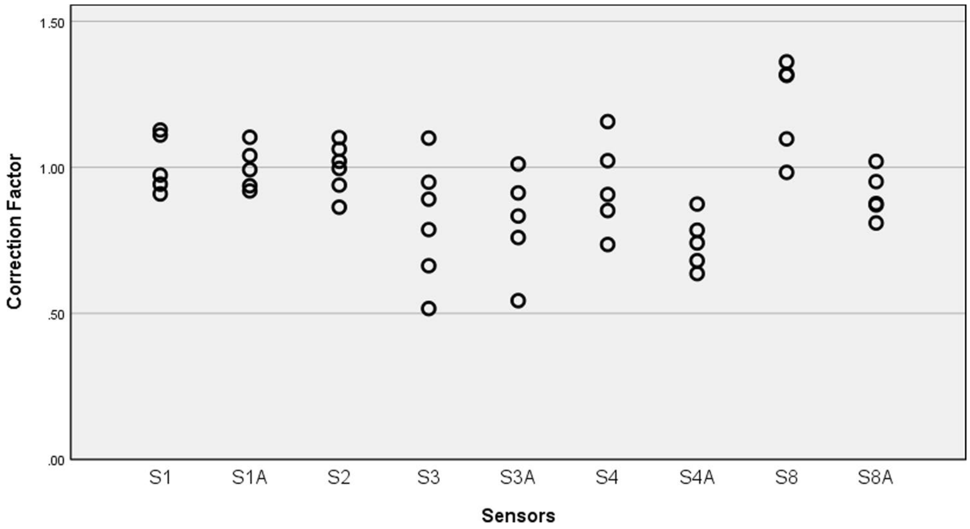


Fig. 9 Correction factor for selected sensor locations

three comprehensive ventilation surveys. In our fire tests, we frequently needed to change the ventilation configuration of the mine by putting up brattices to block airflow to a certain entry, opening doors to bypass airflows, or adjusting the opening of the door at the return portal to change the air quantity flowing through the mine. Whenever changes were made in the entries, the ventilation network model was calibrated correspondingly. Upon knowing the airway with the resistance change, we obtained a 24-h average air velocity of AMS velocity sensor readings for that airway and modified it using the appropriate correction factor to get a more accurate airflow rate for the calibration. In this way, we can adjust the resistance of that airway to match the AMS sensor measured airflow rates or set that airway as the fixed-quantity airway with the measured airflow rate and then use MFIRE to calculate the new resistance for the airway. One of the advantages of using AMS sensor data to obtain airflow rates over the manual spot check is that the AMS method can produce a time-averaged airflow rate while the spot check only produces the airflow at the moment of measurement.

6 CONCLUSIONS

A well calibrated and routinely tuned mine ventilation network is the key for using mine ventilation software for ventilation planning, optimization, as well as mine fire simulation. In this work, a new method was developed to calibrate a mine ventilation network model using the continuously monitored AMS air velocity and other atmospheric data. The method was demonstrated using the mine ventilation network model of the Safety Research Coal Mine and monitored AMS data. Results indicate that the instantaneous air velocity data cannot be used directly for the ventilation network calibration because of fluctuations. The fluctuations in the AMS monitored air velocity exhibit a wave pattern, and as the sensor location is further away from the mine portal, the wave pattern becomes less significant. It is found that temperature and air velocity readings are well correlated indicating that the velocity is affected by the temperature. To achieve better simulation results, it is recommended to use the time averaged air velocity reading to calibrate the ventilation network model. The AMS sensor measured velocity point reading also needs to be converted correctly to the average velocity over the cross section of the airway using the sensor location correction factor. Measurement results in this study show that the sensor location correction factor is location specific and can range from 0.74 to 1.31. Results from this study demonstrate that the continuously monitored AMS air velocity data can help mine ventilation engineers better calibrate their ventilation network models to achieve more accurate ventilation simulation results.

Acknowledgements The authors wish to thank John Soles and Jarod Myers of the Pittsburgh Mining Research Division for conducting the full-scale AMS test. Data from this manuscript had been presented at the virtual 18th North American Mine Ventilation Symposium, June 12-17, 2021.

Declarations

Conflict of Interest The authors declare no competing interests.

References

1. Bahrami, D., Yuan, L., Zhou, L., and Rowland, J.H. (2019). New mine fire location model utilizing real-time gas monitoring Data. 17th North American Mine Ventilation Symposium, Montreal, Canada, pp 30–37.
2. Baris, K., Adydin, Y., (2020). Atmospheric monitoring systems in underground coal mines revisited: a study on sensor accuracy and location. Int. J. Oil, Gas and Coal Technology, Vol. 23, No. 3, 2020.
3. Danko, G., Bahrami, D., Chao, L. (2015). Mine ventilation model calibration with numerical optimization, Proceedings of the 15th North American Mine Ventilation Symposium, Blacksburg, VA, June 20–25 pp.157–162.
4. Howden, VentSim 3D mine ventilation simulation software [Computer Software], retrieved from https://ventsim.com in 2020.
5. Iannacchione A., Joseb A., Hornc, T., Iannacchione, G., Iannacchione, S. (2015). Modeling the ventilation network at NIOSH's Safety Research Coal Mine, Proceedings of the 15th North American Mine Ventilation Symposium, June 20–24, 2015, Blacksburg, VA.
6. McPherson, M.J. (2009). Subsurface ventilation engineering (2nd Edition), published by Mine Ventilation Services, Inc.
7. NIOSH (2020). MFIRE [Computer Software], retrieved from https://www.cdc.gov/niosh/mining/works/coversheet1816.html.
8. Rowland, J.A. (2012). Barometric resistance surveys: a new perspective. Proceedings of the 14th North American Mine Ventilation Symposium, June 17–20, Salt Lake City, UT.
9. Strata Mechanics Research Institute at Polish Academy of Science (SMRI), VentGraph [Computer Software], retrieved from https://imgpan.pl/en/oferta/ventgraph in 2020.
10. Xu, G., Huang, J., Nie, B., Chalmers, D., Yang, Z. (2018). Calibration of mine ventilation network models using the non-linear optimization algorithm. Energies, 2018, 11, 13; doi:https://doi.org/10.3390/en11010031.
11. Zhou L, Yuan L, Thomas RA, Iannacchione A (2017) Determination of velocity correction factors for real-time air velocity monitoring in underground mines. International Journal of Coal Science and Technology 2017(4):322–332
12. Zhou L., Yuan L., Bahrami D., Thomas R.A., Rowland JH (2018) Numerical and experimental investigation of carbon monoxide spread in underground mine fires. J Fire Sci 36(5):406–418
13. Zhou, L., Yuan, L., Bahrami, D., Thomas, R.A., Cole, G. (2019). Study on integration of real-time atmospheric monitoring system monitoring data and MFIRE simulation. Proceedings of the 16th North American Mine Ventilation Symposium, Montreal, Canada, April 28-May 1, pp. 794–803.
14. Zhou, L., Yuan, L., Thomas, R.A., Bahrami, D., Rowland, J.H. (2020). Determination of a mine fire intensity using atmospheric monitoring system in a ventilation network. Proceedings of 2020 SME Annual Conference & Expo, Phoenix, AZ, February 23–26, Preprint 20–005.
15. Zhou, L., Thomas, R.A., Yuan, L., Bahrami, D. (2021). Improving calibration of a mine ventilation network using continuous airflow monitoring, Proceedings of the 18th North American Mine Ventilation Symposium, Virtual, June12–17, pp 518–528.