Underground Ventilation – Tukkaraja (Ed)

Case study on the abnormal airflow diagnosis method using atmospheric monitoring data

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ABSTRACT: A stable and well-maintained mine ventilation system is the key to ensuring a safe and healthy working environment for miners. A sudden, unplanned, and significant change in airflow termed as abnormal airflow is frequently observed in mine ventilation. Some abnormal airflows can return to normal without manual intervention; however, some abnormal airflows may cause catastrophic accidents if left unattended. In addition, abnormal airflow may be a consequence of an accident such as a blocked airflow route due to a roof fall. Promptly diagnosing and locating the cause of abnormal airflow can help prevent accidents. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have developed a method to diagnose the cause of abnormal airflow for underground mine ventilation systems. The purpose of this paper is to verify the developed method using experimental tests conducted at NIOSH's experimental mine. The airflows were monitored by a real-time atmospheric monitoring system installed in the experimental mine during the tests. As demonstrated in this case study, the developed abnormal airflow diagnosing method, based on the resistance sensitivity and matching method, has been proven to be reliable.

Keywords: Mine ventilation, Network modeling, Atmospheric monitoring system, Abnormal airflow

1 INTRODUCTION

Ventilation is the lifeline of underground mines to provide the underground workings with fresh air in sufficient quantity and quality, dilute and remove dust and noxious gases, and regulate temperature and other conditions. A stable and well-maintained mine ventilation system is the key to ensuring a safe and healthy working environment for miners. The efficiency of mine ventilation highly relies on airflow distributions and airflow quantities in the mine ventilation system. The airflow distributions are closely monitored and controlled during the life of an active mine. Changes in airflow quantity or direction are not rare in the routine management of ventilation. The airflow changes can be categorized as: 1) planned changes for the purpose of maintaining a safe and healthy working environment; 2) periodic changes associated with atmospheric conditions such as barometric pressure, temperature, humidity, and so on; 3) expected temporary changes from the interference of moving equipment; 4) sudden, unplanned, and significant changes due to some hidden hazardous conditions or malfunction of ventilation fans. The fourth category of airflow changes can be termed abnormal airflow if the changes in quantity exceed a certain level. The abnormal airflow can be caused by some kinds of failures in ventilation. For instance, unattended opening/closing of a ventilation door, airpath blockage due to roof collapse, fan stoppage, or any other unforeseen hazardous condition. The abnormal airflows may cause catastrophic accidents if left unattended. For example, insufficient air supplies resulting from abnormal airflow may induce elevated levels of hazardous gas accumulation. Therefore, promptly

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diagnosing and locating the cause of abnormal airflow can help prevent accidents. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have developed a method, named as abnormal airflow diagnosis method, to assist the diagnosis of the cause of abnormal airflows for underground mine ventilation systems (Bahrami & Zhou, 2022). Bahrami & Zhou (2022) also verified the abnormal airflow diagnosis method using the cases generated with ventilation network modeling. The method was found to be reasonably accurate in locating an unknown source airway caused by a flow resistance change in a ventilation network. However, the verification was based on model-based numerical data which tends to provide "perfect" cases without involving any interferences from the real world. There is a need to test the proposed method using real-world scenarios. For this reason, we have conducted a ventilation test at NIOSH's experimental mine by changing airflow distribution while monitoring of the Atmospheric Monitoring System (AMS) and testing the abnormal airflow diagnosis method using the experimental data. In this paper, while we refer to our earlier work (Bahrami & Zhou, 2022), the focus is to experimentally verify and demonstrate how to diagnose an abnormal airflow using the proposed method with the monitored AMS data.

2 METHODOLOGY

The abnormal airflow diagnosis method referred to in this paper is based on the availability of the sensitivity matrix for a given mine ventilation network and the matching method which compares the monitored airflow changes with their sensitivities from the sensitivity matrix. For a better understanding of the diagnosis procedure, a brief introduction to the sensitivity matrix and the matching method is necessary. These have been described comprehensively by the authors previously (Bahrami & Zhou, 2022; Zhou & Bahrami, 2022).

2.1 *Sensitivity matrix*

The airflow quantity distributed to each airway of a mine ventilation system depends on the schematic connecting diagram of airways, the resistance of airways, and air pressures produced by mechanical fans or/and natural ventilation. For a given mine ventilation network, a resistance change in an airway will affect the airflow quantities in other airways more or less. The resistance sensitivity is frequently used to quantify airflow change in a certain airway due to resistance change in another airway (Li et al., 2011; Dziurzynski et al., 2017; Griffith & Stewart, 2019; Jia et al., 2020; Zhou & Bahrami, 2022). Mathematically, the resistance sensitivity can be expressed as (Zhou et al., 2007; Jia et al., 2020):

$$s_{ij} = \lim_{|\Delta R_j \to 0|} \frac{\Delta Q_i}{\Delta R_j} = \frac{\partial Q_i}{\partial R_j} \tag{1}$$

Where S_{ij} is the sensitivity of airway i to the change of resistance, ΔR, in airway j; R_j is the resistance in airway j, and Q_i is the volumetric airflow rate in the airway i. Given a ventilation network with N airways, each airway can have N sensitivities to the rest of the airways and itself. Therefore, an $N \times N$ sensitivity matrix S can be formed for the ventilation network (Zhou & Bahrami, 2022):

$$S = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1N} \\ s_{21} & s_{22} & \cdots & s_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ s_{N1} & s_{N2} & \cdots & s_{NN} \end{bmatrix} \tag{2}$$

2.2 *Matching method*

The sensitivity resistance matrix of a ventilation network serves as a benchmark to indicate the interdependence of airflow and resistance of any two airways. If any unexpected airflows are detected in a ventilation system, the airflow changes can be compared to their sensitivity columns in the sensitivity matrix for each airway to find out which airway can cause a similar airflow change pattern and has the closest airflow change quantities. Bahrami & Zhou (2022) employed Root Mean Square Error (RMSE) to measure how well the changed airflows match the sensitivity of each airway. For each airway in the network, a corresponding scale factor is determined by minimizing the corresponding RMSE. It is assumed the airway with the minimum RMSE is the airway that has caused the abnormal airflow due to its resistance change. For detailed information about the matching method, refer to Bahrami & Zhou (2022).

3 VENTILATION TESTS AT THE SAFETY RESEARCH COAL MINE

The Safety Research Coal Mine (SRCM) is one of the two experimental mines located at the Bruceton Campus of NIOSH in Pittsburgh, PA. Despite the smaller size of entry (6.5 ft high by 14 ft wide) compared to the operating mines nowadays, this room-and-pillar mine has a complete ventilation network and has been frequently used for research regarding mine ventilation, mine fires, and other studies (Zhou et al., 2017, 2018, 2019, 2020). 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 main airflow getting into the mine is controlled by the main fan and a door at the main return entry. The layout of the SRCM is shown in Figure 1.

The SRCM is equipped with a mine-wide AMS to continuously monitor the atmospheric condition of the mine. Nine air-velocity sensors are arranged throughout the mine to monitor the real-time air velocity (as shown in Figure 1) for the ventilation tests conducted in this study. The sensors are all mounted close to the roof in the middle of the entry. The airflows are continuously monitored at these locations with a server on the surface to store air-velocity readings every minute.

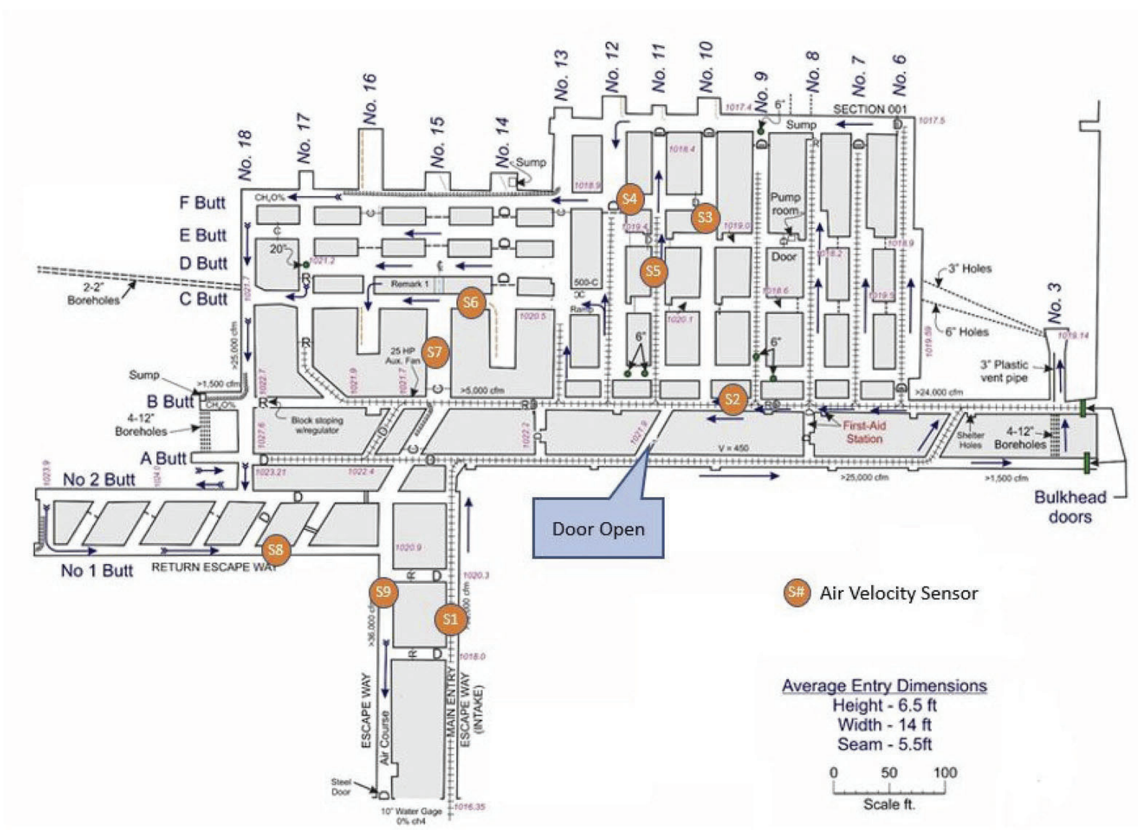

Figure 1. Air-velocity sensor locations within the SRCM.

Within the SRCM, a door in the entry connecting B Butt and A Butt remains closed for normal ventilation (as shown in Figure 1). To create an abnormal airflow scenario, we intentionally open this door and maintain the open status for approximately 17 hours for our testing. The real-time air velocities at the nine AMS monitoring locations were recorded using air-velocity sensors every minute. Figure 2 shows the monitored air velocities from Sensors S2, S3, S4, and S5 during the time the door was open There was a large air-velocity drop at Sensor S2 from around 500 ft/min to 250 ft/min when the door was opened. The air velocity returned to 500 ft/min after the door was closed. Upon opening the door, a slight air-velocity increase can be seen at Sensors S3 and S4. Sensors S1, S6, S7, S8, and S9 do not see significant air-velocity changes upon opening and closing the door. Therefore, they are not plotted in the figure.

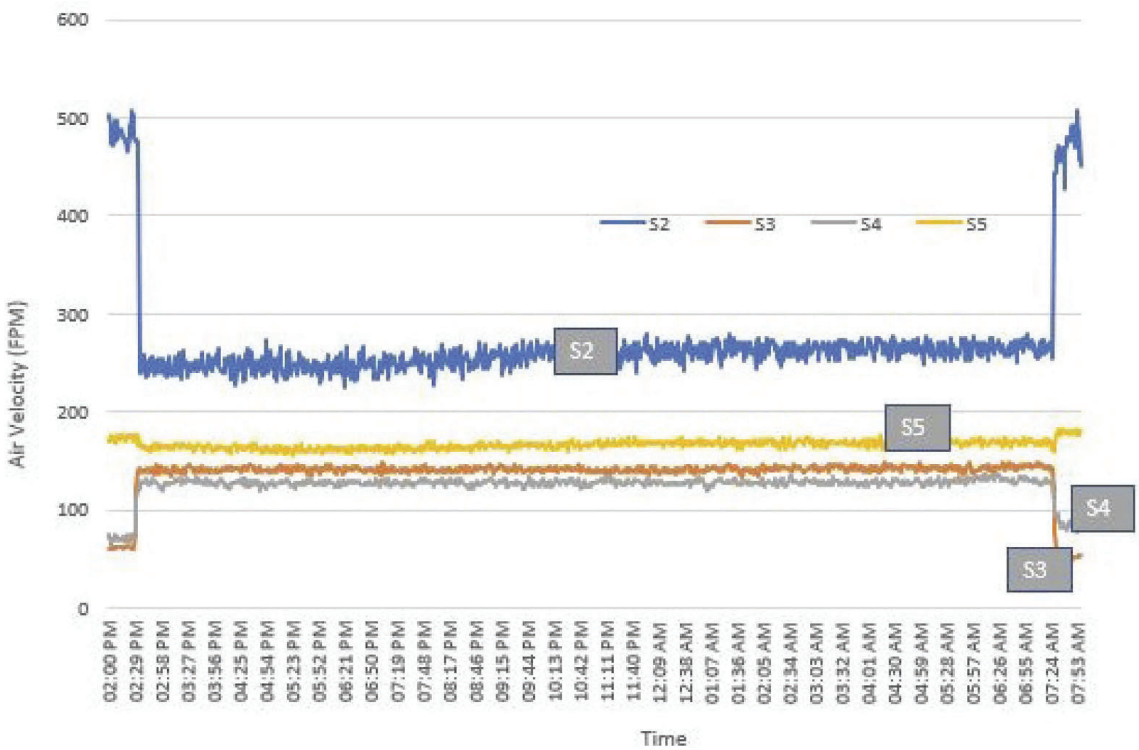

Figure 2. Monitored air velocities at Sensor S2, S3, S4, and S5.

4 SRCM VENTILATION NETWORK MODEL CONSTRUCTION AND CALIBRATION

As it was mentioned above, the abnormal airflow diagnosis method proposed in this paper consists of two major parts: one is the resistance sensitivity matrix for a ventilation network, and the other is the matching method using RMSE. The generation of the resistance sensitivity matrix of a ventilation network is based on one-time ventilation simulation results. Therefore, the collaboration of the network model and the mine is critical to ensure a good application of the abnormal airflow diagnostic method. Continuous efforts have been made to establish and maintain a well-calibrated ventilation network model for the SRCM (Iannacchione et al., 2015; Zhou et al., 2022). The schematic outline drawing of the SRCM ventilation network including 166 airways is displayed in Figure 3. The source airway of the abnormal airflow, where the door is maintained open for the test, is labeled as Airway #40 in the network drawing.

Table 1 displays the comparison of the measured airflows from all nine air-velocity sensors and simulated airflows using MFIRE, which is an open-sourced mine fire simulation program having ventilation network simulation capability. The calculation of resistance sensitivity is

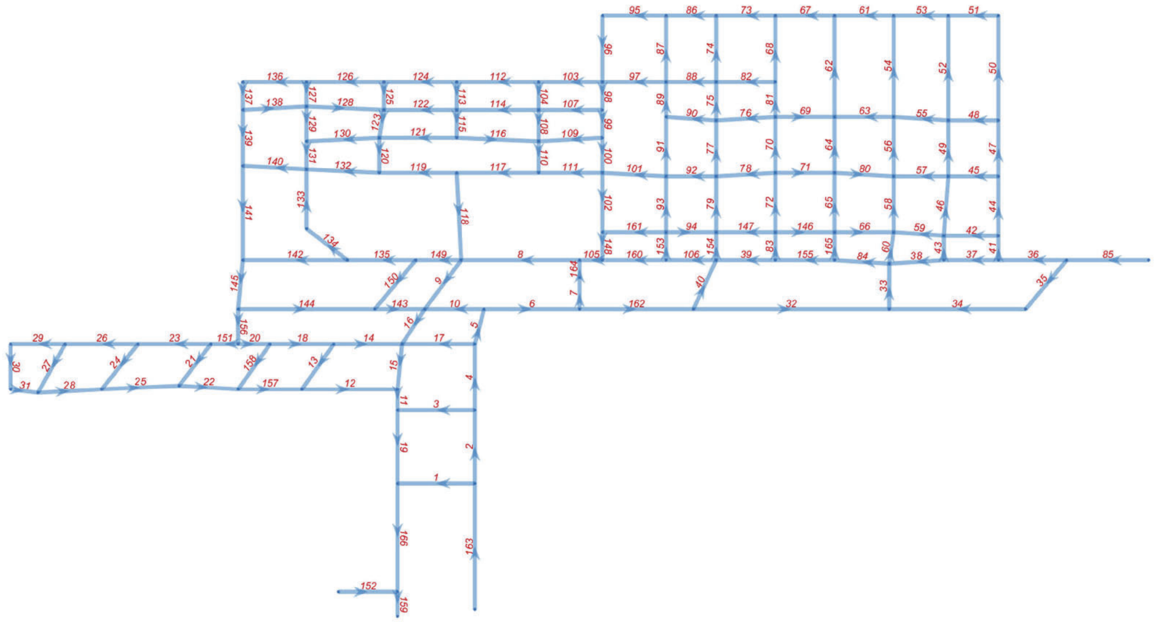

Figure 3. Schematic drawing of the SRCM ventilation network with airway numbers.

implemented in MFIRE as well (Zhou & Bahrami, 2022). Due to the fluctuation in the air-velocity sensor readings, a week-long average air velocity at each sensor was used as the value of the measured air velocity. With the known cross-sectional area for each sensor location, the airflow rate can be obtained by multiplying the average sensor reading by the cross-sectional area at each sensor location. However, the calculated airflow rate is based on the point reading of the air-velocity sensor instead of the average airflow rate through the whole cross-sectional area as the air-velocity sensor measures the air velocity 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. A correction factor for each sensor location was introduced and calculated to convert the point airflow rate to the average airflow rate following the same procedure illustrated by Zhou et al. (2017) and by Zhou & Bahrami (2022). The adjusted airflow rates using these correction factors are considered the final airflow rates. The comparisons were made between the adjusted airflow rates and the simulated airflow rates using MFIRE. The average difference for all the sensor locations was 4.63% with the largest difference occurring at Sensor 4.

Table 1. Comparison of measured and simulated airflow at monitoring locations.

Sensor ID	Measured Velocity (ft/min)	Area (ft^3)	Airflow (kCFM)	Correction Factor	Adjusted Airflow (kCFM)	Simulated Airflow (kCFM)	Difference
1	436.69	65.83	28.75	1.01	28.46	29.56	3.71%
2	449.13	58.00	26.05	1.01	25.79	23.23	–11.03%
3	43.8	73.37	3.21	0.85	3.78	3.29	–14.91%
4	95.44	76.38	7.29	0.81	9.00	7.29	–23.45%
5	186.11	69.30	12.90	0.94	13.72	11.96	–14.73%
6	235.63	97.35	22.94	0.90	25.49	23.64	–7.82%
7	182.57	62.25	11.36	0.95	11.96	12.39	3.45%
8	191.58	62.25	11.93	1.10	10.84	9.43	–14.97%
9	479.2	70.71	33.88	1.13	29.98	30.88	2.90%
Average							4.63%

5 RESULTS AND DISCUSSION

By applying the derivative method implemented in MFIRE (Zhou & Bahrami, 2022), a 166-by-166 resistance sensitivity matrix was obtained for the SRCM ventilation network. In the sensitivity matrix, if we say the rows represent the source airways where resistance changes are made and the columns represent the target airways whose airflow changed according to the resistance change at each airway, an element S_{ij} in the ith row and jth column is the rate of airflow change in airway j responding to the resistance change in row i.

As shown in Figure 2, airflow changes occurred at Sensors S2, S3, S4, and S5 while opening the door at Airway #40.

Table 2 summarizes the monitored airflow changes at all nine sensors and the corresponding airway number (#) of each sensor in the SRCM ventilation network.

Table 2. Airflow changes at all monitoring locations.

Sensor	S1	S2	S3	S4	S5	S6	S7	S8	S9
Airflow change (CFM)	0	13,167	3,413	2,173	–902	0	0	0	0
Airway # of sensor in network	2	155	81	88	77	117	118	157	19

In this case, the airflow change at Sensor S2 located in Airway #155 is obviously abnormal due to the significant airflow reduction of 13,167 cfm. To find out the possible source airway-(s), whose resistance change has caused similar airflow changes in all sensor airways including Airway #155, all the monitored airflow changes, including zero changes, at all nine sensor airways are set as target airflow changes. Then the columns, representing the corresponding sensor airways, in the resistance sensitivity matrix are extracted out to be used to match the input airflow changes. Before applying the abnormal airflow diagnosis method, each row is screened for the sorted sensitivities to eliminate all-zero rows. An all-zero row means that the resistance change in the airway represented by this row has no influence on all monitored airways, and the calculated RMSE of the all-zero row airway will be zero as well. Figure 4 is showing the RMSE for each non-zero sensitivity row. It can be seen that Airway #40 has the least RMSE which indicates Airway #40 is the best matching airway to cause the airflow changes in the monitored airways, as well as the abnormal airflow change in Airway #155. In addition to Airway #40, Airways #145, #155, and a few others can also be the source airways causing the airflow changes in the monitored airways.

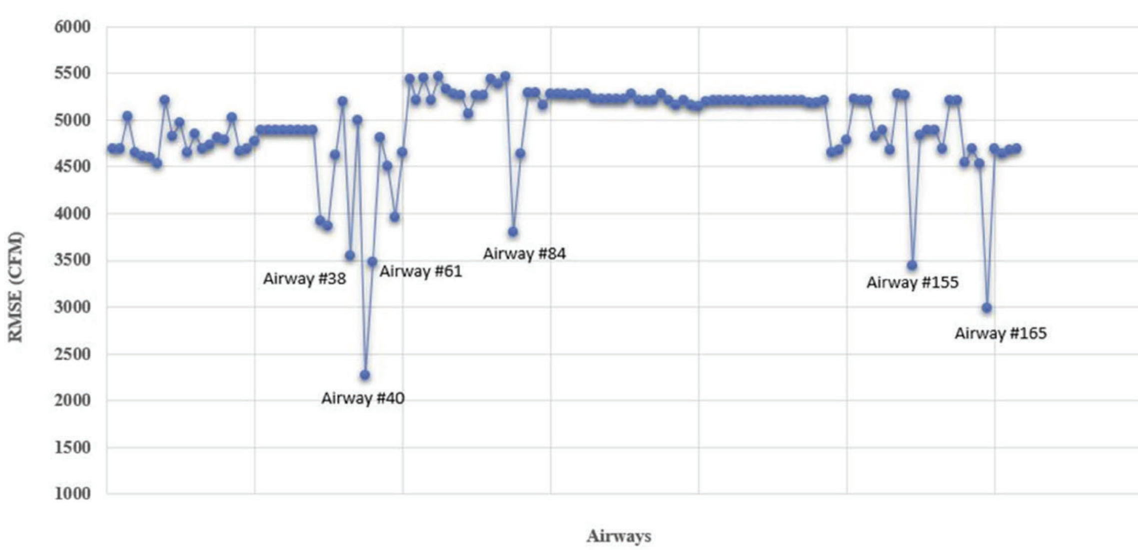

Figure 4. RMSE of non-zero airways for the case.

6 CONCLUSIONS

The abnormal airflow in underground mine ventilation could be an indication of a malfunction of the ventilation system. If left unattended, it may lead to catastrophic accidents. The cause of the abnormal airflow needs to be diagnosed, located, and mitigated to restore a safe working environment. An abnormal airflow diagnostic method has been developed previously by NIOSH researchers. In this work, the diagnostic method is verified experimentally using a ventilation test conducted at NIOSH's experimental mine. This paper has clearly shown that the abnormal airflow diagnostic method can diagnose the cause of abnormal airflow. In the ventilation test, air-velocity sensors from an AMS were used to monitor and collect air-velocity data. It has been demonstrated in this research that air-velocity sensors are a practical tool to detect abnormal airflow. From the research that has been carried out, it is possible to conclude that the abnormal airflow diagnostic method can be potentially used in practice in the future.

To ensure a successful application of the abnormal airflow diagnostic method in a mine ventilation system, the constructed mine ventilation network model must be as close as possible to the real operating condition. The number and the selection of the monitored airflow change inputs also plays an important role in the outcome of the proposed method. The minimum number of input airflow changes is three. Further research has been planned to study the impact of the number and the selection of the input airflow changes regarding the confidence level of the results from the proposed method.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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