Forecasting gob gas venthole production performances using intelligent computing methods for optimum methane control in longwall coal mines

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A B S T R A C T

Gob gas ventholes (GGV) are used to control methane inflows into a longwall operation by capturing it within the overlying fractured strata before it enters the work environment. Thus, it is important to understand the effects of various factors, such as drilling parameters, location of borehole, applied vacuum by exhausters and mining/panel parameters in order to be able to evaluate the performance of GGVs and to predict their effectiveness in controlling methane emissions. However, a practical model for this purpose currently does not exist.

In this paper, we analyzed the total gas flow rates and methane percentages from 10 GGVs located on three adjacent panels operated in Pittsburgh coalbed in Southwestern Pennsylvania section of Northern Appalachian basin. The ventholes were drilled from different surface elevations and were located at varying distances from the start-up ends of the panels and from the tailgate entries. Exhauster pressures, casing diameters, location of longwall face and mining rates and production data were also recorded. These data were incorporated into a multilayer-perceptron (MLP) type artificial neural network (ANN) to model venthole production. The results showed that the two-hidden layer model predicted total production and the methane content of the GGVs with more than 90% accuracy. The ANN model was further used to conduct sensitivity analyses about the mean of the input variables to determine the effect of each input variable on the predicted production performance of GGVs.

1. Introduction

Longwall mining is a continuous process in an extensive area, where the roof is supported only temporarily during mining with hydraulic supports that protect the workers and the equipment on the face. As the coal is extracted, the supports automatically advance with the rate of mining, and the roof strata are allowed to cave behind the supports. The caved zone created by longwall mining is highly fragmented, and generally extends upwards three to six times the thickness of the mined coalbed.

Above the caved zone is a fractured zone characterized by mining-induced vertical fractures and horizontal fractures caused by separations along bedding planes. The thickness of the fractured zone can vary up to 100 times the height of the mined coalbed depending on the characteristics of the associated rock strata, thickness of the overburden, and the size of the longwall panel (Palchik, 2003). Any gas that is contained within the coal beds in this area of relieved stress, which is called "gob", will be released slowly over time, while free gas in other porous formations, such as sandstones, will be released more quickly. Relaxation of the roof rocks and the associated fracture connectivity allows gas to flow from all surrounding gas sources toward the underground workings, which eventually may create an unsafe condition for the underground workforce.

One common technique to control methane emissions is to drill vertical gob gas ventholes into each longwall panel to capture the methane within the overlying fractured strata before it enters the work environment. Although the drilling practices of GGVs may change based on local conditions, most gob gas ventholes are drilled to within a short distance, 10–30 m, of the coal bed being mined and cased with steel pipe. Commonly, the bottom section of the casing (generally about 60 m) is slotted and placed adjacent to the expected gas production zone in the overburden strata. The usual practice is to drill the gob gas ventholes prior to mining. As mining advances under the venthole, the gas-bearing strata that surround the well will fracture and establish preferential pathways for the released gas to flow towards the ventholes (Diamond et al., 1994).

Exhausters are placed on gob gas ventholes to maintain a vacuum on the wellbore to induce gas flow towards the venthole. Gas production may exhibit variable gas quality. In the early stages of production, the gas quality is generally high (>80% methane) after a hole is intercepted by the longwall. Relatively high production rates with high methane quality are usually sustained for a few weeks. Later in time, especially towards the end of the panel or after the panel is completed, gob gas production may exhibit decreased methane levels

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as ventilation air is drawn from the active mine workings. Commonly, when the methane concentration in the produced gas reaches 25%, the exhausters are shut down as a safety measure, and the holes may be allowed to free flow.

It is difficult to predict production performance of gob gas ventholes due to the involvement of multiple influential factors. Currently, a detailed model does not exist that realistically represents the multiple variables associated with underground coal mining operations and their interactions and influences on the performance of gob gas ventholes. Previously, Lunarzewski (1998) used boundary element and sequential bed separation methods for floor and roof strata relaxation and immediate roof bending separation, as well as gas emission rate calculations, to develop "Floorgas" and "Roofgas" simulation programs to characterize the strata relaxation zones, gas emission boundaries, and parameters for gas emission prediction. Palchik (2002) proposed a new mathematical model for estimation of productivity of gob gas ventholes associated with coal mining in the Torezko–Snezhnyanskya coal district in Donetsk, Ukraine. He established, for the specific conditions he studied, a relationship between methane emission from GGVs and the duration of well production using the Gaussian error distribution function and the Gaussian density function. These models allowed prediction of total volume of gas, duration of well production, and the time when maximum production rate occurred. However, he noted that in the mining area he studied that 87–95% of total gob gas originated from the mined coal itself and the contribution from additional gas resources over the extracted seam was insignificant. Also, the ventholes were free flowing without any vacuum pressure. Thus, his analytical model is naturally simplified and may not represent most situations, at least for the mines in the U.S. where the gob gas generally originates from the fractured strata overlying the extracted seam and flow is supported and maintained by an applied vacuum.

Ren and Edwards (2002) used a computational fluid dynamics (CFD) modeling approach to investigate gas capture from surface gob gas ventholes. That paper introduced how this approach could be used to improve the design of surface gob wells for methane recovery while minimizing the leakage of air into the gob. Tomita et al. (2003) developed a three-dimensional (3-D) finite element model (FEM) to predict the volume of methane gas emitted from surrounding coal and rock layers based on stress distribution and permeability changes. Karacan et al. (2005) developed a 3-D model of a longwall mining district to simulate the effects of longwall panel width on methane emissions and on the performance of gob gas ventholes. The focus of that effort was the prediction of the incremental change in methane emissions to be expected due to increasing panel width and the optimization of gob gas venthole completion and placement practices to capture more of this gas, thus preventing it from entering the underground workplace. Karacan et al. (2007) used reservoir simulation to investigate the effects of various completion parameters on gob gas venthole performance. In Karacan et al. (2005, 2007), moving boundary conditions were also added to the simulations, which made them more realistic but extremely difficult to model and simulate.

Despite the improvements in analytical and numerical modeling approaches, experience suggests that it is still difficult to accurately predict methane production for gob gas ventholes and that these predictions may be underestimated relative to actual gob gas venthole production by at least a factor of two or more. The key factor to this underestimation is the difficulty in incorporating in any predictive approach the many factors that affect venthole performance (Zuber, 1998). And in almost all cases, these factors are related non-linearly to each other and to the production performances. Thus, production predictions may be more successful if these non-linearities can be understood and unconventional modeling techniques, such as artificial neural networks (ANN) that can handle these non-linearities, can be used. ANNs are adaptable systems that can determine relationships between different sets of data to solve problems where conventional computer models are inefficient. These problems are either the non-polynomial type or the very complex problems that are difficult to describe mathematically. The key advantage of neural networks is their ability to recognize patterns between input and output space and to generalize solutions. However, a high set of input and output data is required to calibrate the ANN, which some cases limits the applicability of this technique.

ANNs have found their way into many fields of application due to their flexibility and accuracy when compared to statistical models. Patel et al. (2007) used artificial neural networks for estimation of gross calorific values of coals. Bagherieh et al. (2007) used the technique to study the relationships between petrography and grindability of Kentucky coals. Karacan (2007) integrated reservoir simulations during development mining with ANN to predict methane emissions into roadways and to optimize ventilation air requirements. Karacan (2008a, 2009) used artificial neural networks to model ventilation methane emissions from longwall mines and to select a proper degasification system using various factors. Maier and Dandy (2000) provided an excellent overview of modeling issues and applications of ANN for forecasting in engineering problems. The flexibility of ANNs and their accuracy make them a good candidate for use in evaluating and predicting gob gas venthole performances.

1.1. Objective of the study

The aim of this paper is to develop an ANN-based methodology to predict gob gas venthole production rates and methane concentrations based on venthole location, mining parameters, borehole location with respect to panel and surface terrain, and exhauster pressure. The data were obtained from 10 gob gas ventholes drilled over three adjacent panels mined in the Pittsburgh coal bed in the Southwestern Pennsylvania section of the Northern Appalachian basin. The production data were obtained by monitoring these ventholes for flow rate and methane concentration during and after panel extraction. The ANN model was built using a multilayer perceptron (MLP) approach and was trained (calibrated) and tested using the database to achieve minimum mean square error and high correlations between measurements and predictions. After a reasonable prediction with ANN was obtained, sensitivity analyses were run about the means of input variables to better understand the effects of each of these inputs on predicted outputs.

2. Drilling locations and completion parameters of the gob gas ventholes

The Northern Appalachian Basin in Southwestern Pennsylvania is a very important area for coal mining and for mining-related methane emission and capture using conventional boreholes and gob gas ventholes. Gob gas ventholes are commonly used to control the methane emissions from the fractured zone and are drilled from the surface to a depth that places them above the caved zone. The bottom section of the pipe is slotted and placed adjacent to the expected gas production zone.

The production performance of gob gas ventholes can be closely related to their locations, panel parameters, borehole completions, wellhead designs, and operation of the exhausters. Fig. 1 shows the locations of the ventholes that are evaluated in this study. Markowski (1998) reported that the main coal beds that are consistent and continuous in the study area of this paper are the Pittsburgh, Sewickley, and Waynesburg. The Redstone coal bed and Pittsburgh rider coals shown in Fig. 2-A are not continuous and can be present at some locations. In this geology, gob gas ventholes are generally drilled to within 12 m above top of the main coal seam in that mining area and are completed with a 61 m slotted casing at the bottom as shown in Fig. 2-B. Due to different drilling practices, however, the proximity

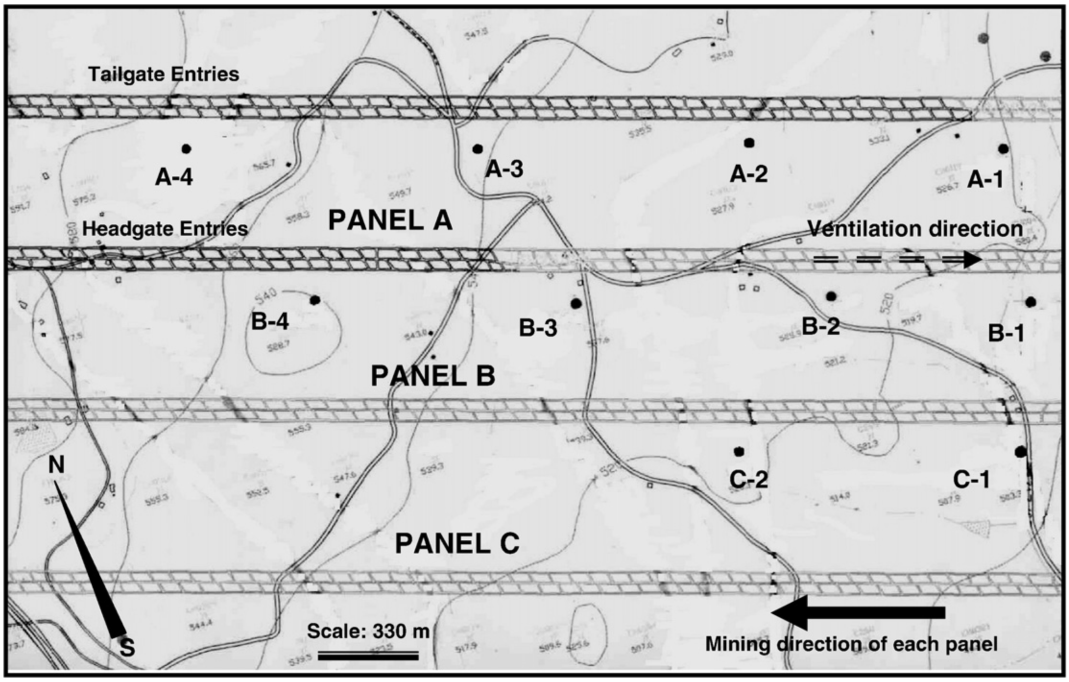

Fig. 1. Map of adjacent panels that were monitored for mining activities. Longwall mining started at Panel A and moved to Panel C as each panel was completed. The drill locations of 10 GGVs that were monitored for their production performances for a period of almost two years are also shown in this figure. Triple-horizontal lines are the entries for each panel.

of slotted casing's bottom to the top of the coal bed may change from venthole to venthole, although the length of the slotted section is kept more or less constant.

The location of a GGV with respect to the panel tailgate and panel start is usually calculated based on the subsidence profiles expected during mining in order to locate the ventholes in tension zones, where most fractures are open, to ensure maximum production from the fractured strata. The distances from the start of the panels and the distances between the ventholes along the panel are again based on maximizing productivity, on expected drainage radius of the ventholes, and on the emissions in the mines. It has been shown that the location of the ventholes on the panel is important for their performance (Diamond et al., 1994). In general, the holes on the ends of the panels are the highest-quantity and longest-duration producers. This is attributed to enhanced mining-induced fractures on the ends of the panels where the overburden strata are in tension on three sides due to the support of the surrounding pillars. Thus, placement of gob gas ventholes in the zone of tension along the margins of a panel, instead of in the traditional centerline location which is in compression due to subsidence and re-compaction of the longwall gob, may lead better production characteristics. Analysis of seven months of gas production from the Lower Kittanning Seam showed that the near-margin holes produced 77% more gas than did centerline holes on the same panel (Diamond et al., 1994).

Although the importance of placement of gob gas ventholes over the longwall panel for optimum productivity are recognized by many mining companies, the desired locations initially planned for drilling may change due to land ownership issues and due to the accessibility of planned drilling locations. These changes may lead to the ventholes being drilled at different locations (hill tops or valleys). Based on an earlier integrated study evaluating hydraulic properties of underground strata and their potential responses to longwall mining, ventholes drilled in the valleys may be more productive than the ones drilled on hill tops (Karacan and Goodman, in press) due to preexistence of structural fractures or fractures that can be extended easily (Wyrick and Borchers, 1981). Karacan and Goodman (in press) observed that the borehole location affects the fracturing time where hill-top boreholes seem to fracture earlier than valley-bottom wells. However, the permeability of the factures at the hill-top wells is less compared to that of valley-bottom wells due to greater overburden depths. Greater overburden depths usually cause lower hydraulic conductivities and potentially less effective boreholes as opposed to shallow GGVs. As the well locations approached the start up entry, average hydraulic conductivities were potentially higher indicating better production performances.

Casing diameter is another factor to be considered in calculating gob gas venthole performances. An earlier study (Karacan et al., 2007) showed that keeping the other completion parameters constant, increasing the gob gas venthole diameter increased cumulative methane production from the subsided strata. Although a marginal decrease in the methane concentration was evident from this change, possibly due to increased mine-air extraction with a larger sink, the increased gas flow rate increased the overall volume of methane produced. Also, casing setting depth with respect to the mined coal seam may play an important role on the amount and concentration of methane captured. Reservoir modeling results (Karacan et al., 2007) showed that when the setting depth was close to or within the caved zone, the methane concentration and the total amount of methane captured decreased. However, one additional consideration for changing the setting depth for the slotted casing may be the competency and productivity of the formations surrounding the slotted casing based on their mechanical properties and gas contents.

Borehole location and completion parameters impact gob gas venthole production performance in many ways and, for this reason, they should not be excluded from performance analyses. Table 1 gives the actual drilling and completion details of the 10 ventholes monitored for their production in this study. As this table shows, panel dimensions and venthole completion details differ. Thus, varying production performances can be expected from these ventholes.

3. Longwall face advance rates of studied panels

Gob gas venthole production performance during longwall mining is closely related to face advance rate that enhances fractures and increases permeability due to dynamic deformation and subsidence (Preusse, 2001). Karacan and Goodman (in press) observed that

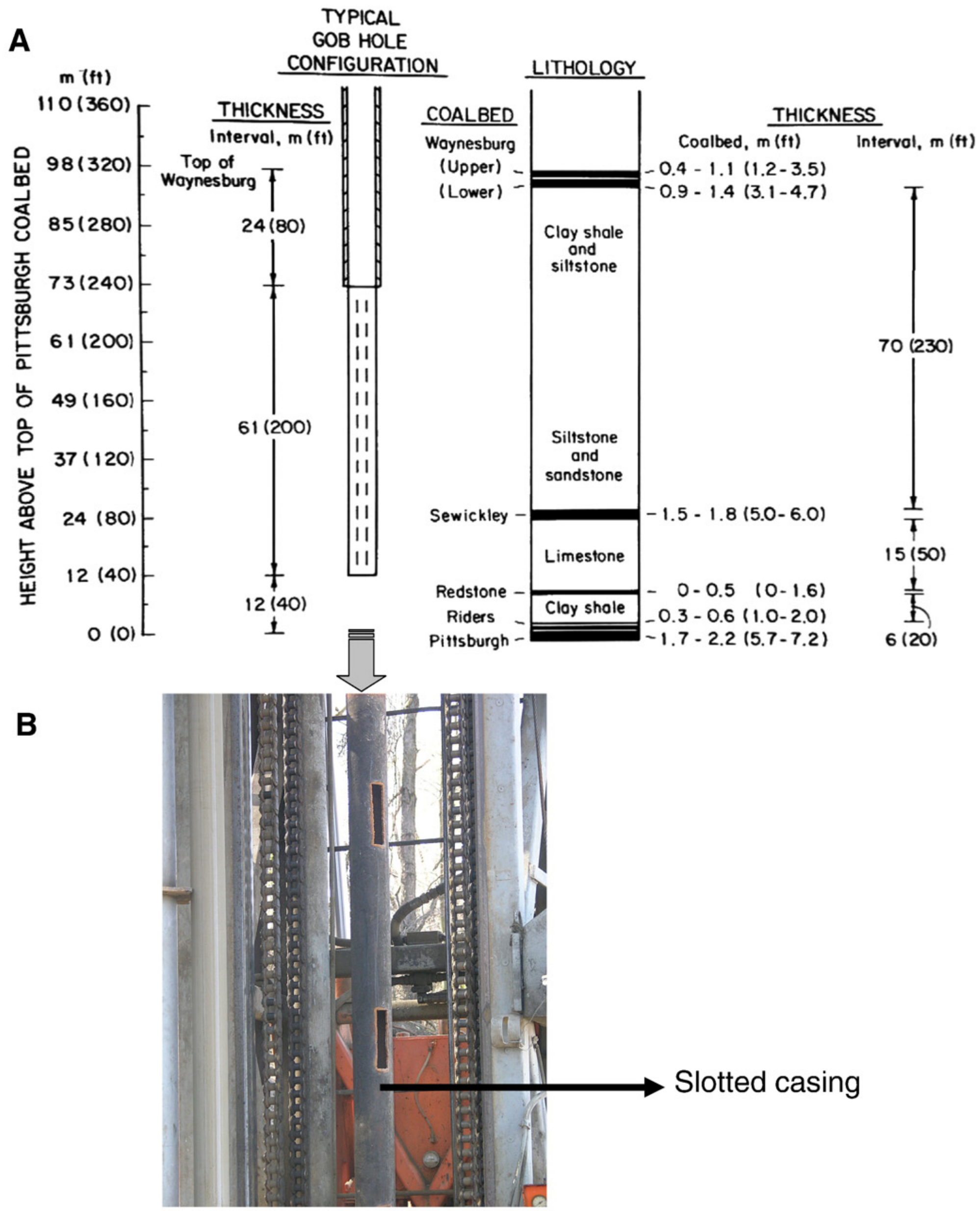

Fig. 2. A schematic representation of general stratigraphy over Pittsburgh coal bed in the Southwestern Pennsylvania section of Northern Appalachian basin and the typical gob gas venthole configuration that is used for methane control in longwall mines in this region (A). The depths and lengths shown in this figure are only representative numbers and can change based on the site-specific conditions. Panel B shows a picture of a typical slotted casing ready on the drill rig to be set into the venthole.

Table 1
Location, drilling and completion parameters of the monitored gob gas ventholes shown in Fig. 1.

Venthole	Surface elevation (m)	Overburden (m)	Distance to coal seam (m)	Casing diameter (cm)	Distance to tailgate (m)	Distance from panel start (m)	Panel width (m)	Panel length (m)
A-1	413.55	252.62	10.67	17.78	76.20	167.64	373.38	3361.94
A-2	379.21	215.23	10.67	17.78	79.25	822.96	373.38	3361.94
A-3	387.65	219.71	10.67	17.78	83.82	1623.06	373.38	3361.94
A-4	384.35	208.79	12.19	17.78	92.66	2404.87	373.38	3361.94
B-1	355.45	196.34	13.72	20.32	99.97	113.39	373.38	3291.23
B-2	402.87	240.72	13.72	20.32	73.15	649.83	373.38	3291.23
B-3	421.79	257.50	13.72	17.78	89.92	1369.16	373.38	3291.23
B-4	394.41	222.81	12.19	17.78	78.03	2094.59	373.38	3291.23
C-1	348.39	192.02	13.72	17.78	92.96	146.91	434.34	3379.01
C-2	444.70	282.85	14.63	17.78	78.03	934.52	434.34	3379.01

higher face advance rates resulted in lower hydraulic conductivity in the fractures, suggesting a possible impact on GGV performance.

Face advance also creates an extensively fractured methane reservoir from which the gob gas ventholes can produce gas. A faster face advance rate causes a larger percentage of the panel to subside and creates a larger fractured reservoir in a given time compared to a slower advance rate. Down times due to mechanical delays or vacation periods halt the expansion of fractured methane reservoir which eventually may affect gas production rates and methane percentages from gob gas ventholes.

The face advance rates reported by the mining company during longwall operation of A–C panels were gathered. The daily advance rates and the cumulative panel lengths mined were plotted. These data are shown in Fig. 3.

Fig. 3 shows the mining durations for each panel from the beginning of longwall operation. It took between 200 and 275 days to mine each of these panels and a total of 730 days to mine them all. In this graph, both daily advance rates and the cumulative panel percentage mined are shown as functions of mining duration. As it is presented in this figure, daily advance rates change from 0 m/day (face stoppage) to 25–30 m/day for all panels. Face stoppages are usually associated with mechanical delays at the face and they do not take too long for the mining to resume. Longest face stoppages occurred during miner's vacation periods as panels A and C were being mined. These periods were usually 14 days. The average face advance rates for these panels were between 10 to 15 m/day and it took approximately 4 months to mine 50% of each panel.

4. Measured wellhead vacuum pressures and gob gas venthole production histories

4.1. Evaluation of atmospheric pressures and the average vacuum values measured at the wellheads

In order to monitor production history of the gob gas ventholes in three adjacent longwall panels, the wellheads were instrumented with flow meters, pressure sensors, temperature sensors and methane detectors that continuously recorded the total gas flow, methane percentage, prevailing wellhead vacuum, temperature and atmospheric pressure data. Vacuum at the wellhead was measured at two points; above and below the flame arrestor to diagnose any plugging or pump operation problems. The average vacuum value reported in this study is the arithmetic average of these two measurements.

Fig. 4 shows the measured atmospheric pressures (top figure) and the average vacuum level prevailing at the wellheads (bottom figure) of each venthole due to operation of methane exhausters. This figure shows that atmospheric pressure fluctuates between 96 and 98 KPa at the monitoring sites. A general trendline in the figure shows the magnitude and characteristics of these fluctuations. These variations in recorded atmospheric pressure are seasonal and also due to the elevation of the boreholes (Table 1). The bottom figure, on the other hand, shows the variations in vacuum pressure and exhibits a more erratic behavior depending on the operation of the methane-driven engines. The exhausters used in monitored ventholes are four stage centrifugal pumps that are normally powered by diesel engines. However, these were converted to operate on methane mixtures for these applications. Thus, the vacuums generated by these systems are quite variable and may depend on fuel quality and air quality.

It is known that atmospheric pressure is an important factor for gas emission and production, especially from uncovered sources, i.e., when the gas source is in direct communication with atmosphere. The impact of barometric pressure fluctuations on the composition and emission of the landfill gas has been investigated (Nastev et al., 2001). They observed that when the barometric pressure increased, gas flux at the landfill surface decreased and even became negative probably because of the counter pressure. This resulted in atmospheric air intrusions in the upper landfill layers. On the other hand, landfill gas emissions increased with decreasing atmospheric pressures. In both cases, all of the gases regained their initial equilibrium fluxes, with a corresponding time delay in the gas composition response. Thus, they concluded that the rate of barometric pressure variation is an important factor to consider when sampling landfill gas. In a different study, the US Environmental Protection Agency (2004) collected gas flow and quality data during the spring of 1999 from a mine that was abandoned but had been venting to atmosphere since 1962. They correlated flow and methane percentage data to changes in atmospheric pressure. That study indicated that there was a strong inverse relationship between barometric pressure and methane emissions from the mine vent. However, this situation can be definitely different for closed sources underground as they will not have direct contact with the atmosphere. Although Mucho et al. (2000) suggested that pump elevation affects its operation because the atmospheric pressure

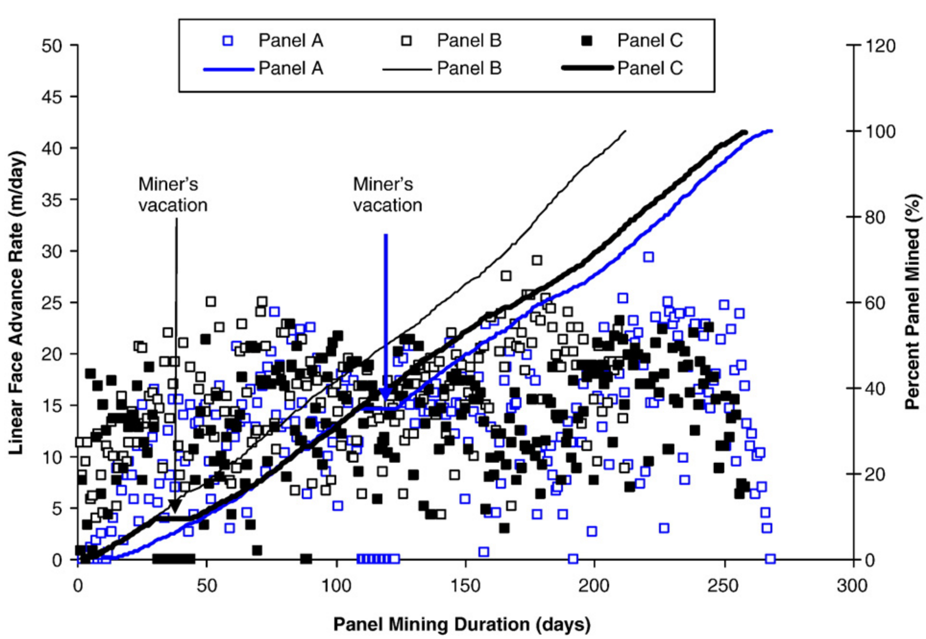

Fig. 3. Daily linear face advance rates and cumulative percentage of the lengths that have been mined for each panel.

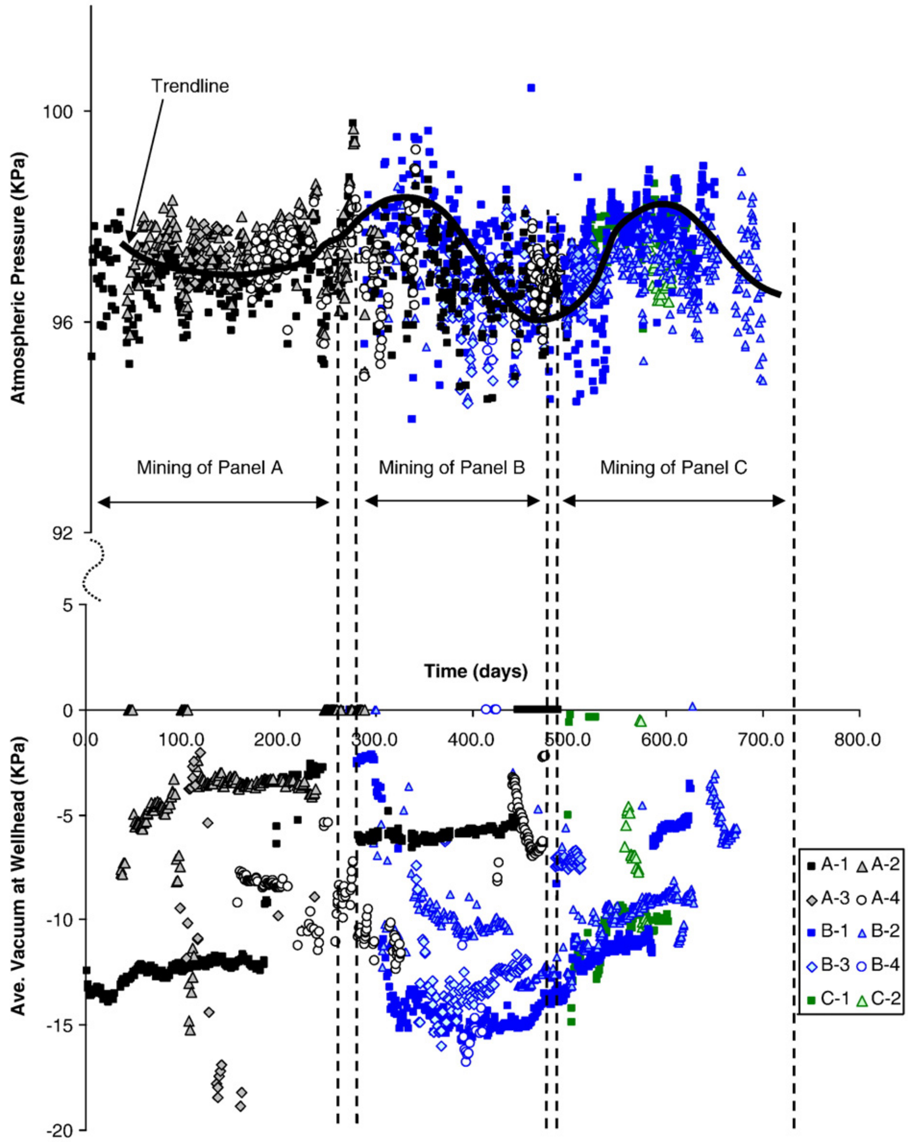

Fig. 4. Atmospheric pressure recordings and average vacuum values applied by the exhauster pump at the wellhead of each venthole. Average vacuum value was calculated based on the measured vacuum values below and above the flame arrestor at the wellhead. Vertical dashed lines indicate the start and completion days of the panels and the durations of mining in each panel. The short intervals between consecutive dashed lines are the durations where longwall moves occurred from one panel location to the next.

and oxygen content change, Fig. 4 does not show a clear relation between atmospheric pressure and the vacuum generated by the pumps because it depends more on the fuel quality.

A vacuum applied to the gob gas wellheads stimulates methane migration into the ventholes from the surrounding strata and prevents occasional flow reversals (Thakur, 2006). However, this advantage may be lost over time as there is tendency for mine air to be drawn into the gob area and dilute the methane (Ren and Edwards, 2002). A higher suction pressure has a positive but relatively small effect on drawing gas from overlying strata into the venthole. There is a limit to the amount by which the capture efficiency of a venthole can be increased by means of higher vacuum pressures. Higher suction pressure causes higher air leakage into the well and reduces the purity of methane (Mazza and Mlinar, 1977; Zuber, 1998; Mucho et al., 2000). In the monitored ventholes, most vacuums were less than 15 KPa (Fig. 4). For instance, during mining of Panel A, the vacuum on A-1 venthole was consistently high (13 KPa) for about 200 days, then decreased to 6–7 KPa during mining of Panel B and stayed at that level until the end of the production from this borehole. On the other hand, A-2 and A-3 ventholes started with pressures less than 5 KPa and, except for short-lived high vacuum values, stayed low (Fig. 4). The average vacuum pressure trends observed in the ventholes of Panel B (B-1 to 4) during mining and after completion of this panel are more expected. They started with low vacuum values, increased as mining continued, and later decreased possibly due to low flow rates.

4.2. Evaluation of total gas production rates—performance parameter 1

A production well's performance can be measured by various parameters, such as oil production (for oil wells), condensate production (for condensate wells), water production, water cut, gas composition, etc. Since the gob gas ventholes do not usually produce water and the main production is the gob gas composed of two main components (air and methane), total gas production and methane percentage, from which pure methane production can be calculated, were selected as performance parameters in this study.

Fig. 5 shows the total gas production history of monitored gob gas ventholes. Although the data is scattered, the general trends in observed gas productions show that the ventholes initially produce at higher gas rates and then enter a decline period with increasing time.

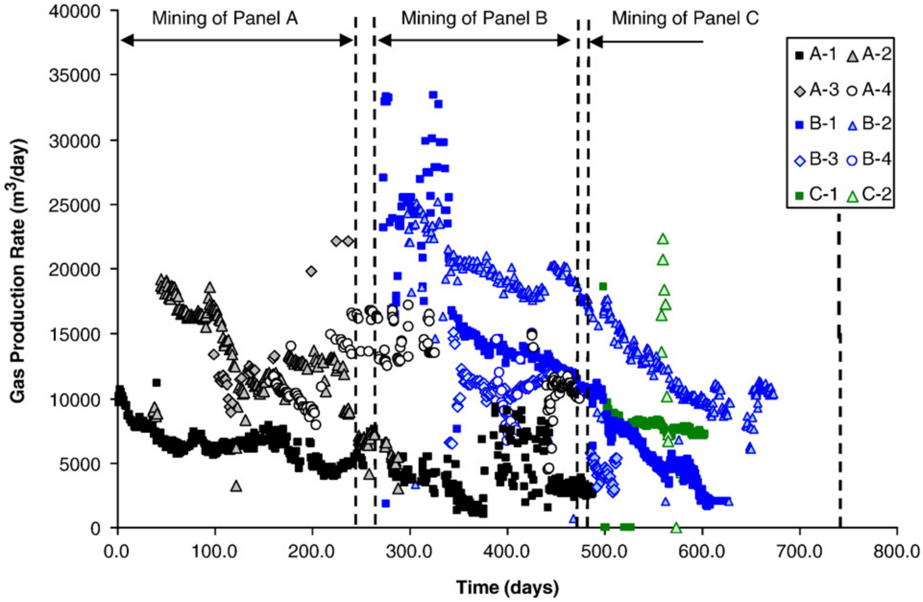

Fig. 5. Total gas production rate from each of the monitored ventholes in the panels. Vertical dashed lines indicate the start and completion days of the panels and the durations of mining in each panel. The short intervals between consecutive dashed lines are the durations where longwall moves occurred from one panel location to the next.

Most of the ventholes continue producing even after the panel, over which they are located, is completed. This figure shows that, even after panel completion, there is still enough gas emission in the gob for the ventholes to continue production. However, comparison of mining and after-mining periods of production generally shows that the production rate decline is faster after the corresponding panel is completed.

Another observation from the data in Fig. 5 corroborates earlier reports from a different site (Mucho et al., 2000); the first boreholes in each panel are the longest producers due to their close proximity to the panel start up entries. They are also expected to be the producers with the highest gas rate (Mucho et al., 2000) but the production history of A-1 shows that this is not always the case. However, they typically produce the highest methane percentage (Fig. 6). This is more obvious in panel A but not in panel B. This may be due to the adjacent nature of these two panels.

The position of the ventholes may affect their production potential. Ventholes drilled into areas where fractures extend towards the methane source are likely to achieve higher capture efficiencies while ventholes drilled into low-permeability strata or compacted portions of the gob will likely have a lower production rate even with a higher suction pressure. Comparison of Fig. 5 with Fig. 4 shows that total gas production rate is generally positively related to applied vacuum. In other words, as a harder vacuum is applied, the production rate from the ventholes somewhat increases. Adapting oil-field terms in this study, this indicates a relatively constant productivity index (PI), which is defined as the ability of a reservoir to deliver fluids to the wellbore and is stated as the volume delivered per pressure drawdown. Based on the data, the PI was calculated to be within 500–3000 m^3/day/KPa for this gob reservoir. This also shows that the productivity of gob gas ventholes can only be increased within a certain range with applied vacuum.

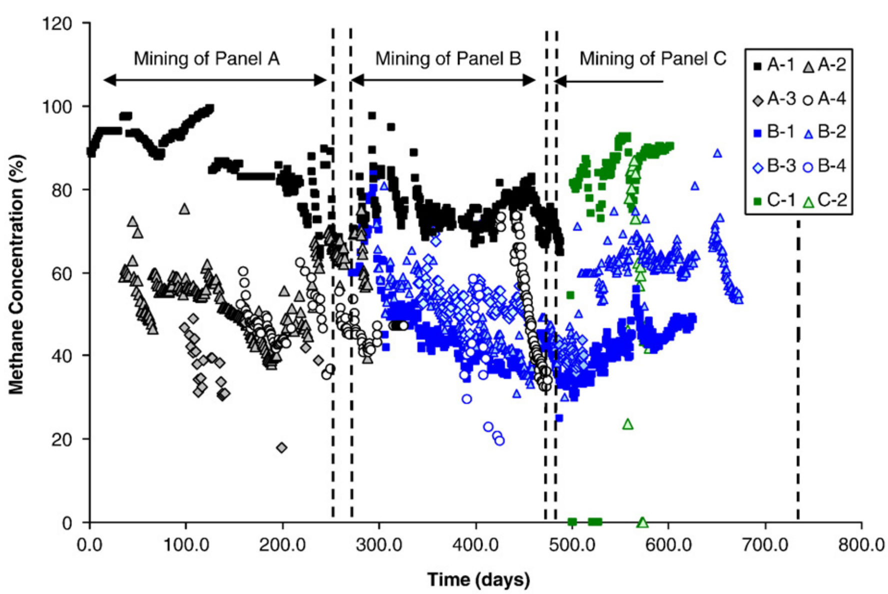

Fig. 6. Methane concentrations measured in the total production gas stream of each of the ventholes. Multiplication of this concentration with the total production gives methane production from each borehole. Vertical dashed lines indicate the start and completion days of the panels and the durations of mining in each panel. The short intervals between consecutive dashed lines are the durations where longwall moves occurred from one panel location to the next.

Tracer gas studies reported in Mucho et al. (2000) showed that gob gas ventholes in their study area were in communication with each other through the fractures within the overlying strata. They observed that SF_6 gas injected into an intaking venthole was detected at the next ventholes within hours to days depending on the distance. A similar observation for pressure communication was reported by Schatzel et al. (2008) who reported a decline in shut-in pressure of a monitoring borehole when a gob gas venthole became operational 76 m away from its location. Although, the ventholes monitored in this study were probably also in communication with each other in some ways, it was difficult to observe these effects from the production histories given in Fig. 5. However, this is another complicating factor in evaluation of gob gas venthole performances.

4.3. Evaluation of methane concentrations—performance parameter 2

The second performance parameter evaluated in this study is the methane concentration measured in venthole productions. Fig. 6 shows that methane concentration changes during the production life of the ventholes. As expected, ventholes generally start with higher methane concentration which then declines with time. That decline may be associated with the changes in wellhead vacuum and also with the production of available methane in the gob. Earlier researchers (Mazza and Mlinar, 1977; Mucho et al., 2000; Ren and Edwards, 2002) suggested that as vacuum is increased, especially close to or after completion of the panel, the venthole may start producing mine air. This suggestion is supported with the data in this study too. As a clear example, the decline in methane concentration from 80% to 40% in A-4 production during mining of Panel B (Fig. 6) is associated with an increase in average wellhead vacuum from −4 to −7 KPa (Fig. 4).

There are also two sets of methane concentration behaviors in Fig. 6 that are notable and worth discussing. The first one is the behavior of A-1 during and after completion of the panel. Although the average wellhead vacuum pressure dropped from ~−15 KPa to ~−5 KPa (Fig. 4), the methane concentration did not change that much. This may be due to the fact that this venthole was the first one in the first panel of a series of new panels to be developed in a new district. Thus, it was surrounded with virgin coal beds and other sources of methane, which might have helped it to produce high quality methane for a long time.

The second observation is the behavior of Panel B ventholes, particularly B-1, B-2 and B-3. During mining of Panel B, methane concentration from these ventholes declined steadily until the completion of Panel B and the start of mining in Panel C (Fig. 6). After Panel C mining starts, methane concentrations from these ventholes increase again towards their original concentrations with associated decreases in wellhead vacuum values, although total gas flow rates continue declining (Fig. 5). This behavior may be due to formation of the gob in Panel C, which extends the size of the methane reservoir available to Panel B ventholes.

5. Development and application of artificial neural networks to predict gob gas venthole performances

The previous sections discussed those factors that affect gob gas venthole performance. The difficulties encountered and the lack of knowledge about the relationships between them when incorporating these factors into a model makes ANNs one of the better candidates to predict gob gas venthole performances. ANNs can recognize the patterns between input and output space where non-polynomial type or mathematically very complex relations are present and can generalize solutions to forecast gob gas venthole performance.

Basically, a neural network is a computing tool that processes information by its dynamic state response to external inputs. One of the most widely used neural network topologies is the multilayer perceptron (MLP) because of its applicability to different problems (Hagan et al., 1997; Schalkoff, 1997) using a non-linear activation function (such as hyperbolic tangent) between its layers of processing elements. The non-linear nature of the activation function plays an important role in the performance of a neural network.

The neural network computes its output at each iteration (epoch) and compares it with the expected output of each input (exemplar) vector in order to calculate the error. The most widely used technique is to propagate the error back (back-propagation) and adjust the initially assigned random weights for each processing element. Minimizing the mean square error (MSE) is the goal of the optimization (training) process. During error minimization, it is preferable to find the global optimum rather than local optima. This situation is helped by applying a *momentum* factor between 0 and 1. Momentum increases the effective step size in shallow regions of error surface (Hassoun, 1995) and helps speed up the training process. This is the training technique used in the modeling described in this paper. Cross validation and testing are the performance measures of the network with new data that give confidence that the network is able to recognize the training patterns and generalize the relationships within a certain degree of acceptable error.

Since it has been established in other studies before (Eberhart and Dobbins, 1990; Mohaghegh, 2000; Maier and Dandy, 2000; Karacan, 2007, 2008a, 2009) the basic principles and components of an ANN model will not be repeated here. Readers are referred to these references for detailed discussions of ANNs and their uses in prediction and classification problems.

5.1. Database preparation and pre-processing for GGV performance prediction

In order to develop a database for modeling gob gas venthole productions and methane percentages, the data given in Table 1 and in Figs. 3–6 were combined and analyzed. These sources provided panel dimensions, venthole location details, venthole completion details, daily mining rate and daily completion percentage of the panels, daily average wellhead vacuum, daily barometric pressure readings, daily average production rate, and daily average methane percentage values. In addition to these, the conditions such as whether the panel was completed (0 for "Yes") or not (1 for "No") – to differentiate between borehole productions during mining and after completion of the panels, and whether there is face advancing (1 for "Yes") or not (0 for "No"), and to differentiate the coal production from idle periods, were introduced as additional parameters. With merging of all these daily data resulted in a database consisting of 16 parameters each having 1972 entries. Of these 16 parameters, 2 of them (gas production and methane percentage) are outputs to be determined using the remaining 14 variables (Fig. 7).

For pre-processing of these 16×1972 data, the whole dataset (exemplars) was first randomized and then separated into three sections for use in the training, cross validation, and testing phases. Randomization was used to prevent the biases and to make different sections of the dataset representative of the whole population. In separating the dataset, 197 out of 1972 exemplars (10%) were saved as cross validation data, 296 exemplars (15%) were saved as testing and 1672 exemplars (75%) were saved for training data. The criterion in breaking up the data was to allocate enough exemplars for the ANN training and testing.

5.2. Development of ANN models

The development and implementation of the ANN model were performed using NeuroSolutions™ v5.70 software (NeuroDimension, 2008). In order to determine an appropriate ANN topology and to identify network parameters for training and testing, various combinations of parameters were tested. Values of minimum and final mean squared error (MSE) were noted for training and cross validation of the ANN. Also, values of nominal mean squared error (NMSE), regression

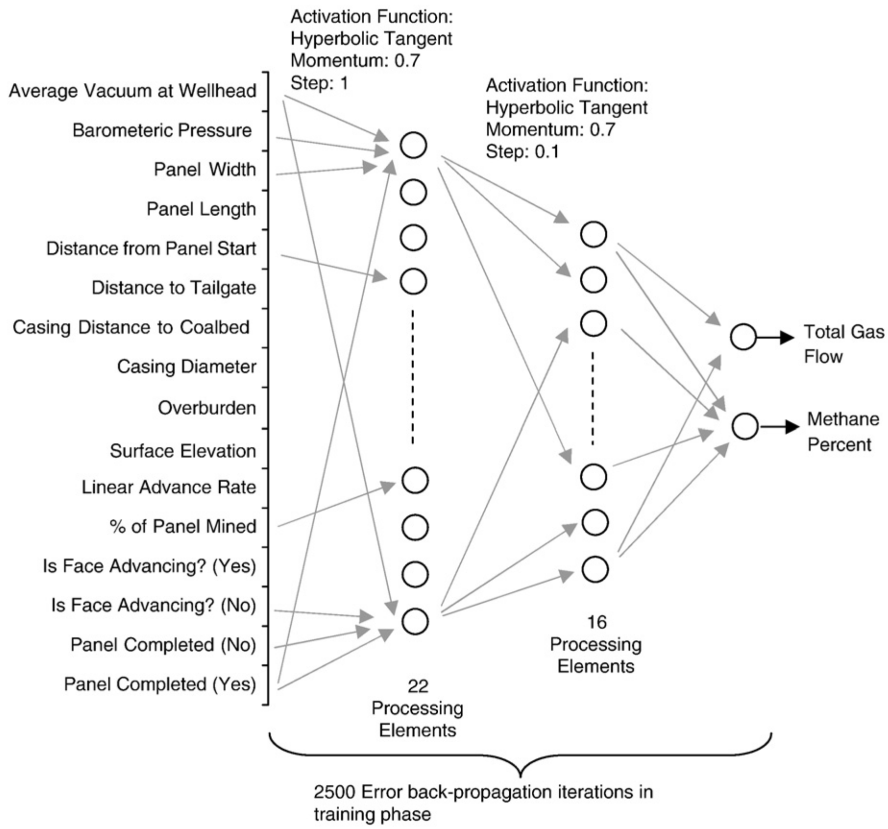

Fig. 7. ANN topology and its parameters that were developed to predict gob gas venthole performances.

coefficient, and absolute error were noted for testing the ANN. The number of hidden layers, the number of processing element in hidden layers, the number of training iterations, the type of transfer function, and the value of momentum were varied. The details of this procedure were given in Karacan (2007, 2008a, 2009). Based on this iterative and interactive procedure, a two-layer model with 22 processing elements in the first hidden layer and with 16 processing elements in the second hidden layer was selected as the basic architecture of the networks. Minimal training errors were noted when using the hyperbolic tangent activation function, "Tanh," between the layers with momentum parameters of 0.7 and 2500 iterations conducted twice. The schematic illustration of the architecture and model parameters, as well as inputs and outputs are shown in Fig. 7.

Table 2 shows the performance parameters for learning with cross validation for the network shown in Fig. 7. These data shows that minimum and final mean squared errors in training for the average of 2 runs are very low, 0.00416 and 0.00426, respectively, and they are close to each other. This shows that the iteration that gives the least error happens before the completion of 2500th (final) iteration. Average mean squared errors in cross validation are low too, 0.00446 and 0.00454 for the iteration that had the minimum MSE and final iterations, respectively. The fact that cross validation errors are slightly higher than, but close to, training errors indicates that the network was optimized and that the network did not memorize the pattern of inputs. In addition, both training and cross validation standard deviations were low, indicating that there was a consistency in the average MSE obtained during runs. These are favorable indications of a good training (Eberhart and Dobbins, 1990; Maier and Dandy, 2000).

Table 2 also shows the best network run and iteration where the minimum MSE for training and cross validation occurred. According to these results the minimum MSE for training and cross validation occurred as 0.00412 and 0.00429 at the 2484th and 2492nd iteration of the 1st training run. Thus, the calibration "weights" obtained during these iterations were saved by the network to be used in the testing and prediction stages.

Table 2
Average (minimum and final) mean squared training errors (MSE) and their standard deviations obtained from the ANN (Fig. 7) using 2×2500 training with cross validation.

	Training minimum	Training standard deviation	Cross validation minimum	Cross validation standard deviation
Average of minimum MSEs	0.00416	0.000049	0.00446	0.000237
Average of final MSEs	0.00426	0.000102	0.00454	0.000124

Best iteration	Training	Cross validation
Run	1	1
Iteration no	2484	2492
Minimum MSE	0.00412	0.00429
Final MSE	0.00434	0.00445

The table also shows the iterations where the best results obtained.

5.3. Testing and prediction capability of developed ANN model for gob gas performance prediction

The trained network was tested in two stages. In the first stage, the network was tested using the cross validation data. The same data set that was used in cross validation in training phase was presented to the network in the testing phase to note the prediction performance. In the second stage of testing, the ANN was exposed to an entirely new data set (testing set) that it had not yet seen. This is an important test to see if the ANN generates acceptable predictions for the new data patterns or, in other words, to see whether it recognizes the patterns and generalizes the results with which it was trained. In some cases, a trained network may give close predictions to the cross validation set, since it has seen it before. However, poor predictive performance towards the testing data set suggests that the ANN cannot generalize

Table 3
Performance of the network when cross validation set was used to test the predictive capability.

Performance indicator	Total flow m^3/day	Percent methane
Nominal MSE	0.08494	0.07493
Mean abs error	1139.55	3.80171
Min abs error	2.09183	0.03078
Max abs error	8047.18	24.7915
R	0.957	0.962

or recognize patterns and this may indicate memorization. Therefore, two-stage testing should give an idea about the performance and thus predictive capability of the trained ANNs.

Table 3 shows the prediction performance of the network using cross validation data set. This table gives the nominal MSE (MSE/variance of the desired outputs), mean, minimum and maximum absolute errors as well as the correlation coefficient, R, when compared with the total flow and methane percentage data of the cross validation set. It is seen that nominal MSE is low for both flow and methane percentage. Absolute errors can be considered low too except for some outliers in flow and percent methane that gave relatively higher maximum absolute errors. Nevertheless, the correlation coefficients (R) are very high, indicating a generally good prediction performance.

In the second stage of testing, the "testing" set which was saved in the pre-processing stage for testing and which was composed of 296 exemplars (data) was given to the network to predict the flow and methane percent values. The performance indicator results are given in Table 4. This table shows that the prediction performance of the data set is generally good again, except for the higher maximum absolute error in the flow data. These extreme points, originating most probably from the outliers in the flow data in any one of the ventholes, are difficult for the network to capture. However, correlation coefficients for both total flow and methane percent are quite high despite the erratic variations in the data shown in Figs. 4 and 5.

Figs. 8 and 9 show the plots of measured total gas flow rates versus predicted value, and measured methane percentages versus the predicted values, respectively, using the ANN model for the testing set. Fig. 8 shows that the ANN model is capable of predicting the total gas flow data reasonably well ($R=0.93$; $R^2=0.85$). Similarly, Fig. 9 shows that methane percentages also can be predicted well using the network. Methane percentages can be predicted with an R of 0.95 and an R^2 of 0.91. In general, the comparison of the measured data with the predicted values in Figs. 8 and 9 shows that the predictive performance of the network is reasonably good despite the large variations in the data. This comparison also indicates the flexibility and interpolation/extrapolation performance of the developed network for predicting gob gas venthole production performance.

The discussions in this and previous sections show that complex relations exist between different factors and the production performance of gob gas ventholes. In fact, these relations are too complex to be explained by simple polynomial relations or statistical methods. The encouraging results obtained in this study suggest that an ANN approach may be a good candidate for predicting gob gas venthole production and the percentage of the methane. In that respect, the flexibility and predictive capability of trained ANNs offer advantages in decision making and in design of gob gas venthole systems.

Table 4
Predictive performance of the network when testing data set was used.

Performance indicator	Total flow m^3/day	Percent methane
Nominal MSE	0.13569	0.08595
Mean abs error	1235.92	3.52427
Min abs error	4.72665	0.02904
Max abs error	20,628.04	24.2980
R	0.930	0.956

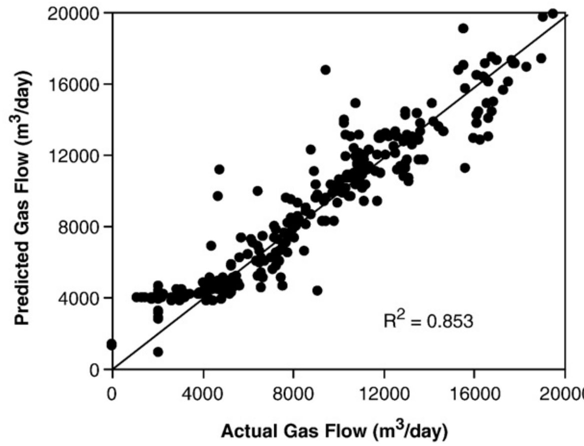

Fig. 8. Actual versus predicted total flow rates of the gob gas ventholes obtained from the ANN model shown in Fig. 7.

5.4. Sensitivity analysis of GGV performance parameters to the inputs

Sensitivity analysis provides a measure of the relative importance among the inputs of the ANN model and illustrates how the model output varies in response to variation of an input (Sokolova et al., 2006). During sensitivity analyses, the weights determined during network training are not changed. Primarily, the network inputs are shifted around their mean values and the corresponding changes in the output are determined. In the NeuroSolutions software, the activation control component generates the input data for the sensitivity analysis by temporarily increasing the actual input by a small value and the corresponding change in output is the sensitivity data.

In this study, each input channel shown in Fig. 7 was varied around its mean ± 1 standard deviation, while all other inputs were fixed at their respective means. The resulting total gas flow and methane percentage for every input were computed for 15 steps above and below the mean value of the varied input. This process was repeated for each input to determine the effects of changes in each input on the network output. Fig. 10A–D shows, as examples, the sensitivity of predicted total gas rate and methane concentration computed by the network as a response to changes in overburden depth, casing diameter, distance of the venthole to the tailgate of the panel and average vacuum at the wellhead of the venthole, respectively. These figures show that increases in overburden (Fig. 10-A) decrease gas flow rate, in accordance with the field observations of Karacan and Goodman (in press). On the other hand, this change increases

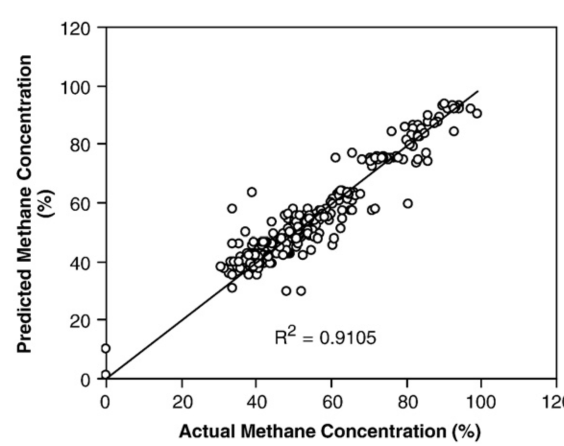

Fig. 9. Actual versus predicted methane concentrations in the gas production of gob gas ventholes obtained from the ANN model shown in Fig. 7.

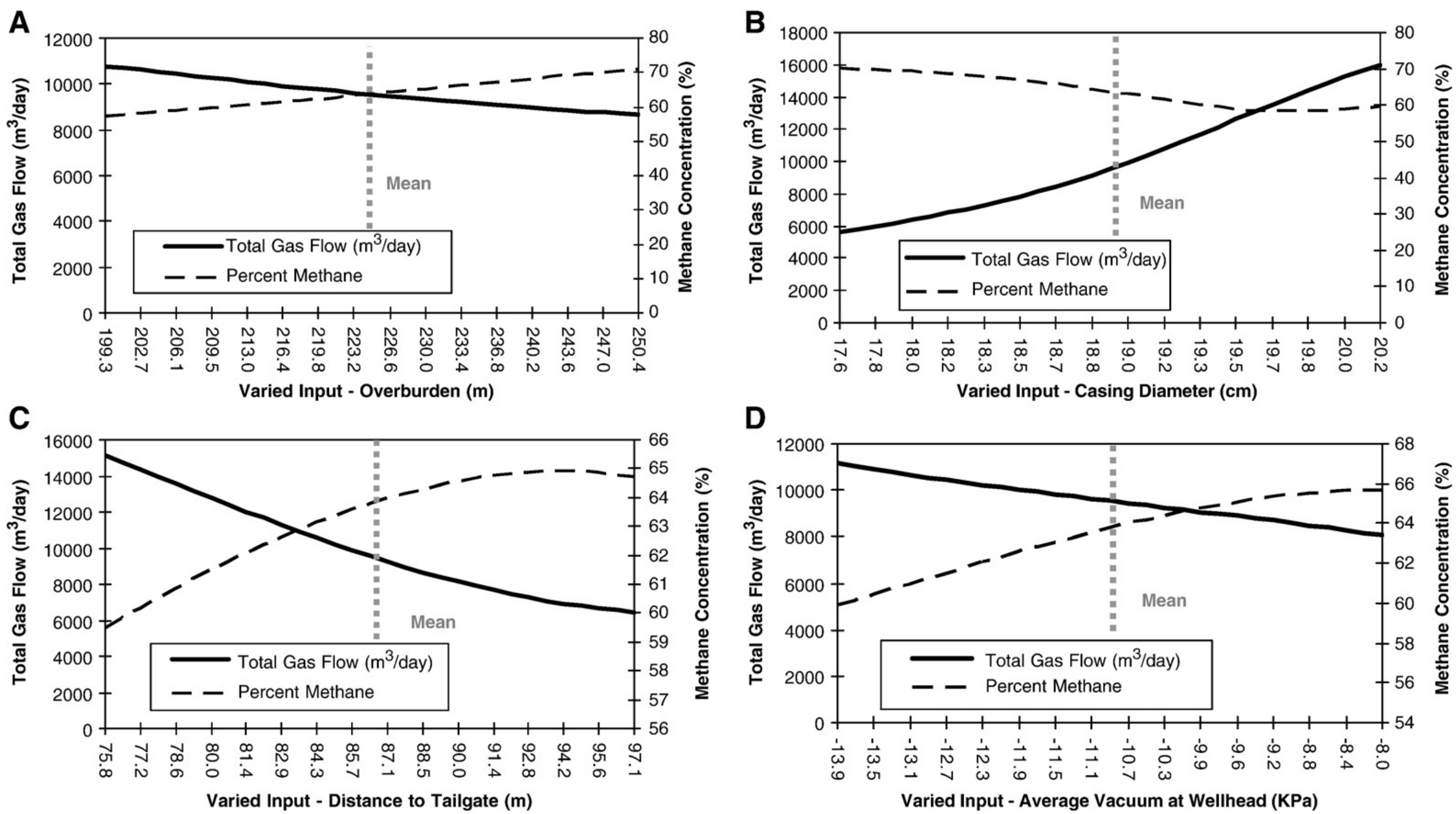

Fig. 10. Response of the ANN outputs (flow rate and methane concentration) to changes in overburden depth (A), casing diameter (B), distance of the venthole to tailgate entries (C) and to applied vacuum at the wellhead (D).

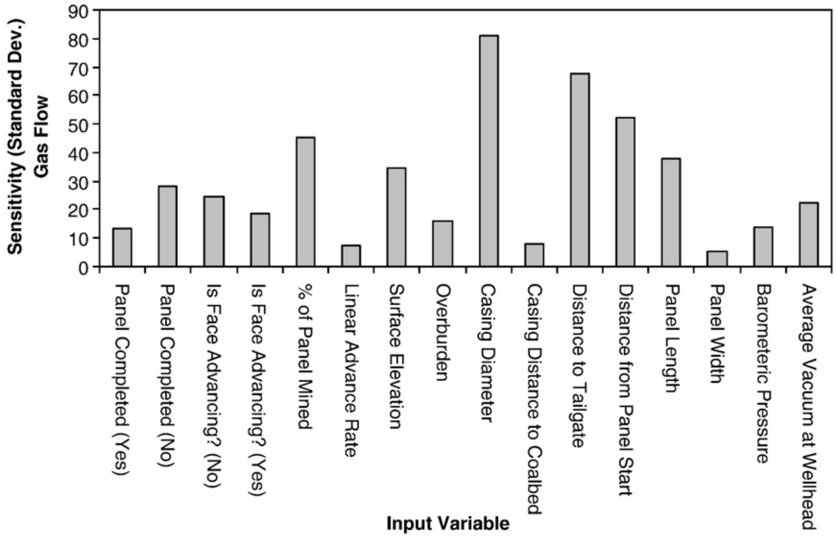

Fig. 11. Cumulative sensitivity analysis diagram for total gas flow produced from gob gas ventholes.

methane percentage in the produced gas, possibly due to increase of gas content with depth. Increasing casing diameter (Fig. 10-B) has a more pronounced effect on increasing gas flow potential. However, diameter increase slightly decreases methane concentration, which may be due to producing more of the mine air, as explained in Karacan et al. (2007). Distance of the venthole to panel tailgate (Fig. 10-C) changes both production efficiency and methane concentration. Increasing distances from the tailgate decreases gas flow rate due to ineffective fracturing and movement away from the higher permeability zone under tension. Methane percentage on the other hand increases slightly since the atmosphere towards the middle of the panel may be richer in methane due to lack of ventilation. Fig. 10-D presents how flow and methane concentration are affected as a function of applied vacuum at the wellhead of a gob gas venthole. According to the sensitivity results, application of more suction by the exhausters at the wellhead results in higher flow rates, whereas methane concentration may decrease due to capturing more methane air from the gob. This is in agreement with Ren and Edwards (2002) who reported that a higher suction pressure has a positive effect of gas capture but this can be offset by diluting the produced gas with mine air.

Figs. 11 and 12 show the cumulative sensitivity data for total gas flow obtained from gob gas ventholes and methane concentration in the gas as a response to variations in the input variables. In these graphs, the sensitivity values were reported as standard deviations of the output when varying the inputs about their means. The cumulative sensitivities shown in Figs. 11 and 12 indicate which of the input variables are more influential on predicted total gas flow and methane percentage produced from the gob gas ventholes.

In Fig. 11, it is apparent that percentage of the panel that has been mined, surface elevation of the ventholes, casing diameter, distance to tailgate, distance of the venthole to the start of panel and panel length are more influential on total gas production compared to other input variables. However, for methane percentage in the total gas produced (Fig. 12), distance of the venthole to the start of the panel, whether or not panel is completed, and whether or not the face is advancing seem more important. The reason for the latter two can be explained as follows. If the panel is completed, then the expansion of the fractured reservoir and generation of extensive methane from the overlying strata will stop or diminish. Methane concentration in the produced gas will decline more rapidly, giving rise to a higher standard deviation in sensitivity analysis. A stoppage in face advance has a similar effect on methane percentage. If the face stops for a long time, then methane percentage in the produced gas will drop quicker. This, again, increases standard deviation in the sensitivity data.

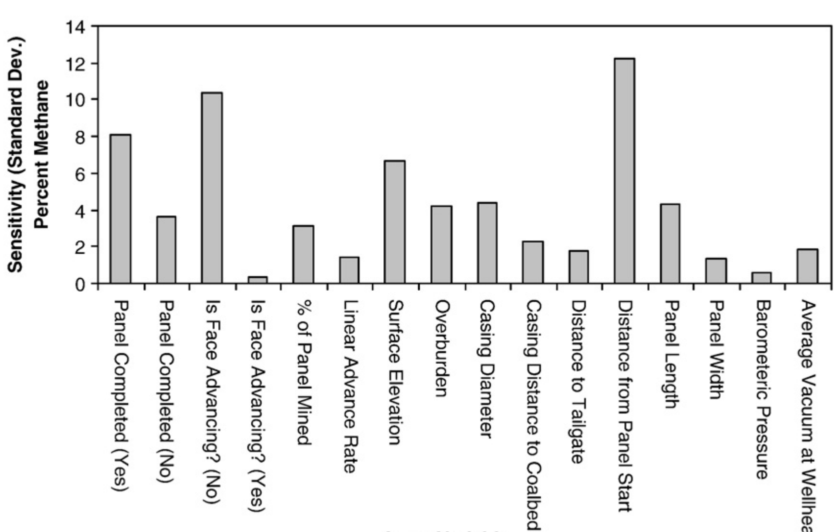

Fig. 12. Cumulative sensitivity analysis diagram for methane percentage in the total gas produced from gob gas ventholes.

Table 5
Sensitivity (in standard deviations) of performance parameters shown in Figs. 11 and 12 (gas flow rate and percent methane) to individual input parameters used in the ANN model and the total sensitivity (third column) when both performance parameters are combined.

Input Variable	Gas flow rate	Percent methane	Total (std. dev.)
Panel completed (Yes)	13.1	8.1	21.2
Panel completed (No)	28.2	3.6	31.9
Is face advancing? (No)	24.3	10.3	34.7
Is face advancing? (Yes)	18.7	0.3	19.0
% of panel mined	45.2	3.1	48.3
Linear advance rate	7.5	1.4	8.9
Surface elevation	34.4	6.6	41.0
Overburden	16.1	4.2	20.3
Casing diameter	81.2	4.4	85.6
Casing distance to coalbed	7.7	2.2	10.0
Distance to tailgate	67.7	1.7	69.5
Distance from panel start	52.3	12.2	64.5
Panel length	37.7	4.3	41.9
Panel width	5.1	1.4	6.5
Barometeric pressure	14.0	0.6	14.6
Average vacuum at wellhead	22.1	1.9	24.0

Shaded cells are the total sensitivity above the average sensitivity value (33.8) calculated using all inputs.

Table 5 shows the sensitivity values presented in Figs. 11 and 12, as well as the total sensitivity in standard deviations about the mean due to sensitivities of gas flow rate and methane percentage to inputs when they are considered together. The average total sensitivity was calculated as the arithmetic average of third data column in Table 5, which gave a value of 33.8. For the sake of this analysis, the total sensitivity values above this average of 33.8 were considered as high sensitivities of gob gas venthole performance to the corresponding input variables. According to this approach and the data in Table 5, (a) face advance (whether it is advancing or not), (b) percentage of the panel that has been mined, (c) surface elevation of the venthole (above sea level), (d) casing diameter, (e) distance of the venthole to the tailgate, (f) distance of venthole to panel start and (g) panel length are more influential for the venthole performance. This may raise the question whether less important parameters based on this sensitivity analyses can be dropped from the inputs to make the computation time less, and to reduce the complexity of the problem. The answer to this question is no: not with this type of analysis. However, if PCA (principle component analysis) or ANOVA (analysis of variance) is used, the relations between inputs and outputs, as well as the relations between inputs can be revealed more precisely and a model simplification can be done. However, this will be at the expense of precision, since all of the variance will not be represented with reduced number of inputs. For a detailed discussion on this, please see (Karacan, 2008a,b, 2009) and the references therein.

6. Summary and conclusions

Prediction of gob gas venthole production is complex due to the various factors affecting its performance and the lack of practical mathematical models that can be used to predict performance. The objective of this work was to evaluate various factors affecting performance and to develop an artificial neural network (ANN)-based model for forecasting gob gas venthole productions (gas flow rate and methane percentage). Sensitivity analyses were also performed to determine the most influential variables that affect venthole performance.

The total gas productions and methane percentages of 10 ventholes located over 3 adjacent panels in SW Pennsylvania section of Northern Appalachian basin were monitored at the wellhead for more than 2 years during and after mining of these panels using pressure, flow, temperature and methane sensors. The measurements were combined with various spatial parameters related to venthole location, borehole completion parameters, mining rate and panel completion data, and exhauster operation to form an extensive database. A 2-hidden layer MLP-based ANN model was developed and optimized for the prediction of total gas flow rate and methane percentage as performance parameters of gob gas venthole production. The ANN model was successful in predicting those parameters with a correlation coefficient, R, of >0.9.

Sensitivity analyses about the mean of the input variables were conducted using the ANN model to identify which input variables had more influence on the performance of gob gas ventholes. The results of these analyses showed that for total gas flow rate (a) percentage of the panel that has been mined, (b) surface elevation of the ventholes, (c) casing diameter, (d) distance to tailgate, (e) distance of the venthole to the start of panel, and panel length were most influential. However, for GGV methane percentage (a) distance of the venthole to the start of the panel, (b) whether or not panel is completed, (c) whether or not face is advancing were most important. When considering the overall performance of gob gas ventholes for both flow and methane percentage, (a) whether or not face is advancing, (b) percentage of the panel that has been mined, (c) surface elevation of the venthole (above sea level), (d) casing diameter, (e) distance of the venthole to the tailgate, (f) distance of venthole to panel start, and (g) panel length were important variables.

The presented approach using input data evaluation, ANN modeling, and integrated sensitivity analyses is currently one of the most systematic and accurate methods to predict production performance of gob gas ventholes. However, such an approach usually requires an extensive data set of high confidence. By incorporating other parameters that may be critical for gob gas venthole production, this approach and the model can be further improved.

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