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CFD modelling of nitrogen injection in a longwall gob area

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Abstract

This paper describes computational fluid dynamics (CFD) simulations conducted to investigate the effectiveness of N_2 injection in an active panel and a sealed longwall gob area to prevent and suppress spontaneous heating of coal using various injection locations and flow rates. In the active panel simulations, a single longwall panel with a bleederless ventilation system was simulated. The spontaneous heating of crushed coal from pillars was simulated and N_2 was injected from different locations on the headgate side and through boreholes from the surface. The N_2 injection rate at each location was varied between 0.18 m^3/s and 0.94 m^3/s (380 and 2000 cfm). In the sealed longwall simulations, seal leakage rate was varied to determine its effect on N_2 injection effectiveness. The results of this study should aid mine ventilation engineers in developing more effective N_2 injection strategies to prevent and control spontaneous heating of coal in underground coal mines.

Keywords

spontaneous combustion; longwall gob; CFD modelling; nitrogen injection; ventilation system

1 Introduction

When spontaneous combustion of coal occurs in an underground longwall gob, it is difficult to effectively combat the heating because most of gob area is inaccessible. Spontaneous heating of coal in the gob is usually detected during its early stages by a continuous increase of carbon monoxide (CO) at one or more sampling locations. However, the specific location of a heating in the gob cannot usually be determined from the CO readings. A common practice to combat a spontaneous heating event in an underground coal mine is to first evacuate the mine, then inject N_2 or another inert gas into the gob to suppress the spontaneous heating. If the CO reading continuously declines for a certain period of time, indicating the heating is suppressed, the mine may be reopened for operation again. In the

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worst case scenario, the longwall panel has to be sealed and the atmosphere completely inerted by N_2 injection to suppress the heating.

Although N_2 injection into the gob to control the spontaneous combustion risk has been used in the mining industry for many years (Both, 1981; Harris, 1981; Garg, 1987; Hermulheim and Beck, 1997; Adamus, 2000; Bessinger et al., 2005), its practical application to a particular panel configuration is still fairly empirical in terms of the choice of the location, the number of N_2 injection points, and injection flow rates. The effectiveness of nitrogen injection on preventing or suppressing spontaneous heating is often complicated by the ventilation flow near the face or by seal leakage in a sealed panel. In order to improve the efficiency of nitrogen injection techniques on the prevention and suppression of spontaneous heating, it is necessary to optimise the nitrogen injection methodology by determining the strategic injection locations and injection flow rates.

Because of the very nature and large size of a longwall gob, it is both difficult and expensive to conduct full-scale experiments to determine strategic nitrogen injection locations and flow rates to control or suppress the spontaneous heating. CFD modelling is an investigative method well adapted to this task. CFD modelling can provide insights into the interaction between the N_2 injection, ventilation, and spontaneous heating. Some previous research on CFD modelling has been conducted to study N_2 injection in preventing spontaneous combustion and methane explosion hazards in underground coal mines. In Australia, CFD simulations and field tests were conducted to optimise inerting strategies to prevent spontaneous heating and fires in longwall gobs for some gassy coal mines (Balusu et al., 2002, 2006). In that study, methane emission plays an important role in gob inerting, but only steady-state gas flow was simulated. In the USA, a CFD program, fire dynamics simulator, was used to study N_2 injection into a sealed mine area (Trevits et al., 2010). The CFD program was calibrated using the in-mine nitrogen injection test results and was used to predict the time needed to inert the larger volume of sealed mine area. However, the sealed area comprised only two mine entries and several crosscuts, and there was no methane emission or coal oxidation in the entries and crosscuts. In our previous studies, a CFD model was first developed to model the spontaneous heating of coal in longwall gob areas (Yuan and Smith, 2007). The CFD model was then calibrated using measured CO data from a western coal mine during a spontaneous heating event (Yuan and Smith, 2012). In this paper, the calibrated CFD model was used to simulate the coal oxidation in a longwall gob area using a bleederless ventilation system for both active and sealed longwall panels, with different N_2 injection locations and injection rates to develop effective N_2 injection strategies for the prevention and suppression of spontaneous heating of coal.

2 Longwall panel layout and ventilation system

In the USA, a bleeder ventilation system is most often used in underground coal mines. A bleederless ventilation system may be approved by the Mine Safety and Health Administration (MSHA) to serve as a spontaneous combustion control method in mines with a demonstrated history of spontaneous combustion. In this study, an active longwall panel using a modified U-type bleederless ventilation system is simulated. Compared with the typical European U-type bleederless system, the US system keeps the headgate entry ventilated for utilisation as the tailgate on the next panel and seals are installed in the headgate entry as the face advances. The seals are accessible for inspection and maintenance but are more exposed to leakage from the development of pressure differential across the seals. The layout of the panel and the ventilation system are shown in Figure 1. The simulated gob area is 1000 m long, 300 m wide, and 10 m high starting from the bottom of the coal seam. The ventilation airways are 2 m high and 5 m wide. In the model, the headgate entry is ventilated and eventually goes to return after passing the back end of the panel. Seals are built between this entry and the active gob.

N_2 can be injected into the gob through seals on the headgate side or through boreholes on the surface. In practice, N_2 can be supplied through an on-site generation facility via membrane separation (Bessinger et al., 2005), or by an in-mine mobile generation unit using pressure swing adsorption technology (Trevits et al., 2009). The former can provide larger injection flow rates, but is usually expensive and it takes a long time to build the entire plant, while the latter provides lower injection rates, but is economical and it is easier to build the unit. In this research, the N injection rate varies from 0.18 m^3/s and 0.94 m^3/s (380 cfm to 2000 cfm) at a pressure range of 345–1724 kPa (50–250 psig) at each injection location, representing the injection rate range of both N_2 generation methods. To evaluate the effect of injection location for the N_2 injection, six typical injection positions are considered in the simulations. Figure 1 illustrates the locations of these injection positions, designated as Location 1 to Location 6. The detailed locations of these positions are given in Table 1.

3 Modelling of spontaneous heating of coal

To simulate the spontaneous heating of coal in the longwall gob area, the source of heating needs to be defined. In a typical longwall gob, the heating source can be from coal in crushed coal pillars along the perimeter of the gob, from rider coal seams in the roof or floor, or from coal left from the mined coal seam, depending on the specific geological conditions and mining method in the mine. The oxidation of coal can occur on any available coal surface including both external and internal pore surfaces. The available surface area for oxidation depends on the particle size distribution of the coal in the gob. It is difficult to define a coal particle size distribution for the coal left in the gob area because of the complexity of the gob. The available coal surface area used in these simulations is based on an estimation made by matching the predicted CO concentrations at three regulator sampling points with the measured CO data in a western coal mine experiencing the spontaneous heating event (Yuan and Smith, 2012).

A typical bituminous coal with a high spontaneous combustion potential was modelled in this study. The physical and kinetic properties of this coal are listed in Table 2.

The chemical reaction between coal and oxygen at low temperatures is complex and still not well understood. In this study, the chemical reaction between coal and oxygen is simplified so that one mole of coal reacts with one mole of oxygen to generate one mole of carbon dioxide and 0.1 mole of carbon monoxide plus the heat of coal oxidation (Smith et al., 1991). The heat generated from coal oxidation is dissipated by conduction and convection, while the oxygen and oxidation products are transported by convection and diffusion. The dependence of the rate of oxidation on temperature and oxygen concentration is expressed in the form:

$$\mathrm{Rate}{=}A[\mathrm{O_2}]^n exp\left(-E/RT\right)$$

where the chemical reaction rate is defined as the rate of change in the concentrations of the reactants and products, *A* is the preexponential factor (in K/s), E is the apparent activation energy (in kJ/mol), *R* is the gas constant, *n* is the apparent order of reaction, *T* is the absolute temperature (in K), and $[O_2]$ is the oxygen concentration (in $kmol/m^3$).

4 Numerical modelling and boundary conditions

A commercial CFD software, FLUENT[1] from Ansys, Inc., was used in this study to simulate gas flow and spontaneous heating in the longwall gob area. The gas flow in the longwall mine gob area was treated as laminar flow in a porous media using Darcy’s law, while the gas flow in the ventilation airways was simulated as fully developed turbulent flow.

Typical ventilation pressures for a US bleederless ventilation system were used as boundary conditions in the simulation. The intake airflow rate was 30 m^3/s (64,000 cfm). The pressure was −747 Pa (−3.0 inches water gauge) at the intake inlet and −872 Pa (−3.5 inches water gauge) at the return outlet. The longwall face is assumed stationary and the barometric pressure is constant.

The permeability and porosity distributions of the gob were based on geotechnical modelling of longwall mining and the associated stress-strain changes using a fast Lagrangian analysis of continua (FLAC) code. The permeability and porosity values in a specific gob area depend on the geological conditions, the mining method, the panel layout, etc. In this study, a permeability value in the gob area ranging from 3.0×10^6 to 8.5×10^7 millidarcies (md) was used. A porosity value in the range of 0.17 to 0.41, based on the modelling result from FLAC, was used (Esterhuizen and Karacan, 2007). Around the perimeter of the gob and immediately behind the face shields, the permeability and porosity values were the largest, while near the centre of the gob, these values were the smallest due to compaction. The porosity profile in the gob was similar to the permeability profile. It is assumed that these permeability and porosity profiles do not change with the gob height.

5 Simulation results and discussion

Simulations were first conducted for the active longwall panel using the bleederless ventilation system shown in Figure 1 to study the effects of injection location and the number of injection locations on the effectiveness of N_2 injection to prevent spontaneous heating in the longwall gob area. Then, simulations were conducted for the same longwall panel sealed to investigate the most effective N_2 injection strategy to suppress the spontaneous heating.

[1]Reference to a specific product is for informational purposes and does not imply endorsement by NIOSH.

5.1 Effect of injection location

To study the effect of injection location, it is important to understand the flow pattern in the gob with the bleederless ventilation system. In order to visualise the flow patterns inside the gob, a virtual horizontal reference surface was created 1 m from the bottom of the mined coal seam floor to compare the results with respect to this horizontal reference surface. Figure 2 shows the flow path lines coloured by velocity magnitude in the gob area. The path lines show that flow through the gob itself was mainly concentrated behind the shields. At the headgate side, air leaked through the shields, extending about four crosscuts into the gob, and flowed back into the face again through the shields near the tailgate side. The flow line deeper in the gob represents the limit of flow in the gob.

CFD simulation of coal oxidation in the gob without any N_2 injection was then conducted. The coal source in the simulation is from a 4-m-wide area of crushed coal pillars extending 500 m from the back end of the panel towards the face on the headgate and tailgate sides. Figure 3 shows the temperature distribution in the gob after seven days caused by spontaneous combustion of this coal. The coal oxidation occurred at the leading edge of the coal source on the headgate side.

Simulations were conducted to examine the impact of varying a single N_2 injection location on its effectiveness in preventing the spontaneous heating of the coal in the gob. Ventilation and gob conditions were kept constant during this period as the face was assumed to be stationary. Figure 4 shows the N_2 concentration distribution in the gob after seven days of N_2 injection at a rate of 0.18 m^3/s (380 cfm) at the pressure of 345 kPa (50 psig) at location 1. Because of the porosity and permeability characteristics of the gob, some of the injected N_2 flowed along the perimeter of the gob while some flowed across the gob and towards the return. Figure 5 shows the N_2 concentration distribution in the gob after seven days with an injection rate of 0.18 m^3/s (380 cfm) at the same pressure at location 2. Because the flow becomes weaker deeper in the gob because of compaction, no injected N_2 flowed to the return. Most of the N_2 flowed with the ventilation along the perimeter of the gob while some N_2 flowed against the ventilation along the perimeter for about 120 m, indicating that ventilation flow in gob is less than N_2 injection flow rate. In the third simulation, N_2 was injected at location 3 at the same flow rate, and N_2 flowed against the ventilation for about 340 m after seven days, as shown in Figure 6.

These simulation results indicate that the N_2 injection location affects N_2 distribution in the gob significantly, which in turn affects the ability of the N_2 to control and suppress the spontaneous heating of coal in the gob. Figure 7 shows the maximum temperatures in the gob vs. time with N_2 injected at the three locations. Without any N_2 injection, the maximum temperature in the gob continually increased with time, reaching 331 K, as shown in Figure 7. When N_2 was injected at location 1, the maximum temperature increased faster than without injection at the beginning, probably because of slightly increased air velocity caused by the injection increasing the amount of O_2 at the hot spot. After reaching about 320 K, temperature started to decrease quickly because the N_2 dilution injection blocks the airflow pathway to the hot spot. With N_2 injected at location 2, the maximum temperature was 306 K and the temperature quickly decreased, and the coal oxidation was suppressed because of dilution by the N_2. When N_2 was injected at location 3, the maximum temperature increase was less than 2 K, again by the rapid dilution of O_2 by N_2. These results indicate that when the injection location is closer to the hot spot, it is more effective in preventing spontaneous heating.

5.2 Effect of multiple injections

In real mine conditions, the coal source can be anywhere in the gob depending on the geological conditions and mining method. If coal is left near the centre of the gob, more than one injection location may be required to effectively prevent the spontaneous heating. As shown in Figures 4–6, with N_2 injected at one location and the injection rate of 0.18 m^3/s (380 cfm), the area inerted in the gob after seven days is relatively small, completely inerting about 15% of the gob. Many factors can affect the effectiveness of N_2 injection. In this study, only was the effect of injection location studied. The reason why only about 15% of gob was inerted is probably because of the low injection rate, the low injection pressure, and the nature of the active panel. To inert a larger area in the gob at the low injection flow rate of 0.18 m^3/s (380 cfm) could require multiple injection points and longer injection times. Figure 8 shows the N_2 concentration distribution in the gob 20 days after N_2 was injected at both locations 1 and 2 at a rate of 0.18 m^3/s (380 cfm) at each location. Because some of the N_2 injected was carried away through the return, only about 40% of the gob area was inerted. The gob area on the tailgate side and near the back end of the headgate side could not be inerted. Because of the flow pattern in the gob, it is difficult to inert the back end corner in the gob using N_2 injections on the headgate side.

In order to attempt to inert the back end corner on the tailgate side, N_2 was injected through a surface borehole at location 4 at a rate of 0.18 m^3/s (380 cfm), in addition to the injection at locations 1 and 2. Figure 9 shows the N_2 concentration distribution in the gob 20 days after the injection. It should be noted that the borehole injection had a large effect on the N_2 distribution resulting from the injection at locations 1 and 2. Without the borehole injection at location 4, the injected N_2 at locations 1 and 2 reached to about 750 m from the face on the headgate side, as shown in Figure 8. However, with the borehole injection, the N_2 injected at locations 1 and 2 reached only about 400 m on the headgate side because of the pressure created from the borehole injection. This also indicates that more injected N_2 was carried out of the gob by the ventilation. Again it is noted that the tailgate side of the gob could not be inerted.

Figure 10 shows the N_2 concentration distribution in the gob 20 days after N_2 injections from locations 1 and 2 on the headgate side and the borehole at location 5 at an injection rate of 0.18 m^3/s (380 cfm) at each location. In this case, the part of the gob at the centre could not be inerted. Lastly, Figure 11 shows the N_2 concentration distribution in the gob 20 days after N_2 injections at0.18 m^3/s (380 cfm) from locations 1 and 2 on the headgate side and the borehole at location 6. Under this circumstance, the tailgate side of the gob and the area behind the shields were inerted, but the headgate side near the back end corner could not be inerted. These experimental results indicate that N_2 injections at different locations affect each other because of the pressure created by the injection and have a significant effect on the N_2 distribution in the gob.

5.3 N_2 Injection in a sealed longwall panel

If a spontaneous heating of coal in the gob cannot be controlled quickly, the longwall panel may need to be sealed and full-panel N_2 injection attempted. In a sealed panel, the leakage of the seals plays an important role in the N_2 injection process and resulting N_2 distribution in the gob. When N_2 is injected into the sealed gob, the gas will leak out of the gob into the headgate entry. The seal leakage rate is in the unit of cfm. The N_2 concentration in the entry becomes higher than that in the atmosphere, resulting in lower O_2 concentration in the entry. Thus, the entry may not be safe for the workers any more. The leakage rate of a seal varies with the pressure differential across the seal. The effect of seal leakage on the spontaneous heating of coal in the gob was investigated in a previous study (Smith and Yuan, 2010). In this study, the longwall panel shown in Figure 1 is sealed at intake and return. N_2 is injected on the headgate side and/or through the boreholes to suppress the spontaneous heating of coal in the gob. The seal leakage rate in these simulations is set at 35 cfm. The injection rate at each location is 0.18 m^3/s (380 cfm). The seal leakage rate increases with the increase of the total injection rate due to increased pressure in the gob. To evaluate the effectiveness of N_2 injection in the sealed gob to suppress the spontaneous heating, simulations of coal oxidation in crushed pillars, 4 m wide by 2 m high, on the entire perimeter of the headgate, tailgate, and back end of the panel were conducted. N_2 was injected at locations 1 and 2 on the headgate side and through the borehole at location 5.

Figure 12 shows the N_2 concentration distribution in the gob 20 days after the injection. The N_2 distribution is quite different from the distribution in the active panel under similar conditions, shown in Figure 10. Without the pressure differential created by the face ventilation, the movement of the injected N_2 in the gob was influenced only by the pressure differential created by the injection, and by the pressure differential between the gob and the headgate entry which caused gob gas to leak out the gob through the seals. The result was that much less area of the gob was inerted by the N_2 injection in Figure 12 than in Figure 10, with the same total amount of N_2 injected. In the sealed panel, the N_2 injected at location 1 flowed through the face to the original tailgate corner. However, the N_2 injected at location 2 could not flow deeper into the gob because there was no pressure differential created by the ventilation; instead some N_2 leaked out of the gob through the seals. The N_2 injected at borehole location 5 could not flow to the tailgate side, instead flowing to the headgate side because of pressure differential across the seals. Figure 13 shows temperature distribution in the gob 20 days after injection. The coal oxidation occurred near the seals at the locations that were not inerted by the injected N_2. The maximum temperature was 338 K at the back tailgate corner.

5.4 Effect of injection rate

In order to effectively suppress the spontaneous heating of the coal in the sealed gob simulation, a larger N_2 injection rate was required. Figure 14 shows the N_2 concentration distribution in the gob 20 days after the injection at the injection rate of 0.47 m^3/s (1000 cfm) at each location. When compared to Figure 12, it is apparent that even though the injection rate was increased nearly three times, the inerted area in the gob in Figure 14 only increased significantly on the tailgate side, since the injected N_2 at location 1 could flow through the face entry to reach the tailgate side at both injection rates. The size of the inerted area from N_2 injected at location 2 and at borehole location 5 increased insignificantly because the increase in flow rate was offset by the increase of the seal leakage rate. Figure 15 shows the temperature distribution in the gob 20 days after N_2 injection. The spontaneous heating took place on the headgate side near the backend seals in the area that was not inerted by the injected N_2. With the increased injection rate, more oxygen left in the gob was pushed towards the spontaneous heating spot where the permeability is high, and the velocity increase resulted in a higher temperature after 20 days. Figure 16 shows the history of the maximum temperatures in the gob at the two different injection rates. In the sealed gob, the increased injection rate actually exacerbated the spontaneous heating, resulting in a higher maximum temperature that was still rising after 40 days. Because there is no ingress of O_2 to the gob, the available O_2 in the gob will be consumed more quickly.

5.5 The most efficient N_2 injection strategy

In order to effectively suppress the spontaneous heating resulting from crushed coal pillars on the headgate side, tailgate side, and back end of the sealed panel, various injection strategies using different combinations of injection location and injection rate were investigated. Three injection strategies were found to be more efficient than the scenario at locations 1, 2, and borehole 5 using the injection rate of 0.47 m^3/s (1000 cfm), shown in Figure 14. Strategy 1 was to inject N_2 at location 1 and at borehole location 5 using an injection rate of 0.47 m^3/s (1000 cfm). Strategy 2 injected N_2 at borehole location 5 only using the injection rate of 0.47 m^3/s (1000 cfm). Strategy 3 injected N_2 at borehole location 5 only using an injection rate of 0.94 m^3/s (2000 cfm). Figure 17 shows the comparison of maximum temperatures in the gob between the 5 different injection strategies. Strategy 1 resulted in a lower maximum temperature than the case with the injection rate of 0.47 m^3/s (1000 cfm), but a higher maximum temperature than the case with the injection rate of 0.18 m^3/s (380 cfm), shown in Figure 12. Strategy 3 is more effective than strategy 1. However, it had higher maximum temperature than the case with the lower injection rate for the first four days, though a lower maximum temperature after four days. As shown in Figure 17, injection strategy 2 is the most efficient injection strategy out of those investigated in this study. With this injection strategy, the maximum temperature was the lowest. Figure 18 shows N_2 concentration distribution in the gob 20 days after the injection for strategy 2.

6 Conclusions

CFD simulations were conducted to investigate the effectiveness of N_2 injection into a longwall gob area to prevent the spontaneous heating of coal from crushed coal pillars on the perimeter of the gob for both the active panel with a bleederless ventilation system and for the same sealed longwall panel. For the active longwall panel, the simulations results indicate that the flow of injected N_2 was greatly affected by the flow pattern in the gob. When N_2 was injected near the face at the rate of 0.18 m^3/s (380 cfm), some N_2 flowed to the return across the gob. Injected further from the face, N_2 was more likely to flow deeper into the gob. When the injection location was closer to the beginning of the crushed coal pillar, it was more effective in preventing the spontaneous heating. To inert the centre of the gob, multiple injection locations on the headgate side were needed at the rate of 0.18 m^3/s

(380 cfm). To inert the back end corner on the tailgate side, injection from a borehole was necessary. Different borehole locations also affected the injected N_2 movement in the gob.

For the same sealed longwall panel, seal leakage significantly reduced the area inerted by the N_2 injection compared with the active panel simulation using the same injection rate. The simulation results show that the higher total injection rate did not necessarily render a more effective inerting strategy because it also caused a higher seal leakage rate. A higher injection rate actually enhanced the spontaneous heating in one of the simulations. To suppress the spontaneous heating of coal from the crushed coal pillars on the entire perimeter of the gob, the most efficient injection strategy was to inject N_2 from borehole location 5 with an injection rate of 0.47 m^3/s (1000 cfm). It should be noted that the simulation results are valid only for the longwall panel layout and mining conditions used in this study. Nevertheless, these results provide insight into the transient character of the N_2 injection process and can be helpful to better prevent spontaneous heating through choosing the appropriate injection locations and injection flow rates.

Biographies

Liming Yuan has been working in Office of Mine Safety and Health Research at National Institute for Occupational Safety and Health as a lead research engineer since 2002. His research focus on mine fire prevention, control and suppression including water mist extinguishing of diesel fuel pool fires in underground diesel fuel storage areas, flammability study of conveyor belts and hydraulic fluids used in mining industry, smoke control and management in underground mine fires and CFD modelling of spontaneous heating of coal in long-wall gob areas. He has a PhD in Mechanical Engineering.

Alex C. Smith is the Deputy Chief of the Fires and Explosions Branch of the Office of Mine Safety and Health Research, NIOSH, in Pittsburgh, PA, USA. He has an MS in Chemistry from Duquesne University and has been with NIOSH for 30 years. His main area of research is the prevention of spontaneous combustion in underground coal mines. He has also conducted research in mine fire prevention, detection and extinguishment.

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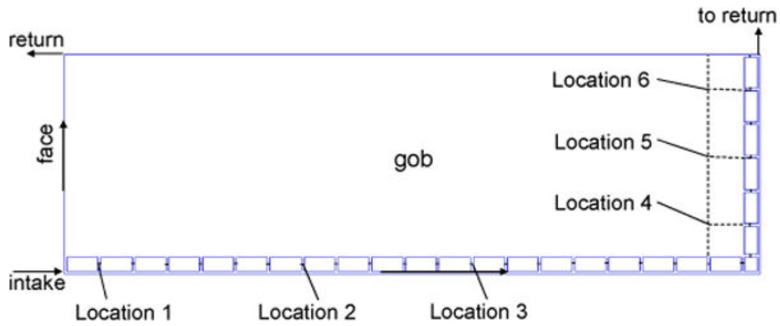

Figure 1.

Layout of longwall panel and N_2 injection locations used in simulations (see online version for colours)

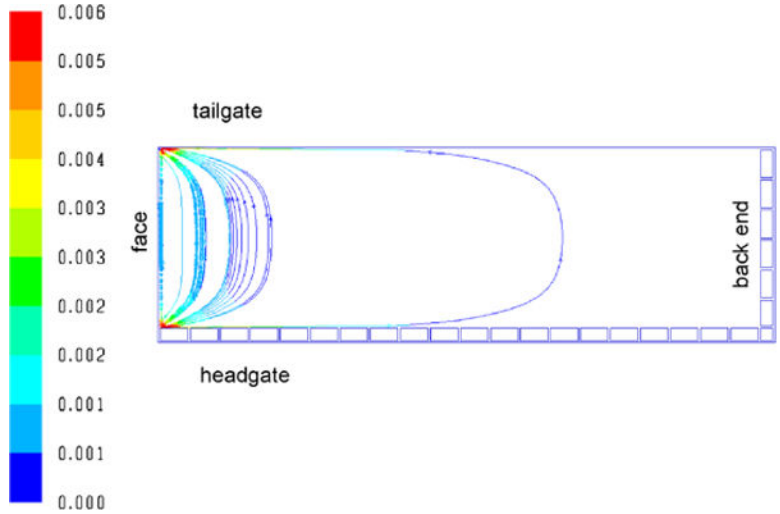

Figure 2.
Flow path lines coloured by velocity magnitude (m/s) in gob area (see online version for colours)

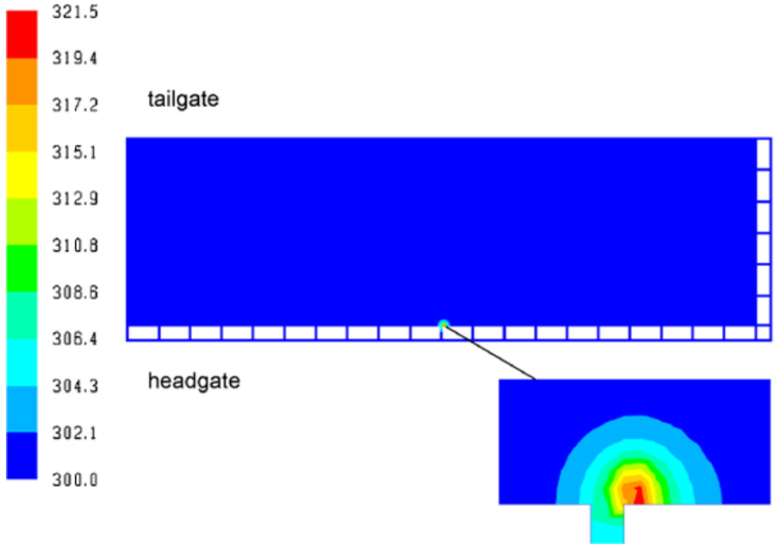

Figure 3.
Temperature distribution (K) in the gob after seven days: without N_2 injection (see online version for colours)

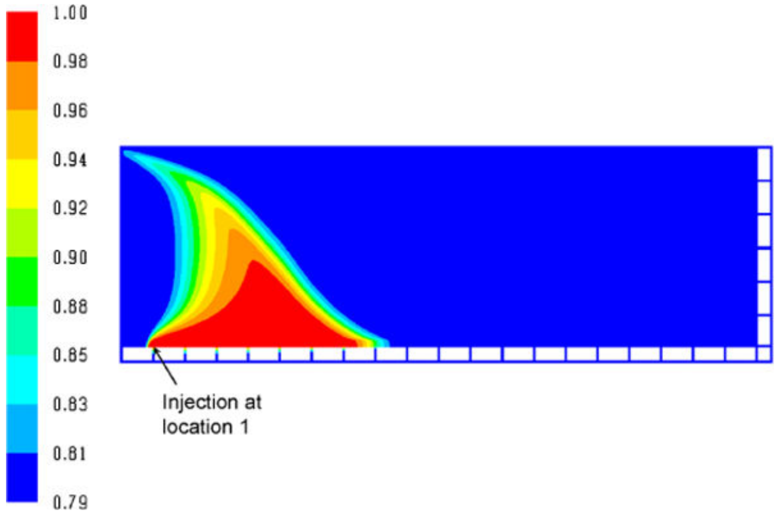

Figure 4.
N_2 concentration distribution (1 = 100%) in the gob seven days after being injected at location 1 with an injection rate of 380 cfm (see online version for colours)

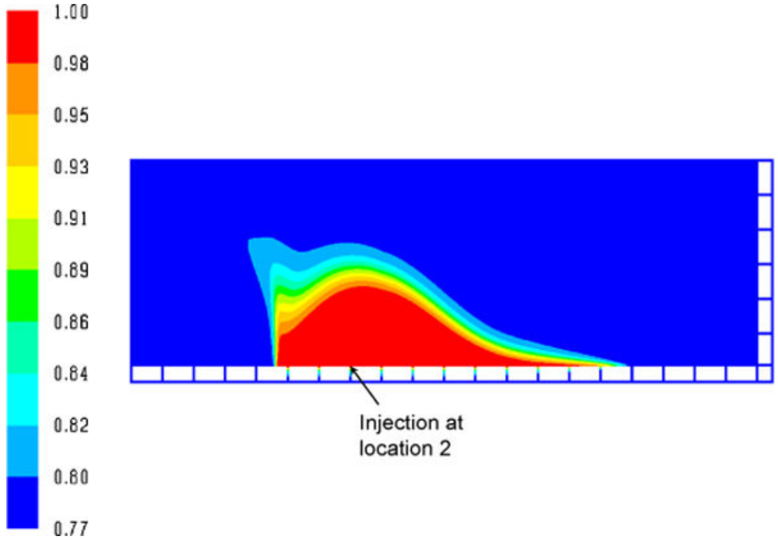

Figure 5.

N_2 concentration distribution (1 = 100%) in the gob seven days after being injected at location 2 with an injection rate of 380 cfm

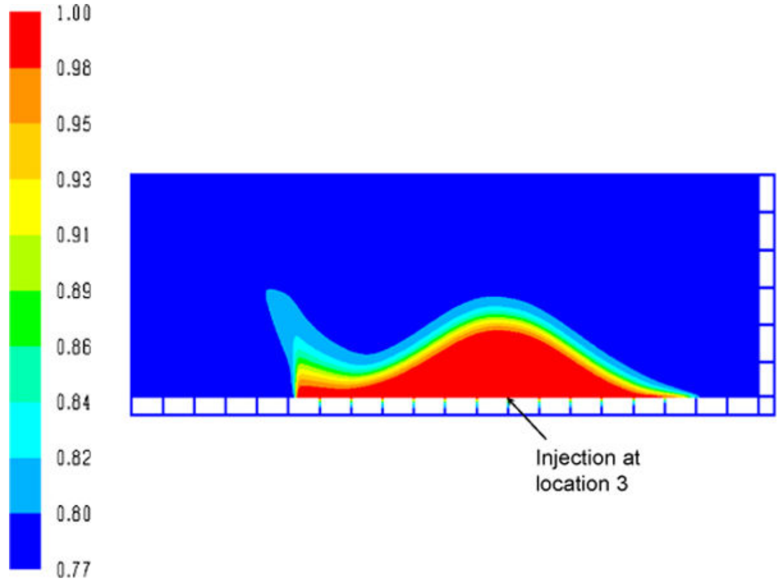

Figure 6.
N_2 concentration distribution (1 = 100%) in the gob seven days after being injected at location 3 with an injection rate of 380 cfm (see online version for colours)

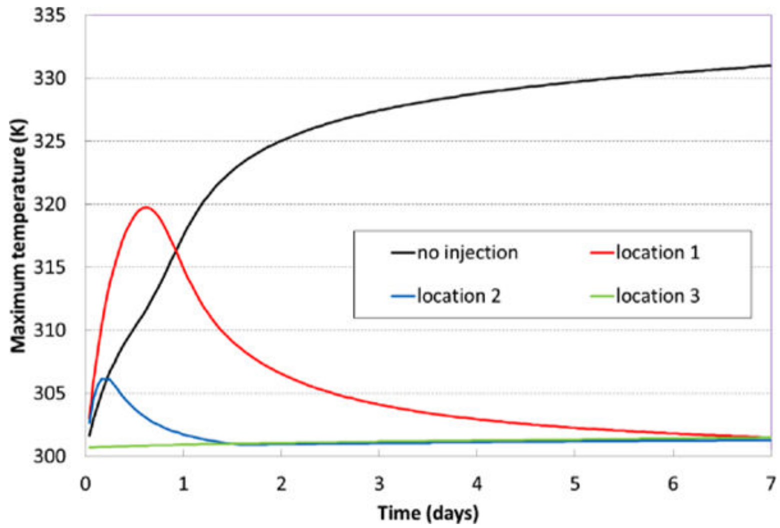

Figure 7.

Maximum temperatures (K) in the gob vs. time with N_2 injected at three locations (see online version for colours)

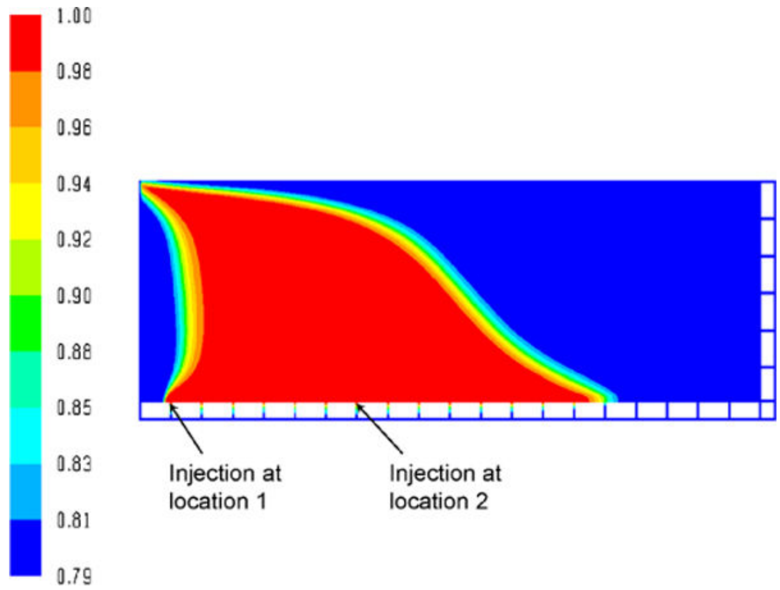

Figure 8.

N_2 concentration distribution (1 = 100%) in the gob 20 days after N_2 was injected at both locations 1 and 2 with the rate of 380 cfm (see online version for colours)

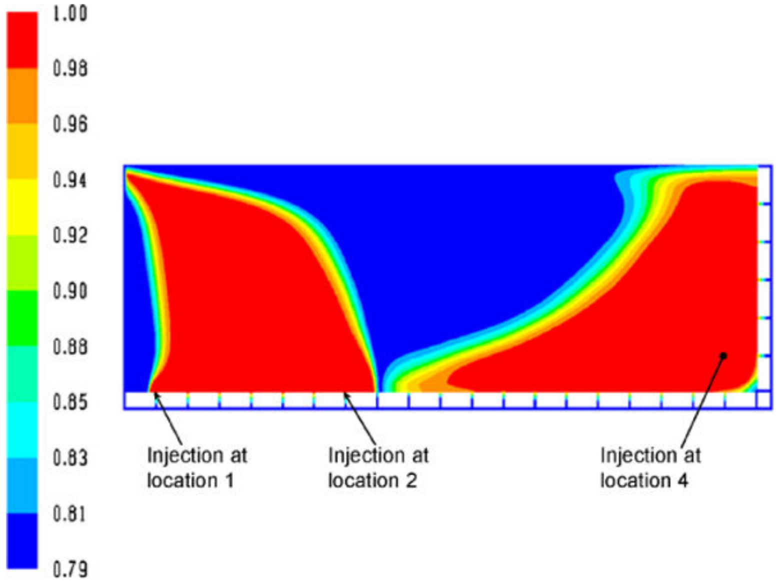

Figure 9.

N_2 concentration distribution (1 = 100%) in the gob 20 days after N_2 was injected at both locations 1 and 2 and at borehole 4 with the rate of 380 cfm (see online version for colours)

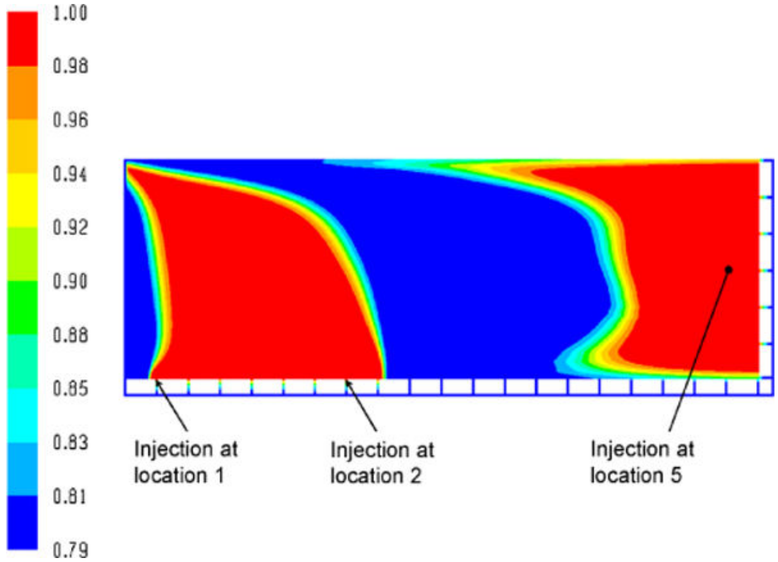

Figure 10.

N_2 concentration distribution (1 = 100%) in the gob 20 days after N_2 was injected at both locations 1 and 2 and at borehole 5 with the rate of 380 cfm (see online version for colours)

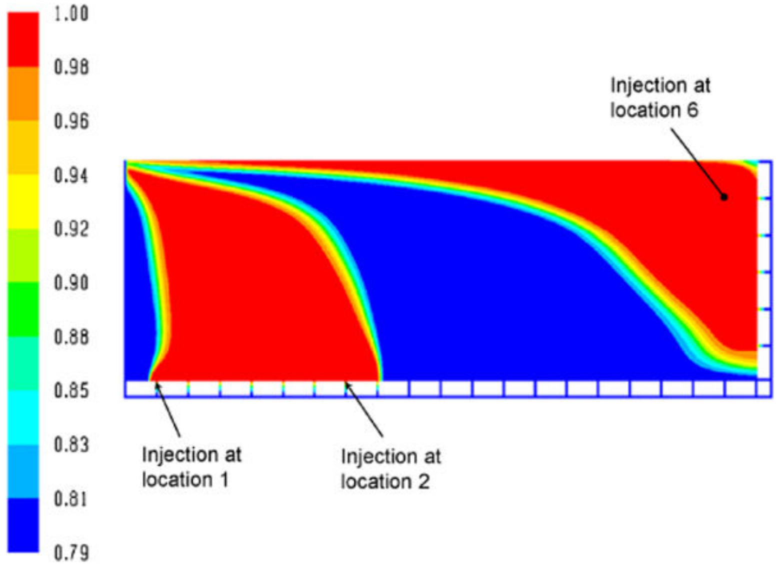

Figure 11.

N_2 concentration distribution (1 = 100%) in the gob 20 days after N_2 was injected at both locations 1 and 2 and at borehole 6 with the rate of 380 cfm (see online version for colours)

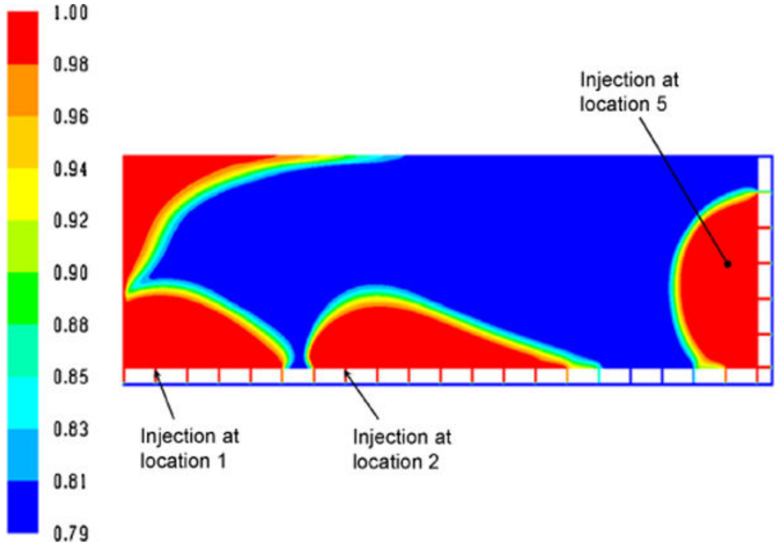

Figure 12.
N_2 concentration distribution (1 = 100%) in the gob 20 days after the injection for case 3: 380 cfm at locations 1 and 2 and at borehole 5 (see online version for colours)

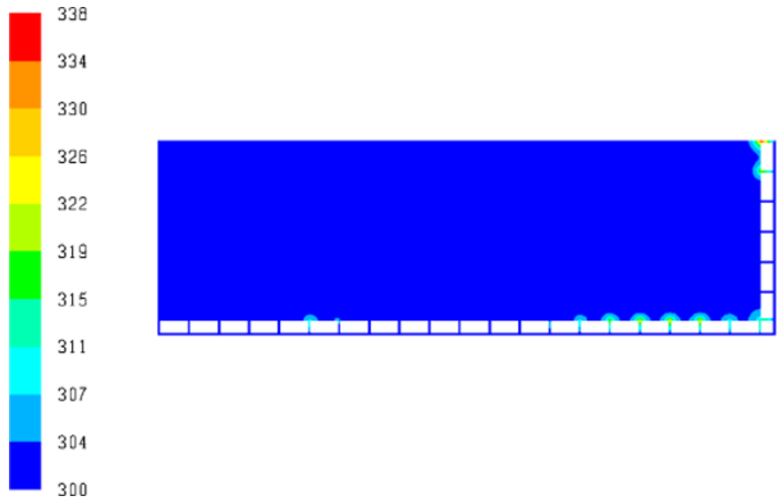

Figure 13.
Temperature distribution (K) in the gob 20 days after N_2 injection: 380 cfm (see online version for colours)

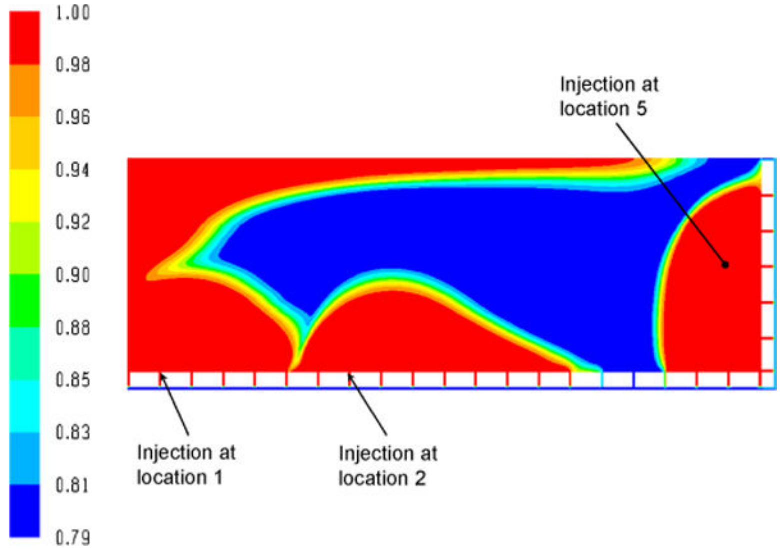

Figure 14.
N_2 concentration distribution (1 = 100%) in the gob 20 days after the injection: 1000 cfm (see online version for colours)

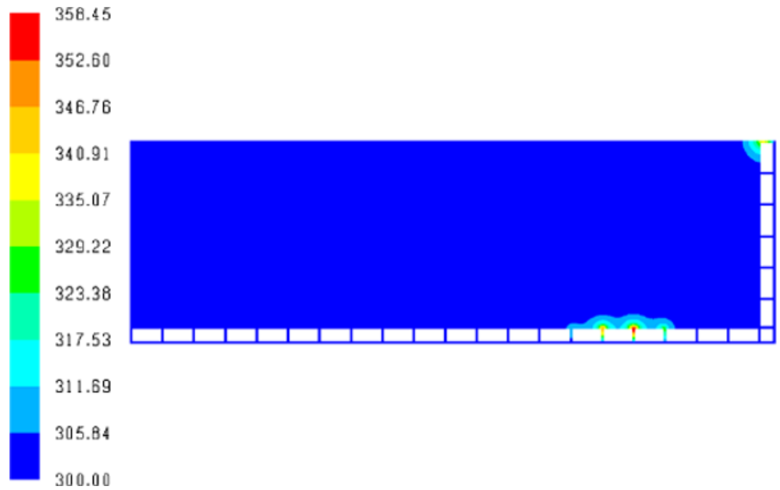

Figure 15.
Temperature distribution (K) in the gob 20 days after N_2 injection: 1000 cfm (see online version for colours)

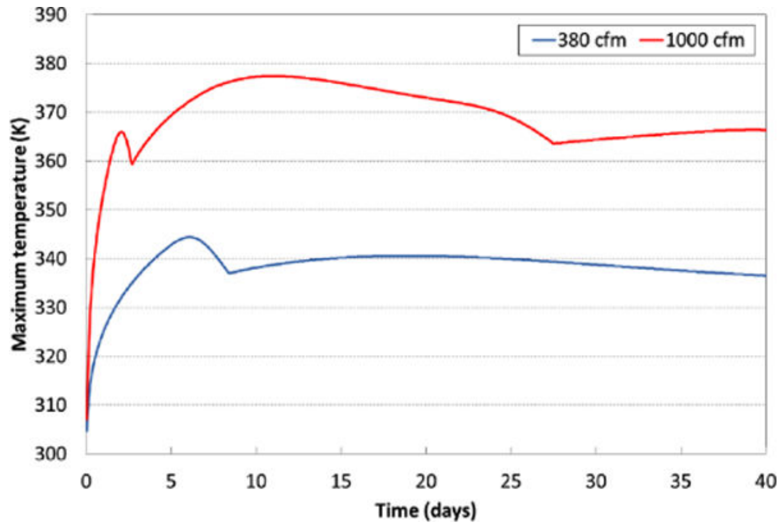

Figure 16.
Maximum temperatures (K) vs. time in the gob with different injection rates (see online version for colours)

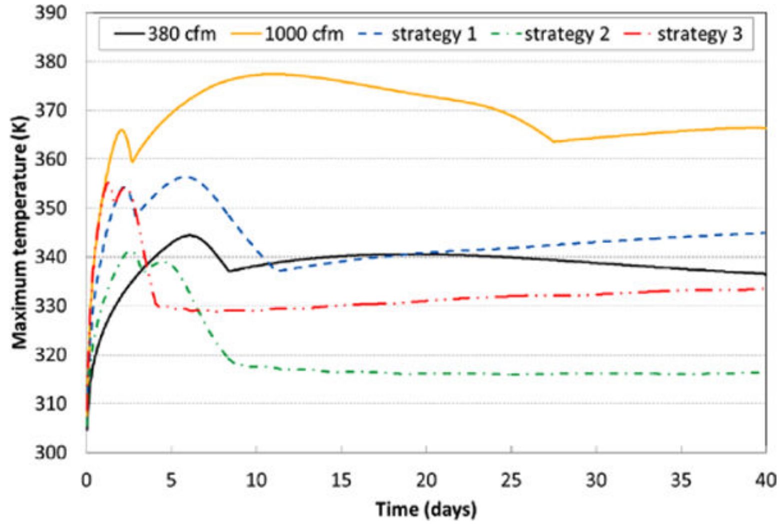

Figure 17.

Comparison of maximum temperatures (K) in the gob between different injection strategies (see online version for colours)

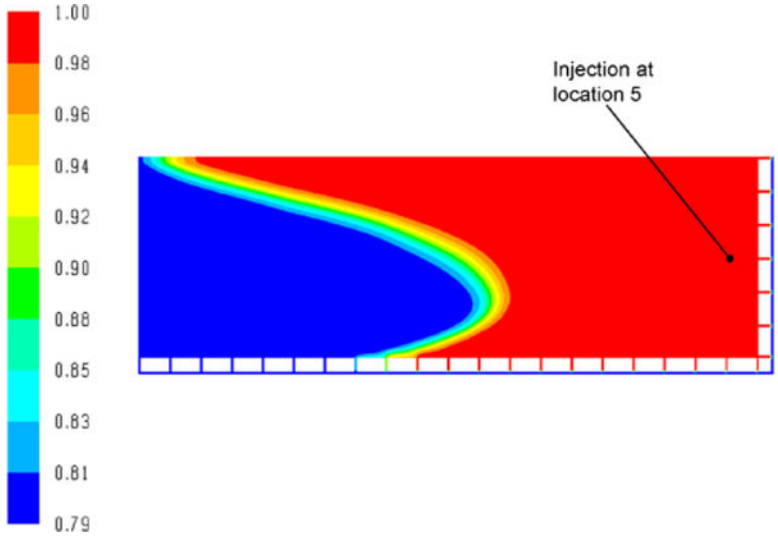

Figure 18.
N_2 concentration distribution (1 = 100%) in the gob 20 days after the injection for strategy 2 (see online version for colours)

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Table 1

Locations of N_2 injection positions

N_2 injection position	***Location***
Location 1	50 m from face, through seal on headgate side
Location 2	350 m from face, through seal on headgate side
Location 3	600 m from face, through seal on headgate side
Location 4	50 m from back end and 50 m from headgate perimeter, through borehole
Location 5	50 m from back end and 150 m from headgate perimeter, through borehole
Location 6	50 m from back end and 50 m from tailgate perimeter, through borehole

Table 2

The physical and kinetic properties of coal modelled in this study

Coal density	1300	kg/m^3
Coal specific heat	1003.2	J/kg-K
Coal conductivity	0.1998	W/m-K
Heat of reaction	300	kJ/mol-O_2
Activation energy	73.6	kJ/mol
Pre-exponential factor	1.1×10^7	K/s
Initial coal temperature	300 (27)	K (°C)

Source: Smith and Lazzara (1987)