The University of Southern Queensland
Faculty of Engineering and Surveying

Ventilation of Highwall Mining to Control Methane Concentration at the Moura Mine

A dissertation submitted by

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Abstract

Methane is a highly explosive gas released during coal mining that presents an imminent problem when mixed with oxygen in regard to maintaining safe working conditions in underground and highwall mines.

The Moura Mine's current Addcar highwall coal mining operation in Central Queensland has identified that high methane concentrations on the northern side of the mine have restricted production rates and penetration depths of mining equipment in comparison to the southern side, with lower methane concentrations (Conway, B 2006, pers. comm., 11 April). Research has identified that gaining an understanding of the migration of methane in underground mining applications using computational fluid dynamics (CFD) software is the key to improving methane control (Ren, Edwards & Jozefowicz 1997). Further research has suggested that injection of inert gases can provide an effective means to control methane concentrations in highwall mining applications (Volkwein 1993 & 1997). Trials at the Moura Mine of the injection of various inert gases (nitrogen, boiler gas and carbon dioxide) at different injection configurations on the current highwall mining operation have been inconclusive (Kunst, G 2006, pers. comm., 16 July).

In this investigation, a simplified two-dimensional CFD model was produced using Fluent software in order to determine the most effective inert gas and injection angle for a number of different penetration depths. Results indicated that carbon dioxide was the most effective of the three gases trialled (carbon dioxide, nitrogen and boiler gas), at an injection angle parallel to the profile of the highwall drive (i.e., at 0 degrees). The boiler gas and nitrogen provided similar results to one another and were also most effective when injected parallel to the drive for all penetration depths. Additional research is required to further understand how to maximise methane control measures at the Moura Mine. Specifically, for example, a three-dimensional CFD analysis would provide a more comprehensive representation of the current highwall mining operation. The results of this investigation, however, should aid in understanding the migration and control of methane concentrations within the current highwall mining operation, leading to improved penetration depth, production rates and safety at the Moura Mine.

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ENG4111 & ENG4112 *Research Project*

Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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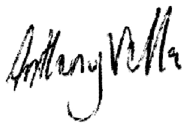

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1. Introduction

The background to the investigation and its objectives are outlined in this chapter. An introduction to the highwall coal mining operation at the Moura Mine details the need for effective control of methane during mining and provides an understanding and appreciation for the necessity of this project.

1.1. Rationale

This dissertation is an industry-generated project in cooperation with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Moura Mine highwall coal mining operation in Central Queensland. In some regions of the Moura Mine, high methane concentrations result in limited highwall coal mining production. Specifically, when methane is combined with oxygen this gas mixture has the potential to be highly explosive, limiting production due to the safety risk to both personnel and equipment. Currently, the Moura Mine uses a ventilation system to attempt to control methane/oxygen concentrations to within safe working limits. Thus far, however, this system has proven to be ineffective at certain penetration depths where methane/oxygen concentrations are dangerously high. This study aims to develop new, more effective ventilation system configurations for the Moura Mine highwall mining operation so that coal mining production can be maximised whilst maintaining safe working conditions. The purpose and scope of the study are detailed in Section 1.4 Research Objectives.

1.2. Background

The mining industry is a major contributor to the Australian economy as Australia is one of the major coal producers of the world. The two main mining methods currently used in Australia for extracting coal are surface mining (opencut) and underground mining, as shown in Figure 1-1.

Surface, or opencut, mining is where overburden (dirt and rock above the coal seam) is removed by large machinery such as draglines (see Figure 1-1) in order to expose the coal seam, which is then removed by additional machinery. Overburden is then replaced and the site is rehabilitated. Presently, surface mining is the most cost-

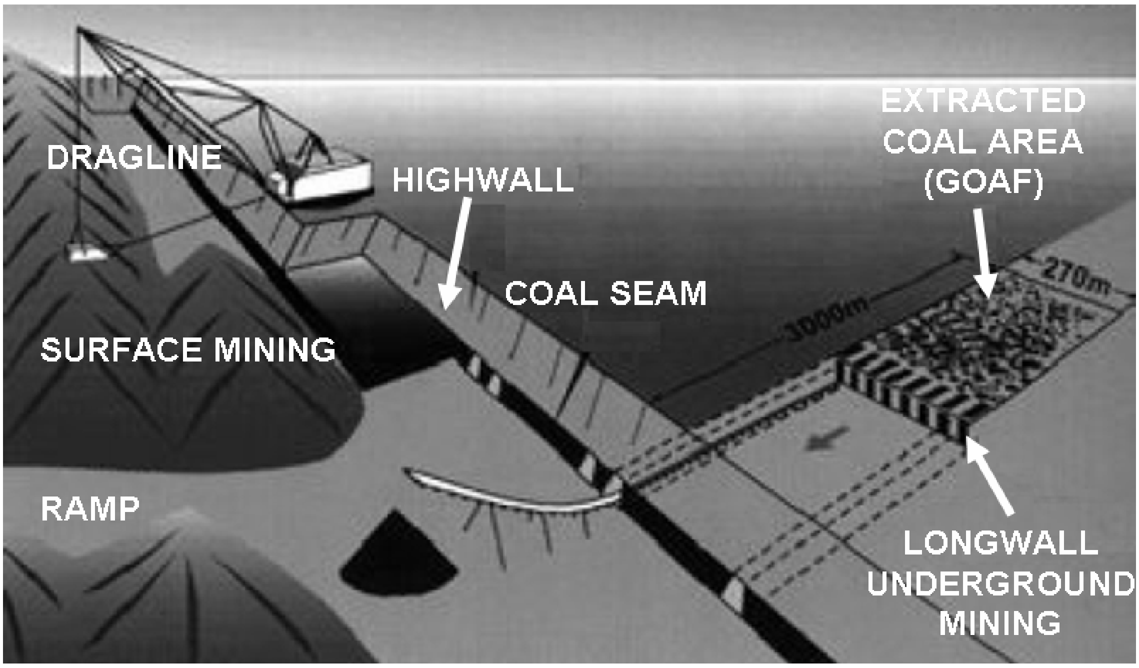

Figure 1-1 Coal Mining Methods **(Trevor 2004)**

effective mining method when the coal seam is a fixed distance from the surface. This distance is based on an economic depth limit called the strip ratio, which is the ratio between the overburden and the coal seam thickness. When the coal seam drops below the economic limit for opencut mining it becomes more economical to mine the coal using underground mining methods. There are two main underground mining methods, including the board and pillar method and the longwall method. Longwall mining is the most common underground mining method used in Australia (Trevor 2004) and involves the development of large rectangular blocks of coal, called panels. These panels are extracted through a single continuous process using a longwall mining machine called a 'shearer' which traverses the coal face, as shown in Figure 1-2. Self-advancing hydraulic roof supports hold up the roof above the shearer as it advances and then move forward, allowing the roof behind to collapse.

As many surface coal mines near the end of their economic lives, new mining methods must be employed in order to maintain production. Highwall mining and trench mining are relatively new mining methods that have been introduced to Australian surface mining operations. Highwall mining was developed specifically to extract additional coal from surface mining operations when underground mining methods are found to be unjustified. It is a cheaper and safer method of extracting coal than underground mining methods. The method involves unmanned equipment that is used to cut unsupported

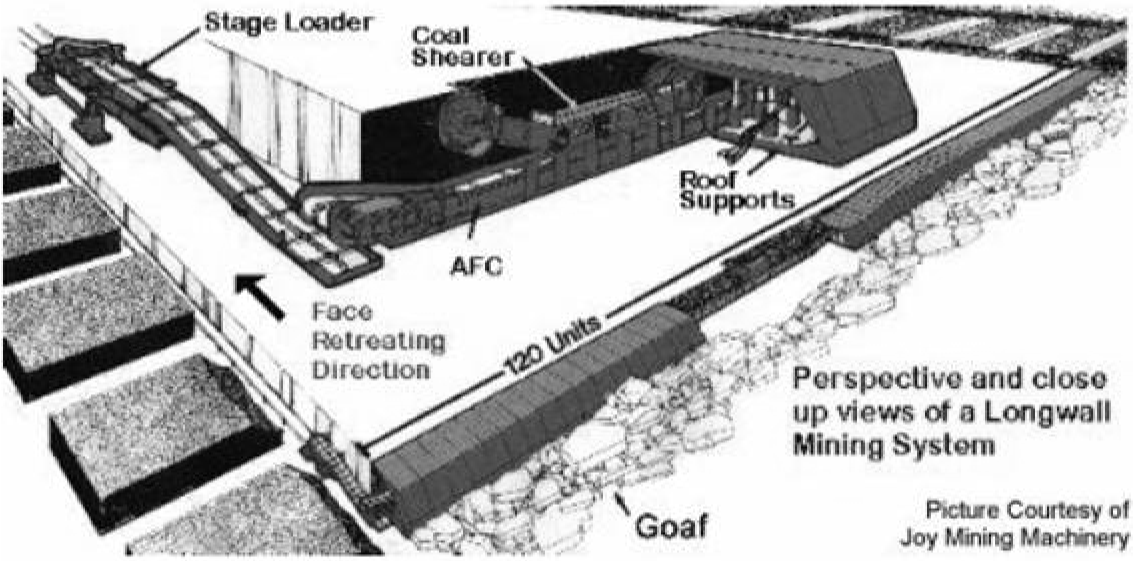

Figure 1-2 Underground Longwall Mining **(Trevor 2004)**

drives into the opencut highwalls, as shown in Figure 1-3 (Hargraves & Martin 1993). As such, this is a rapid method of extracting coal before roof strata within the drive begin to fail. Trench mining uses a combination of conventional surface mining and highwall mining. Specifically, draglines are used to uncover coal which is then removed, forming trenches that outline large blocks. The coal beneath these blocks is then extracted using the highwall mining method, as shown in Figure 1-3 (Hargraves & Martin 1993). Advances in modern highwall mining equipment have not been fully utilised in some mines because of an inability to maintain safe methane/oxygen

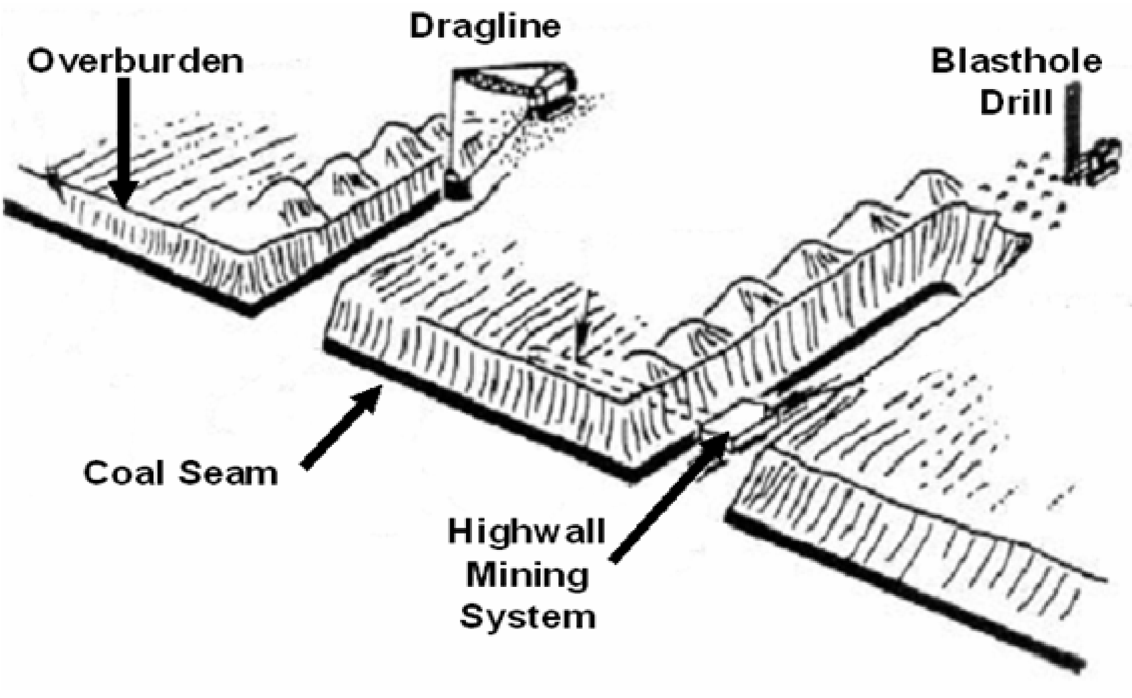

Figure 1-3 Trench Mining **(Holman, McPherson & Loomis 1999)**

concentrations. Highwall mining ventilation systems are used to dilute methane concentrations through the injection of inert gases, providing safer working conditions to the highwall mining environment for both personnel and equipment. Improving the effectiveness of the ventilation system has the potential to maximise both the production and safety of the mine.

1.3. The Problem

The Moura Mine was the first coal mine in Australia to introduce the highwall mining method. This mine has long been considered a 'gassy' mine, meaning there are large quantities of methane found within the coal seam. It has been identified that the penetration depth of highwall mining equipment has been limited in some parts of the mine by the ventilation system's inability to minimise methane/oxygen concentration levels to within safe working limits (Kunst, G 2006, pers. comm., 16 July). As noted above, the ventilation system uses inert gases injected into the highwall drive during mining in order to maintain safe methane levels. It has been found to be effective at predetermined penetration depths for the various regions of the mine (Balusu, R 2005, pers. comm., 3 October) Full details of these conditions are provided in Chapter 2.

1.4. Research Objectives and Overview of Methodology

The primary objective of this project is to identify ways to reduce methane/oxygen concentrations as much as possible so that highwall coal mining can be extended to deeper penetration depths, extracting as much coal as is possible without increasing safety risks. Using computational fluid dynamics (CFD) software (specifically, Fluent), a number of models will be generated incorporating three specific factors: penetration depth, injection of inert gas (in this case, carbon dioxide, nitrogen and boiler gas) and angle/direction of injection of the inert gas. In this way, the study aims to identify the effectiveness of the use of each of the different inert gases, at different angles of injection into the drive and at varying penetration depths.

In order to achieve this objective, background information and research relating to the ventilation of highwall coal mining, in general, and at the Moura Mine, specifically, will be explored and a detailed literature review will be completed. Proficiency in the CFD software program Fluent will also be developed in order to perform the necessary analyses. Finally, CFD analyses will be carried out using Fluent in order to predict the behaviour of gases with regard to mixing and diffusion within the highwall drive for each model generated, incorporating the three factors, as noted. Specifically, these analyses will aim to identify the benefits and limitations of each of the models generated and, ultimately, to determine the optimum configuration with regard to the control of methane/oxygen concentrations during highwall coal mining.

1.5. Dissertation Overview

This dissertation begins with an introduction outlining the objectives of the investigation and the methodology undertaken in order to meet those objectives. Chapter 2 provides a background into coal mining and the various methods of mining, as well as the significance of methane in coal mines and at the Moura Mine, specifically. Chapter 3 provides further background with a detailed review of recent and relevant research into the control of methane in highwall mining applications. Chapter 4 discusses the computational fluid dynamics (CFD) approach and outlines the methodology used to investigate the highwall mining operation at the Moura Mine. The results of the CFD analyses are then presented and discussed in Chapters 5 and 6, respectively. Finally, a conclusion to the investigation is presented in Chapter 7.

1.6. Conclusion

By identifying ways to reduce explosive methane/oxygen concentrations at the Moura Mine's highwall coal mining operation, this investigation is expected to provide a greater understanding of the behaviour of gases within the highwall drive. It is also expected to elucidate various possible ventilation configuration systems that might be utilised during mining, based on varying the type of inert gas used and the angle of injection of the inert gas at various penetration depths. The outcome of the study should provide a more effective means to control methane at the Moura Mine which should subsequently lead to improved productivity and safety.

2. Background

Background information on highwall mining and methane, in general, and at the Moura Mine, specifically, is detailed in this chapter, before reviewing findings from previous research studies in Chapter 3. A variety of information resources were accessed, including online sources (databases, websites and on-line texts), books and journals as well as material provided by both the CSIRO and the Moura Mine in regards to methods and equipment specifications.

2.1 Highwall Mining

The highwall mining method was specifically developed to recover additional coal from surface mines once the economic limit for overburden removal (strip ratio) had been reached and underground mining methods were not justified (Schafer 2002). In the past, when the economic limit for overburden removal of coal was reached, the final highwall marked the shift from surface mining to underground mining (Schafer 2002). However, the capital investment necessary for underground mining could not always be justified (Schafer 2002). For these situations, an economical recovery method for the coal was required, hence the development of the highwall mining method (Schafer 2002). Highwall mining is a hybrid mining system with high recovery returns capable of accessing reserves at substantially less capital cost and lead time compared with underground mining methods. Highwall mining is also less labour-intensive than underground mining (Shen & Duncan Fama 2000).

The original highwall mining system was developed 60 years ago in the United States in order to mine thin coal seams in the Appalachian Mountains (Hargaves & Martin 1993). That method evolved when contractors realised that auger drills used for drilling blast holes in opencut mines could be turned horizontally to extract coal from the otherwise inaccessible final highwalls. However, this augering was found to be very hazardous and was thus limited to penetration depths of 50-60 metres, making coal recovery poor (Hargaves & Martin 1993).

Current highwall mining methods also originated in the United States in the mid-1970s and have been used commercially since the early 1980s. These systems involve mining

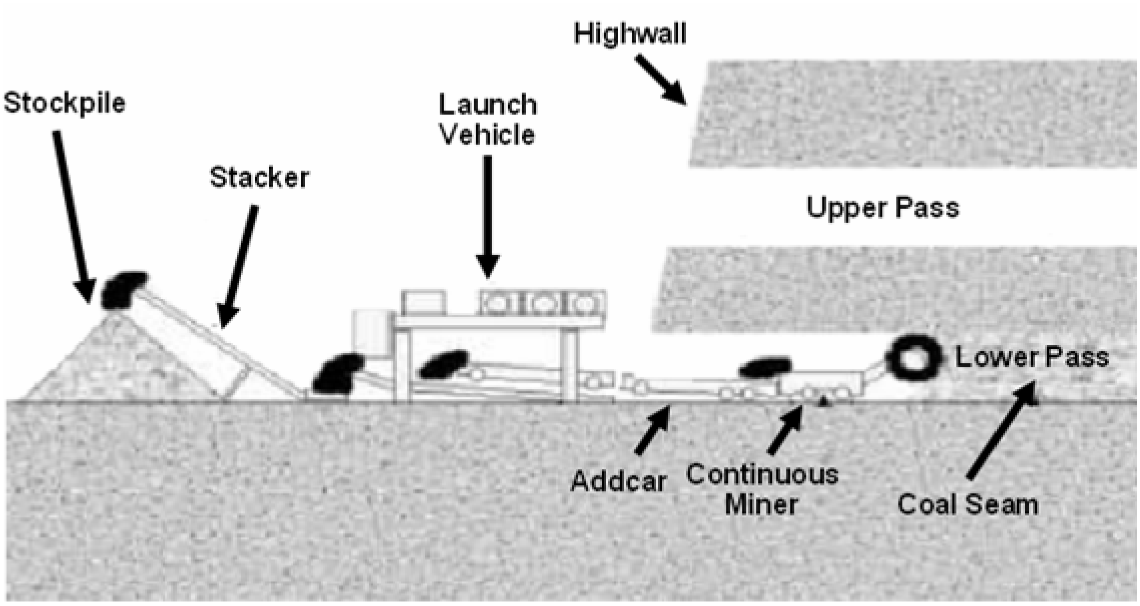

Figure 2-1 Addcar Highwall Mining Operation (Hainsworth, Reid & McPhee 2006)

or boring a series of parallel entries into the final highwall coal seam. This is a rapid method of extraction of coal before roof strata within the drive begin to fail. Unmanned equipment is used to cut unsupported drives into the final surface mine highwalls (Hargaves & Martin 1993). One of these methods is the Addcar Highwall Mining system, shown in Figure 2-1. A coal rib or pillar is left on either side of the highwall drive (hole) to support the highwall above. The thickness of the rib, generally one to two metres, is important in that it must provide adequate support (Hargaves & Martin 1993). If the rib is too thin the risk of ground fall increases with the potential to bury expensive equipment. Conversely, if the rib is too thick the excess coal within the rib becomes unrecoverable (Hargaves & Martin 1993). The depth of each highwall drive is determined by a variety of operational factors. These factors include the capability of the equipment and the method used, the concentration of methane/oxygen within the drive, geological factors influencing roof falls and, finally, the equipment position in relation to pillars and the coal seam. Mined out regions are then sealed off after mining to prevent spontaneous combustion of coal resulting in methane/oxygen explosions (Hopkins 1999).

The areas best suited for highwall mining are thick seams where at least one of the following conditions applies:

- regions of rapid increase in the strip ratio from an economic surface mining range to non-viable values; may occur due to exceptional topography, unusually

- steep grades and/or lenticular interburden (expansion of overburden between seams)
- service corridors, which are areas unavailable to conventional surface mining methods due to public roads, railways, water courses or other service access
- regions where there is underground activity in lower seams below the highwall which can cause strata subsidence; highwall mining can recover the highwall coal prior to strata movement (Hargaves & Martin 1993)

2.1.1 Highwall Mining Systems

Highwall mining equipment continues to improve, governing the way in which coal is recovered from the highwall. A variety of highwall mining systems are available, including the Addcar, Archveyor, Auger, Metec and Superior methods. Each of these is discussed in detail below.

2.1.1.1 Addcar Highwall Mining System

The Addcar or Continuous Highwall Mining system (CHM) was developed in the 1980s and 1990s and is significantly different from the earlier designs described above (Schafer 2002). This system involves an adaptation of an underground continuous miner which is fully remote-controlled and uses a series of 12-metre-long cars (Addcars). Each Addcar has its own separately driven conveyer belt to transport the coal from the cutting face to the platform and stacking conveyer, as shown in Figure 2-2. The conveyer belts reduce the degradation of the coal during transportation, have a higher transport capacity and are less likely to jam and clog as with auger-type systems (Schafer 2002).

In a typical Addcar Highwall Mining system, a rectangular hole approximately 3.6 metres wide and 3.8 metres high is cut by a remote-controlled continuous miner to penetration depths of up to 500 metres (Shen & Duncan Fama 2001). A continuous miner uses a rotating drum with cutting picks to cut the coal from the coal face which then drops to the drive floor, as shown in Figure 2-2. Rotating paddles on the front of the continuous miner transfer the cut coal on the drive floor to an internal conveyor which transports the coal to the Addcars or conveyor cars behind it. The Addcars are individually powered and use a conveyor system to transport coal to the highwall face. A launch vehicle is used to add and remove Addcars through the use of an upper and

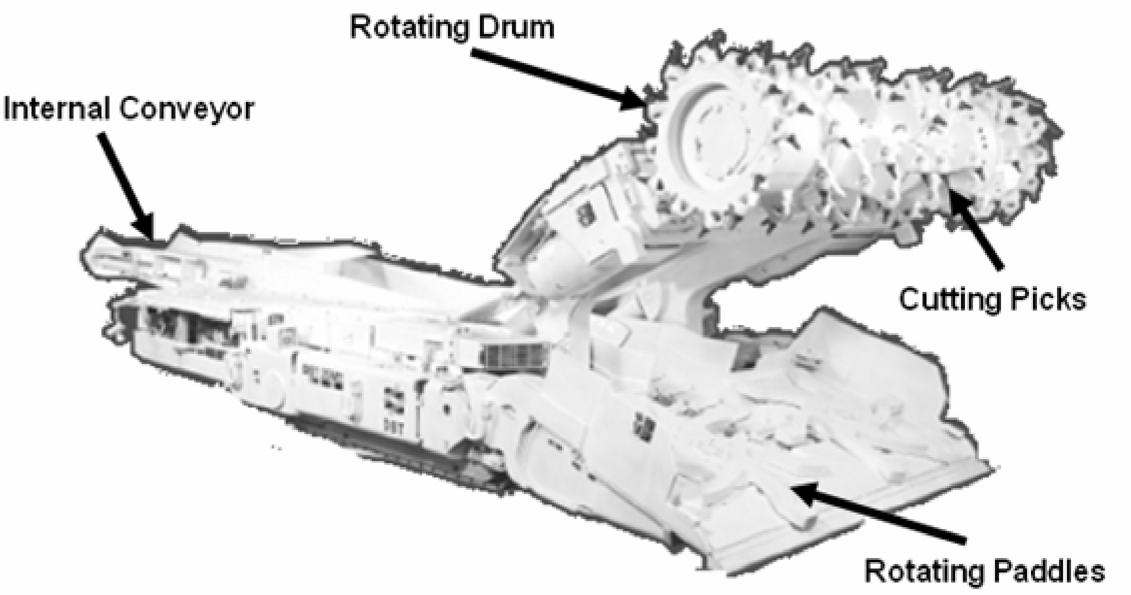

Figure 2-2 Continuous Miner (Holman, McPherson & Loomis 1999)

lower deck during the mining operation, as shown in Figure 2-3. This launch vehicle has an electrical power centre and power supply cables and it provides ventilation gases and a water hose to aid visibility at the face by suppressing dust. The system can tolerate minor roof falls of less than 0.2 metres thick, but major falls of more than 0.3 metres can cause serious damage and the entrapment of equipment, significantly undermining this method and making this system unsuitable under poor geological conditions. This system has a maximum production rate of 124,000 tonnes of coal per month (Shen & Duncan Fama 2000). It is capable of recovering from 54-67% of the coal in a highwall (Holman, McPherson & Loomis 1999). Greater penetration depths are achievable with the Addcar system due the continuous miner's ability to power tram (self-propel) as it pulls itself into the cutting face, rather than to be pushed as with earlier methods. The power tramming provides more options for direction correction, however, it must overcome the rigidity of the connected string of cars (Schafer 2002). A larger work area is required for the Addcar system. A stabiliser system has also been introduced to this system in order to aid steering and tracking and improving the accuracy of the coal removal. Laser guiding and 3D mapping systems, along with better directional control, have led to a reduction in misalignment problems (Schafer 2002). This system has been known to accommodate coal seams with dips of up to 16 degrees. Penetration depth at steep angles, however, is limited by the platform's inability to overcome floor friction and the weight of the cars due to slipping or skidding (Schafer 2002).

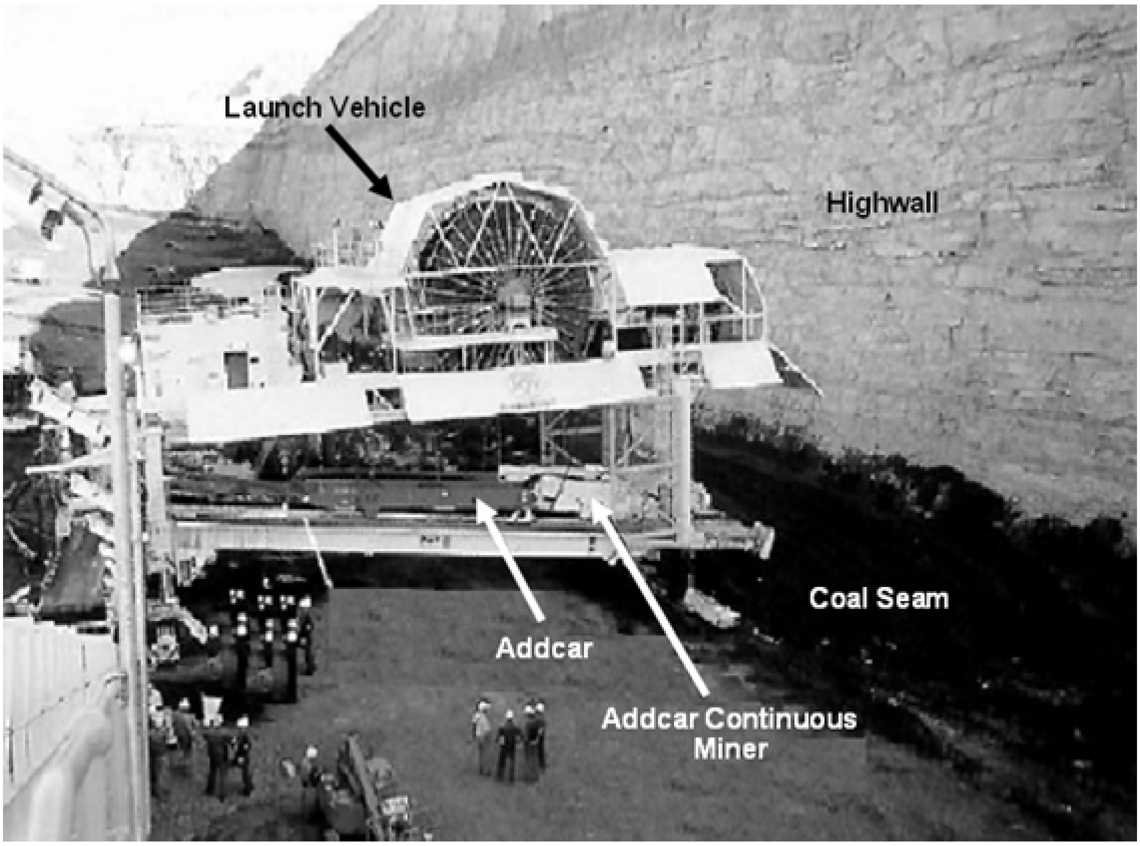

Figure 2-3 Addcar Highwall Mining System (Holman, McPherson & Loomis, 1999)

In 1995, a conglomeration consisting of the Moura Mine (under the ownership of BHP), Mining Technologies Australia (MTA, distributors of the Addcar Highwall Mining system in Australia), the CSIRO, Joy Mining and Honeywell developed its own Addcar highwall mining technology to suit Australian conditions, as technology at the time was focused on American thin-seamed highwall coal mining conditions (Syddell 1995a). Completed in 1997, the Addcar Steep Dip Highwall Mining system is capable of steep dip mining, working on steeper inclines from 7 to 12º. A navigational guidance system enables a penetration depth of up to 500 metres. The system uses an inert gas generation system based on the Tomlinson boiler system to neutralise methane emissions during mining (Syddell 1995a).

In comparison with its competitors, the Addcar Highwall Mining system claims to have 150% more penetration depth, 90% more annual production, 82% more installed horsepower and the production of the same amount of tonnage for a reduced highwall length (Holman, McPherson & Loomis 1999).

2.1.1.2 Archveyor Highwall Mining System

The Archveyor Highwall Mining system is the newest of the highwall mining systems.

It uses a computer-controlled continuous miner attached to an integrated, bendable, continuous haulage chain conveyor with a load-out vehicle and control centre, as shown in Figure 2-4. It has a penetration depth of 305 metres and requires only two operators per machine (Syddell 1995e).

The Archveyor system is both horizontally and vertically flexible, with drive units every 7.5 metres to drive small sections of the conveyor. This is advantageous in mining and traversing through undulating coal seams, as the system is capable of turning at ninety degrees (Holman, McPherson & Loomis 1999). During mining, hydraulic jacks lift the Archveyor clear of the ground, allowing the conveyor to transport the coal. A main drive unit at the end of the conveyor supplies power to the unit. The Archveyor system can operate at seams that dip at 30º while operating well below maximum power (Holman, McPherson & Loomis 1999). A flexible ventilation duct is mounted above the conveyor. The miner is capable of cutting a 3.8 metre wide opening that is from 1.8 to 4.9 metres high. The continuous miner cuts and loads the coal onto the Archveyor. At this point, the Archveyor is in its conveyor mode with the unit raised on the hydraulic jacks. The miner then advances forward and begins to cut the coal which begins to build up in front of the miner. Meanwhile, the Archveyor is advanced forward. The Archveyor jacks are retracted and the conveyor is powered in reverse in order to advance the unit. Difficulties can arise in thin seams where there is no room to store coal in front of the miner while the Archveyor advances. In this case, an auger-headed continuous miner is used (Holman, McPherson & Loomis 1999).

The operators are not required to be situated in front of the drive, as the control centre and load-out vehicles are located off to the side. This provides greater safety in the case of a coal dust or methane explosion. A methane monitoring system is also incorporated into the system that warns the operator at 1% concentration and shuts down the highwall mining machine at 2% concentration (Syddell 1995e). The system has a fully automated mining cycle controlling cutting, loading and conveying of coal, all of which are computer-controlled. The continuous miner is programmed to progress through its cutting cycle with the conveyor following behind. Machine navigation and coal quality are maintained by instruments located on the miner and are analysed by the computer (Syddell 1995e).

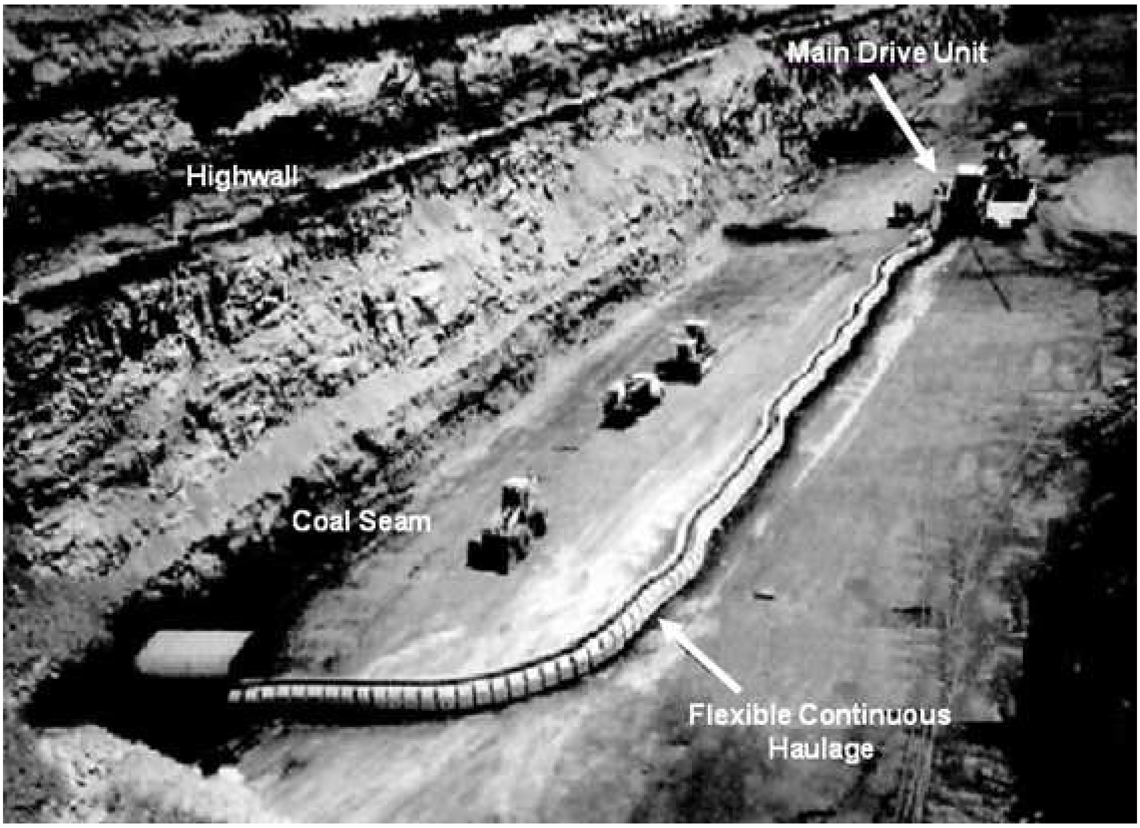

Figure 2-4 Archveyor Highwall Mining System (Holman, McPherson & Loomis 1999)

2.1.1.3 Auger Highwall System

The Auger Highwall Mining system involves drilling and augering the coal from the final highwall coal seam. It is the simplest and most cost-effective extraction method. Large diameter augers are used to bore into the coal seam in order to extract the coal and additional auger segments of flights are added as boring continues into the face, as shown in Figure 2-5 (Schafer 2002). The direction of the auger is determined by the initial alignment of the auger platform and the rigidity of the connections between flights in order to provide adequate stiffness during boring. Augering provides a means both to cut and to transport the coal to the surface. This system is capable of working under difficult geological conditions due to the strong circular profile cut and substantially lower cost of auger flight replacement in the case of roof failure, in comparison to other highwall systems. However, the Auger system is very difficult to guide due to the soft and hard roof and floor conditions and the tendency for the auger to drift downwards due to its weight, all of which contribute to directional problems associated with deflections during drilling. The depth of the auger holes is limited by the horsepower of the rotary drive and the out-of-seam contamination resulting from the lack of guidance (Schafer 2002). Currently, this system has a maximum penetration

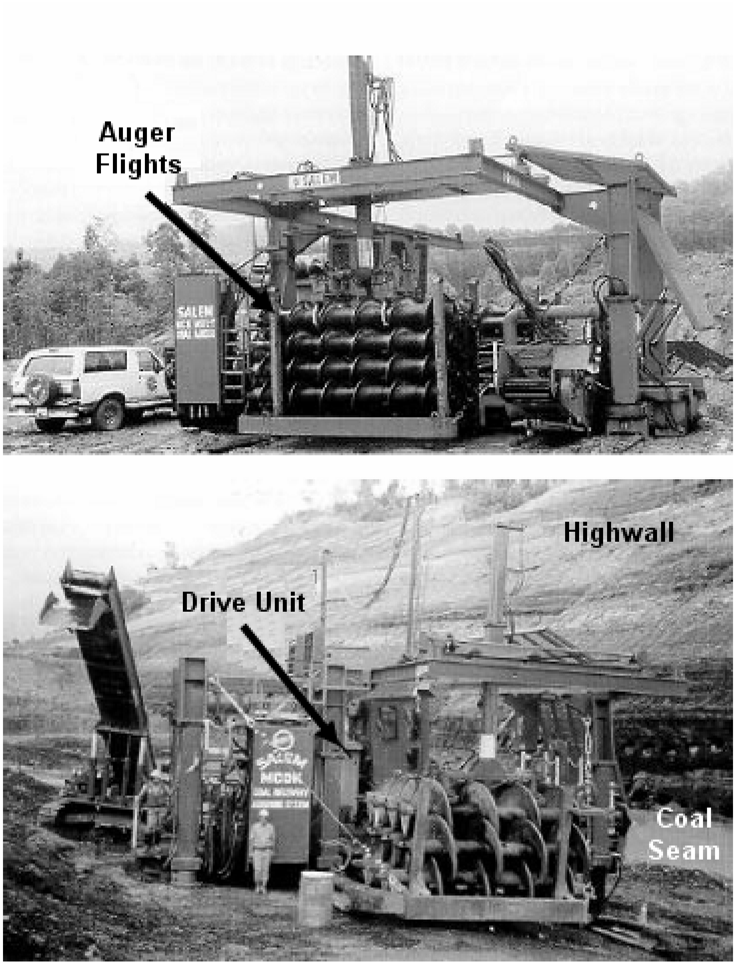

Figure 2-5 Auger Highwall System (Holman, McPherson & Loomis 1999)

depth of 200 metres with a maximum production rate of 60,000 tonnes per month (Shen & Duncan Fama 2000). A variety of different sized augers can be used in succession during the process. Small augers create unsaleable fines resulting from the coal grinding upon itself due to the lack of space within the auger flights as it is moved to the surface. Large diameter augers have a reduced production of fines due to the greater space between flights, minimising the grinding of the coal upon itself (Schafer 2002).

Significant improvements have been made to Auger Highwall Mining machines through more powerful drives, multi-speed transmissions and greater flight lengths, which have all contributed to the improved productivity of the Auger Highwall Mining system. The advantages of this system in relation to the others described are its ease of operation and maintenance, ability to work under difficult geological conditions, strong circular profile in boring and requirement of minimum capital investment. These advantages make the system more favourable for poor roof and floor conditions (Shen & Duncan Fama 2000).

2.1.1.4 Metec Highwall Mining System

The Metec highwall miner uses a cutting head and gathering pan from a conventional underground continuous miner to feed a string of enclosed augers which are added as the miner advances forward. A push beam is used to force the cutting head forward from an outside platform. Conveyers transfer the coal from the auger to the platform and onto a stacking conveyer. When originally introduced, this system had improved productivity rates compared to the Auger system. However, this is no longer the case due to improvements to the Auger system. Applying the force through the push beam over long distances is a major disadvantage to this system, limiting the penetration depth. The augers used to transport the coal to the surface grind the coal producing unsaleable fines, as indicated with the Auger Highwall Mining system (Schafer 2002).

2.1.1.5 Superior Highwall Mining System

The Superior Highwall Mining system is an extension of the Metec system with programmable controllers and cutter-head options to accommodate various seam heights. The Superior system has a rear discharge option, however, it is still reliant on proper alignment and lateral stiffness for directional control and push in order to advance the cutter head. Penetration depths are limited by the platform's inability to provide sufficient pressure for the cutter-head to advance (Schafer 2002).

2.1.2 Highwall Coal Mining in Australia

The first highwall coal mining operations were introduced to Australia in 1989 by BHP at the Moura Mine in Central Queensland. Ten rectangular openings were driven into the highwall to a depth of 30 metres using an experimental Addcar Highwall Mining system (Shen & Duncan Fama 2000). In 1991, Callide Mine was the first to commercially use an Auger Highwall Mining system. Soon after the trial at Callide, Auger mining was also employed at the German Creek and Oakey Creek Mines. The two main highwall mining systems currently used in Australia are the Addcar and the Auger Highwall Mining systems. Since the introduction of highwall mining in 1991, there are highwall coal mining operations today in at least 13 mines throughout Australia (Shen & Duncan Fama 2000).

Highwall mining methods that originated in the United States have had to be adapted in some cases for use in Australia due to the variation in mining conditions. The differences between Australian

Table 2-1 Highwall Mining Conditions Comparison **(Seib & Boyd 1995)**

United States	Australia
Highwalls: 10-30m	Highwalls: 40-160m
Seams: 0.5-2.5m	Seams: up to 4m
Single pass highwall mining generally	Multiple pass mining generally
Machinery exposed to minimal risk	Collapse would have major costs
Final highwalls readily available (contour mining)	Different regions of interest
Recoveries of approximately 60% from thin seams	Recoveries of approximately 30% from thick seams
Operator Judgement	Geotechnical studies
Relatively simple scheduling	Complex interactions due to multiple passes

and American highwall mining conditions are outlined in Table 2-1. Highwall mining methods have a substantially lower capital cost, only ¼ to ⅓ the cost of conventional dragline surface mining operations. The annual output per employee of 30-40,000 tonnes is 3 to 4 times that of the surface mining average (Pinnock 1997). The major disadvantage of highwall mining is the risk that the mining machine will be buried and potentially unrecoverable. Improved engineering and geological knowledge, however, have led to a reduction in this risk. With a large number of surface mines nearing the end of their economic lives, highwall mining offers operators a means to extend the life of a mine and this is likely to become a more prominent mining method in the future (Pinnock 1997). The Moura Mine is an example of a coal mine where highwall mining techniques have been introduced with good results.

As new surface mine deposits are diminishing, the industry is moving toward highwall and longwall mining methods for Australian coal seams. The development of highwall mining technology offers great potential, although it has yet to produce substantial output due to a lack of widespread utilisation at this stage (Pinnock 1997). Methane released from coal during mining poses an imminent risk in regard to explosions, and this risk has been associated with coal mining operations from their beginning. Controlling methane with regard to reducing potentially fatal explosions is an important factor in providing miners a safe place to work, as well as improving productivity. It is important for Australia to continue to support research and development, embrace new technology and invest in new equipment in order to maintain itself as a market leader in coal mining throughout the world.

2.2 Methane

Methane is an odourless, colourless and tasteless gas, also referred to as natural gas. It consists of one atom of carbon and 4 atoms of hydrogen (CH_4). High methane concentrations can cause oxygen deficient atmospheres, flammable situations or explosive environments. Combustion requires fuel (methane), oxygen and a source of ignition. Methane burns with a pale blue flame (Eltschlager et al. 2001).

Concentrations of methane at a point source into the atmosphere with an excess of 5% are readily ignitable. Atmospheric methane concentrations between 5 and 15% can ignite and explode at standard pressure and temperature. The most powerful explosive methane/air mixture is where there is 9.5% methane, as the combustion process consumes all methane (CH_4) and oxygen (O_2), producing carbon dioxide (CO_2) and water (H_2O), as a result (Eltschlager et al. 2001). The reaction between the methane and oxygen can be depicted as:

$$\mathbf{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

High levels of methane can quickly dilute from an ignitable to a flammable level. In either case, an explosive environment can be created if methane is allowed to accumulate in an enclosed space. An explosive environment exists when methane and oxygen combustion can self-propagate throughout a mixture, independent of the ignition source. Ignition sources can be generated through electrical connections, sparks from tools or machinery and/or open flames (Eltschlager et al. 2001).

Methane propagates from high to low pressure zones, from higher to lower concentrations and by molecular diffusion. Molecular diffusion is a prominent factor in the distribution of methane when flow rates are extremely low to stagnant. Methane has a high diffusion rate. The concentration of a gases is reported as a percentage or as

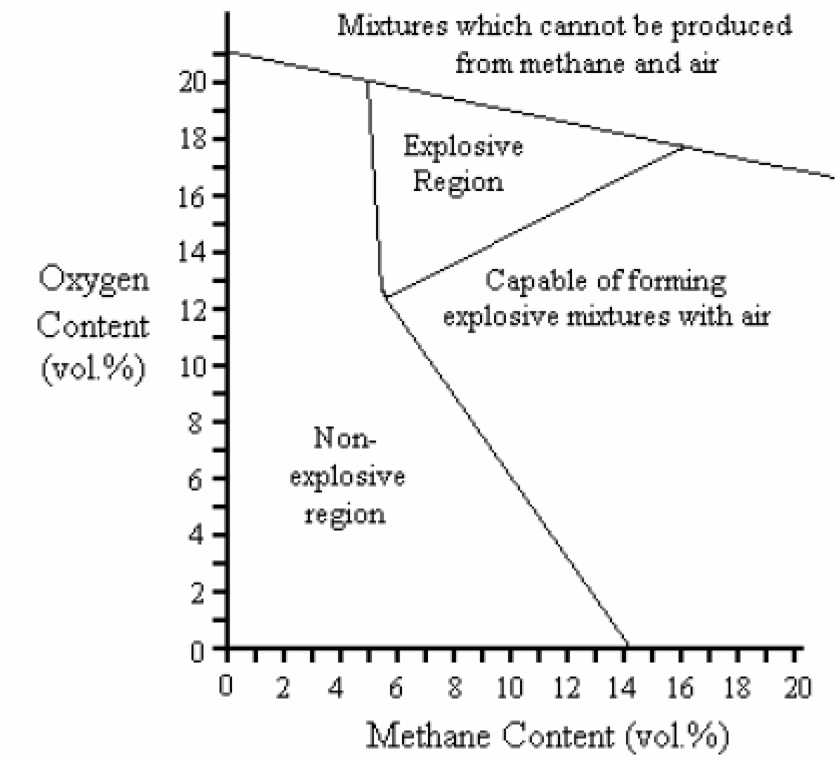

Figure 2-6 Coward Diagram **(Gillies & Jackson 1998)**

parts per million (Eltschlager et al. 2001). Explosive gases are most commonly reported as a percentage of their explosive limit. The Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) are limits used to define the range at which flammable gases or vapours become explosive when mixed with air. Methane concentrations of between 5% (its LEL) and 15% (its UEL) at standard temperature (20ºC) and pressure (1atm) will explode given an ignition source (Eltschlager et al. 2001). In 1929, Coward determined a methane/oxygen relationship from empirical data which indicates whether mixtures of methane and oxygen in mine air are in an explosive range (Gillies & Jackson 1998). The Coward Diagram is shown in Figure 2-6.

2.2.1 Coal Bed Methane

As noted earlier, methane is a natural gas that is produced during the coalification process. Coalification is the biochemical and geochemical process whereby, through time, heat and pressure, dead and buried plant (organic) material is transformed into the combustible carbonaceous material known as coal (Eltschlager et al. 2001). As much as 98% of the gas stored in coal beds can be methane with the remaining gas made up of carbon dioxide (CO_2), nitrogen (N_2) and trace amounts of hydrogen sulphide and higher hydrocarbons (such as ethane, propane and butane) (Lyman 2001).

The first stage of coalification begins with exposure of the dead plant to aerobic (oxygen-utilising) bacterial decay that metabolises most of the oxygen present and produces carbon dioxide. The second stage of decay requires anaerobic (non-oxygen-utilising) bacteria, where the first phase of methane is produced through the respiration of the bacteria. The remaining oxygen found in hydrocarbons is released as waste in the form of methane and carbon dioxide in a process is known as biogenic methane formation (Lyman 2001). If the coalification process is deep enough to be thermally altered (thermogenic process), a second phase of methane production can occur. When the temperature rises above 50ºC through increased depth or geothermal gradient, a thermogenic process begins producing additional water, carbon dioxide and nitrogen, as well as a small amount of methane. However, if the coal temperature is greater than 120ºC, the production of methane exceeds carbon dioxide with maximum methane production at temperatures of 150ºC (Lyman 2001).

The most common gases, by-products of the coalification process, found in coal are carbon dioxide and low molecular weight hydrocarbons such as methane and ethane (Eltschlager et al. 2001). Coal is a porous material with macro-pores and micro-pores. The macro-pores are mainly formed by the joint systems, cracks and fractures in the coal. The majority of the gas is absorbed by the micro-pores providing a large surface area of 200-300 square metres per gram of coal. This gas within the coal can be liberated when environmental conditions change. Due to the large surface area within the micro-pores, coal has the capacity to store large volumes of gas (methane) within its pores. Saturated coal can hold up to 21 cubic centimetres of methane per gram of coal (Eltschlager et al. 2001). As coal is mined, the methane flows in two ways: from the solid coal to fractures and wells, and through these fractures and wells into the mine. Deeper underground mines are usually gassier than shallower mines and produce the highest daily methane emission during mining. The overburden thickness and type of rock generally affect the amount of methane trapped within the coal seam. The actual methane emission rate is relative to the production rate, type of mine and amount of methane in the coal (Eltschlager et al. 2001).

2.2.2 Spontaneous Combustion of Coal

The low temperature of oxidisation, in combination with the absorption of moisture of the dry or partially dry coal, creates sources of heat which can lead to the spontaneous combustion of coal. The oxidisation process is complex, however, a simplified basic reaction of carbon (C) and oxygen (O2) producing carbon dioxide (CO_2) and heat can be depicted as:

$$\mathbf{C + O_2 \rightarrow CO_2 + Heat}$$

This chemical reaction is exothermic (releases heat) and the rate of the reaction will double for every increase in 10ºC (Lyman 2001). If the heat produced cannot escape, the coal temperature will pass its ignition point and a coal fire will occur. Other key factors that influence the combustibility of the coal are air flow, particle size, rank (description of the type of coal), temperature, pyrite content (presence of sulphur materials that may accelerate spontaneous heating), geological factors and mining methods (Lyman 2001). Accumulation of fine coal particles within underground and highwall mining regions also increases the potential risk of spontaneous coal fires. Some mines control these vulnerable coal regions by spreading out the coal to dissipate the heat or re-compacting the coal in order to cut off the oxygen and release heat produced by the coal through radiation (Lyman 2001).

2.2.3 Methane in Coal Mines

Mine gases, principally methane, have been a hazard to miners since the beginning of underground coal mining. Many coal miners have died from asphyxiation or explosion migration and accumulation of methane during mining (Eltschlager et al. 2001). Methane is considered to be the most frequent constituent found in mine explosions. Generally, the ignition of the methane/oxygen mixture raises and disperses flammable coal dust from the ribs and floor of the coal mine creating an atmosphere capable of rapid combustion. Explosive methane/oxygen concentrations, when ignited, can be isolated and rely on coal dust in the air to propagate the combustion flame throughout the mine, including to other potentially dangerous methane/oxygen concentrations (Lyman 2001). Today, underground mines use fans to create low pressure zones to move fresh air throughout the mine in order to dilute and remove the hazardous gases. However, modern mining equipment and methods are capable of the high production rates which also release increased levels of methane and coal dust into the mining environment, increasing the risk of explosions. Ventilation systems help to distribute finer coal particles throughout the mine which, in gassy mines, can result in the liberation of significant volumes of methane with the formation of coal dust (Eltschlager et al. 2001). Methane hazards during surface mining are rare, as gas is freely vented to the open atmosphere. Furthermore, coal seams near the surface have, over time, bled a large percentage of their methane to the surface (Eltschlager et al. 2001).

Methane in underground mines is a substantial problem that must be constantly monitored and controlled as the mining process exposes large surface areas of coal in confined spaces. Under these conditions, methane can quickly accumulate to explosive levels if not properly controlled (Eltschlager et al. 2001). The principal method of controlling methane in underground mines is ventilation. Close monitoring by personnel and machinery of methane levels at the working face and all other parts of the mine is essential to maintaining a safe working environment. High methane or gassy coal seams require additional degassing of the seam before mining. This is accomplished through the use of drilling degasification wells to remove methane; however, this process is time consuming. In some cases the methane is collected and marketed to the natural gas industry and this is an increasingly common contributor to the production of natural gas (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005).

2.2.4 Inert Ventilation Gases Used to Control Methane Concentration in Coal Mines

Ventilation systems using inert gases provide an effective means of controlling methane concentrations to predetermined depths under a variety of highwall mining conditions. Currently, three commercial inert gases are available to coal mines for use in the ventilation and control of methane concentrations for highwall mining operations. These three gases are nitrogen, carbon dioxide and boiler gas (Balusu, R 2005, pers. comm., 3 October).

Boiler gas is the product of a combustion process used to consume and convert oxygen, producing a mixture of nitrogen (85%), carbon dioxide (14%) and oxygen (1%) (*Inert Gas Generators* 2004). The composition of this mixture is influenced by its constituents, with a density of 1.23 kilograms per cubic metre (1.23kg/m^3) at 27 degrees Celsius (300K) (Kreith & Bohn 2001). The inert gas is produced at the highwall site as required by a Tomlinson Boiler, as shown in Figure 2-7. The boiler is available in a number of different capacities with regard to the production of boiler gas. The carbon

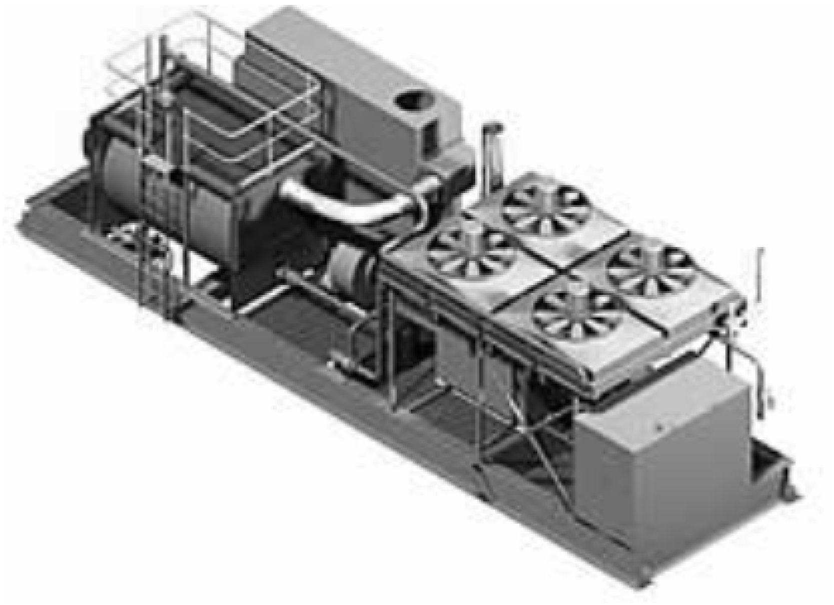

Figure 2-7 Tomlinson Boiler **(Inert Gas Generators 2004)**

dioxide and nitrogen gases cannot be produced on site and must be purchased and transported onto the mine site. The densities of the carbon dioxide and nitrogen are 1.80 kilograms per cubic metre (1.80kg/m^3) and 1.14 kilograms per cubic metre (1.14kg/m^3), respectively, at 27 degrees Celsius (300K) (Kreith & Bohn 2001). The injection temperatures of gases vary greatly with the boiler gas provided at cooled post-combustion temperatures of 40-60 degrees Celsius, while the liquid nitrogen is well below 0 degrees Celsius (Balusu, R 2005, pers. comm., 3 October).

2.2.5 Regulation of Methane in Queensland Coal Mines

Regulation of coal mines in Australia is the responsibility of the State governments. In the past, States were totally responsible for coal mine regulations. These regulations were highly prescriptive, describing in detail how safety could best be achieved with the presumption that the government was in the best position to determine the health and safety of miners using inspectors to ensure compliance (*Queensland Coal Mining Safety and Health Act 1999* 2006). In the 1970s, a trend toward the self-regulation of occupational health and safety in coal mines began which provided workers with various rights to be involved in decision-making about safety, as well as the right to information and training. Self-regulation is not de-regulation, as companies are still accountable to the government. Self-regulation frees employers from abiding by State-set rules, allowing them, instead, to opt to meet government performance or goal-setting standards in regard to particular issues (*Queensland Coal Mining Safety and Health Act 1999* 2006). Governments write codes of practice as guides to achieving determined goals; however, employers are under no obligation to follow these rules if an equally effective system is otherwise in place. The failure of an employer to exercise their duty of care can lead to substantial penalties. The 1999 Queensland Coal Mining Safety and Health Act states that coal mines are required to protect the safety and health of persons involved in, or who may otherwise be affected by, the operation of coal mines.

Under the 1999 Queensland Coal Mining Act, coal mines are responsible for the identification and assessment of risks and analysis and management of hazards, along with relevant reporting and recording of safety and health information. Under these regulations, an individual may not enter a highwall mining excavation area unless:

- abnormal circumstances are declared
- a competent person is present to supervise ERZ operations (explosive risk zones; refer to following paragraphs)
- risk assessment has been carried out
- adequate controls are in place to measure safety at all times
- the individual is competent to work safely underground and carries a self-contained self-rescuer

If highwall mining is carried out in conjunction with opencut mining, the mine is also responsible for providing the safety and health management system for the highwall mining activity. This system must adequately address:

- entry and evacuation of the individual from the highwall
- fire prevention and fire fighting equipment
- identification and marking of explosive areas along with safe areas for cutting and welding
- continual monitoring of oxygen and methane at the cutting face of the highwall
- measurement of control flooding
- communication on the surface when an individual is working within the excavation (Queensland Coal Mining Act 1999)

Gas monitoring systems are required to detect gas concentration levels within the mine which are relayed to personnel at the surface. These levels must be recorded to a log in a way that can be easily accessed by all employees and those employees must have the ability to activate an alarm if gas levels are exceeded. Coal-cutting machines are required to have at least one methane monitor fitted to detect methane concentration near the cutters. They must be able to automatically activate a visible alarm if methane concentration exceeds 1% and trip electricity supply to the machine if concentration exceeds 2% (Queensland Coal Mining Act 1999).

The Queensland State Government has identified three major risk zones in regard to methane concentrations within a mine. These zones are generally referred to by their acronyms ERZ0, ERZ1 and NERZ. Firstly, the ERZ0 is an explosive risk zone category zero, whereby the general body of the concentration of methane exceeds 2%. An ERZ1 is an explosive risk zone category one, whereby the general body of the concentration of methane is between 0.5% and 2%. Also included in this category are situations where coal or other material is being mined, regions of poor ventilation, goaf areas (collapsed and post-mined underground regions) and a number of other specialised cases. Finally, the third risk zone is an NERZ, negligible explosive risk zone, whereby the general body of methane concentration is below 0.5% (*Queensland Coal Mining Safety and Health Act 1999* 2006).

2.3 Moura Mine

The Moura Mine is located 450 kilometres northwest of Brisbane in the southeast corner of the Bowen Basin coal reserve, as shown in Appendix B. The Moura Mine is part of the recently formed Dawson Complex, made up of a number of surrounding mines. The mine first commenced mining in 1961 and is one of the longest established coal mining operations in Central Queensland. The mine has changed ownership several times over the past 20 years and is currently owned by Anglo Coal Australia Pty Ltd (51%) and Mitsui Coal Holdings Pty Ltd (49%) (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005)

Both surface and underground mining have been used for the extraction of coal since the mine began operations. A highwall mining operation was first trialled in 1989 and, recently, the first coal bed methane recovery operation was established (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005). The coal at the Moura Mine is contained within six major seams that average 3.5-4 metres in thickness and dip at 5 to 12º, comprising highly volatile, low ash bituminous coking and steaming coal. These seams merge, split and thin out in different regions of the Moura Mine mining leases. Seams are given alphabetical titles with the 'A' seam comprising that closest to the surface (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005).

The Moura Mine currently has the capacity to produce 2.5Mt/y of thermal coal and 4.5Mt/y of soft coking coal. Coking coal reserves are estimated at 771Mt and are accessible only by underground mining methods. Non-coking coal reserves are estimated at 234Mt, of which three quarters is accessible only through underground mining methods. The coal is exported to Australia's major export markets of Asia, particularly Japan, and Europe. The Moura Mine is currently expanding its operations, combining with the adjacent Dawson and Theodore deposits into the Dawson Complex mine, which has a capacity of 5.6Mt/y of thermal coal for power generation and 7.1Mt/y of coking coal (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005).

2.3.1 Coal Mining Operations at the Moura Mine

Surface mining has accounted for all coal produced at the Moura Mine since 1994. The underground mining operation ceased in August 1994 due to a fatal methane-related accident in the No 2 underground mine. Since then, the mine has focused on using alternative methods such as trench and highwall mining to recover some of the coal from its substantial underground reserves (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005).

Blasting and draglines are used to carry out the primary waste stripping in the surface mining operation. Wheel loaders and bottom dump haulers (large trucks) are then used to extract the coal. A highwall mining system is also used to extract additional coal from final highwalls that would otherwise be inaccessible through the current surface mining operation. The coal is transported 16 kilometres to a preparation plant via an overland conveyor belt. The coal is then crushed, washed and sized before transport to the port of Gladstone, where it is shipped to the international markets (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005).

2.3.2 Highwall Mining at the Moura Mine

The highwall mining system was commissioned at the Moura Mine in mid-1997 with the estimation that there would be 127Mt of highwall reserves in the mine by 2012. In addition, the Moura Mine is considered to have tens of square kilometres that are suitable for highwall trench mining. However, 80% of these coal reserves are held in seams in that slope down between 6 and 12º and are, thus, unable to be mined using conventional highwall mining equipment (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005).

Under the ownership of BHP, an Addcar Steep Dip Highwall Mining system was developed specifically for the mining conditions at the Moura Mine, as shown in **Figure 2-8**. The system uses a modified Mining Technologies Addcar Highwall Mining system, with the remote controlled Joy 12CM12B continuous miner used to cut the coal (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005). A maximum penetration depth of 360 metres is possible, with the use of 29 Addcars and a cut profile 3.6 metres wide by 3.8 metres high. The miner is capable of producing 720t/hr, equivalent to approximately 1.6Mt/y, of coal. Initially, methane monitoring was used only for the first 50 metres of the drive before a Tomlinson boiler (producing inert ventilation gas) was activated, at which point only oxygen monitoring of the inert gas continued in the drive (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005). Currently, methane and oxygen monitors are strategically placed around the continuous miner and at 36 metre intervals along the Addcars (Kunst, G 2006, pers. comm., 16 July).

Two Archveyor Mining systems were introduced after 1999 with the change in ownership of the mine (*Anglo Coal: Moura Coal Mine, Queensland, Australia* 2005). However, these are no longer in use today as this system required high maintenance and had lower production and cut rates compared to the previous Addcar system. The Addcar Steep Dip Highwall Mining system was, therefore, reintroduced due to its greater reliability, production and cut rates, and it is the only highwall mining system currently in use at the mine (Kunst, G 2006, pers. comm., 16 July).

Highwall mining is carried out in four separate seams at the Moura Mine, with seam thickness varying from 2.2-4.8 metres (Shen & Duncan Fama 2001). The typical roof of all seams is a thinly bedded or laminated mudstone with some pits having a stronger laminated siltstone. The highwall roof at the Moura Mine is considered to be adequate, with some roof falls of between 0.1 and 0.3 metres. Where frequent falls are expected or encountered, a layer of coal is added for additional support, and this has been demonstrated to be an effective tool in stopping minor roof falls (Shen & Duncan Fama 2001). However, this approach has been ineffective in some pits where the coal has been determined to be unstable and weaker than the roof. Three major instabilities have been recorded over the duration of the highwall operation at the Moura Mine, resulting in the trapping of the continuous miner on two occasions prior to the change in ownership to the current proprietors (Shen & Duncan Fama 2001).

2.3.3 Methane at the Moura Mine

In the past 30 years, three major mining disasters at the Moura Mine have killed 36 miners, in total. Two of the explosions were attributed to the spontaneous combustion of coal, while the third is thought to have been ignited by either a frictional ignition or a flame (*Report on an Accident at Moura No. 2.Underground Mine Sunday, 7th of August, 1994* 1994). As noted above, the underground mining operation ceased in August 1994 due to the third methane-related accident. These explosions illustrate the risk and danger that require constant monitoring and management of methane concentrations in order to provide a safe working environment for personnel and equipment.

Moura Mine is considered to be a gassy mine with large deposits of methane (CH_4) released by the coal (*Major GHG Emissions Savings at Moura Coal Mine Seamgas Operation* 2003). Traditional mining practices involved releasing some methane into the atmosphere by drilling holes from the surface into the coal seam as a safety measure due to methane's toxic nature to humans and the gas's high flammability (*Major GHG Emissions Savings at Moura Coal Mine Seamgas Operation* 2003). The Moura Mine has recognised methane as a potential energy source. By harnessing it for energy, the mine is able to reduce its greenhouse gas emissions, as methane is a greenhouse gas. Specifically, the mine has initiated a drainage operation for the collection of methane for commercial use (*Major GHG Emissions Savings at Moura Coal Mine Seamgas Operation* 2003).

Topographically, the depth of the coal increases from east to west at the Moura Mine. Experience at the mine has shown that the southern side of the mine has no significant methane in comparison to the northern side, which has been found to have high methane concentration levels. Highwall mining operations on the southern side, with lower methane concentration levels, have an average penetration depth of 360 metres. Methane concentrations have affected the highwall mining operations on the northern side of the mine as safe methane concentrations cannot be maintained by the Tomlinson

Figure 2-8 Addcar Steep Dip Highwall Mining Machine at Moura Mine (Shen & Duncan Fama 2001)

Boiler for penetration depths greater than 160 metres (Kunst, G 2006, pers. comm., 16 July). Methane monitor results indicate the high methane concentrations experienced on the third Addcar behind the continuous miner as shown in Appendix C (Kunst, G 2006, pers. comm., 16 July).

Maintaining safety has been an important aspect of the highwall mining operation. Blast shields move down across the highwall drive opening to protect operators once a 10 metre entry has been made. Both methane and oxygen monitors are currently used, mounted on the miner, lead car (conveyor car following the miner) and every third conveyor car onward (i.e., every 36 metres). These monitors are required to be operational at all times. Additionally, inert boiler gas is injected through a 150mm flexible hose mounted on the lead car 15 metres from the coal face (Kunst, G 2006, pers. comm., 16 July).

The Moura Mine has developed a Gas Management Plan to suit the conditions of the mine. This plan is considered to be a 'live' document, meaning it is continually evolving through constant reviews and changes as problems are identified and rectified (Kunst, G 2006, pers. comm., 16 July). The Gas Management Plan uses a four-level system based on the Coward Triangle, and can be seen in Appendix C. Zone 1 constitutes normal mining where methane and oxygen mixture concentrations pose no risk. Zone 2 refers to restricted mining requiring additional monitoring. Under Zone 3, mining ceases, with monitors tripping electrical power to shut down machines. Finally, Zone 4 encompasses the explosive zone where the highwall is evacuated and all power to the site is tripped. The boiler gas generator and gas monitoring devices are left running. In time, the boiler gas flushes the methane and oxygen from the drive, allowing the safe return of personnel, and mining can then continue. In some cases, a Zone 4 situation can occur and, after the drive has been flushed, reoccur. When mining under these circumstances, it is uneconomical to continue and the miner during flushing is considered to be ‘gas bound’ (Kunst, G 2006, pers. comm., 16 July).

It should be noted that it is safe to have high concentrations of methane as long as the accompanying oxygen concentrations remain low, below a 12% concentration. This is the case, for example, for the region around the miner which, at the Moura Mine, has been observed to sit in around 3% oxygen due to the injection of boiler gas, creating an inert zone during mining. The majority of the methane is produced from the breaking coal at the face, releasing the greatest amount of methane during mining. The walls or ribs also produce a substantial quantity of methane, although far less than that of the face (Kunst, G 2006, pers. comm., 16 July).

2.4 Commonwealth Scientific and Industrial Research Organisation (CSIRO): Exploration and Mining

The CSIRO Exploration and Mining division is the largest strategic research and development supplier to the exploration mining industry in Australia. The organisation conducts research at every stage of the mining process. The Australian mining industry is highly productive and technologically intensive, with a focus on global markets, international opportunities and capital competitiveness. This division of the CSIRO has undertaken numerous research projects, including gas characterisation and control. This has been identified as a major issue in gassy Australian coal mines where sole ventilation dilution is unfeasible and thick seams are prone to spontaneous combustion.

In 1997, the CSIRO commenced implementation of the Triennium Plan for coal exploration and mining research. This plan focuses on project initiatives in six broad areas, including resource assessment, operations improvement, gas control and utilisation, automation, safety and material characterisation for fines control. The plan is still in progress and this research project is encompassed under its initiatives. The plan aims to investigate ways to extend and optimise established surface and highwall mines and to improve the viability of underground mines in order to provide new techniques for current and future mines. The plan also aims to investigate the extraction and control of hazardous gases to improve overall safety (Kelly 1998).

As noted earlier, this research project, in collaboration with the CSIRO, specifically aims to investigate the control of hazardous gases (methane) in highwall mining operations. Its objective is to improve the safety and, potentially, the productivity of highwall mining operations at the Moura Mine through the study of current and new ventilation configurations.

2.5 Conclusion

The highwall mining method continues to develop and to offer mine operators the ability to recover coal that would otherwise be unable to mined using conventional methods. This mining method has become widely implemented at Australian coal mines, including the Moura Mine. Potentially explosive methane gas released from coal during mining poses substantial risks, including the loss of equipment and fatalities of mine workers. It has been determined that the Moura Mine has high methane concentrations in some regions of the mine which have limited highwall mining operations. Ventilation using inert gases provides a means to control methane concentrations and, thus, optimise these systems, with the potential to improve both the productivity and the safety of the mine.

3. Literature Review

A detailed literature review was carried out in order to fully appreciate the importance of effective ventilation systems to control methane/oxygen concentrations within highwall coal mining operations. Previous research into the areas of highwall mining and, specifically, ventilation systems was explored and is summarised here. As with the background section, a variety of information resources were accessed including online sources (databases, websites and on-line texts), books and journals as well as material provided by both the CSIRO and the Moura Mine in regards to methods, equipment specifications and results from previous research studies.

3.1 Use of Inert Gas in Auger Highwall Mining

The United States Mine Safety and Health Administration and the Department of Interior, Bureau of Mines, in response to methane explosions resulting in injury, discussed the development of technology to enable the safe resumption of Auger highwall mining. It was identified that difficulties in ventilating shafts filled by augers and the potential ignition source from cutting bits were the most likely causes of explosions due to a lack of adequate ventilation and water for cooling (Volkwein 1993).

The use of inert gases was considered to be a potential solution. This process had been considered in the past, yet had never been implemented (Department of Interior, cited in Volkwein 1993). There were three primary considerations, including the source of the inert gas, its placement and monitoring of the hole (Volkwein 1993). Any gas source with an effective inert gas concentration of greater than 34% volume is noted to prevent methane from igniting (Zabetakis, cited in Volkwein 1993). Sources of inert gases that were considered included liquid nitrogen, modified shipboard inert gas generators, jet turbine engines, the highwall auger's diesel engine and gasoline engines. Of these, the auger's diesel engine and a gasoline engine were chosen to be used simultaneously, based primarily on cost and availability. The oxygen concentrations produced by the auger's diesel engine during loading and unloading were inconsistent, and it was too small to meet the capacity requirements of the operation on its own, thus the gasoline engine was used in addition in order to provide sufficient inert gas to the hole (Volkwein 1993). The exhaust gases of the two engines were fed into a collar positioned at the end of the drive. Remote sampling and handheld monitors were used to measure methane and oxygen concentrations at the collar of the hole, both during and after mining. It was determined that inert gas flow should be maintained until the auger is removed from the hole. Results indicated that methane rapidly diffuses when the auger is removed (Volkwein 1993). Long term ventilation was considered by leaving one hole open overnight and another partially covered. In this case, results revealed that methane concentrations had diminished and that leaving holes open to self-ventilate resulted in a greater reduction in methane concentrations than with the partially closed hole. The use of a shroud to cover the collar of the hole in order to inject the inert gas was found to be a simple and effective means of eliminating possible methane explosions with adequate methane monitoring (Volkwein 1993).

In another study, building upon his 1993 findings, Volkwein (1997) described various methods to monitor and control methane risks in Auger type highwall mining. Methane liberated during mining can result in unsafe concentrations as it migrates to the surface. There are three major options available to mine operators to help prevent ignitions, including the use of blast shields, ventilation (creating low pressure systems in order to move gases throughout the shaft) and pumping inert gas through the shaft. Blast shields are unacceptable, as any unplanned explosion is potentially unsafe, and ventilation is unpredictable, as it is difficult to implement effectively, cannot be monitored and increases the risk of a coal dust explosion (Volkwein 1997). Pumping inert gas through the shaft appears to be the only effective means of preventing methane ignitions and has led to a greater understanding of how methane accumulates in Auger type highwall mining (Volkwein 1997).

Volkwein's (1997) study used handheld monitors to record methane concentrations throughout the shaft during mining. The investigation revealed that gas must replace the volume of coal removed from the mining face. In most cases, it is replaced with air from the collar of the hole or surface end of the hole, as well as methane liberated from the coal. The greatest concentration of methane has been identified at the coal face or cutting face where the majority of methane is liberated as the coal is cut. This replacement phenomenon occurs in any dead heading or blind hole situation, as is the case with all highwall mining. Use of inert gases has been identified in the past as a means of preventing highwall ignitions in Auger type highwall mining (Cyrus, cited in

Volkwein 1997; Poundstone, cited in Volkwein 1997). However, the system was never implemented primarily due to an inability to deliver inert gas to the coal face because the auger filled the entire cross-sectional area of the hole. Volkwein's (1997) technique involves filling the collar of the auger hole with inert gas and using the displaced coal to provide a motive force to transport that inert gas to the coal face, thus preventing ignition of methane and coal dust by reducing oxygen levels to below explosive limits. The inert gas is generated from a diesel and gasoline combustion process similar to that of boiler gas. Results of samples tested during mining gassy coal indicate that all conditions remained non-explosive. High methane concentrations were recorded, however, the oxygen concentrations remained below the 10% required for explosion. Volkwein (1997) notes that one million tonnes of gassy coal have been mined in the United States using this system and that the improved knowledge of gas movement in the auger hole has led to this simple and effective gas system to protect mine workers.

3.2 CFD Modelling of Methane Flow

Ren, Edwards and Jozefowicz (1997) identified that the accurate prediction of methane emissions into mine workings is important in the design of adequate ventilation systems and methane control, specifically for longwall mining. This study developed a numerical method to simulate methane flow through strata or unmined coal involving CFD analysis and laboratory tests. Results from the laboratory tests were incorporated into the CFD model.

In longwall mining, most of the methane originates from the source beds above and below the coal face rather than from the face itself. The release of methane from source beds and migration is dependant on the changing stress pattern within the strata (Ren, Edwards & Jozefowicz 1997). Gas emission can be predicted using any of three approaches, including empirical results of models, statistical analysis and numerical analysis (CFD) involving an understanding of the underlying principles of methane flow transport in coal seams (Dixon, cited in Ren, Edwards & Jozefowicz 1997). CFD analysis can be supplemented with field testing and at a fraction of the cost of underground testing. A number of mathematical models and computer programs have been developed over the past 40 years to predict methane flow from coal seams. However, these models and programs were unable to provide detailed information on a variety of phenomena in order to fully understand methane flow migration, as can be done with CFD software. Fluent CFD software was used to perform both two- and three-dimensional analyses using a porous medium model and general momentum sink which was able to simulate flow media through rock beds (Ren, Edwards & Jozefowicz 1997). The geometry of the mine was an important consideration in creating the model. Permeability characteristics of the rock were taken from laboratory results of rock samples. Atmospheric pressure was considered for the roadways used to develop or access a longwall panel. Results indicated that the roadways acted as pressure sinks through which the methane migrated. More methane migrated from the ends of the panel where the mining induced fractures were less compacted than those at the centre of the panel. These results were validated with field data (Ren, Edwards & Jozefowicz 1997).

Given specific mining and geological conditions, these models can predict methane emissions and the pattern of migration within longwall mining operations. This information provides both a means of effective ventilation systems and optimisation of methane drainage schemes. Ren, Edwards and Jozefowicz (1997) suggested further research into the development of new methods to predict methane emissions from mine openings, gas migration in adjacent areas and the optimisation of methane drainage schemes, which may benefit further methane control.

3.3 CFD Analysis of Methane Safety of a Continuous Miner

Methane ignitions from the cutting picks of continuous miners are a hazard in all underground coal mining operations. A study conducted by Cook (1995) aimed to quantify methane flow and behaviour around continuous miners during mining operations. Six methane monitors mounted at different locations on a continuous miner logged the methane concentrations during mining over a ten-hour period, with readings recorded every ten seconds.

Minimal variation in methane concentrations between sensors was recorded over short two-hour trials for a confined region where the ventilation was restricted. However, this was not the case over the extended six- and seven-hour periods, during which substantial variation in methane concentrations was recorded between sensors, in this case, ranging from 0.6 to 3% methane (Cook 1995). The left-hand side of the continuous miner experienced the highest methane concentrations, influenced by the face scraping action of the cutting drum and directional water sprays used to prevent ignitions from the cutting picks (Cook 1995).

A CFD analysis was carried out using STAR-CD software in order to evaluate different ventilation practices for the continuous miner. The results of the two- and three-dimensional CFD analyses showed methane concentrations that were three times larger than those recorded earlier in an actual mining situation. This difference was determined to be due to an exaggeration of methane emissions in the computer analyses in order to ensure sufficient variation for the methane concentration contours graphically shown in the CFD results (Cook 1995).

Methane levels were found to drop rapidly within the first few metres of the coal face and there was no evidence of layering around the continuous miner, as long as sufficient ventilation was provided. The methane was also found to mix rapidly, and to remain mixed, with no tendency to layer, all due to the turbulence (Cook 1995). This study also found that, for blind headings or holes, the methane required a greater distance to dilute via mixing with ventilation air, as less air reached the coal face. Additionally, the lack of sufficient ventilation in these blind headings or holes resulted in the diminished effectiveness of the directional sprays clearing methane from the face, causing methane concentrations of greater than 2% in the cutting drum and its supporting boom. Methane monitors located at the rear of the continuous miner (a cleaner environment than the front of the machine where monitors can become blocked with dirt and mud) generally produced similar results to the data generated from the CFD analysis. However, the highest methane concentrations were recorded by the sensors located toward the front of the machine, as indicated earlier (Cook 1995).

3.4 Control of Methane at the Moura Mine

The Moura Mine has identified that the average penetration depth of the steep-dip Addcar highwall mining operation is limited to 160 metres on the northern side of the mine in comparison to 360 metres on the southern side, due to high methane concentrations (Conway, B 2006, pers. comm., 11 April). It reportedly takes an average of 15 hours to achieve a penetration depth of 350 metres on the southern side, where methane concentrations are low, compared with 18 hours to achieve a penetration depth of 200 metres on the northern side (Kunst, G 2006, pers. comm., 16 July). Recent trials carried out at the Moura Mine, in conjunction with the CSIRO Exploration and Mining division, sought to improve the control of methane by trialling new inert gases and injection configurations (Balusu, R 2006, pers. comm., 24 June). These trials included the injection of three inert gases, including nitrogen, carbon dioxide and boiler gas provided by two Tomlinson Boilers with a combined capacity of 0.8 metres cubed per second ($0.8m^3/s$). The inert gases were trialled at a variety of injection angles and locations (Kunst, G 2006, pers. comm., 16 July). Methane/oxygen concentrations were monitored at the continuous miner, the lead car (the first Addcar) and at 36-metre intervals, thereafter (Conway, B 2006, pers. comm., 11 April). The trials found that the inert gas injected 15 metres from the coal face resulted in the greatest control of methane/oxygen concentrations (Kunst, G 2006, pers. comm., 16 July). However, the findings were inconclusive with regard to the type of inert gas and the injection angle required to provide the optimum control of methane/oxygen concentrations within the highwall drive (Balusu, R 2006, pers. comm., 24 June). Currently, inert boiler gas from a Tomlinson Boiler is provided through a 150 millimetre pipe located 15 metres from the coal face, with the last five metres of the pipe slotted to act as a diffuser (Kunst, G 2006, pers. comm., 16 July). A greater understanding of methane migration and the type of inert gas and injection angle needed would further improve the safety and production of the current highwall mining operation at the Moura Mine (Balusu, R 2005, pers. comm., 3 October).

A confidential study of the safe operation of BHP's Moura Mine highwall mining operation was also carried out by Safety in Mines, Testing and Research Station (SIMTARS) in Brisbane in the late 1990s (Brady, D 2006, pers. comm., 10 July). Unfortunately, however, these findings are currently unavailable to the general public.

3.5 Conclusion

Recent research has illustrated that the control of methane concentrations is an important factor in improving the safety and productivity of highwall mining operations. A greater understanding of methane migration within underground mining operations appears to be the key to improving current methane control systems. In highwall mining applications, inert gases have been trialled in ventilation systems and, in some cases, successfully implemented. CFD modelling provides an inexpensive and effective means to improve current ventilation systems with regard to methane control within underground mines, and this method can also be directly applied to highwall mining. The Moura Mine has identified that a greater understanding of the current highwall methane control measures could lead to improvements that potentially may improve safety and production with the ability to reach greater penetration depths on the gassy northern side of the mine.

4. Numerical Analysis and Methodology

A brief introduction into the governing equations used in this study, along with an overview of computational fluid dynamics (CFD), in general, and Fluent, the specific CFD software package used in this investigation, is provided in this chapter. The overall methodology used for the study is also outlined.

4.1 Governing Equations

A fluid is a liquid or a gas that deforms continuously under shear stress, no matter how small the shear stress (Fox, McDonald & Pritchard 2004). The flow of fluids is governed by five fundamental principles: the first law of thermodynamics (the conservation of energy), the second law of thermodynamics, the conservation of mass (continuity), the principle of angular momentum and Newton’s second law of motion (the conservation of linear momentum), each of which can be expressed as a basic mathematical equation (Fox, McDonald & Pritchard 2004). In addition, a number of mathematical relationships describing the behaviour of fluids with regard to diffusion (mass transfer), and turbulent and laminar flow are given, as these are relevant to this investigation.

4.1.1 First Law of Thermodynamics

The first law of thermodynamics is a statement regarding the conservation of energy (Cengel & Boles 2002). The basis of this law is that energy can neither be created nor destroyed, but can only change forms. Energy can be transferred in the form of heat (Q), work (W) and mass flow (E_{mass}) (Cengel & Boles 2002). The energy of the mass flow (E_{mass}) consists of the rate of change in internal (ΔU), potential (ΔPE) and kinetic (ΔKE) energies. This first law of thermodynamics, or the conservation of energy, is shown in Equation 4-1. This equation relates the stored rate of change of the energy of the system with time to the net rate of heat into the system and the net rate of work out of the system.

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

Equation 4-1

Energy Equation **(Cengel & Boles 2002)**

4.1.2 Second Law of Thermodynamics

The second law of thermodynamics states that processes occur in a specific direction and not just in any direction (Cengel & Boles 2002). The amount of heat (Q) transferred to a system at a given temperature (T) must be less than the change in entropy (S) of the system, as shown in Equation 4-2 (Fox, McDonald & Pritchard 2004). Entropy is a measure of the molecular disorder. Entropy transfer is associated only with the transfer of heat and not with work. Heat is a form of disorganised energy, and some entropy flowing from a hot body to a cold body results in a decrease in entropy of the hot body and an increase in entropy of the cold body (Cengel & Boles 2002).

$$\left(\frac{dS}{dt}\right)_{system} \geq \frac{1}{T}\dot{Q}$$

Equation 4-2

Second Law of Thermodynamics **(Fox, McDonald & Pritchard 2004)**

4.1.3 Conservation of Mass (Continuity)

The conservation of mass is a principle which states that the net mass transfer to or from a system during a process is equal to the net increase or decrease in the total mass of the system throughout that process (Cengel & Boles 2002). There are two forms of the continuity equation, including the integral and the differential. The integral form of the continuity equation describes the gross behaviour of a system and is useful in predicting the effects of various devices, while a differential approach enables detailed, point-by-point knowledge of the flow field which is used in computational fluid dynamics (CFD) analysis (Fox, McDonald & Pritchard 2004). The differential form of the continuity equation is shown in Equation 4-3. The equation states that the sum of the rate of change of mass within the control volume and the net rate of change of mass flowing out of the control surface is equal to zero (Munson, Young & Okiishi 2002). This equation uses the partial derivatives of the density (ρ) and velocity (u, v, w), with regard to time (t) and displacement (x, y, z), respectively.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

Equation 4-3

Continuity Equation **(Munson, Young & Okiishi 2002)**

4.1.4 Principle of Angular Momentum

The angular momentum principle of a system states that the rate of change of angular momentum (H) equals the sum of all the torques (T) applied to the system (Fox, McDonald & Pritchard 2004). This principle is shown in Equation 4-4.

$$\vec{T} = \left.\frac{d\vec{H}}{dt}\right)_{system}$$ **Equation 4-4**

Principle of Angular Momentum (Fox, McDonald & Pritchard 2004)

4.1.5 Newton's Second Law of Motion

When a particle moves from one location to another, it generally experiences some kind of acceleration or deceleration. The force action on the particle, according to Newton's second law, is equal to the mass of the particle times its acceleration, as shown in Equation 4-5 (Fox, McDonald & Pritchard 2004).

$$F = ma$$ **Equation 4-5**

Newton's Second Law Equation (Fox, McDonald & Pritchard 2004)

The conservation of linear momentum is a dynamic equation based on Newton's second law of motion, applied to an infinitesimal system of mass that describes the fluid motion of a particle (Fox, McDonald & Pritchard 2004). As with the continuity equation, there are two forms of the conservation of momentum equation, including the integral and the differential. The integral form of the momentum equation describes the gross behaviour of a system and is useful in predicting the effects of various devices, while the differential approach enables detailed, point-by-point knowledge of the flow field which is used in CFD analysis. The differential form of the momentum equation for an incompressible Newtonian fluid is broken into rectangular coordinates, referred to as the Navier-Stokes equations and shown in Equation 4-6 (Fox, McDonald & Pritchard 2004). These equations consist of acceleration terms on the left-hand side and force terms on the right-hand side for each of the rectangular coordinates (x, y and z) (Munson, Young & Okiishi 2002). The respective velocities for the rectangular coordinates are u, v and w, density is ρ, pressure is p, gravity is g and viscosity is μ. The equations, due to their complexity (non-linear, second order, partial differential equations), limit analytical solutions to simple geometries and boundary conditions. In recent years, the computational fluid dynamics (CFD) method has been developed to solve the Navier-Stokes equations for real world problems (Fox, McDonald & Pritchard 2004).

$$x-direction$$
$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\rho g_x+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$
$$y-direction$$
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$ **…………Equation 4-6**
$$z-direction$$
$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\rho g_z+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

Navier-Stokes Equation (Munson, Young & Okiishi 2002)

4.1.6 Diffusion

Diffusion is the gradual mixing of two or more gases that come into contact with one another, each with the tendency for their molecules to move from higher concentrations to lower concentrations until they are uniform throughout the system (Turns 1996). This mixing occurs even without mass air movement, as molecules are continuously moving. Diffusion rates increase with higher temperatures and decrease with lower temperatures. Figure 4-1 shows a diffusion process whereby a diaphragm separates species a from species b. When the diaphragm is removed, after some time has passed, the mass fraction gradient of species *a* into species *b* can be seen after diffusion has occurred (Turns 1996). For steady state bi-molecular diffusion, Fick's Law, shown in Equation 4-7, states that the diffusional mass flow ($m''_{a,diff}$) is related to the species mass fraction gradient (dY_a/dx) and the flow of species from high concentration to low concentration regions (Turns 1996). The flow of species is governed by the molecular diffusivity (D), and the density of the gas is 'ρ'. This equation can be expanded in order

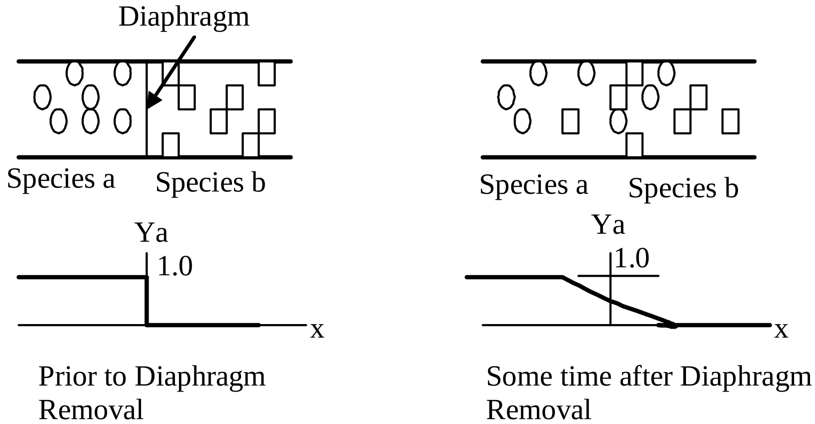

Figure 4-1 Diffusion of Two Fluids (Turns 1996)

to be applied to multi-component diffusion cases. Laws of diffusion are based on the principles of the continuity equation stated earlier (Turns 1996).

$$\dot{m}''_{a,diff} = -\rho D_{ab} \frac{dY_a}{dx}$$ **Equation 4-7**

Fick's Law of Diffusion **(Turns 1996)**

4.1.7 Steady and Unsteady Flow

The principle of steady flow states that the velocity at a given point in space does not vary with time. In reality, most flows are unsteady with some degree of variation in velocity making them more difficult to analyse (Munson, Young & Okiishi 2002). If the variation between velocities is minimal, the assumption of steady flow can greatly simplify the analysis without compromising the usefulness of the results.

4.1.8 Laminar and Turbulent Flow

Laminar flow can be characterised by the smooth layers in which fluid particles flow. For turbulent flow, fluid particles mix rapidly as they move along random, three-dimensional velocity fluctuations (Fox, McDonald & Pritchard 2004). Reynolds number is a dimensionless parameter used to categorise flow as laminar, turbulent or transitional (combination of laminar and turbulent) (Fox, McDonald & Pritchard 2004). The Reynolds number is the ratio of inertial forces (forces that increase fluid motion) to frictional or viscous forces (forces that slow the fluid down). The Reynolds number is calculated using Equation 4-8 for internal flow where ρ is the density, U is the average velocity, d is the diameter or the hydraulic diameter for non-circular ducts and μ is the viscosity of the fluid. For internal flow, laminar flow occurs for Reynolds numbers up to 2300 and turbulent flow for Reynolds numbers above 4000. A transition occurs with Reynolds numbers between 2300 and 4000, before the fluid is considered to be fully turbulent (Fox, McDonald & Pritchard 2004).

$$\mathrm{Re} = \frac{\rho U d}{\mu}$$ **Equation 4-8**

Equation for Reynolds Number **(Fox, McDonald & Pritchard 2004)**

4.2 Numerical Analysis Methods

Differential equations like the Navier-Stokes equations that govern the behaviour of Newtonian fluids were derived many years ago (Munson, Young & Okiishi 2002). However, due to their complexity, as outlined earlier, their solutions have been limited to extremely simple geometrical models. The advent of high speed computers in recent times has made it possible to obtain approximate numerical solutions for these equations for more complicated geometrical models (Munson, Young & Okiishi 2002).

According to Munson, Young and Okiishi (2002), the three most commonly used numerical methods for modelling fluid flow using computers are the finite difference, finite element (or finite volume) and the boundary element methods. Each of these methods considers a continuous flow field (velocity or pressure as a function of space and time) that is described by discrete (rather than continuous) values at prescribed locations. For each method, in this way, the differential equations are replaced with sets of algebraic equations which can then be solved by computers (Munson, Young & Okiishi 2002).

The finite difference method for computational fluid dynamics is the simplest and most widely used of the three numerical methods. This method dissects the flow field into a set of grid points and the continuous functions (velocity, pressure, etc.) are approximated by discrete values calculated at the grid points (Munson, Young & Okiishi 2002). The derivatives of the functions are approximated using the differences (using Taylor expansion) between function values of neighbouring grid points divided by the grid spacing. In this way, differential equations can be transferred to algebraic equations and simply solved by computers (Munson, Young & Okiishi 2002).

Munson, Young and Okiishi (2002) state that in the finite element (or finite volume) method, the flow field is broken into a set of small fluid elements (either triangular or square, in the case of 2D analysis). The conservation equations (conservation of mass, momentum and energy) are appropriately applied in differential form to each element converted to a set of algebraic equations which can be solved for the flow field.

Finally, in the boundary element method, the boundary of the flow field, and not the flow field itself, is broken into discrete segments and appropriate singularities such as sinks, sources and doublets are defined for the boundaries. This method is mathematically sophisticated, however, in some cases, provides less computational time and space to predict the boundary behaviour of a flow field than does the finite element method (Munson, Young & Okiishi 2002).

4.3 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) is a powerful numerical simulation tool that uses the numerical analysis methods described above to predict the behaviour of fluid flow, transfer of heat and mass, phase change (e.g., freezing or boiling), chemical reactions (e.g., combustion), mechanical movement (e.g., fan rotation) and stress and deformation of solid structures affected by fluids (e.g., mast bending in the wind) (*Fluent: The World's Leading Commercial CFD Code* 2006).

CFD software provides the user insight, foresight and efficiency. Insight is provided into devices and systems that would otherwise be difficult to prototype, providing the user with a means of visualising as well as an enhanced understanding of a design. Foresight is provided for a given set of circumstances along with predicting outcomes for a range of variables in order to determine an optimal result. Finally, the efficiency of CFD software allows better and faster designs to be produced, saving time and money and getting products to market faster (*Fluent: The World's Leading Commercial CFD Code* 2006).

CFD software, such as Fluent (the package used in this investigation), is based on the finite difference numerical methods described in the previous section. The flow field or fluid domain is dissected into discrete control volumes using a computational grid made up of discrete grid points that are linked together and contained within fluid boundaries in a process referred to as discretization (Munson, Young & Okiishi 2002). The boundaries can be defined as inlets, outlets, walls and/or a number of other conditions which can be directly applied and which influence the fluid domain. A set of differential equations is created for the discrete grid points that can be transferred to algebraic equations and solved using an iterative process until convergence is reached. Convergence is a point when the solution is no longer changing with successive iterations, or when it reaches a stage at which it satisfies the governing equations within predetermined tolerances called residuals (*Fluent: The World's Leading Commercial CFD Code* 2006).

4.4 CFD Software Selection and Access

This investigation of the Moura Mine highwall operation to control methane concentrations required a CFD software package that was capable of modelling a non-reacting flow, providing information pertaining to mass fraction, temperature and velocity and pressure fields of gases, specifically methane and oxygen, within the highwall drive.

Fluent (specifically, Fluent version 6.2.16 solver and Gambit 2.2.30) CFD software met these specifications and was chosen for this investigation due to its widely accepted status within the field of the ventilation simulation of coal mines, and for its availability to the user through the University of Southern Queensland. Fluent software is capable of modelling a diffusion process of a non-reacting flow, as required for this analysis. CFD analysis requires large amounts of computing power due to the re-iterative process. The author was able to gain access to the University of Southern Queensland's mainframe computer through its hpc0 server enabling faster solution speeds than those of a conventional desktop.

4.5 Fluent

Fluent is the largest global supplier of CFD software in the world due to its technological leadership (*Fluent: The World's Leading Commercial CFD Code* 2006). The company's strong and stable history and its well-respected service and support have all contributed to the success of the Fluent CFD software. Fluent software actually encompasses two separate programs, the Fluent solver program and Gambit, a pre-processor for geometry and mesh generation.

Fluent CFD software offers users ease of use through its intuitive user interface, ability to import CAD (computer aided design) geometry, and ease of customisation (*Fluent: The World's Leading Commercial CFD Code* 2006). The software package provides efficient two- and three-dimensional modelling and meshing capabilities and produces reliable physical models for a multitude of conditions, including chemical species mixing, multiphase and steady or transient flow modelling capabilities, to name only a few (*Fluent: The World's Leading Commercial CFD Code* 2006). Finally, Fluent software offers the user the ability to utilise a variety of visualisation tools in order to provide images and animations.

4.5.1 Fluent Software Structure

The process for creating and solving CFD models in Fluent is outlined in Figure 4-2. A

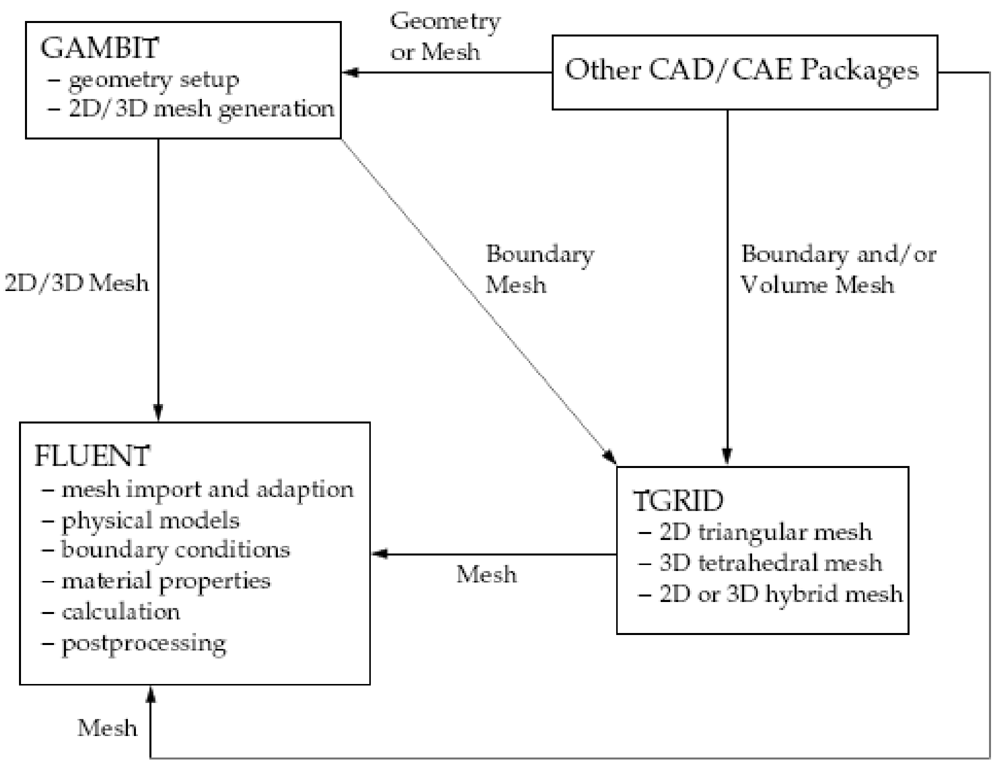

Figure 4-2 Fluent Program Structure (*Fluent: The World's Leading Commercial CFD Code* 2006)

two- or three-dimensional geometry or model of the fluid domain can be generated in either Fluent's own pre-processing software program, Gambit, or a separate CAD package. This model is then meshed using Gambit or exported into a separate meshing program, TGRID, as with the case of CAD created models. Gambit models, as well, can be meshed using this program (*Fluent: The World's Leading Commercial CFD Code* 2006). The meshed geometry is then exported from the meshing program into the Fluent solver where the physical models (chemical species mixing, multiphase, steady or transient flow models, etc.) based on the governing equations are applied to the model. The software applies the appropriate governing equations to the model in order to predict behaviour based on these different physical models. The boundary conditions and material properties are applied to the model before calculations can begin. The algebraic equations generated by the software, as mentioned, are then solved in an iterative process until the solution has converged. Convergence, as mentioned earlier, is a point when the solution is no longer changing with successive iterations. This process is outlined in Figure 4-3 for Fluent's segregated solver. The results of the model analysis can be presented and interpreted in graphical or tabular form (*Fluent: The World's Leading Commercial CFD Code* 2006).

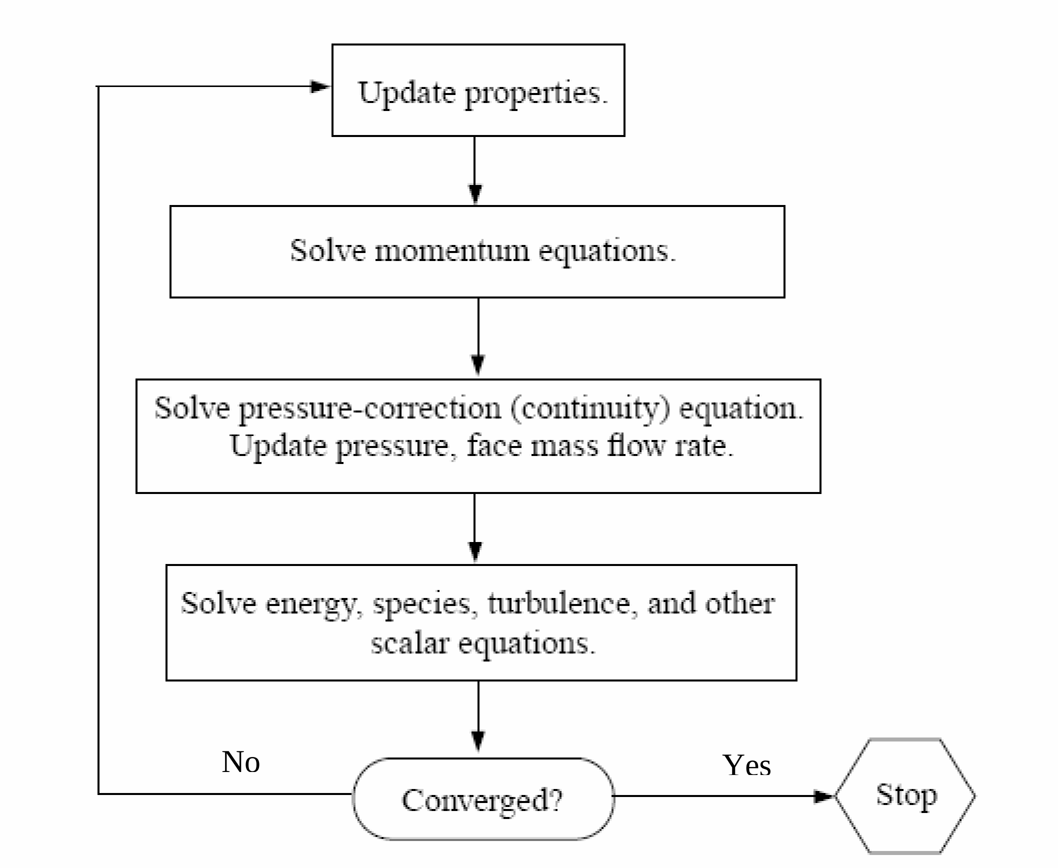

Figure 4-3 Fluent Segregated Solver Flowchart (*Fluent: The World's Leading Commercial CFD Code* 2006)

4.5.2 Basic Steps in CFD Analysis

When using CFD, the following are important steps to a successful analysis. The salient features of the problem must first be identified and defined before these basic procedural steps can be undertaken:

- define the model goals
- create the model geometry and grid
- set up the solver and physical model
- compute and monitor the solution
- examine and save the results
- determine if revisions to the numerical or physical parameters are necessary

(*Fluent: The World's Leading Commercial CFD Code* 2006)

4.6 Model Goals

As noted earlier, this study aims to improve the ventilation using inert gases of the highwall mining operation at the Moura Mine. The investigation considers the effects of a number of factors and their influence on the overall effectiveness of the highwall ventilation system. These factors include the type of inert gas injected into the highwall, the angle at which the inert gas is injected at the injection point and the penetration depth of the drive at a constant temperature. These parameters have each been identified as important influences with regard to the effectiveness of the current ventilation system.

4.7 Modelling Assumptions

The CFD model used in this investigation has been simplified in regard to its geometry, boundary conditions and CFD physical models applied.

The geometry of the models was simplified in order to improve the quality of mesh and solution time for each of the models generated. The boundary conditions applied to the CFD model were based on the experience of the Moura Mine employees, research experts and visual observations of the highwall operations. The flow rate for each of the inert gases injected in the highwall drive was assumed to be constant at 0.15 cubic metres per second ($0.15m^3/s$). The inert gas was injected 15 metres from the end of the coal face through a 0.15 metre pipe. The methane entering the drive was assumed to be only from the coal face and floor when, actually, the walls and roof of the drive contributed significant, although secondary, amounts of methane. However, this factor could not be considered due to the use of a two-dimensional model. The flow rates of methane for the coal face and floor were 0.04 cubic metres per second ($0.04m^3/s$) and 0.06 cubic metres per second ($0.06m^3/s$), respectively, combined to give a total flow rate of 0.1 cubic metres per second ($0.1m^3/s$). A two-dimensional model was used for purposes of simplification as well as to improve the solution speed by reducing the number of discrete elements required for the various configurations analysed, giving a good indication of the fluid behaviour within the drive. This enabled far more possibilities and ventilation configurations, thus providing a wider scope of study. However, the two-dimensional analysis failed to truly represent all fluid behaviour within the actual three-dimensional highwall drive. Assumptions were made that no heat transfer occurred (drive remained at a constant 27° Celsius), and that there was a non-reacting flow (no chemical reactions between gases) within the drive, as these parameters were considered to be beyond the scope of this study. Additionally, making these assumptions reduced the governing equations required, thus, once again, reducing the solution time for the models. Finally, the surface roughness was also ignored for this investigation, as noted, as this was not considered to be a critical factor in the diffusion and mixing processes at this early stage. However, this should be considered in future studies in order to determine what influence it has on the fluid flow within the drive.

4.8 Gambit CFD Model

The model generated in Gambit version 2.3.30 for this investigation was based on geometrical information and data regarding the physical properties of the Moura Mine highwall operation that were provided by a variety of sources, including the Moura Mine, the CSIRO and equipment manufacturer specifications.

4.8.1 Two-Dimensional Gambit Model

The development of a two-dimensional model was created solely in the Gambit pre-processor. This involved the generation of the geometry and mesh of the model which are discussed in further detail below.

4.8.1.1 Gambit CFD Model Geometry

A two-dimensional view of the Moura Mine highwall operation is shown in Figure 4-4 detailing the position of the continuous miner and the Addcars in relation to the highwall during mining at a particular penetration depth. The two-dimensional geometry of the highwall operation is based on dimensions from equipment manufacturers, the Moura Mine and the CSIRO. This geometry was then used to create a model in Gambit, as shown in Figure 4-5, in which the boundary conditions have been labelled and defined. The geometry was created for four separate models with different

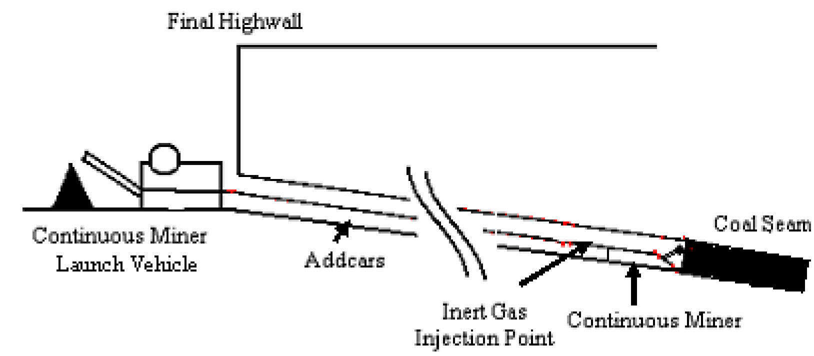

Figure 4-4 Two-Dimensional View of Moura Mine Highwall Operation

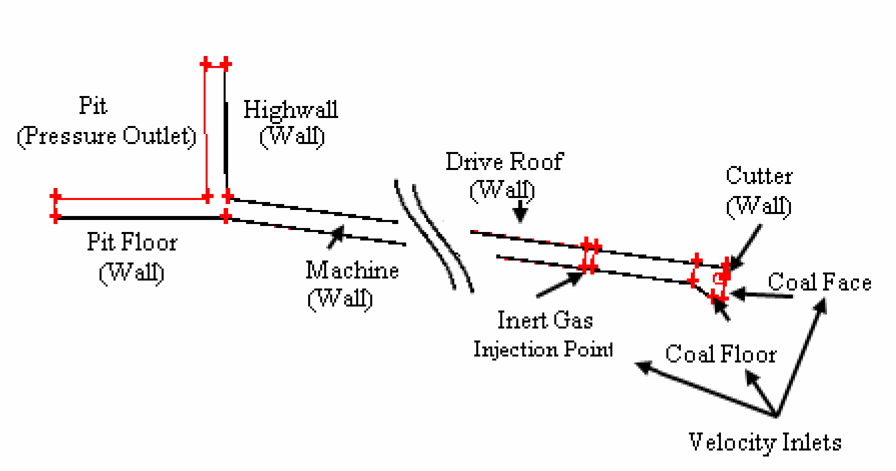

Figure 4-5 Two-Dimensional View of Gambit Model and Boundary Conditions

penetration depths of 150, 200, 250 and 300 metres, all dipping down at an 8˚ angle. In the model, the highwall drive is 3.8 metres in height at the coal face, the coal floor length is 1 metre long and there is a distance of 2.4 metres between the top of the Addcars and the drive roof. The inert gas is injected through a 0.15 metre hose coming from a vertical vent on the top of the machine, located 15 metres from the coal face. Finally, the coal cutting drum on the miner is 1.2 metres in diameter.

4.8.1.2 Gambit CFD Model Mesh

The Gambit geometry model was also meshed (discretisation of the domain into elements) in Gambit, as shown in Figure 4-6. It is important that elements indicate gradual change throughout the domain by using smaller elements in critical regions and larger elements in less critical regions. The latter type aids in reducing the solution speed due to the decrease in the number of elements.

The domain was first divided into a number of sub-domains to improve its shape, leading to a higher mesh quality through the availability of different elements, and providing greater control. Two element types were utilised for the two-dimensional analysis, including the quadrilateral and the triangular, as seen in Figure 4-7. Quadrilateral elements were used in conjunction with a mapped meshing function (which creates a uniform brick wall patterned mesh), used due to the ability to produce accurate results with a reduction in the number of elements required. Triangular elements were used with a paved meshing function (irregular mesh) that provided a mesh for the more difficult geometrical domain at the coal face. An increased element count in this region offset any inaccuracies encountered with this type of element. The

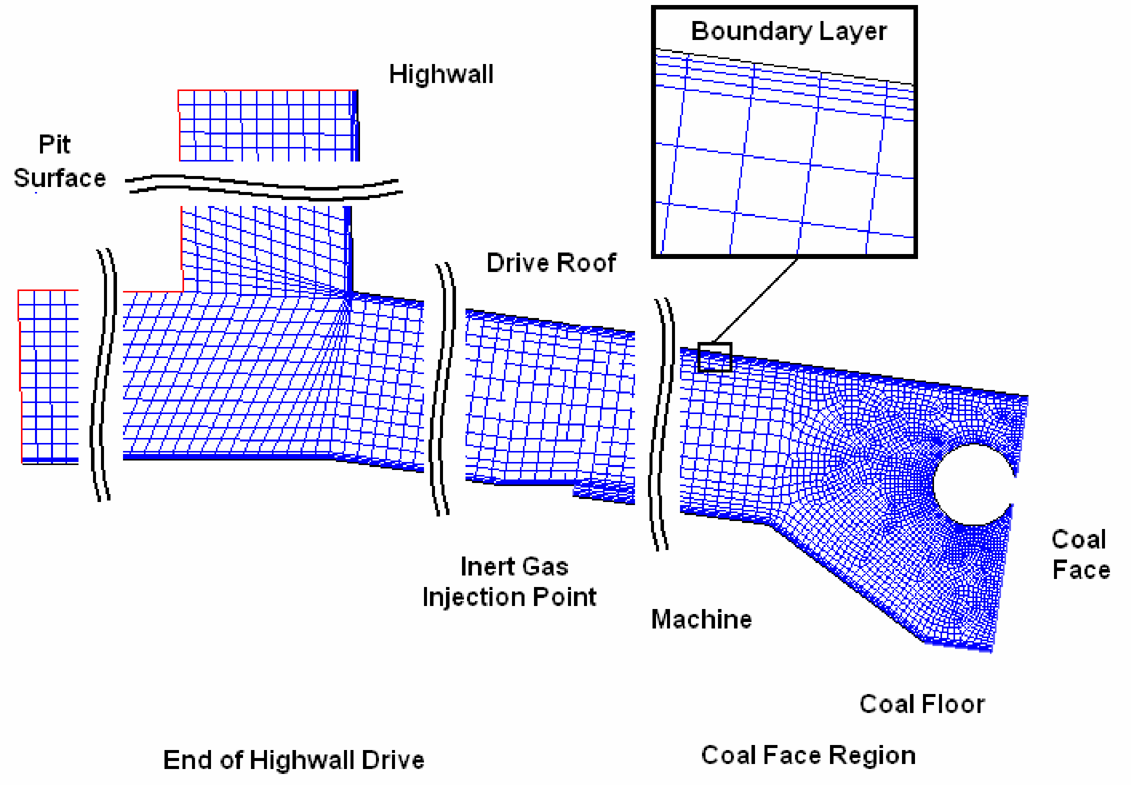

Figure 4-6 Sectioned View of Two-Dimensional Mesh of Highwall Mining Operation

mesh quality is important as the shape of the elements influences the accuracy of the numerical predictions made by the software. The aspect ratio of an element is the ratio between the length and width of that element and it is advised that this should remain below 7:1 (*Fluent: The World's Leading Commercial CFD Code* 2006). Aspect ratios above this threshold will be inaccurate in predicting domain behaviour. The highest aspect ratio in the models for this investigation was found to be 5:1. The skewness of an element is a measure of the deformation of that element on a scale of 0-1, with zero representing no skewing. Skewness should remain below 0.6 in order to ensure accurate prediction of domain behaviour (*Fluent: The World's Leading Commercial CFD Code* 2006). In this investigation, the models were found to be acceptable with a maximum skewness of 0.59. The variation of element size should be gradual throughout the domain, as noted earlier, in order to accurately transfer properties between elements. In regions of the domain where a high variation of properties is anticipated, the element size should be reduced in order to predict the fluid flow accurately. The boundary layer of the domain, due to the 'no-slip' condition, influences the fluid flow and, therefore, requires a greater density of elements near the boundary in order to predict the behaviour of the fluid (*Fluent: The World's Leading Commercial CFD Code* 2006). A boundary layer function was used in this analysis in order to

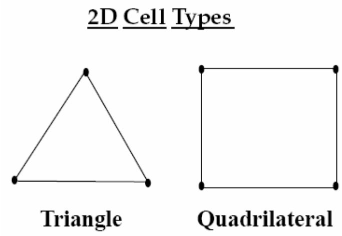

Figure 4-7 Gambit Two-Dimensional Elements (*Fluent: The World's Leading Commercial CFD Code* 2006)

provide an increasing element size gradient from the boundary walls, so that the effects of the boundary layer on the fluid flow within the domain could be considered, as shown in Figure 4-6. A y-plus function in Fluent provides the user with a gauge (a numerical value) of the near-wall resolution or boundary layer requirements when analysing a mesh. The y-plus value is required to remain within set limits. For this investigation, the y-plus was 320 for each of the cases, well within the required 0 to 500 range provided by Fluent.

Finally, the boundaries throughout the model were defined as shown in Figure 4-5, along with the fluid domain. A variety of different boundary types are available to the Gambit user. The models in this investigation used the velocity inlet, pressure outlet, wall and interior boundary types. Fluent 6/7 solver was selected before the model mesh was exported for use in Fluent.

4.8.2 Three-Dimensional Gambit Model

The development of a three-dimensional model was created using a combination of Gambit and a separate CAD package. This involved the generation of the geometry and mesh of the model, which are discussed in further detail below.

4.8.2.1 Gambit CFD Model Geometry

The geometry of the model in the three-dimensional case was generated quite differently to that of the two-dimensional model. The geometry of the continuous miner and Addcars was generated in SolidWorks, a separate CAD package, shown in Figure 4-8, and then exported to Gambit as an ACIS file. The SolidWorks program was used to generate this complex geometry due to its ability to quickly and easily generate three-dimensional geometries. The geometry of the drive was then created in Gambit around the geometry of the mining equipment. The volume occupied by the mining equipment was then subtracted from that of the drive to produce the final fluid domain which the gases move through during mining. The geometry of the three-dimensional model, as

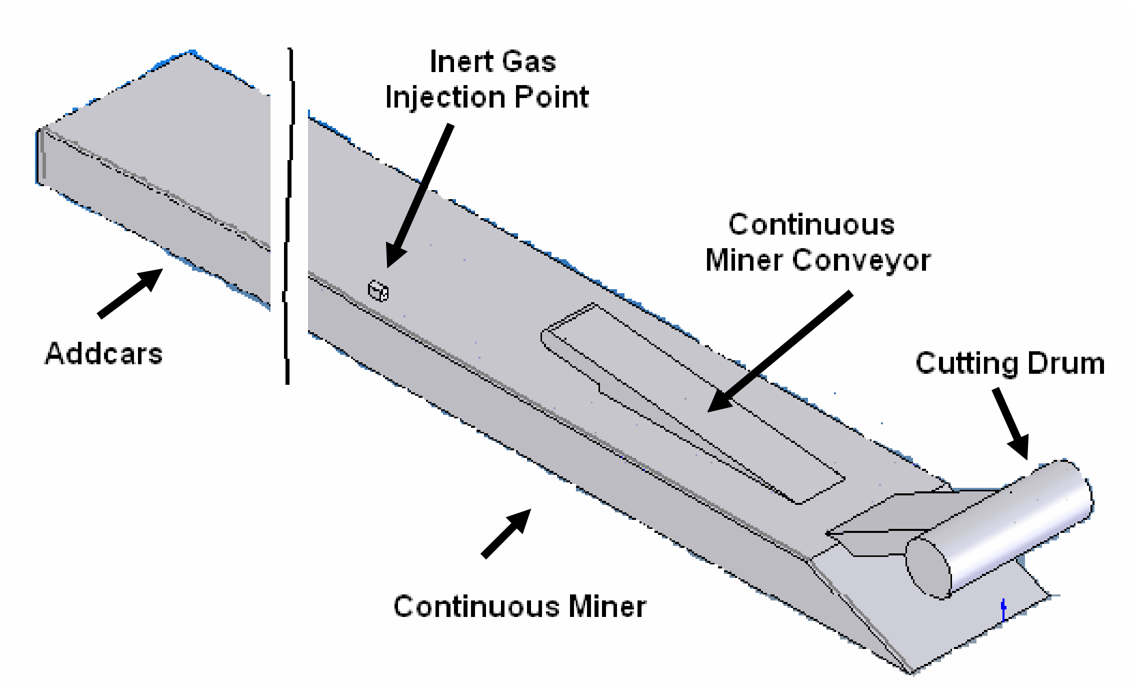

Figure 4-8 Continuous Miner and Addcars Generated in SolidWorks

with the two-dimensional model, was, once again, based on dimensions provided by manufacturer specifications, the Moura Mine and the CSIRO. Only one model, at a penetration depth of 150 metres, has thus far been created.

4.8.2.2 Gambit CFD Model Mesh

The Gambit geometry model, once again, as with the two-dimensional case, was meshed in Gambit, as shown in Figure 4-9. The mesh for this model was generated using a sizing function which allowed the initial size of the elements at the boundary surface, as well as a growth rate, to be defined such that the elements enlarged as they moved away from these surfaces. In this case, the element used was tetrahedral shaped, and Gambit's TGRID mesh generator was used to create the mesh. Similar factors apply to the elements with regard to mesh quality, as outlined in the two-dimensional model. These factors include the aspect ratio, skewness, boundary layer, element size gradient and y-plus value. The mesh for this geometry model requires further refinement with regard to quality before reliable results can be attained using the Fluent solver. Figure 4-9 shows the additional geometrical detail of the actual highwall mining operation with regard to the conveyor, inert gas injection point and boom supporting the cutter drum. The three-dimensional analysis provides a greater understanding of the flow of gases within the highwall drive and overcomes some of the limitations of the two-dimensional analysis, as described.

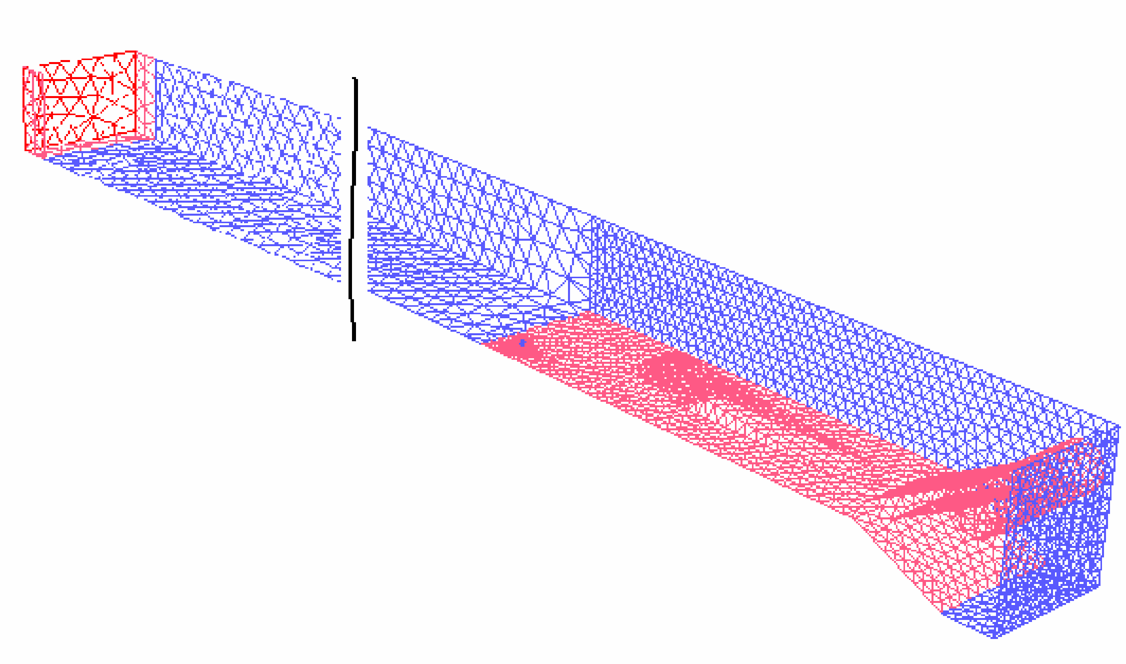

Figure 4-9 Sectioned View of Three-Dimensional Mesh of Highwall Mining Operation

4.9 Fluent CFD Solver

The Fluent solver uses a geometrical model produced in Gambit, as well as the initial conditions defined by the user. This fully-defined model is then used to create a set of algebraic equations that can be solved using an iterative process that is graphically displayed for interpretation by the user.

4.9.1 Fluent CFD Solver Set-up

The Gambit model mesh was imported into the Fluent solver program, in this case version 6.2.16. The model was first checked for any inconsistencies in the defined boundaries, elements and the mesh of the domain. The model parameters were then established in order to define the properties of all the fluids and solids used, the type of solver to be used, the governing equations to be enabled and, finally, the boundary and operating conditions that were applied to the system in order to determine a solution.

4.9.1.1 Material Properties

The materials used were from a predefined species transport model for methane and oxygen. All the fluids required for this investigation were found to be available in this model including methane (CH_4), water (H_2O), oxygen (O_2), nitrogen (N_2) and carbon dioxide (CO_2). Depending on the particular model analysed, gases that were not used were deleted in order to reduce the computational time, as they were not required. The density of each of the gases was considered based on a volume weighted mixing law. The specific heat was based on the mixing law for a species mixture.

4.9.1.2 Governing Equations

This analysis used a two-dimensional segregated solver, described earlier in Figure 4-3, for a steady state condition. The extended duration experienced during the mining process to reach each of the penetration depths allowed ample time for the system to reach a steady state. Therefore, it was assumed that steady state conditions applied to the highwall drive in each of the cases. This analysis, as noted earlier, uses a non-reacting flow process, meaning that no chemical reaction occurs between gases. The non-reacting flow model is able to simulate both the mixing and diffusion of gases within a domain. The energy equation was enabled for the volume weighted mixing law required, in order to calculate the material properties. Viscous forces within the domain were considered using a k-epsilon realisable model due to the turbulence experienced at the inert gas injection point.

4.9.1.3 Boundary and Operating Conditions

The boundary conditions of a model specify the flow and thermal variables at the boundaries of the CFD model, similar to those in an actual highwall mine. As noted earlier, the models in this investigation used the velocity inlet, pressure outlet, wall and interior boundary conditions, as shown in Figure 4-5.

The velocity inlet is a boundary defined by the velocity attributes of the flow of the fluid entering the domain. Establishing this boundary condition involves defining the flow velocity and the relevant scalar properties, including the magnitude and direction of the flow at the inlet, the chemical species mass fraction of inlet gases, the temperature and the turbulence parameters. For this analysis, the velocity inlet boundary condition was applied to the coal face and floor (methane) and inert gas injection point (nitrogen, carbon dioxide and boiler gas), whereby the appropriate parameters were defined for different models, as shown in Table 4-1. Various angles of injection of the inert gases were trialled in order to determine the optimum angle. The three injection angles considered were 0, 30 and 60 degrees, measured from the top surface of the machine, with a 0 degree angle parallel to the surface, as shown in Figure 4-10. The x and y

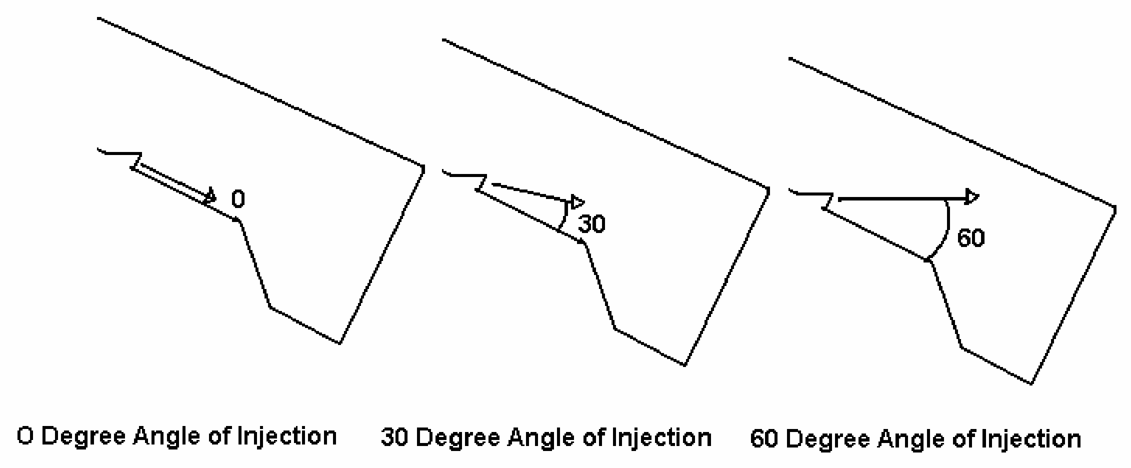

Figure 4-10 Inert Gas Angles of Injection at Injection Point

components of the velocity were varied in order to produce the three injection angles of 0, 30 and 60 degrees.

Table 4-1 Inlet Boundary Conditions

Inlet Boundary Name	Inlet Tempe -rature (K)	Hydraulic Diameter (m)	Turbulence Factor	Flow Rate (L/s)	Velocity (m/s)	Species (%)			
						Methane	Carbon Dioxide	Nitrogen	Oxygen
Coal Face	300	2.4	2	40	0.0166	100	0	0	0
Coal Floor	300	1	2	60	0.06	100	0	0	0
Inert Gas: Boiler Gas	300	0.15	8	150	8.5	0	14	85	1
Inert Gas: Carbon Dioxide	300	0.15	8	150	8.5	0	100	0	0
Inert Gas: Nitrogen	300	0.15	8	150	8.5	0	0	100	0

The pressure outlet boundary condition was defined by the pressure at the boundary. This boundary condition allowed the static pressure to be set at the outlet plane when the flow was subsonic. This pressure was then extrapolated from the flow from the interior of the domain. This boundary condition was capable of a backflow of gases at a defined mass fraction of species. In this analysis, the pressure outlet boundary condition was applied to the four faces in the surface region within the pit of the surface mine, and is shown in Table 4-2.

Table 4-2 Outlet Boundary Conditions

Outlet Boundary Name	Temperature (K)	Pressure (atm)	Species (%)	
			Oxygen	Nitrogen
Pit	300	1	21	79

The wall boundary condition allows the user to define thermal, momentum and species at the boundary. For this analysis, all external boundaries not previously defined were considered to be wall boundaries at a constant temperature (300K). The wall boundary condition was used to model fluid bounded by solid regions. By default, a ‘no-slip’ condition (fluid at the boundary has zero velocity) was applied to all boundaries.

The final boundary condition used was the interior boundary connecting separate fluid domains together, allowing the fluid to flow between them. The interior boundary condition was used in this analysis to link separate domain faces used, in order to improve the mesh.

The operating conditions for these analyses considered standard gravity and atmospheric pressure to be acting on the domain at all times. Once the model had been set up in the Fluent solver program, the iterative process in order to determine the solution could begin.

4.9.2 Fluent CFD Solver Solution and Validation

The iterative process as described above continued until the solution had converged. Convergence is the point at which the solution was no longer changing with successive iterations. The solution was monitored through the residuals or differences between the values of consecutive iterations, in order to determine the convergence. In this investigation, for each of the models solved using Fluent CFD software, the double precision convergence criteria outlined was met, requiring a smaller difference between successive solutions than for the single precision convergence criteria. The convergence criteria ensured that the fundamental principles outlined by the governing equations (conservation of mass, energy and momentum) were, in fact, imposed on these models.

Validation of the results was essential with regard to attaining realistic and reliable results from the CFD software. A number of validation procedures were available, including applying fundamental equations, comparing results to experimental data and, finally, determining whether the model was mesh independent. Due to the uniqueness and complexity of this model, fundamental equations were unable to be applied in order to evaluate the behaviour of the fluids at different points within the domain, and this was an important consideration in the decision to use CFD software. No experimental data was available pertaining to the unique model geometry used to verify the values throughout the highwall drive. This technique was further restricted by the number of assumptions made in order to simplify the model initially. The model mesh was refined and then re-solved in order to compare the solutions for each case. Results showed that the solution did not change with a finer mesh, indicating that the model was mesh independent.

4.10 Conclusion

Numerical analysis is a powerful tool based on fundamental equations of fluid flow for predicting the behaviour of fluids. This investigation used Gambit, a geometry and mesh- generating program, to create a model of the Moura Mine highwall operation that was later solved in Fluent, a CFD solver program. In producing a model of the highwall mining operation, certain assumptions were required and parameters were defined based on information that was provided to the author from a variety of sources. The models were ultimately solved and the results are detailed in the following chapter.

5. Results

The results of the two-dimensional CFD Fluent software analyses using the CFD models explained in Chapter 4 are summarised below. As noted earlier, the CFD models aimed to improve the ventilation of the Moura Mine highwall operation by considering the effects of the type of inert gas used, the angle of injection of the inert gas and the penetration depth. This chapter presents the results of the specific models generated for the different configurations based on these three factors. The complete set of results is provided in Appendices D, E and F.

5.1 Injection of Various Inert Gases

Three inert gases were trialled in this investigation, including boiler gas, carbon dioxide and nitrogen. The general behaviour of each of these gases within the highwall drive is outlined below. The influence of the penetration depth and angle of injection into the highwall drive on the behaviour of each of the inert gases is then discussed in more detail later in this chapter.

5.1.1 Boiler Gas

Boiler gas primarily consists of nitrogen with carbon dioxide and oxygen making up the remaining constituents. Figure 5-1 shows lines indicating the path of particles, in this case released from the three inlets: the inert gas injection point, the coal face and the coal floor. The coloured contours on the pathlines relate to the velocity with respect to the key that appears to the left. As shown in Figure 5-1, the circulation within the highwall drive expands with penetration depth, demonstrated by the increase in area covered by the contours. The velocity of the inert gas is reduced after it is released and,

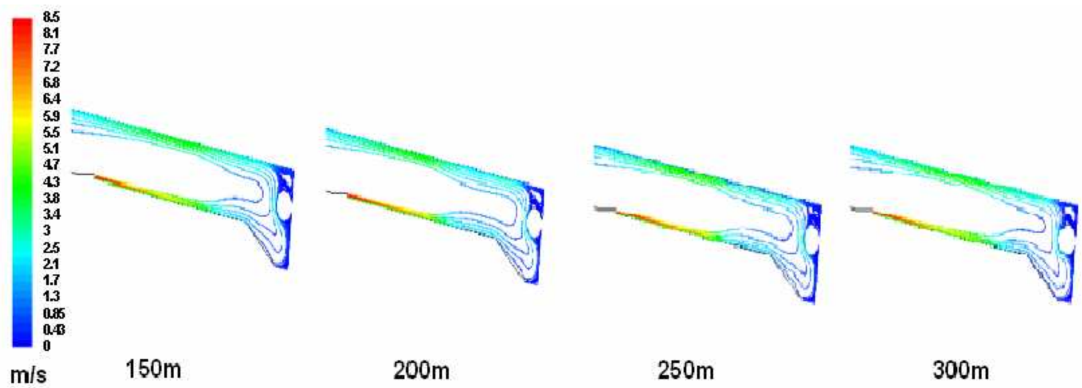

Figure 5-1 Boiler Gas Velocity Pathlines for Various Penetration Depths in Coal Face Region

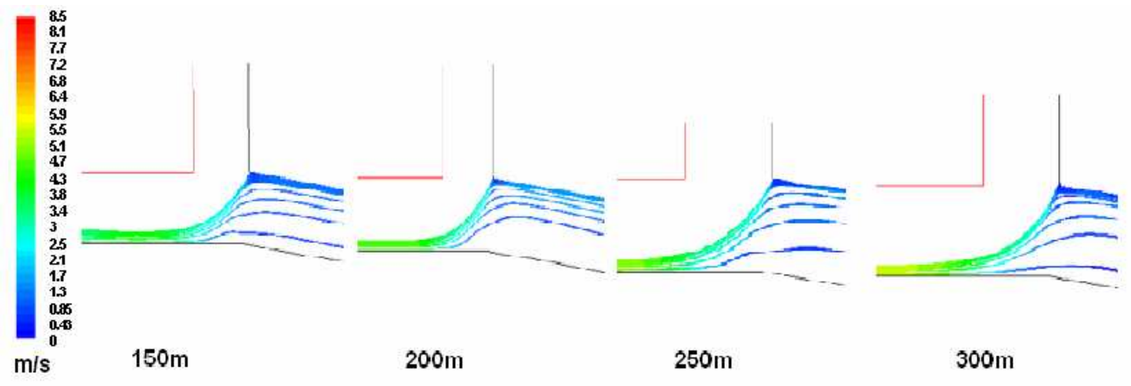

Figure 5-2 Boiler Gas Velocity Pathlines for Various Penetration Depths at End of the Highwall Drive

later, momentarily increased when it circulates past the top of the drive above the injection point. The region of the drive at the highwall was identified with a potential explosive zone for each and all of the cases. Figure 5-2 shows the velocity pathlines at the highwall or end of the drive. The pathlines of the mixture that have predominantly travelled along the upper half of the drive are now forced down and out of the end of the drive with a resulting increase in the velocity of the gases observed. This may occur due to the influence of the outside air or, perhaps, the behaviour of the mixture itself. Further discussion of the behaviour of the boiler gas is included in subsequent sections of this chapter.

5.1.2 Carbon Dioxide

The carbon dioxide velocity pathlines for the various penetration depths are shown in Figure 5-3 for the coal face region. The pathlines, as in the case of the boiler gas, decrease in velocity when released and, later, increase in a region of the drive roof. The mixture returning past the injection point shows that the carbon dioxide pathlines drop rapidly toward the drive floor leading to a divergence of the inert gas pathlines from those of the methane, coming from the coal face and floor. This divergence can be

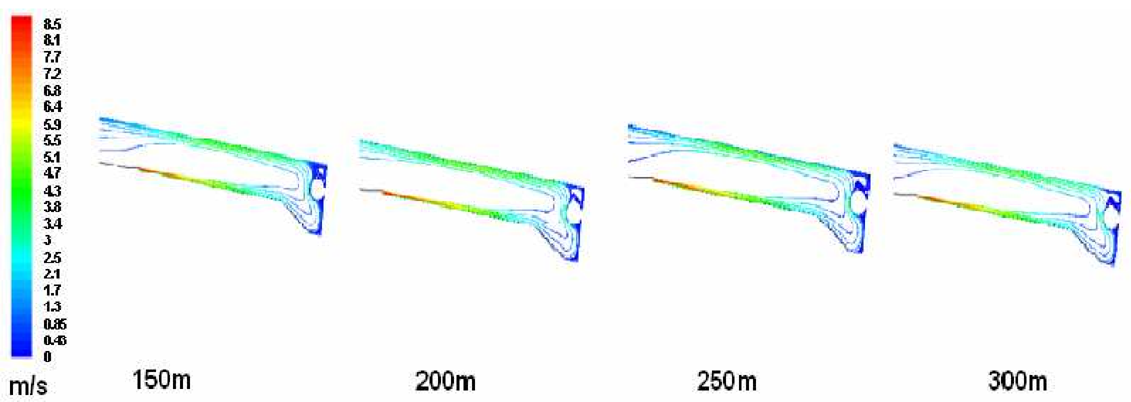

Figure 5-3 Carbon Dioxide Velocity Pathlines for Various Penetration Depths in Coal Face Region

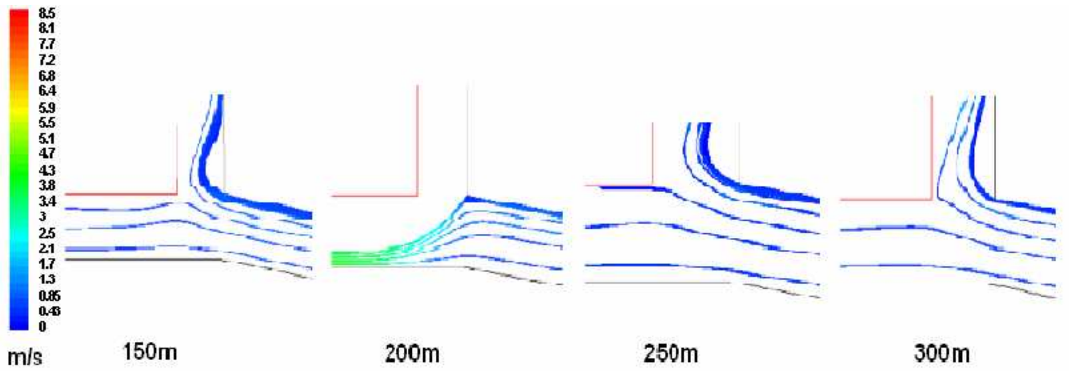

Figure 5-4 Carbon Dioxide Velocity Pathlines for Various Penetration Depths at End of the Highwall Drive

further observed at the highwall end of the drive, as shown in Figure 5-4. A greater difference in the distance between pathlines, in comparison to the boiler gas, is observable. The darker, more concentrated, region located toward the top of the drive shows the pathlines from methane sources while the lower pathlines are from the inert carbon dioxide gas. At penetration depths of 150, 250 and 300m, turbulence occurs at the top of the end of the drive as the methane rises out from the end of the drive roof. The inert carbon dioxide continues to travel parallel to the floor surface. However, at a penetration depth of 200m, this is not the case; the gases leaving the drive appear to be influenced by the outside air forcing the gases down and increasing the velocity of the mixture.

5.1.3 Nitrogen

The nitrogen velocity pathlines for the various penetration depths are shown in Figure 5-5 for the coal face region. The pathlines of the nitrogen are similar to those of the boiler gas with respect to the magnitude and position of contours. The velocity of the nitrogen decreases as it approaches the end of the drive and increases as it circulates past the injection point on the drive roof. As the penetration depth increases, the boiler gas. The pathlines are dispersed evenly across the end of the drive region, unlike those

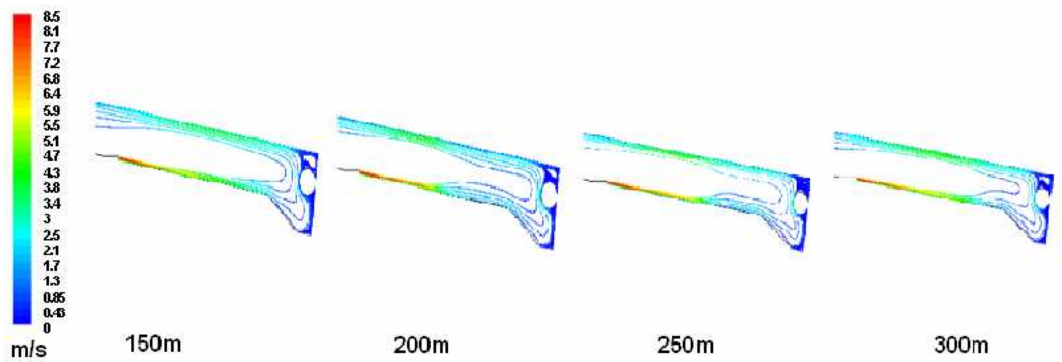

Figure 5-5 Nitrogen Velocity Pathlines for Various Penetration Depths in Coal Face Region

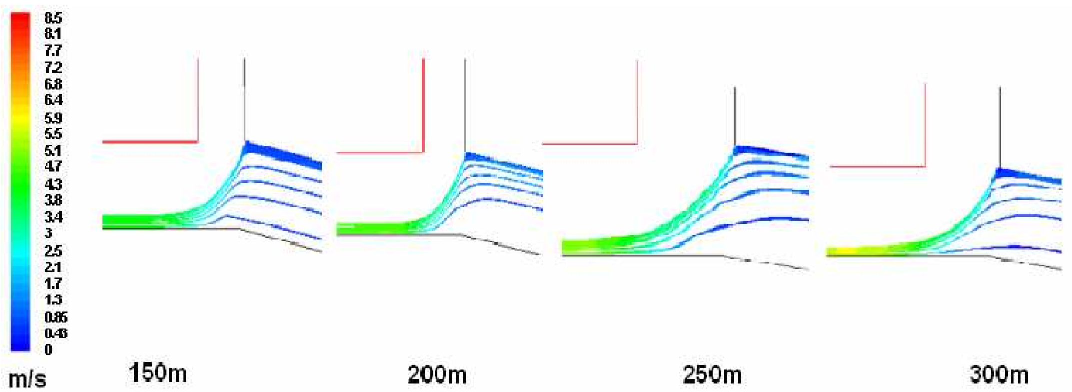

Figure 5-6 Nitrogen Velocity Pathlines for Various Penetration Depths at End of the Highwall Drive

of the distance between contours increases and takes up a greater area of the coal face region. This expansion may be due to additional diffusion or mixing as penetration depth increases. Figure 5-6, once again, shows the velocity pathlines at the highwall. As with the coal face region, the velocity pathlines of the nitrogen are similar to those of the carbon dioxide, which have a distinct separation and concentration.

5.2 The Angle of Injection for Various Inert Gases

The angle at which the inert gas was injected into the highwall drive varied between 0, 30 and 60 degrees. Each of the inert gases was trialled at the various angles at a penetration depth of 150 metres, in order to determine the optimum injection angle for each. The methane and oxygen concentrations are expressed here as a fraction of the total mixture in the figures. These concentrations were used to identify potential explosive zones within the highwall drive. The oxygen concentration in the coal face region was found to be zero for all two-dimensional steady CFD Fluent analyses undertaken in this investigation. Therefore, there was no potential for an explosion occurring in this region. Although no explosive zones were identified at the coal face region, the behaviour of the gases in this region had a direct influence on the explosive zone located at the highwall end of the drive.

5.2.1 Inert Gases Injected at 0 Degrees

At an injection angle of 0 degrees, the methane diffusion and mixing at the coal face was found to be minimal in comparison to that of the larger injection angles. Figure 5-7 shows that the methane concentration is largest at both the coal face and floor with a mass fraction of one. The inert gas from the injection point (not shown in the figure) is represented by the blue region, indicating that mixing is confined to the region near the coal face and toward the upper area of the drive. The inert gas at this injection angle

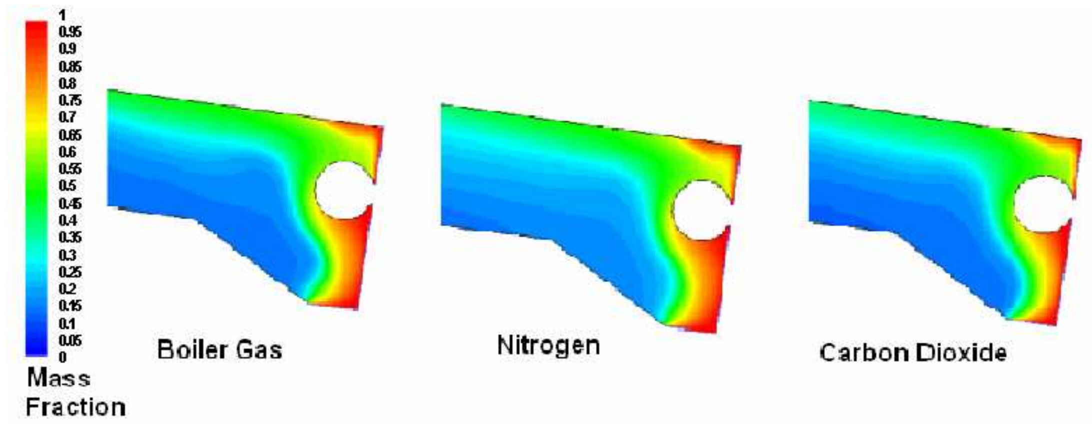

Figure 5-7 Methane Concentrations in Coal Face Region with Inert Gas Injected at 0 Degrees (150m penetration depth)

primarily follows the contours of the machine, again, as shown by the blue region. The nitrogen and the boiler gas equally provided the largest amount of mixing in the coal face region while the carbon dioxide produced the least amount of mixing, indicated by the greater percentage of blue contours throughout the region. The carbon dioxide removed more of the methane from the coal floor and face inlets than did either the nitrogen or the boiler gas, allowing for more accumulation of methane. Figure 5-8 shows the highwall end of the drive where the explosive zone was identified for each of the cases. As noted earlier, an explosive zone exists when a mixture of 5-17% methane

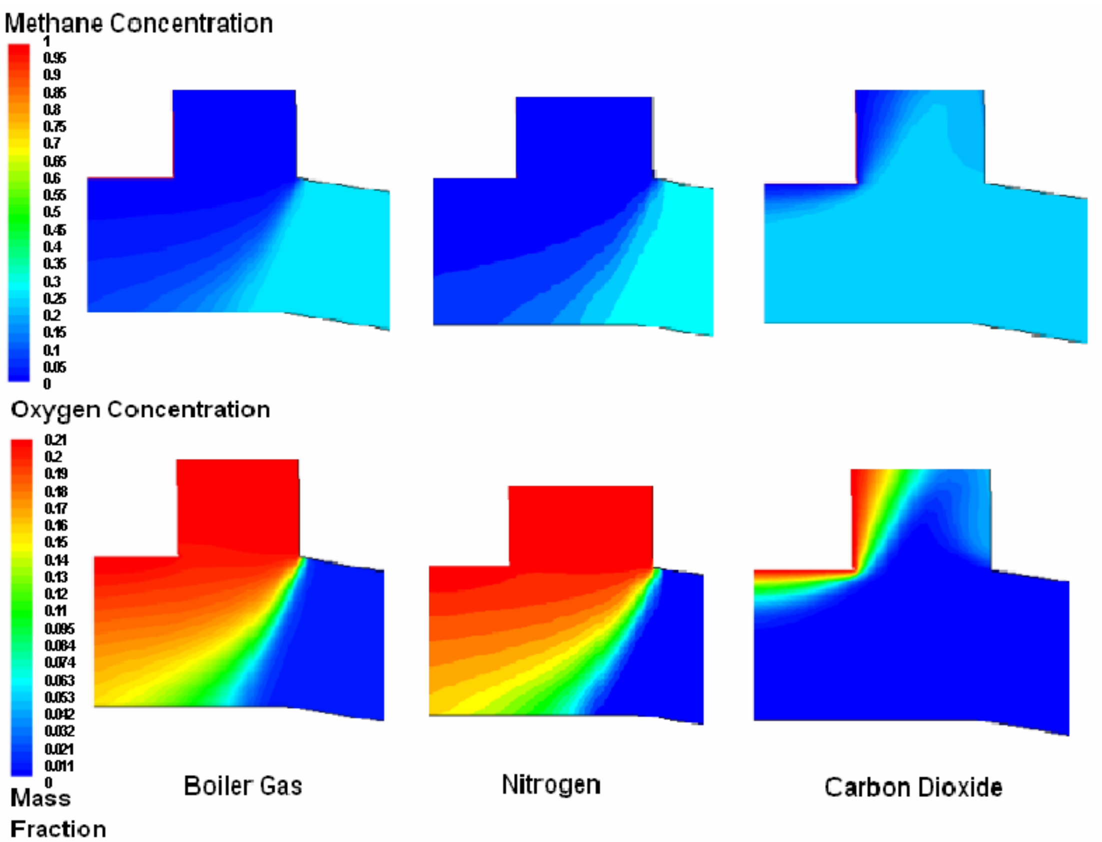

Figure 5-8 Methane/Oxygen Concentrations at Highwall Region with Inert Gases Injected at 0 Degrees (150m penetration depth)

and 12-20% oxygen exists. The carbon dioxide produced the smallest explosive zone of the three gases, at only a few metres from the end of the drive. The mixture leaving the drive forced the atmospheric air and oxygen away from the end of the drive. The boiler gas produced an explosive zone almost equal in shape and size to that of the nitrogen. These two gases produced an explosive zone at the end of the drive that was more pronounced at the floor and tapered toward the top of the end of the drive.

5.2.2 Inert Gases Injected at 30 Degrees

At an injection angle of 30 degrees, the methane diffusion and mixing at the coal face increased in comparison to an injection angle of 0 degrees. Figure 5-9 shows that methane concentrations are larger at both the coal face and floor with a mass fraction of one. The inert gas from the injection point that (not shown in the figure) is represented by the blue region indicating that mixing is confined to the area near the coal face and toward the upper section of the drive. The inert gas injected at this angle primarily follows the contours of the machine, as was demonstrated in the earlier case, shown by the blue region. The carbon dioxide provided the greatest mixing in the coal face region at this injection angle while both the boiler gas and the nitrogen equally had the least amount of mixing, indicated by the greater percentage of darker blue contours throughout the region. The carbon dioxide was found to remove more of the methane from the coal floor and face inlets than did either the nitrogen or the boiler gas, which led to more accumulation of methane at these faces. The boiler gas and nitrogen, once again, produced similar methane contours in this region. Figure 5-10 shows the highwall end of the drive where the explosive zone was identified for each of the cases. Again, as noted earlier, an explosive zone exists when a mixture of 5-17% methane and

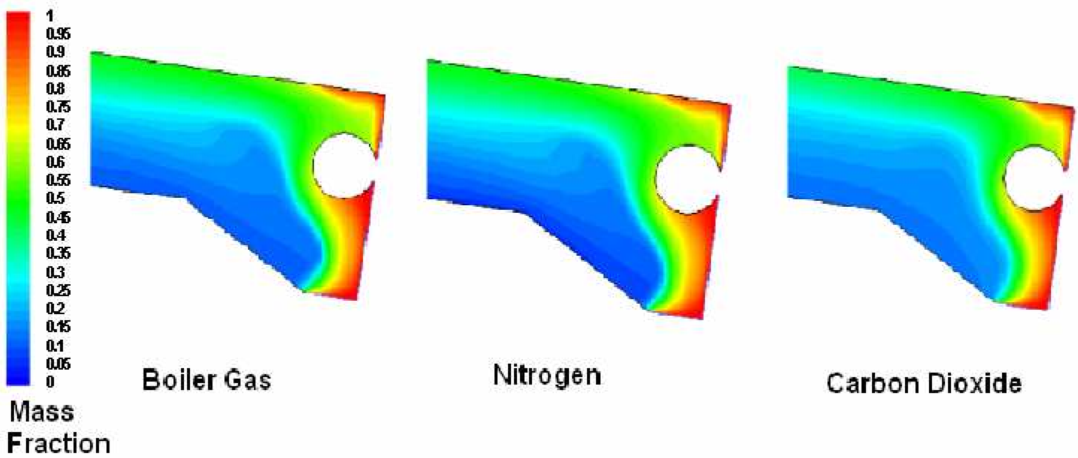

Figure 5-9 Methane Concentrations in Coal Face Region with Inert Gas Injected at 30 Degrees (150m penetration depth)

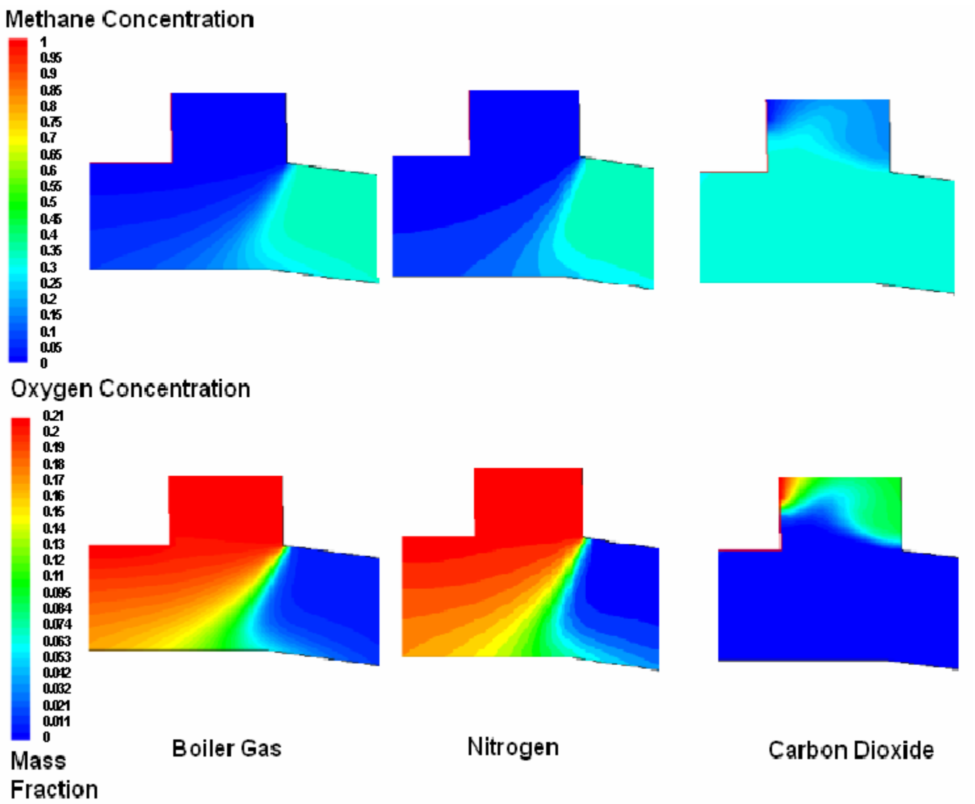

Figure 5-10 Methane/Oxygen Concentrations at Highwall Region with Inert Gases Injected at 30 Degrees (150m penetration depth)

12-20% oxygen exists. The figure shows that the explosive zone has progressed toward the end of the highwall drive, in comparison to an injection angle of 0 degrees. The carbon dioxide produced the smallest explosive zone of the three gases, located outside and above the end of the highwall drive. The mixture leaving the drive has forced the atmospheric air and oxygen away from the end of the drive. The boiler gas produced a slightly smaller explosive zone than did the nitrogen, although it was closely related to the shape and position of that of the nitrogen. The explosive zones for these gases expand into the lower corner of the end of the highwall drive. This contributes to the increased size of the explosive zone at a 30 degree angle of injection compared to a 0 degree angle. Finally, once again, the nitrogen and boiler gas produced a similarly shaped and sized explosive zone.

5.2.3 Inert Gases Injected at 60 Degrees

At an injection angle of 60 degrees, the methane diffusion and mixing at the coal face was the largest of all the injection angles. Figure 5-11 shows that the methane concentrations are largest at the coal face and floor with a mass fraction of one. The inert gas injected at this angle provides a large degree of turbulence within the coal face region. The inert gases for this injection angle were mixed into the surrounding gas and

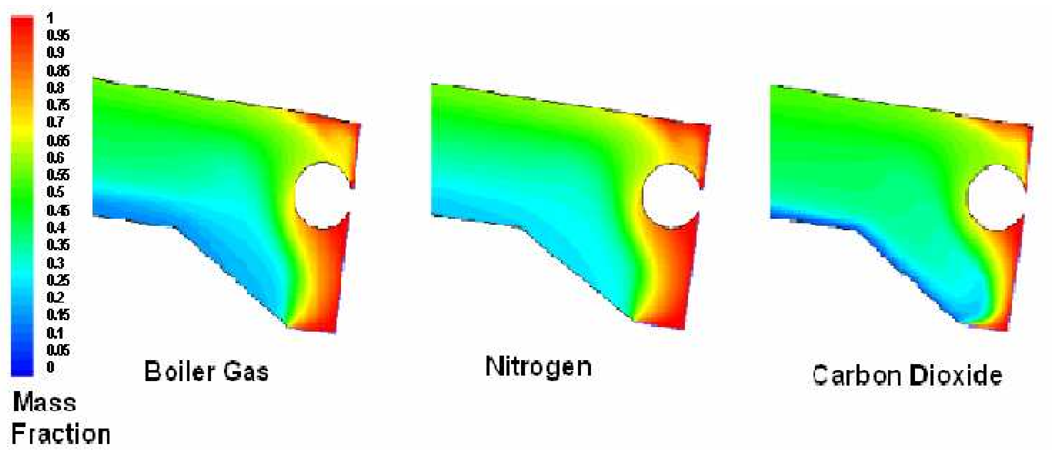

Figure 5-11 Methane Concentrations in Coal Face Region with Inert Gases Injected at 60 Degrees (150m penetration depth)

did not concentrate along the contour of the machine, as previously shown. Instead, they contributed to an increase of methane mixing and diffusion. Additionally, the carbon dioxide removed more of the methane from the coal floor and face inlets than did either the nitrogen or the boiler gas, allowing for more accumulation of methane at these faces. Profound mixing occurred throughout the entire coal face region, with all areas containing some degree of methane concentration not seen at the previous injection angles. For each of the three inert gases, in comparison to the other injection

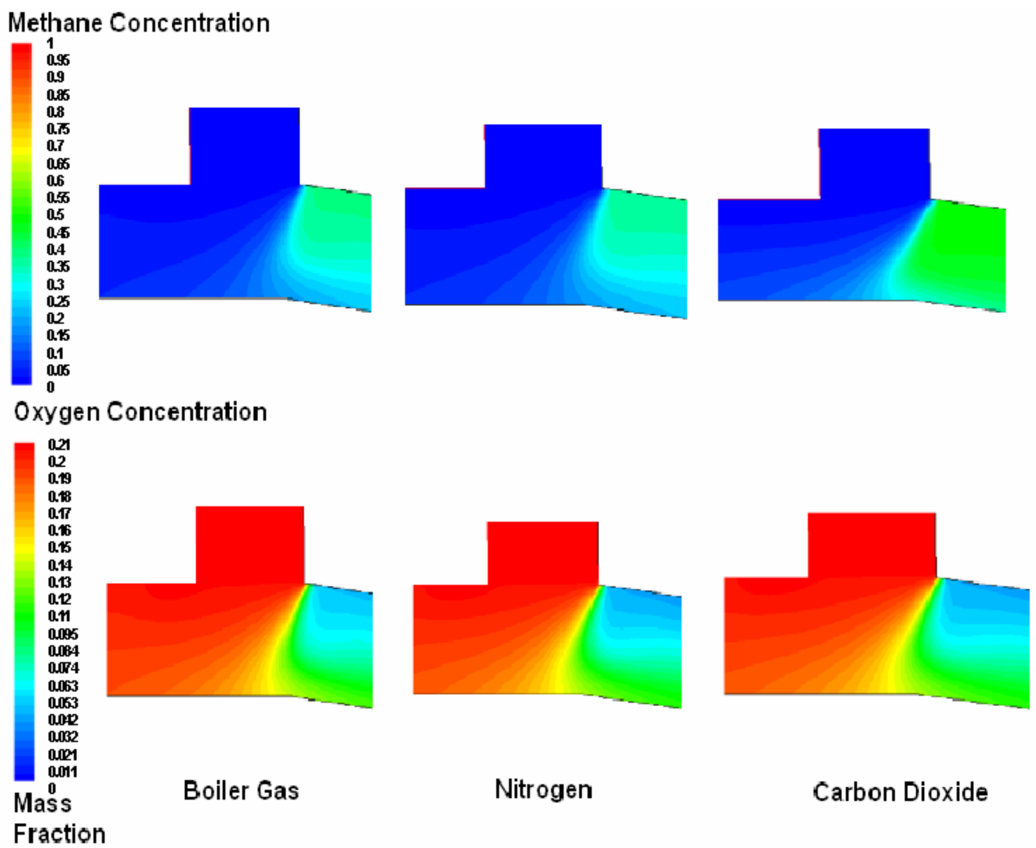

Figure 5-12 Methane/Oxygen Concentrations at Highwall Region with Inert Gases Injected at 60 Degrees (150m penetration depth)

angles trialled, the largest amount of methane accumulation was experienced at the coal face and floor, as expected, given that these were defined as methane inlets. The carbon dioxide provided the largest methane mixing and diffusion in the coal face region. Both the boiler gas and the nitrogen produced similar, though slightly less, methane mixing and diffusion compared with the carbon dioxide.

Figure 5-12 shows the highwall end of the drive where the explosive zone was identified for each of the cases. The explosive zone has, once again, progressed toward the end of the highwall drive and has greatly expanded in size, in comparison to the other injection angles. All three inert gases produced a similarly sized and shaped explosive zone located at the highwall end of the drive. The explosive zone for these gases expanded further into the lower corner of the end of the highwall drive, contributing to the increased size of the explosive zone compared to the other injection angles. The carbon dioxide, in this case, produced a similarly sized and shaped explosive zone compared to both the nitrogen and the boiler gas. The shape of the explosive zone tapers towards the top end of the highwall drive and expands at the lower end.

5.3 Effect of Penetration Depth for Various Inert Gases

The highwall drive was varied from 150 to 300m, in 50m increments, in order to simulate the change in penetration depth during mining. Each of the inert gases and injection angles were considered in order to determine the influence of the penetration depth. Again, the methane and oxygen concentrations were used to identify potential explosive zones within the highwall drive and are expressed as a fraction of the total mixture. The oxygen concentration in the coal face region was found to be zero for all two-dimensional steady CFD Fluent analyses undertaken in this investigation.

5.3.1 Penetration Depth of 150 Metres

Figure 5-7 shows that the mixing of inert gases at the coal face was minimal at a penetration depth of 150m, in comparison to the other penetration depths trialled. The carbon dioxide produced the least methane diffusion and mixing at this penetration depth at the coal face region. The nitrogen and the boiler gas equally experienced the most methane mixing and diffusion of the three inert gases at this depth.

For each of the three cases, the explosive zone produced at the end of the highwall was found to be the smallest at a penetration depth of 150m. The carbon dioxide produced the smallest explosive zone of the three gases, as shown in Figure 5-8. The position was influenced by the inert gas injection angle. Both the boiler gas and the nitrogen produced a larger diagonally tapered explosive zone, compared to carbon dioxide, at the end of the highwall drive, which was also influenced by the inert gas angle of injection.

5.3.2 Penetration Depth of 200 Metres

CFD analyses indicated, as the penetration depth increased from 150 to 200m, that methane mixing and diffusion at the coal face also increased slightly. All three of the inert gases had similar methane mixing and diffusion at the coal face region, as shown in Figure 5-13. The carbon dioxide produced the greatest mixing of the three inert gases and the nitrogen produced the least. The contours of the nitrogen and boiler gas are very similar, as shown to be the case previously.

For each of the three cases, the explosive zone located at the end of the highwall drive increased in size and moved closer into the highwall drive, as shown in Figure 5-14. The carbon dioxide produced an enlarged explosive zone close to the end of the highwall drive. This was irregular in comparison to the size and position of the explosive zone, as demonstrated for the other penetration depths. This behaviour occurred for both the injection angles of 0 and 30 degrees, with only a slight variation. The nitrogen and boiler gas behaved similarly with regard to the explosive zones, increasing in size in comparison to the 150m penetration depth. The shape of the explosive zone indicated that the lower corner of the diagonally tapered explosive zone expanded into the highwall drive. The boiler gas produced a slightly smaller explosive

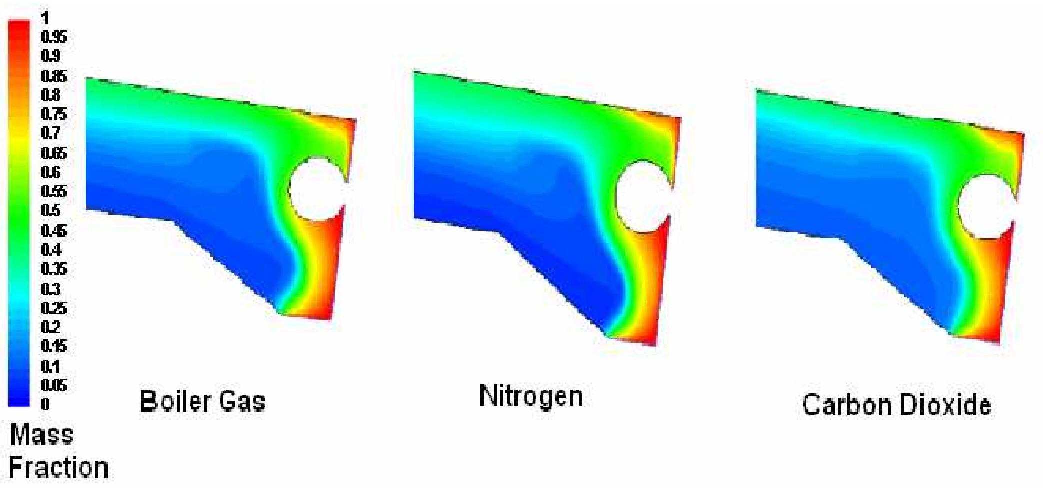

Figure 5-13 Methane Concentrations in Coal Face Region at a Penetration Depth of 200m (Inert Gas Injected at 0 Degrees)

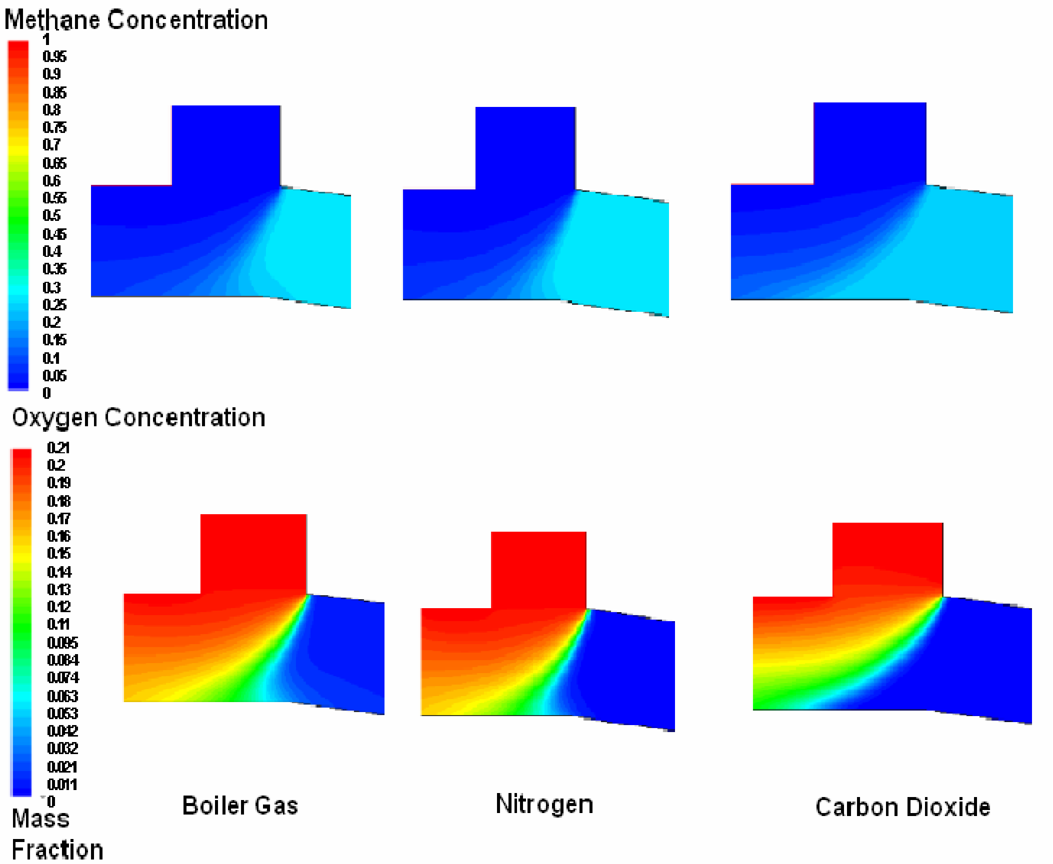

Figure 5-14 Methane/Oxygen Concentrations at Highwall at a Penetration Depth of 200m (Inert Gas Injected at 0 Degrees)

zone in comparison to the nitrogen. The angle of injection of the inert gas also influenced the size of the explosive zone.

5.3.3 Penetration Depth of 250 Metres

CFD analyses indicated, as the penetration depth increased from 200 to 250m, that methane mixing and diffusion at the coal face also increased slightly. The carbon dioxide provided the largest amount of methane mixing and diffusion of the three gases,

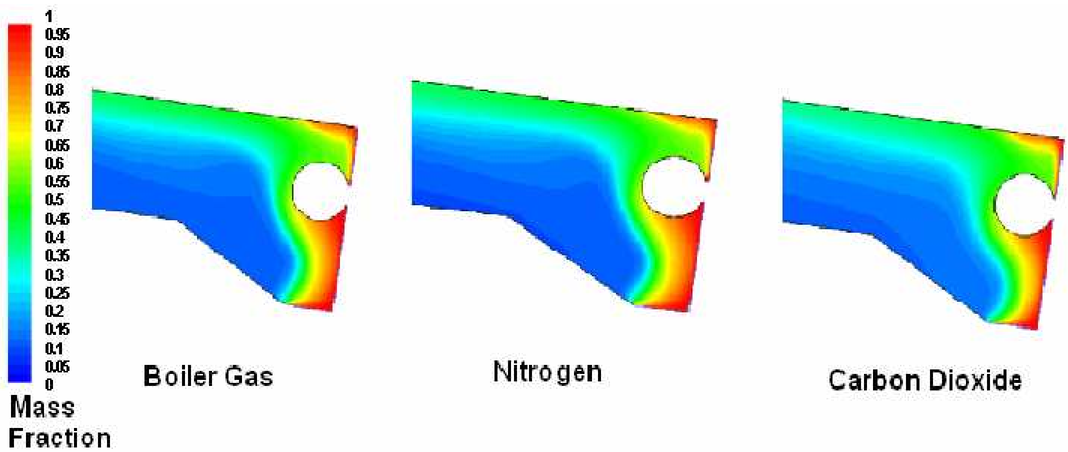

Figure 5-15 Methane Concentrations in Coal Face Region at a Penetration Depth of 250m (Inert Gas Injected at 0 Degrees)

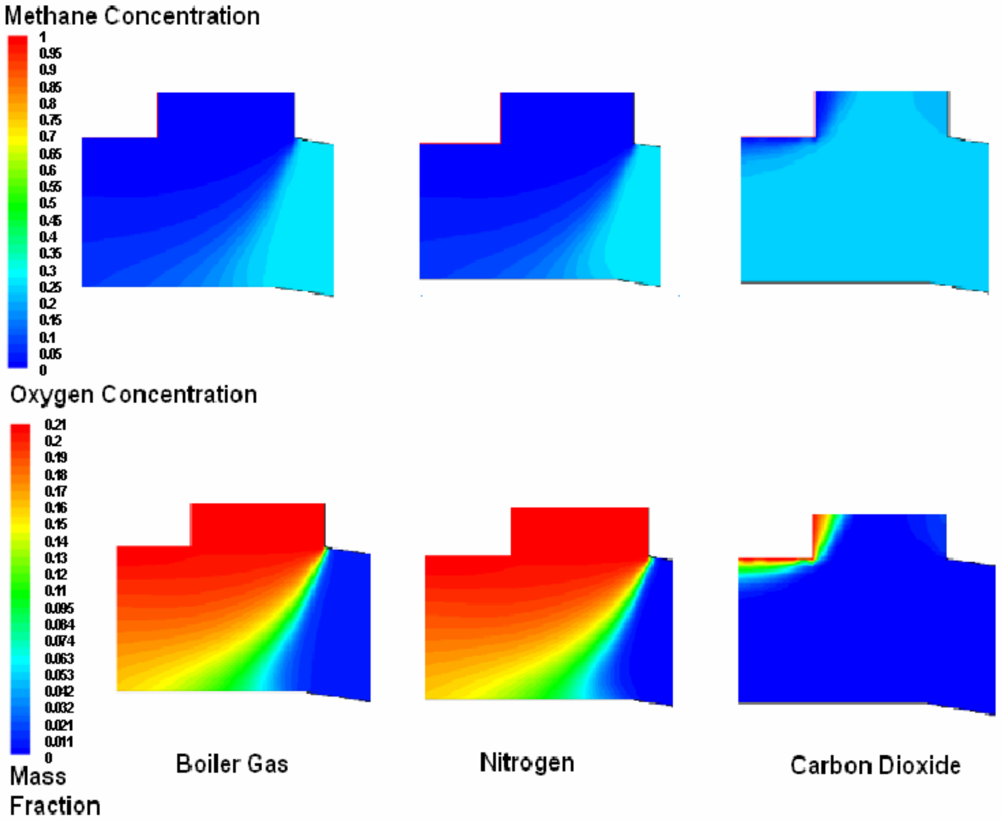

Figure 5-16 Methane/Oxygen Concentrations at Highwall at a Penetration Depth of 250m (Inert Gas Injected at 0 Degrees)

as shown in Figure 5-15. It should also be noted that, of the three gases, the carbon dioxide had the smallest amount of methane accumulation at the coal face and floor regions. The nitrogen and boiler gas had similar methane concentration contours with substantially larger amounts of methane accumulated at the coal face and floor. The boiler gas provided slightly more methane diffusion and mixing than did the nitrogen.

The explosive zone for each of the three cases increased slightly in size at the highwall end of the drive, as shown in Figure 5-16. The carbon dioxide produced an explosive zone located a few metres from the end of the highwall drive, consistent with penetration depths of both 150 and 300m. The nitrogen and boiler gas, once again, behaved similarly with regard to the explosive zones, increasing in size in comparison to the 150 and 250m penetration depths. With regard to shape, the lower corner of the diagonally tapered explosive zone expanded slightly further into the highwall drive.

5.3.4 Penetration Depth of 300 Metres

Once again, as the penetration depth increased from 250 to 300m, CFD analyses indicated that methane mixing and diffusion at the coal face region also increased slightly. The carbon dioxide provided the largest amount of methane mixing and

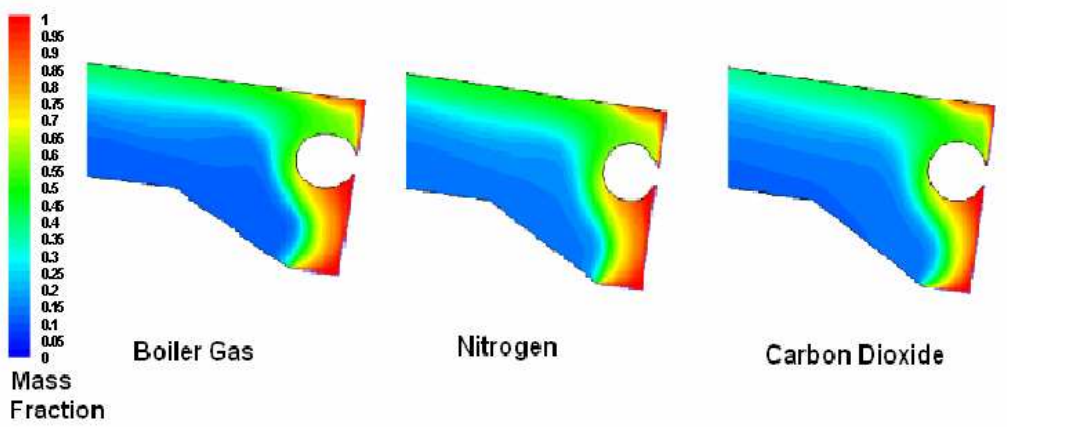

Figure 5-17 Methane Concentrations in Coal Face Region at a Penetration Depth of 300m (Inert Gas Injected at 0 Degrees)

diffusion of the three gases, as shown in Figure 5-17, with the boiler gas producing the least methane mixing. The nitrogen and the boiler gas had similar methane concentration contours with substantially larger amounts of methane accumulated at the coal face and floor. The nitrogen provided slightly more methane diffusion and mixing than did the boiler gas. It should also be noted that the carbon dioxide had the smallest amount of methane accumulation at the coal face and floor regions. The explosive zone began to decrease in size and moved away from the highwall drive, as seen in

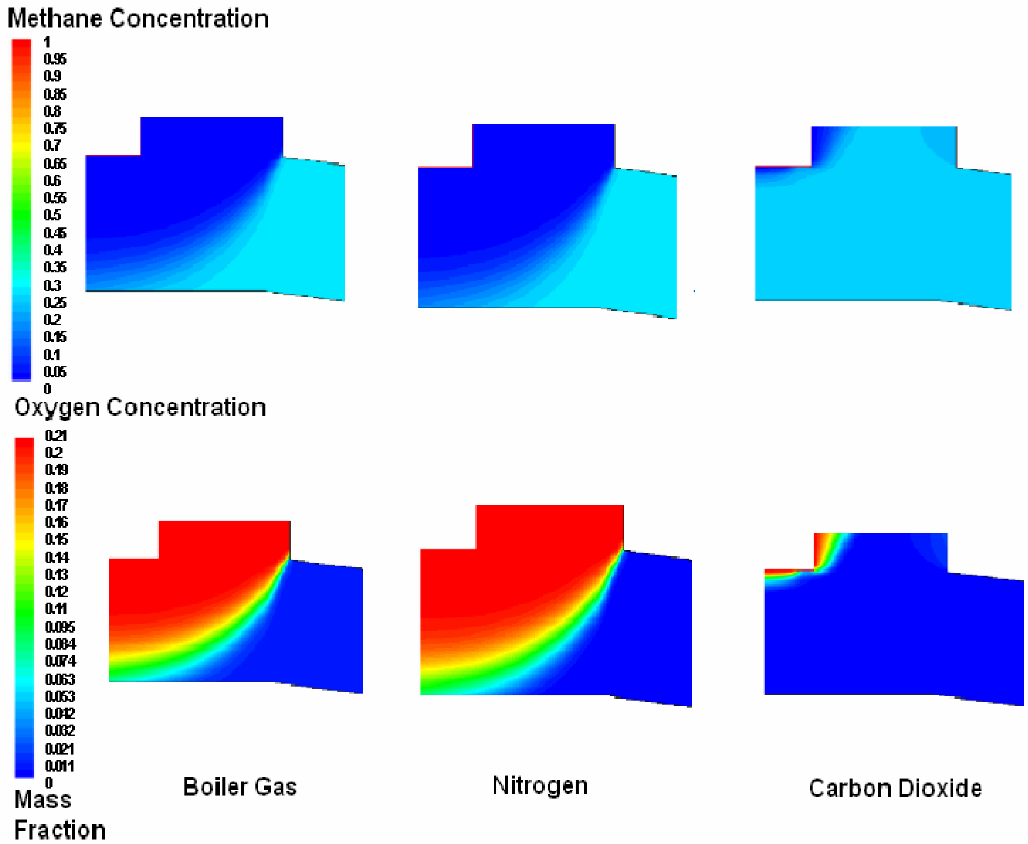

Figure 5-18 Methane/Oxygen Concentrations at Highwall at a Penetration Depth of 300m (Inert Gas Injected at 0 Degrees)

Figure 5-18. The carbon dioxide produced an explosive zone located only a few metres from the end of the highwall drive, consistent with the penetration depths of both 150 and 250m. Once again, the nitrogen and boiler gas behaved similarly with regard to the explosive zones, in this case decreasing in size compared with the 150, 200 and 250m penetration depths. The shape of the explosive zone indicated that the lower corner curved away for the highwall drive and tapered towards the top of the highwall drive.

5.4 Conclusion

These analyses provide valuable insight into understanding the behaviour of methane under varying conditions. The three major parameters investigated included the penetration depth of the drive, type of inert gas used and angle at which the gas is injected. Results of the analyses identified the contribution of each of these parameters to the individual behavioural properties of each of the three inert gases trialled. In general, results indicated that the carbon dioxide, at a 0 degree angle of injection, was most effective in controlling methane/oxygen concentrations. As discussed in the proceeding chapter, these results may greatly assist in determining how to safely maximise current highwall mining operations at the Moura Mine.

6. Discussion

A detailed discussion of the results presented in Chapter 5 is provided below, including the significance and limitations of the findings and their overall implications for highwall coal mining at the Moura Mine.

6.1 Comparison of Inert Gases

Results of the CFD analyses indicated that the type of inert gas injected into the highwall drive during coal mining is a significant factor in determining the effectiveness of the ventilation system with regard to minimising and controlling oxygen and methane concentration levels. The behaviour of the methane mixing and diffusion in the coal face region when inert gases are injected into the highwall drive has a direct influence on various characteristics of the explosive zone at the highwall end of the drive.

Methane released by coal has the lowest density (0.668kg/m^3) of all the gases within the highwall drive and, naturally, it would be expected that this gas would move toward the highest point in a given region (Kreith & Bohn 2001). Recognising this natural tendency of methane is beneficial in determining effective mechanisms by which to move the gas through the drive with the use of a ventilation system.

For all three of the inert gases trialled in this investigation (nitrogen, carbon dioxide and boiler gas), the velocity of the pathlines at a 0 degree injection angle, or parallel to the sides of the drive, provided the least turbulence at the coal face region with little to no turbulence elsewhere in the drive. The velocity increase observed above the injection point on the roof of the drive was apparently due to the change in pressure caused by the injection of the inert gases, leading to a pressure drop towards the top of the drive and velocity gradient across that section of the drive.

The CFD analyses consistently indicated that the behaviour of the boiler gas and of the nitrogen was, in most cases, very similar. The comparable behaviour of these two gases can be attributed to the fact that 85% of the boiler gas consists of nitrogen. The high percentage of nitrogen in the boiler gas strongly influenced the overall properties of the mixture including the overall density of the gas. The 14% carbon dioxide in the boiler gas, to a lesser extent, also influenced the behaviour of the mixture, resembling some of the characteristics observed of the pure carbon dioxide gas. Based on the initial angle of injection (0 degrees), the gas followed the contours of the machine due to its high injection velocity parallel to the surface of the machine. The mixing of the three inert gases in the coal face region produced similar results to one another, due to the fact that the same high initial velocity of the inert gas injected into the drive created a comparable degree of turbulence for each of the gases. The diffusion of gases, or lack of diffusion, observed along the length of the drive after mixing at the coal face had occurred, played a major role in the concentration of gases in the mixture at the surface at an injection angle of 0 degrees. Greater diffusion occurred for the nitrogen and boiler gas, relative to the carbon dioxide. When the nitrogen and boiler gas, along with the methane, reached the surface, the mixture was forced down by outside air moving down the highwall face. The resulting decrease in the cross-sectional area of the velocity pathlines led to a subsequent increase in the velocity of the mixture leaving the drive. The distance between the velocity pathlines increased with penetration depth, indicating that there was a decrease in the velocity of the mixture throughout the domain. This decreased velocity also allowed more time for the diffusion of gases making their way to the surface.

The large variation in density of the carbon dioxide (1.80kg/m^3) and methane (0.668kg/m^3), along with the minimal turbulence within the drive, compared with the other injection angles trialled, contributed to the divergence of the gases within the drive at a 0 degree injection angle. This behaviour was observed behind the injection point of the mixture returning to the surface. This separation was particularly pronounced at the highwall end of the drive. Here, the carbon dioxide was dispersed throughout the drive and a concentration of the lighter methane was evident at the top of the drive. This was demonstrated by a concentration of velocity pathlines along the roof of the drive and, later, ascending up the highwall. Due to the carbon dioxide's higher density, it was also able to force a greater amount of the methane from the coal face and floor, acting as a single body of fluid in order to displace the methane. Mixing in the coal face region was dominant in comparison to diffusion, influenced by the turbulence created by the high velocity and angle of inert gas injected into the drive. The carbon dioxide like the nitrogen and boiler gas followed the contour of the machine and acted like a body of fluid due to the lack of turbulence produced within the drive. As the angle of injection increased, the turbulence in the drive also increased. This, along with the higher density of the carbon dioxide relative to the other inert gases, resulted in greater mixing of the methane. Density is generally considered to be an important factor in the diffusion of two or more gases, as stated by Fick's Law of Diffusion (Turns 1996). However, over the length of the drive, between the injection point and surface, diffusion was minimal for the carbon dioxide illustrated by the clear separation of the gases.

Generally, at most penetration depths, the separation of carbon dioxide and methane observed at the highwall leads to the methane rising from the end of the drive. However, an interesting anomaly occurred in this investigation at a penetration depth of 200m, where the velocity pathlines were similar to those of the nitrogen and boiler gas. In this case, the mixture leaving the end of the drive was forced down and out by the outside air at the surface moving down the highwall. Contrary to the other penetration depths, the separation and concentration of the methane along the roof of the drive was not present. This unexpected result is inconsistent with the other findings, where a reduction in the separation of gases was found as penetration depth increased, observed at all three of the remaining penetration depths trialled. The unusual finding was observed at the penetration depth of 200m on two different occasions, including for inert gas injection angles of both 0 and 30 degrees, indicating that it was not due to a CFD operator error. Further analysis is required at similar penetration depths in order to further understand these findings.

For all three cases, the degree of mixing of gases in the coal face region and diffusion along the length of the drive strongly influenced the size of the explosive zone at the end of the highwall drive. Specifically, when a high degree of mixing in the coal face region (due to the injection angle) and diffusion over the length of the drive occurred, there was a resulting increase in the size of the explosive zone, while minimal mixing and diffusion resulted in the smallest explosive zone. The amount of mixing and diffusion experienced was also directly affected by the angle at which the inert gas was injected into the drive, as well as the penetration depth of the drive.

Overall, results indicated that the carbon dioxide was the most effective of the three inert gases trialled in controlling methane concentrations within the highwall drive. The boiler gas was found to be the second most effective and the nitrogen the least effective, although these latter two gases produced generally similar results.

6.2 Comparison of Inert Gas Injection Angles

The angle at which the inert gas was injected into the highwall drive was also found to be a critical factor in the effectiveness of the ventilation system with regard to minimising oxygen and methane concentration levels. The angle of injection was found to directly influence the mixing behaviour of the gases at the coal face. For each of the three inert gases trialled, this investigation considered three different injection angles of 0, 30 and 60 degrees. CFD analyses indicated that, as the angle of the inert gas was increased, the mixing of the gases in the coal face region also increased for each of the inert gases.

When the inert gas was injected at 0 degrees, the methane mixing was found to be minimal in the coal face region, in comparison to the other injection angles trialled. For each of the inert gases, at a 0 degree injection angle, the gas followed the contour of the machine. The reduced mixing at the coal face directly influenced the size of the explosive zone produced at the end of the drive. The smallest explosive zones were produced for each of the inert gases at a 0 degree injection angle, and this can be attributed to the minimal mixing of methane observed at this particular angle in comparison with the other injection angles trialled, both of which resulted in greater mixing of methane. The velocity pathlines indicate that, at a 0 degree injection angle, the inert gases were able to push the methane up and out of the drive. This occurred due to the smooth circulation pattern of gases in which particles released from the inlets (inert gas injection point, coal face and coal floor) were observed. The carbon dioxide produced the least mixing of the methane and inert gas than did either the nitrogen or the boiler gas. As described in the previous section, in relation to different densities, the carbon dioxide was able to assist in pushing the methane up and out of the drive. The carbon dioxide thus produced the smallest explosive zone, located away from the end of the drive. The separation of the gases occurring within the highwall drive, as described in the previous section, resulted in less influence of the outside air on the carbon dioxide. This was due to the higher density and reduced methane mixing and diffusion at this angle of the carbon dioxide, in comparison to the other inert gases trialled. In contrast, the nitrogen and the boiler gas mixed with the methane, reducing the ability of these inert gases to push the methane from the drive. These two inert gases produced similarly shaped and sized explosive zones at the end of the highwall drive. With these gases, the low density and slow velocity of the mixture leaving the end of the drive was directly influenced by the heavier atmospheric air moving down the face of the highwall, pushing the mixture down and out of the drive.

For all three of the inert gases trialled, as the angle of injection increased, the mixing with methane also increased in the coal face region, producing a larger explosive zone. At a 30 degree angle of injection, it was found that the inert gas injected still predominantly followed the contours of the machine. This assisted the gas, to a varying degree, to push the methane from the coal face and floor and out of the drive, aiding the natural tendency of the methane. The carbon dioxide provided the largest amount of diffusion of the three gases and this was influenced by its higher density, consistent with Fick's Law (Turns 1996). The boiler gas and the nitrogen were very similar to one another in their behaviour, with less mixing observed compared to the carbon dioxide. As noted previously, due to the low density of these two inert gases, they were ineffective in removing as much methane from the coal face and coal floor as did the carbon dioxide. The increase in the size of the explosive zone was apparently due to the additional mixing with methane experienced in the coal face region and, later, in the drive due to the increased turbulence and diffusion. Specifically, the increased mixing and diffusion increased the volume fraction of the mixture such that there was a potentially explosive methane concentration when mixed with the atmospheric air at the surface, increasing the size of the explosive zone. The tendency of the explosive zone to move toward the end of the drive is due to the reduced velocity of gases leaving the end of the drive, owing to the additional turbulence experienced.

At a 60 degree angle of injection, each of the three inert gases experienced the largest mixing with methane, contributing to the largest explosive zones created. At this injection angle, none of the inert gases followed the contours of the machines, as was true with each of the previous cases. The increased injection angle produced a large degree of turbulence which contributed to the rapid mixing of the gases within the coal face region. Once again, the carbon dioxide produced the greatest mixing of methane in the coal face region. The nitrogen and the boiler gas produced similar mixing and diffusion contours due to their similar properties. The increased turbulence experienced in the coal face region due to the large injection angle assisted in producing the largest explosive zone for each of the three gases. This result was due to the greater distribution of methane throughout the inert gas leaving the highwall drive. Once again, the smallest explosive zone was produced by the carbon dioxide, for the same reasons as previously described. The boiler gas and the nitrogen, as before, produced similar methane/oxygen distributions. The explosive zone, again, moved toward the end of the drive due to the reduced velocity of gases leaving the end of the drive, owing to the additional turbulence experienced.

Overall, these results indicated that for each of the three inert gases trialled, an angle of injection of 0 degrees produced the least mixing of methane in the coal face region, contributing to the greatest reduction in the size of the resulting explosive zone. It was concluded that, as the angle of injection increased, mixing due to turbulence at the coal face region also increased, along with the size of the explosive zone. Additionally, as the angle of injection increased, there was a marked shift in the location of the explosive zone toward the end of the highwall drive.

6.3 Comparison of Inert Gas Penetration Depths

The penetration depth of the highwall drive was also determined by the two-dimensional CFD analysis to be an important factor in the size of the explosive zone produced. For each of the three inert gases trialled, as the penetration depth of the drive increased, diffusion of methane and gases within the drive also increased due to the additional length of the drive and the time required for the gases to reach the surface, resulting in an increase in the size of the explosive zone. However, this increase in the size of the explosive zone was minimal in comparison to that which occurred as a result of mixing of the gases as the angle of injection increased, as described above. Though minimal in this analysis, the increase in the size of the explosive zone due to increased penetration depth resembles that which occurs in actual mining situations.

As the penetration depth of the drive increased the corresponding time for the gases to reach the surface also increased providing a greater time for gases to diffuse on their way to the surface. The increased diffusion provided a greater volume of gas with dangerous quantities of methane when later mixed with the oxygen in the air on the surface leading to an enlargement of the explosive zone. Therefore, in this case, enlargement of the explosive zone can be attributed to an increase in penetration depth with a concomitant increase in diffusion of gases over the greater length of the drive.

The nitrogen and the boiler gas, as in the previous cases, behaved similarly. For these gases, the mixing and diffusion experienced in the coal face region was minimal with an increase in penetration depth. With greater depth, only a slight increase due to the additional diffusion was experienced in the region in comparison to that observed with the change in the inert gas injection angle. Diffusion for each of the inert gases increased with penetration depth. This diffusion influenced the explosive zone with a clear increase in size as the penetration depth increased. The nitrogen and boiler gas's change in velocity at the end of the highwall drive was not clearly seen in the velocity pathlines, due to the slight change in relation to the faster outside air at the highwall. The faster outside air and the additional volume with a dangerous methane concentration contributed to the explosive zone expanding into the lower corner of the drive as the penetration depth increased from 150 to 250m. A reverse in the profile of the explosive zone was seen at 300m, curving away from the base of the drive. This result was due to the outside air dragging the slow mixture of inert gas and methane leaving the drive, away from the end of the drive. The mixing and diffusion experienced with the boiler gas was slightly less than that with nitrogen, due to the influence of the carbon dioxide and oxygen which provided a slight variation in the individual properties of the mixture.

The carbon dioxide, as with the other inert gases trialled, experienced a minimal increase in the mixing and diffusion of methane in the coal face region with an increase in penetration depth. An increase in the diffusion along the length of the drive was indicated by the slight reduction in separation of the gases within the drive. The explosive zone reduced in size at the 0 degree angle of injection at penetration depths of 150, 250 and 300m, indicating that the decreased velocity and turbulence of the carbon dioxide and methane over the greater length contributed to this occurrence. The carbon dioxide acted as a single body of fluid, pushing the lighter methane out of the drive. An anomaly occurred at a penetration depth of 200m, however, requiring further investigation, as noted previously. Generally, an increase in penetration depth was found to improve the control of methane/oxygen concentrations within the highwall drive. A reduction in the flow rate of the gases in the drive due to pressure applied from the top of the drive led to reduced turbulence and a greater ability for the carbon dioxide to push the methane from the drive. This appears to indicate that a reduction in the injection velocity and flow rate has the potential to further improve the ventilation.

However, at an increased angle of injection, significant mixing of carbon dioxide and methane resulted in a similar shape, size and position of the explosive zone to those produced by the other inert gases.

Overall, results indicated that the shape and the size of the explosive zone are directly influenced by the penetration depth of the highwall drive. At penetration depths of 150, 250 and 300m, the nitrogen and the boiler gas led to an increase in the size of the explosive zone in comparison to the carbon dioxide, which led to a reduction in the size of the explosive zone with greater depth. An anomaly occurred at one penetration depth trialled, that of 200m, for the carbon dioxide, requiring further investigation. The possibility of a reduction in the flow rate of the inert gas has economic potential in regard to both the cost and the effectiveness of the highwall mining operation.

6.4 Conclusion

This investigation has identified that the penetration depth, type of inert gas and the angle at which it is injected are all important parameters in optimising the current highwall mining operation at the Moura Mine. The two-dimensional CFD Fluent highwall drive analysis indicated that carbon dioxide provided the greatest control of methane concentrations. The boiler gas appears to have been influenced by its small amount of carbon dioxide, and it was found to be the second most effective of the three inert gases trialled. The results of the nitrogen were very similar to those of the boiler gas, however, they were slightly less effective. Each of the inert gases was most effective at a 0 degree angle of injection and deteriorated as the injection angle increased. Finally, an increase in penetration depth led to an improvement in methane control for the carbon dioxide, suggesting that a reduction in the flow rate should be considered in future work. For both the nitrogen and the boiler gas, the control of methane decreased at greater penetration depths.

7. Conclusions

This investigation aimed to identify ways to reduce explosive methane/oxygen concentrations at the Moura Mine's highwall coal mining operation and, thus, to provide a greater understanding of the behaviour of gases within the highwall drive so that both safety and productivity could be maximised. The study used Fluent CFD software to elucidate various possible ventilation configuration systems with regard to the control of methane, involving variations in the type of inert gas used and the angle of injection of the inert gas at different penetration depths.

A review of the background and relevant literature illustrated that the highwall coal mining method is continuing to develop and to offer mine operators the ability to recover coal that would otherwise be unable to mined using more conventional methods. The highwall method is becoming more widely implemented at Australian coal mines, including at the Moura Mine, particularly over the past 10 years. However, as this method becomes more widely utilised, the risks involved have also become increasingly problematic. Primarily, potentially explosive methane gas released from coal during mining has been determined to pose a substantial risk, including the loss of equipment and fatalities of mine workers.

The Moura Mine has shown high methane concentrations in some regions of the mining operation which have limited overall highwall coal mining production. Recent research has illustrated that the control of methane concentrations is an important factor in improving the safety and productivity of highwall mining operations. A greater understanding of methane migration within underground mining operations appears to be the key to improving current methane control systems. Ventilation using inert gases provides a means to control methane concentrations and, thus, optimise this system of mining. In highwall mining applications, as well, inert gases have been trialled in ventilation systems and, in some cases, have been successfully implemented. In other cases, however, the use of inert gases to improve methane control has proven to be less than optimal with substantial explosive zones still evident.

Computational fluid dynamics (CFD) provides an inexpensive and effective means to generate and test various ventilation configuration models in an attempt optimise the methods utilised within underground mines. This type of modelling can be directly applied to highwall mining, as well, including at the Moura Mine. This mine has specifically identified that a greater understanding of the current highwall methane control measure could potentially improve safety and production with the ability to reach greater penetration depths, particularly on the 'gassy' northern side of the mine.

Numerical analysis is a powerful tool that uses fundamental equations for fluid flow to predict the behaviour of fluids. As noted, this investigation used Fluent CFD software to create and analyse a two-dimensional model of the Moura Mine highwall operation. In producing this model, certain assumptions were required and parameters were defined based on information that was provided to the author from a variety of different sources.

Results of these analyses provide valuable insight into understanding the behaviour of methane under varying conditions at the highwall coal mining operation at the Moura Mine. The three major parameters investigated included the specific type of inert gas used, the angle at which the gas is injected and the penetration depth of the drive. Results illustrated the contribution of each of these parameters to the individual behavioural properties of each of the three inert gases trialled and each was found to have a significant influence. Specifically, the CFD analysis indicated that, of all the inert gases trialled, carbon dioxide provided the greatest control of methane concentrations. As the boiler gas appears to have been influenced by its small amount of carbon dioxide, it was found to be the second most effective of the three inert gases trialled. The findings for the nitrogen were very similar to those of the boiler gas, however, this gas was determined to be slightly less effective. Each of the inert gases trialled was most effective in regard to the control of methane at a 0 degree angle of injection, parallel to the surface of the continuous miner, and deteriorated as the injection angle increased. Finally, unexpectedly, an increase in penetration depth appears to have led to an improvement in methane control for the carbon dioxide. This may have been due to the decrease in velocity resulting from the increased penetration depth, with a secondary reduction in flow rate. For both the nitrogen and the boiler gas, the control of methane decreased at greater penetration depths.

The findings of this study should provide an increased understanding of methane migration and, thus, a more effective means to control methane at the Moura Mine highwall mining operation, which should subsequently lead to improved productivity and safety. As described below, however, research opportunities still exist to further optimise and improve the safety and production of highwall mining operations.

7.1 Implications of the Findings

This study was the first of its kind to be undertaken with regard to the control of methane concentrations at the Moura Mine highwall coal mining operation. Although the results of this initial investigation do not strongly correlate with data collected directly from the mine with regard to the position of the explosive zone, they provide a great insight into the behaviour of inert gases and methane within the highwall drive. The findings offer an indication of the effectiveness of different inert gases, including carbon dioxide, nitrogen and boiler gas, with regard to the penetration depth and injection angle of the gas. Specifically, as noted, the findings indicate that carbon dioxide injected at a 0 degree angle into the highwall drive results in the optimum ventilation configuration with regard to the control of methane. This information should be extremely useful in the development of an effective ventilation system to control methane concentrations and, thus, to improve safety and productivity at the Moura Mine. The model could prove to be useful in an attempt to improve methane control in other highwall coal mining operations and in other similar mining operations, as well.

7.2 Limitations of the Study

The simplification of the analyses utilised in this investigation has illuminated important characteristics, in regard to geometry and fluid flow, that were not previously considered. Specifically, for the two-dimensional CFD analysis used, it was assumed that the width of the drive was infinite in comparison to the height, and this, in fact, was not true. This inappropriate assumption affected the behaviour of the flow within the drive due to the lack of friction that, in an actual situation, would have been applied by the ribs or walls. Additionally, methane released from the walls, roof and conveyer, as a secondary methane source for the drive, was not able to be effectively introduced to the model. The two-dimensional CFD analysis also failed to consider that the inert gases are injected from a 150mm pipe and not from a vent across the width of the drive, as assumed. The assumption of a steady state condition due to a slow progression of mining failed to provide for an explosive zone consistent with real data collected from the mining operation, where an explosive zone near the inert gas injection point was identified. Parameters such as the temperatures of the gases, the surface roughness and material of the walls and machine and precise geometry were all ignored in this study, and these may each have an important influence that needs to be determined. Finally, the flow rates of methane into the drive were based on reports of expert observation and not on scientific evidence, due to the wide variety of geological conditions experienced. Therefore, they cannot be considered to be directly related to the data in regard to the position of the resulting explosive zone.

7.3 Directions for Future Research

Future investigation into improving the ventilation of highwall coal mining in order to control methane concentrations should consider applying strategies that will reduce or eliminate the limitations of this investigation, as outlined above. This is important both in future research at the Moura Mine, specifically, and in research into other mining applications. Primarily, future research should aim to avoid the inappropriate assumptions made during this investigation as well as the over-simplified representation offered by the two-dimensional analysis. A three-dimensional unsteady CFD model with a moving mesh would provide greater insight and foresight into improving highwall ventilation systems in the future. Additionally, as noted earlier, other parameters such as the temperatures of the gases trialled, the surface roughness and material of the walls and machine as well as precise geometry are all important to explore in future research in regard to the impact they may have on the fluid flow within the drive.

Finally, as noted above, an increase in penetration depth unexpectedly led to an improvement in methane control for the carbon dioxide. It is possible that the decrease in velocity of a gas that occurs with an increase in penetration depth results in a reduction in the flow rate of that gas. This surprising finding suggests that a reduction in the flow rate of carbon dioxide should be considered in future work.

The findings of this investigation illustrate the significant potential for this type of research to aid in a greater understanding of the migration of gases within highwall coal mining operations. Further, these methods could potentially be applied within any mining applications that require an in-depth understanding of the behaviour of fluids in confined or poorly ventilated spaces. In the future, simple, pre-defined models that can be easily adapted for various applications could be created for use by operators while mining operations are actually in progress. Overall, there are exciting possibilities for this type of research to continue to be utilised in working toward the optimisation of mining safety and productivity in Australia and worldwide.

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Appendix A: Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

<u>ENG4111/2 *Research Project*</u>

PROJECT SPECIFICATION

FOR: **Anthony VELLA**

TOPIC: Ventilation of Highwall Mining to Control Methane Concentration at the Moura Mine

SUPERVISOR: Dr Ruth Mossad

ENROLLMENT: ENG4111 – S1, 2006
ENG4112 – S2, 2006

PROJECT AIM: This project seeks to identify, investigate and improve current methane ventilation practices within highwall mining at the Moura Mine in Central Queensland using computational fluid dynamic (CFD) software.

PROGRAMME: **<u>Issue A, March 2006</u>**

1. Research background information about coal mining methods in particular highwall mining in both Australia and at the Moura Mine and the importance methane ventilation systems during mining.
2. Conduct a literature review on research undertaken on how methane ventilation impacts on highwall mining methods and practices at the Moura Mine.
3. Select an appropriate technique to model highwall mining ventilation systems at the Moura Mine.
4. Develop a thorough understanding of the CFD software package in order to be able to analyse a number of different highwall methane ventilation scenarios and determine which scenario gives the optimum result.
5. Apply CFD techniques to a number of 2-D highwall methane ventilation configurations.
6. Process and interpret the results. Report the benefits and limitations of various ventilation configurations and recommend a process that will achieve the objective.
7. Complete dissertation.

As time permits:

8. Apply CFD techniques to a number of 3-D highwall methane ventilation configurations.

AGREED: ___________________ (Student) ___________________ (Supervisor)

15 / March / 2006 15 / March / 2006

Appendix B: Moura Mine

Figure B-1 Map of Bowen Basin Queensland (*Australia's Identified Mineral Resources* 2005)

Appendix C: Moura Mine Methane Gas Charts

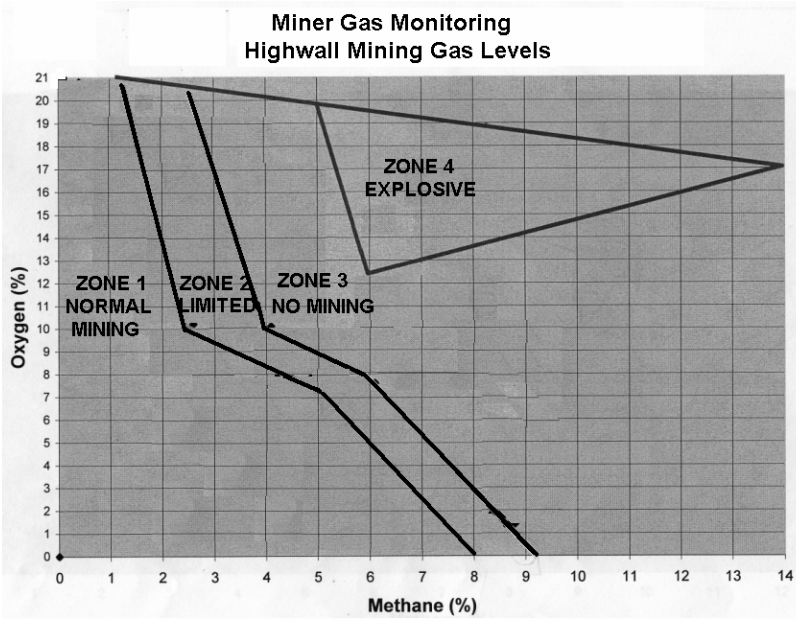


Figure C- 1 Moura Mine Highwall Coward Diagram for Methane (Kunst, G 2006, pers. comm., 16 July)

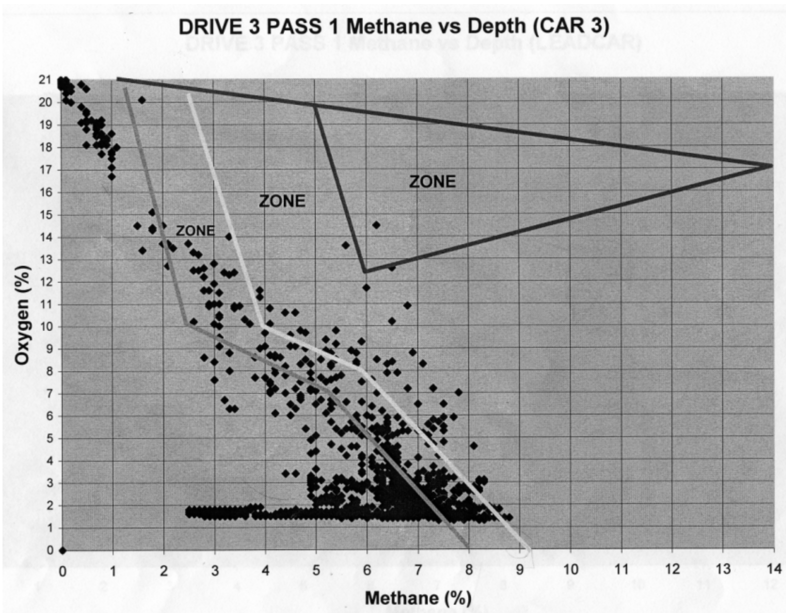


Figure C-2 Moura Mine Highwall Coward Diagram Methane/Oxygen Concentration Results (Kunst, G 2006, pers. comm., 16 July)

Appendix D: CFD Results for Boiler Gas

D.1. Gas Injected at 0 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the boiler gas is injected at 0 degrees.

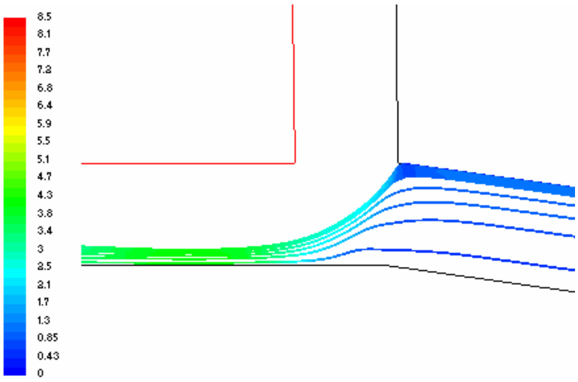


Figure D-1 Velocity Path Lines at 150m

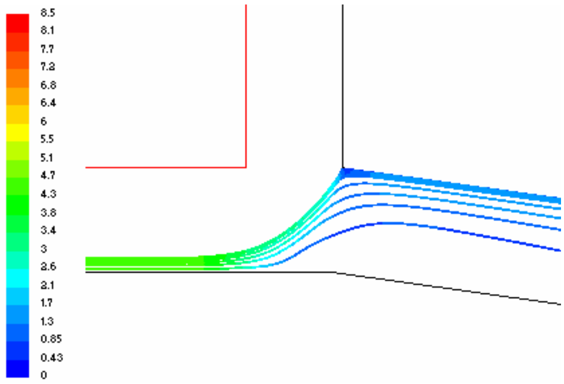


Figure D-2 Velocity Path Lines at 200m

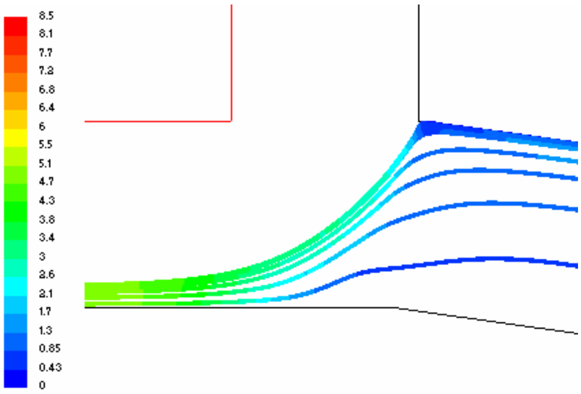


Figure D-3 Velocity Path Lines at 250m

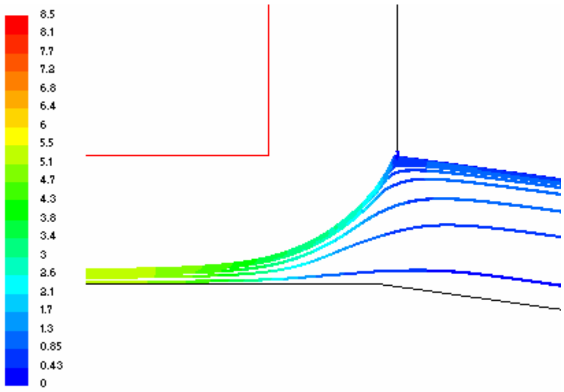


Figure D-4 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the boiler gas is injected at 0 degrees.

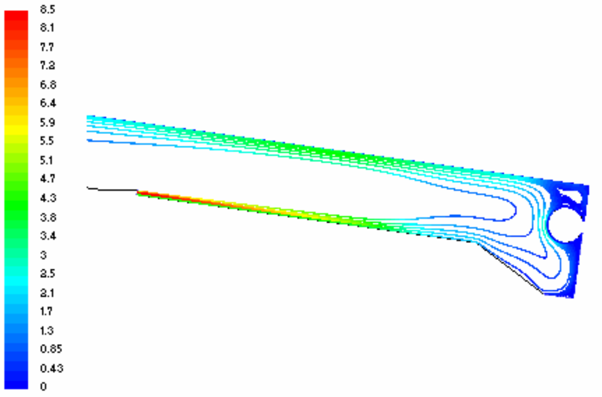


Figure D-5 Velocity Path Lines at 150m

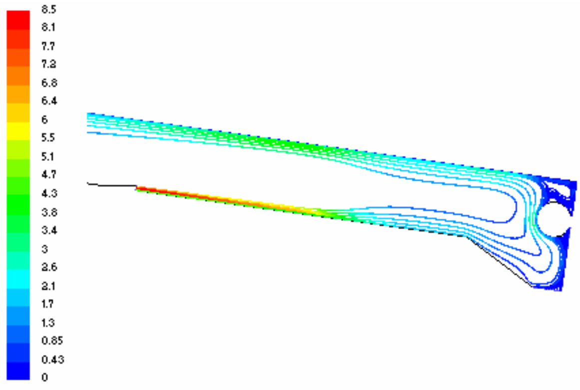


Figure D-6 Velocity Path Lines at 200m

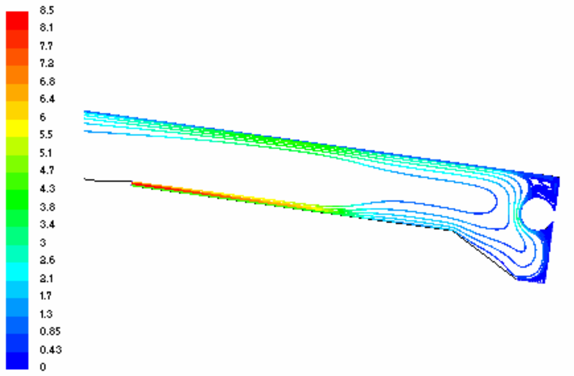


Figure D-7 Velocity Path Lines at 250m

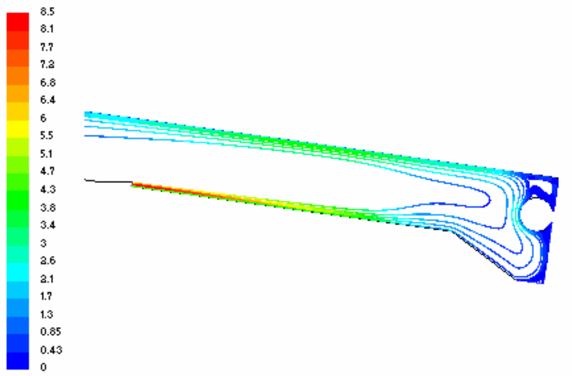
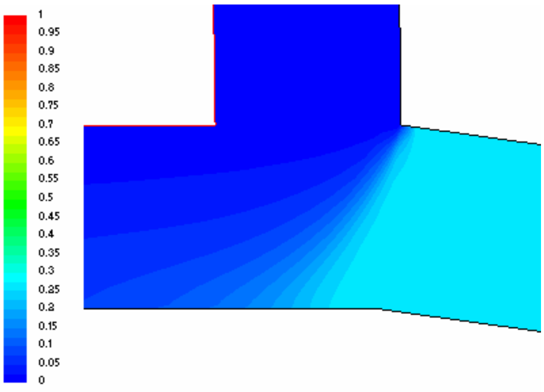
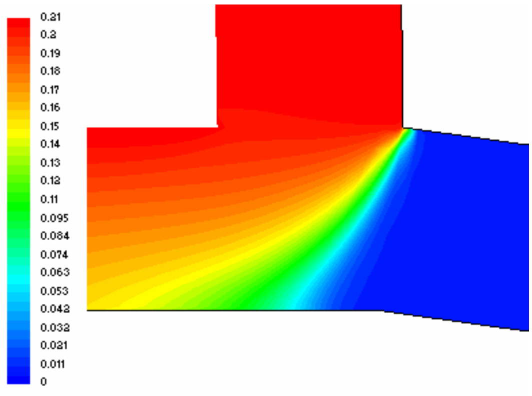
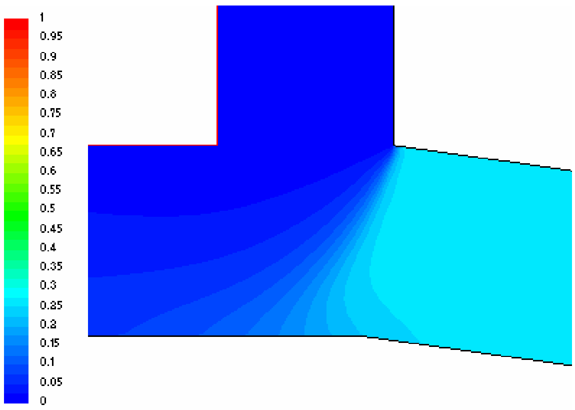


Figure D-8 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 0 degrees.







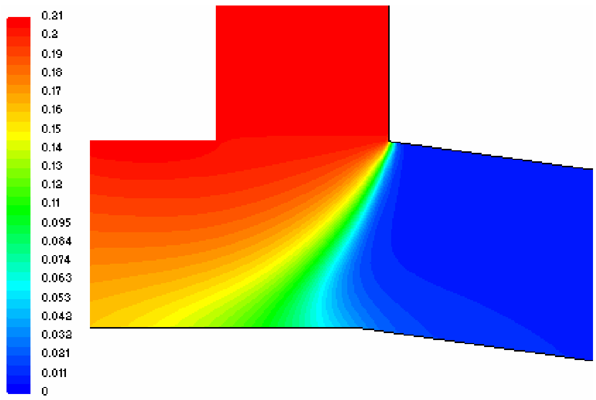


Figure D-9 Methane Concentration at 150m

Figure D-10 Oxygen Concentration at 150m

Figure D-11 Methane Concentration at 200m

Figure D-12 Oxygen Concentration at 200m

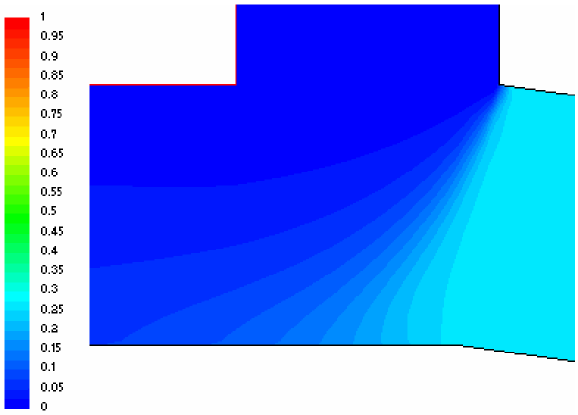


Figure D-13 Methane Concentration at 250m

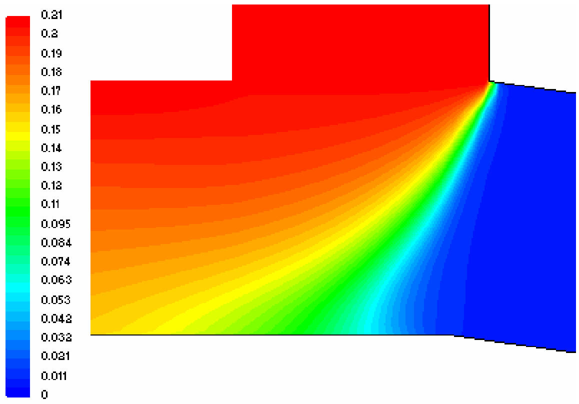


Figure D-14 Oxygen Concentration at 250m

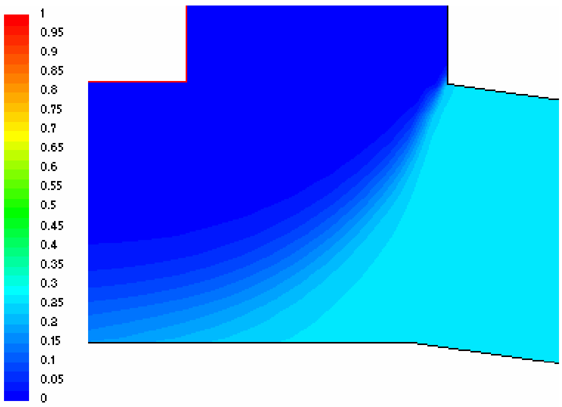


Figure D-15 Methane Concentration at 300m

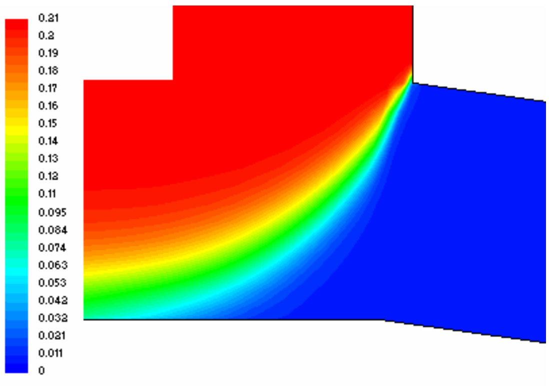


Figure D-16 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the boiler gas is injected at 0 degrees. Note that 0% oxygen concentration was indicated in this region.

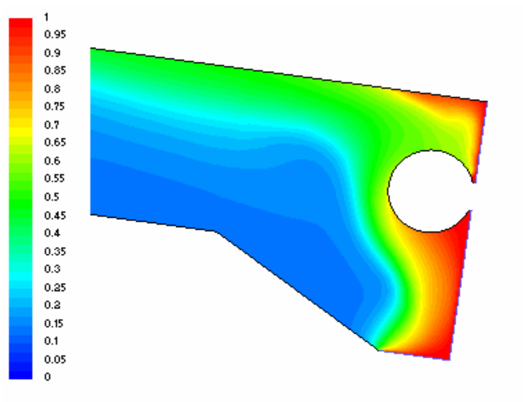


Figure D-17 Methane Mass Fraction at 150m

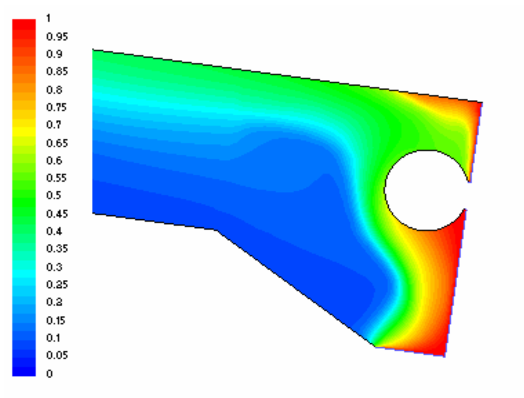


Figure D-18 Methane Mass Fraction at 200m

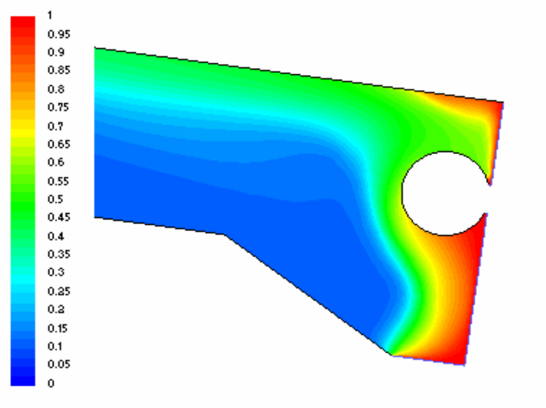


Figure D-19 Methane Mass Fraction at 250m

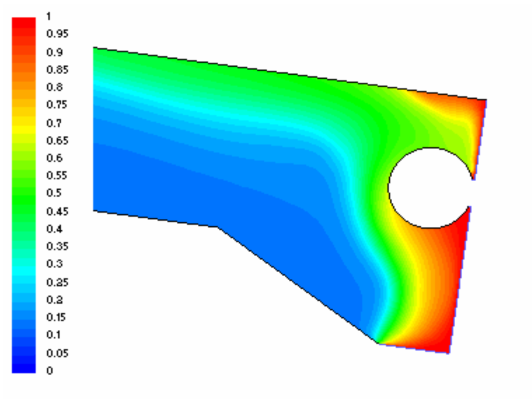


Figure D-20 Methane Mass Fraction at 300m

D.2. Gas Injected at 30 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the boiler gas is injected at 30 degrees.

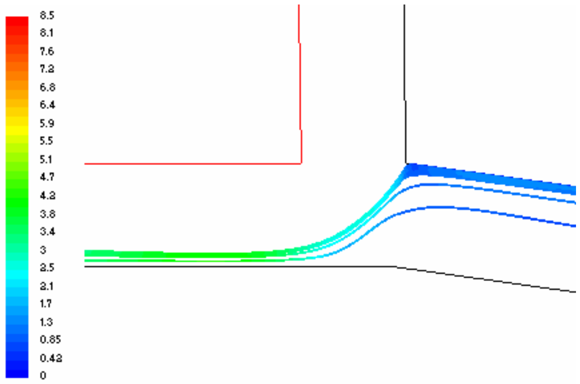


Figure D-21 Velocity Path Lines at 150m

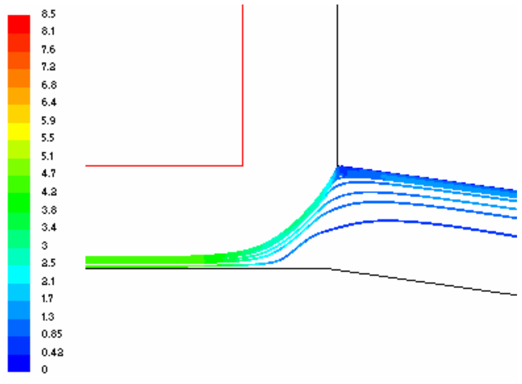


Figure D-22 Velocity Path Lines at 200m

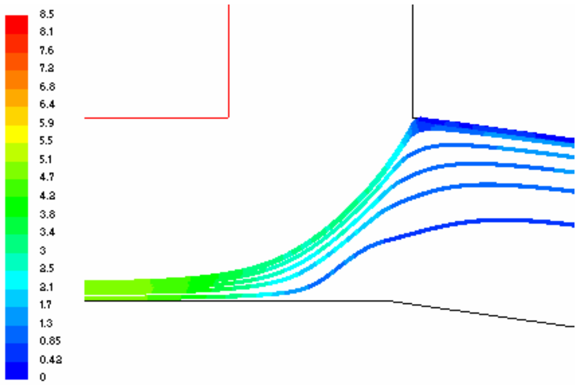


Figure D-23 Velocity Path Lines at 250m

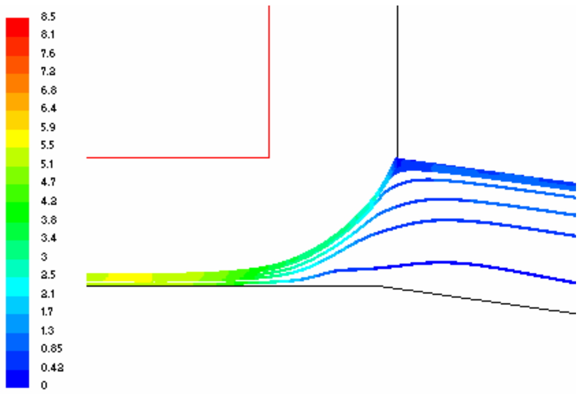


Figure D-24 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the boiler gas is injected at 30 degrees.

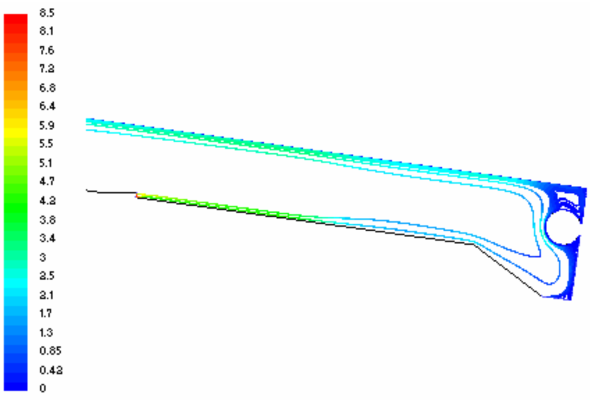


Figure D-25 Velocity Path Lines at 150m

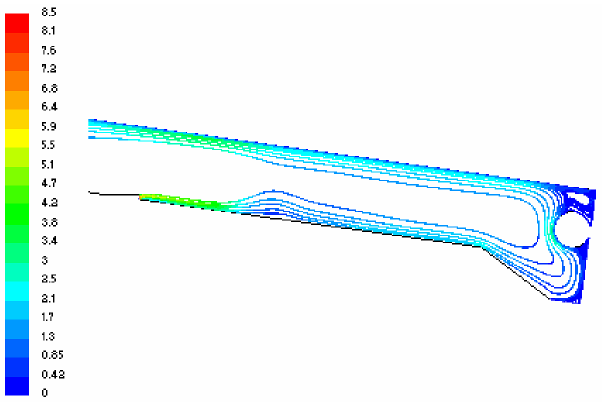


Figure D-26 Velocity Path Lines at 200m

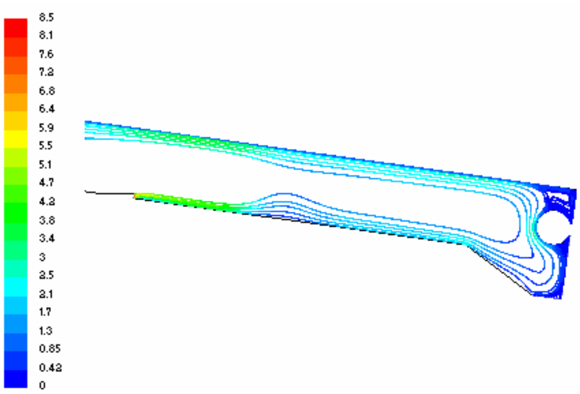


Figure D-27 Velocity Path Lines at 250m

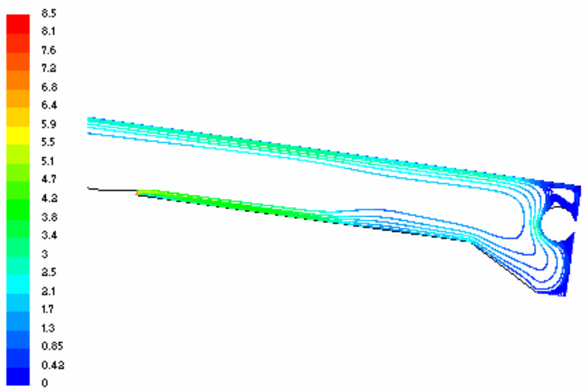


Figure D-28 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 30 degrees.

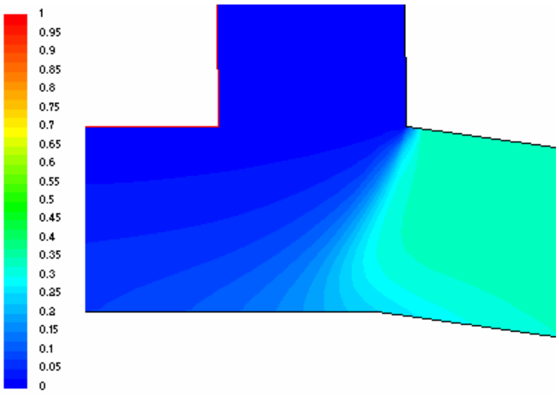


Figure D-29 Methane Concentration at 150m

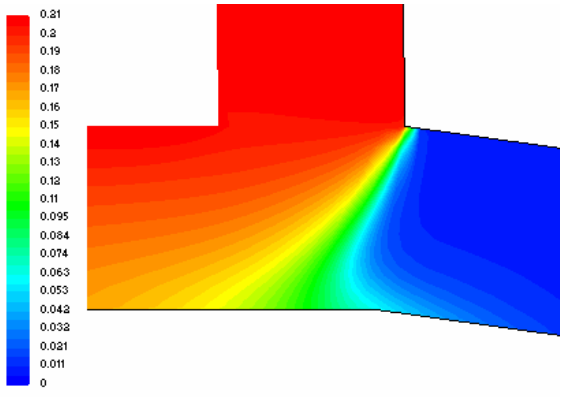


Figure D-30 Oxygen Concentration at 150m

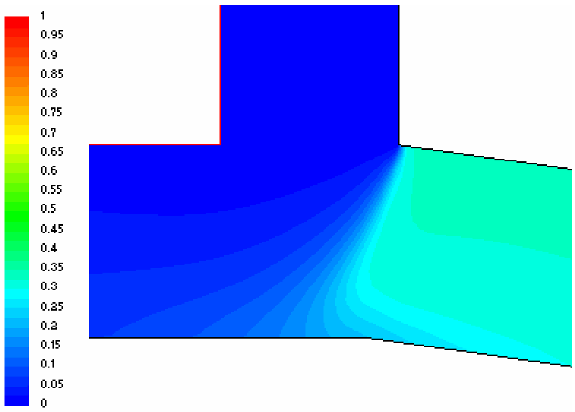


Figure D-31 Methane Concentration at 200m

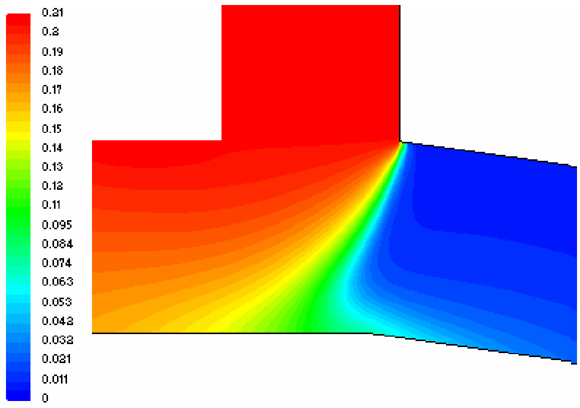


Figure D-32 Oxygen Concentration at 200m

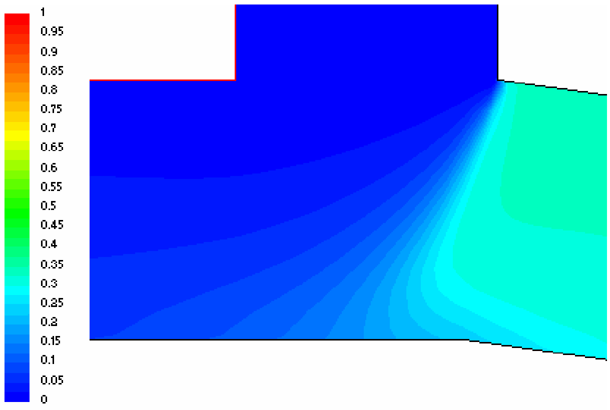


Figure D-33 Methane Concentration at 250m

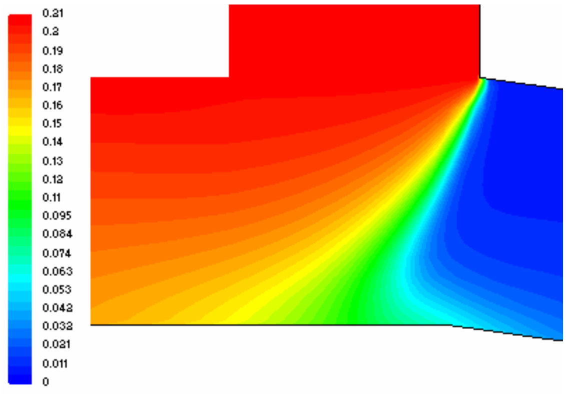


Figure D-34 Oxygen Concentration at 250m

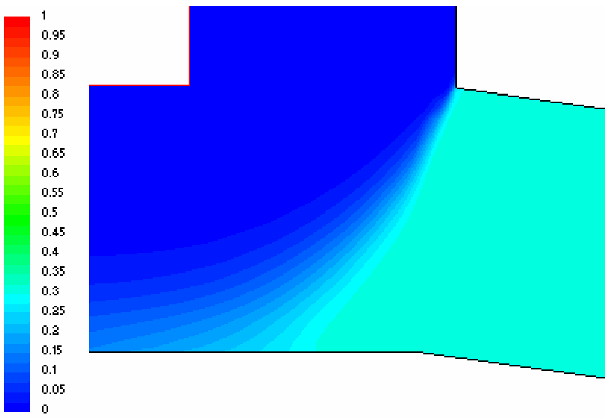


Figure D-35 Methane Concentration at 300m

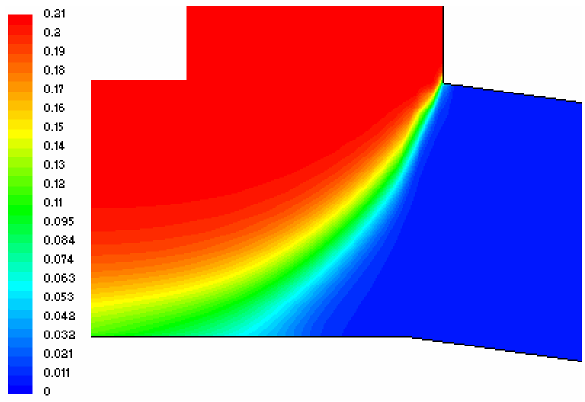


Figure D-36 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the boiler gas is injected at 30 degrees. Note that 0% oxygen concentration was indicated in this region.

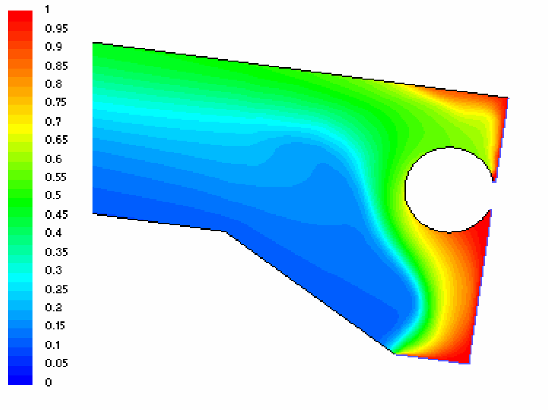


Figure D-37 Methane Mass Fraction at 150m

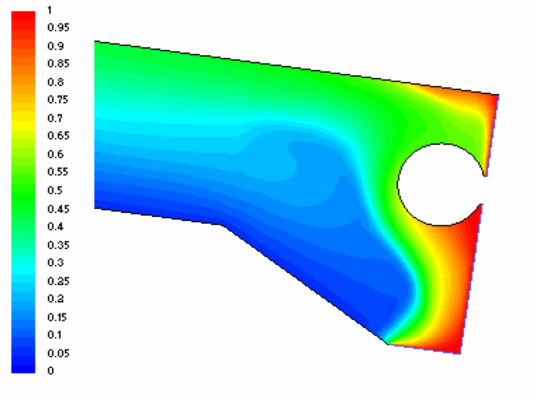


Figure D-38 Methane Mass Fraction at 200m

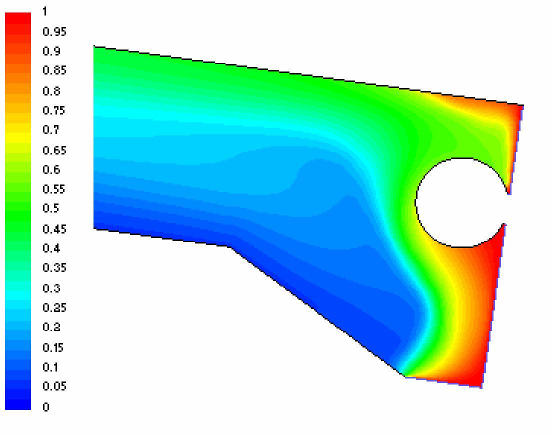


Figure D-39 Methane Mass Fraction at 250m

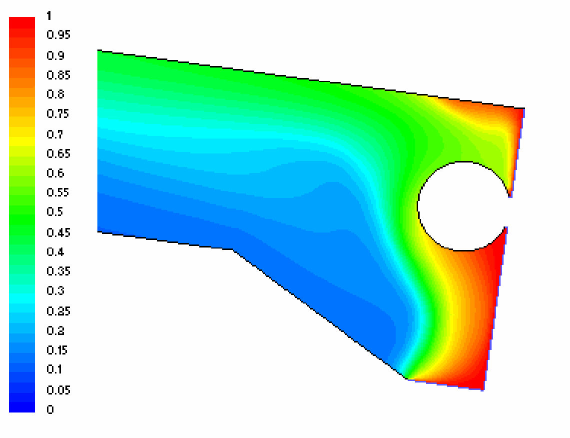


Figure D-40 Methane Mass Fraction at 300m

D.3. Gas Injected at 60 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the boiler gas is injected at 60 degrees.

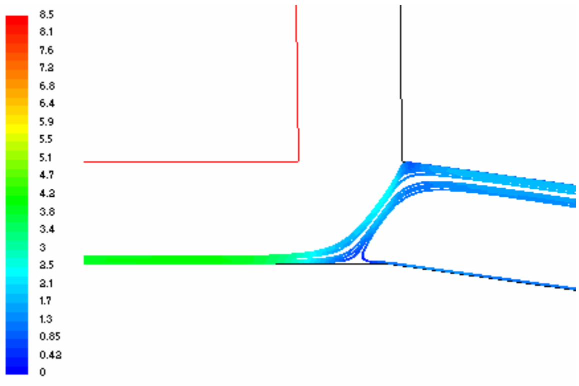


Figure D-41 Velocity Path Lines at 150m

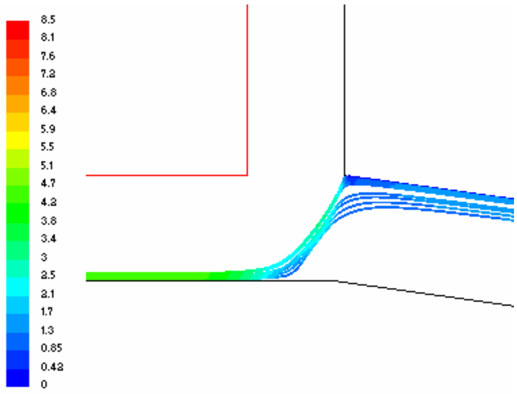


Figure D-42 Velocity Path Lines at 200m

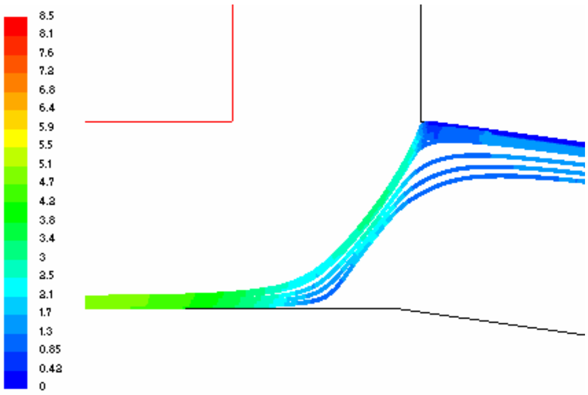


Figure D-43 Velocity Path Lines at 250m

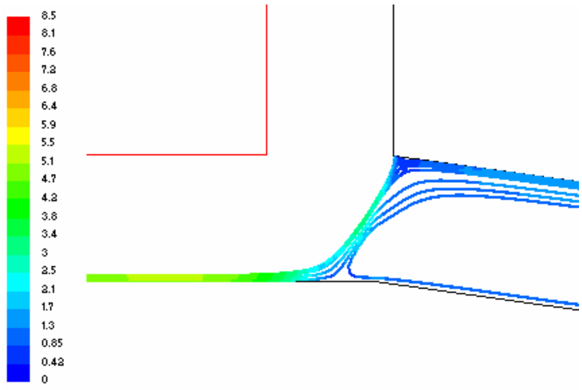


Figure D-44 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the boiler gas is injected at 60 degrees.

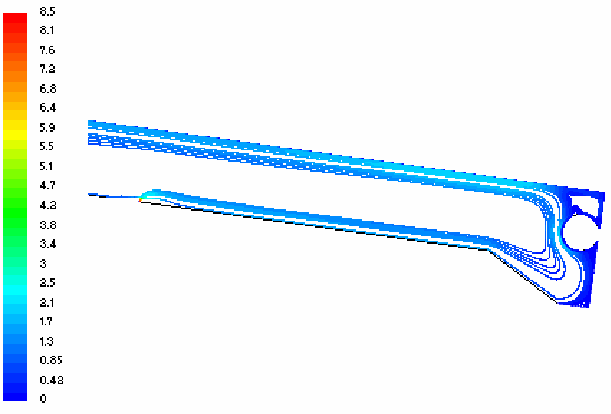


Figure D-45 Velocity Path Lines at 150m

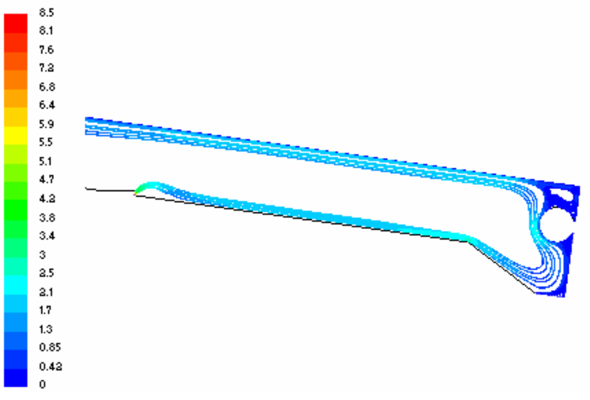


Figure D-46 Velocity Path Lines at 200m

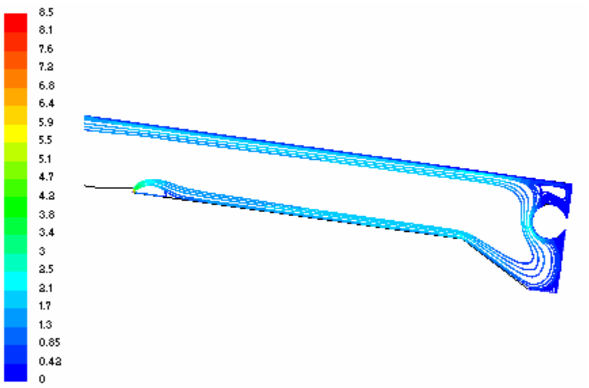


Figure D-47 Velocity Path Lines at 250m

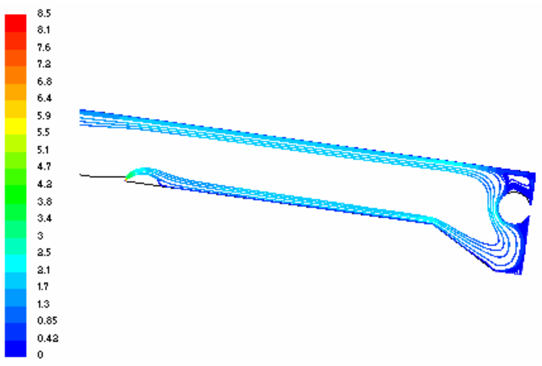


Figure D-48 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 60 degrees.

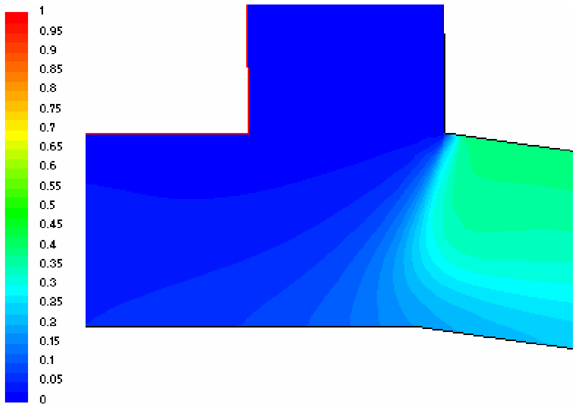


Figure D-49 Methane Concentration at 150m

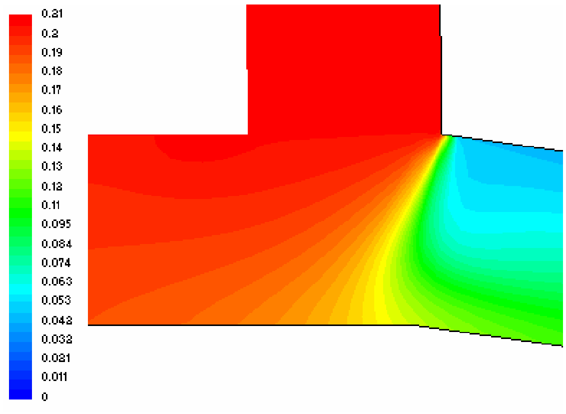


Figure D-50 Oxygen Concentration at 150m

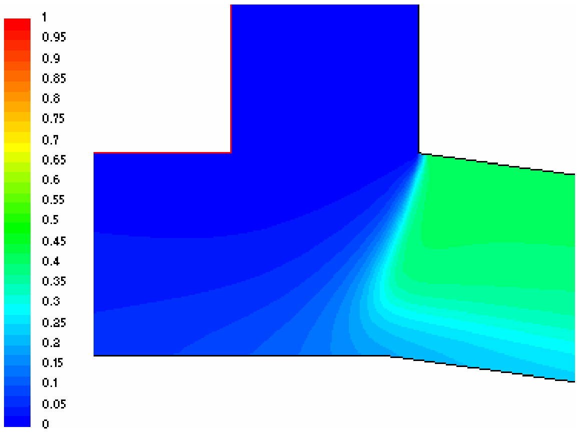


Figure D-51 Methane Concentration at 200m

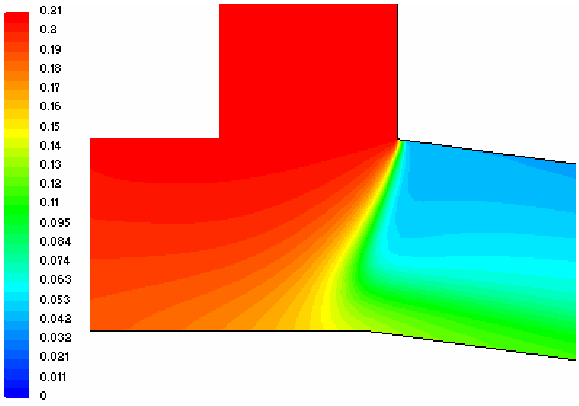


Figure D-52 Oxygen Concentration at 200m

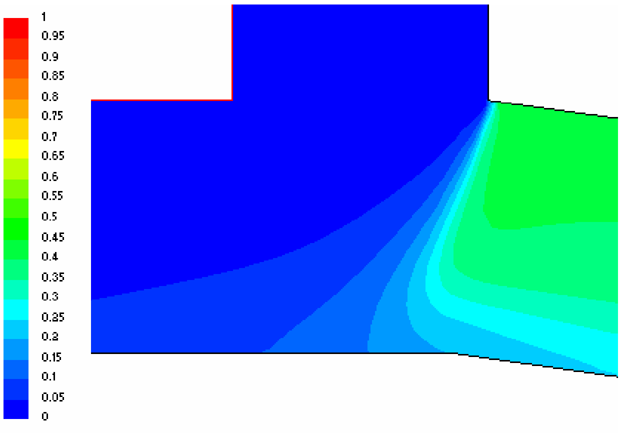


Figure D-53 Methane Concentration at 250m

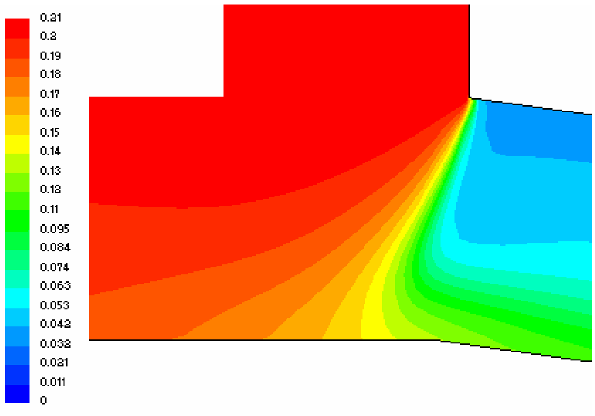


Figure D-54 Oxygen Concentration at 250m

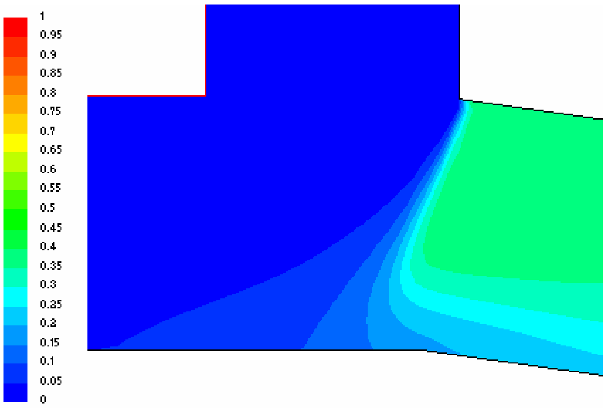


Figure D-55 Methane Concentration at 300m

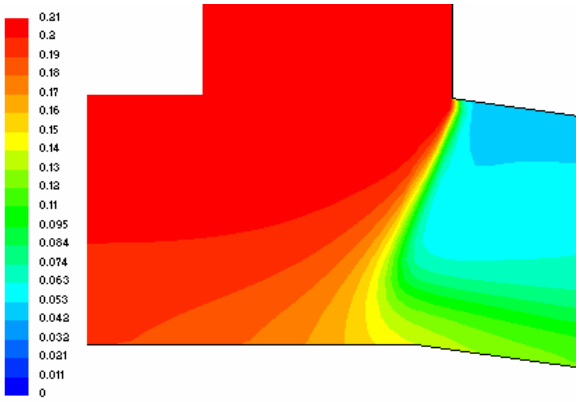


Figure D-56 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the boiler gas is injected at 60 degrees. Note that 0% oxygen concentration was indicated in this region.

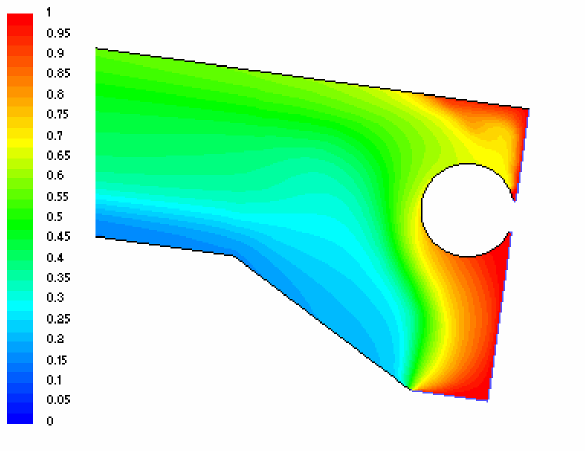


Figure D-57 Methane Mass Fraction at 150m

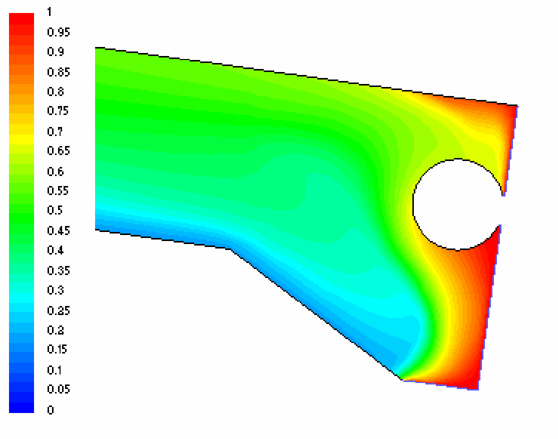


Figure D-58 Methane Mass Fraction at 200m

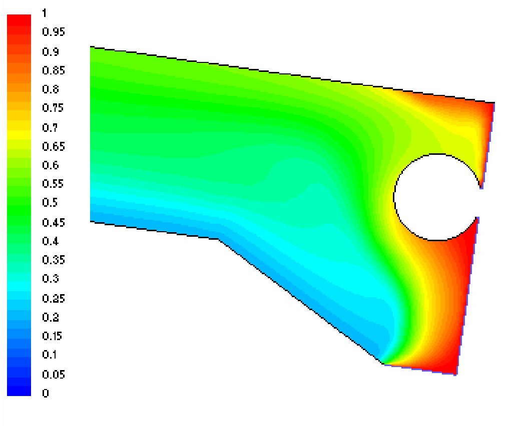


Figure D-59 Methane Mass Fraction at 250m

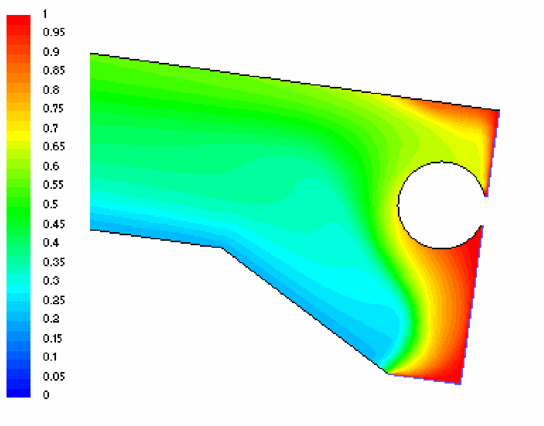


Figure D-60 Methane Mass Fraction at 300m

Appendix E: CFD Results for Carbon Dioxide

E.1. Gas Injected at 0 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the carbon dioxide is injected at 0 degrees.

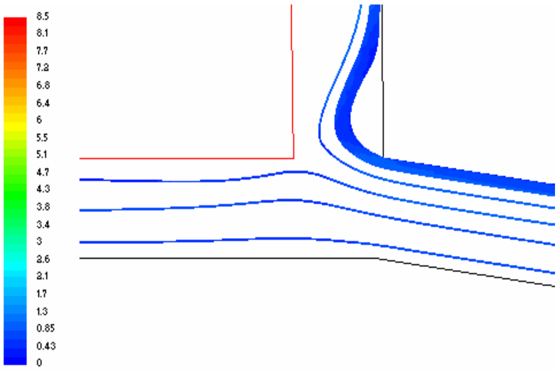


Figure E-1 Velocity Path Lines at 150m

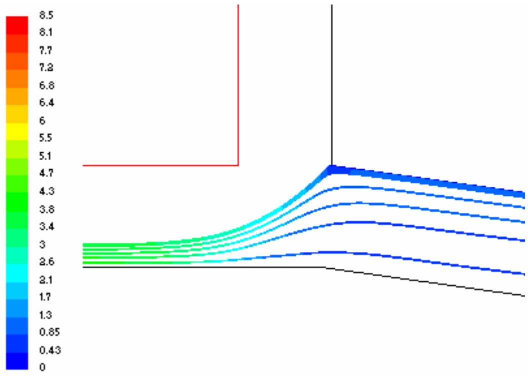


Figure E-2 Velocity Path Lines at 200m

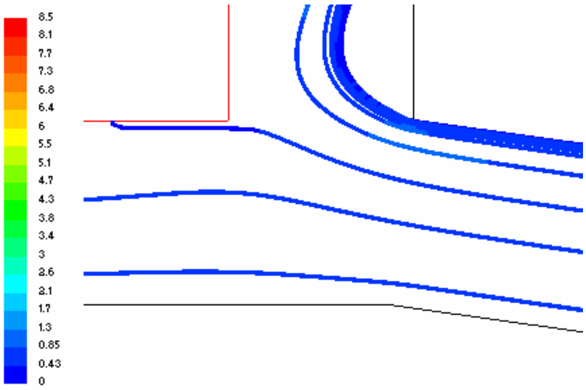


Figure E-3 Velocity Path Lines at 250m

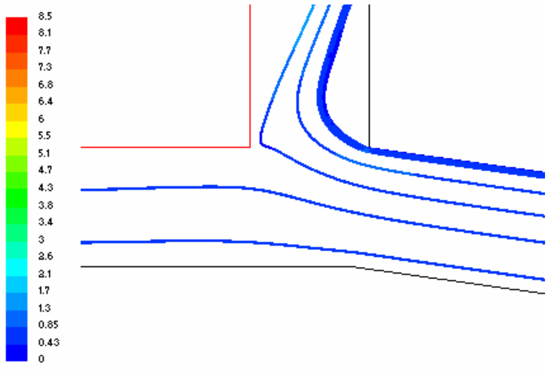


Figure E-4 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the carbon dioxide is injected at 0 degrees.

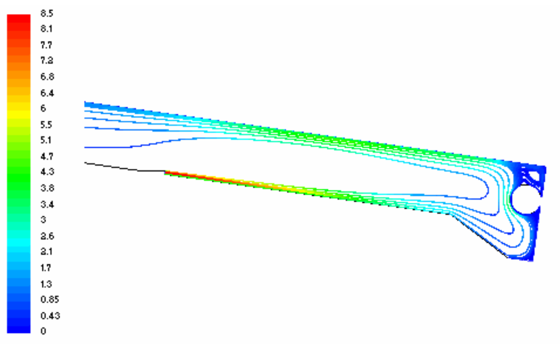


Figure E-5 Velocity Path Lines at 150m

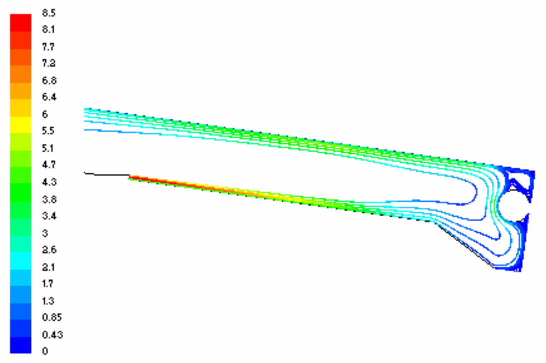


Figure E-6 Velocity Path Lines at 200m

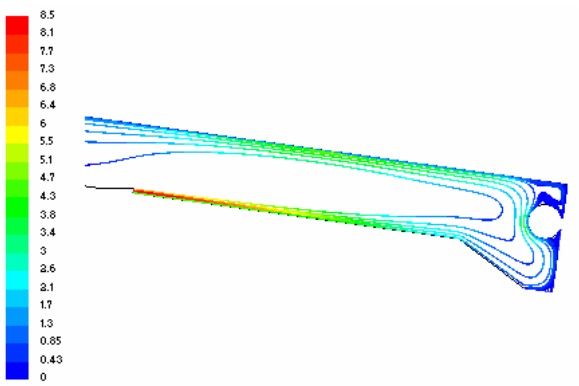


Figure E-7 Velocity Path Lines at 250m

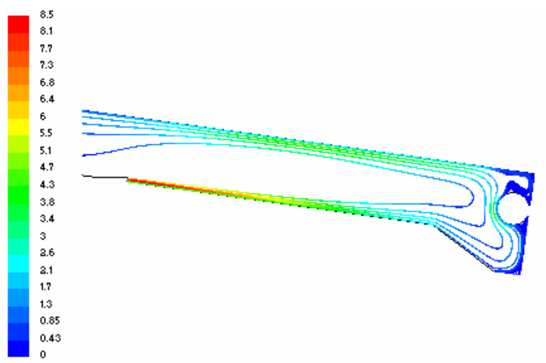
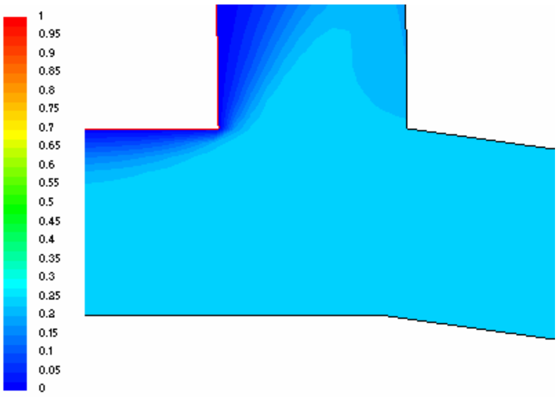
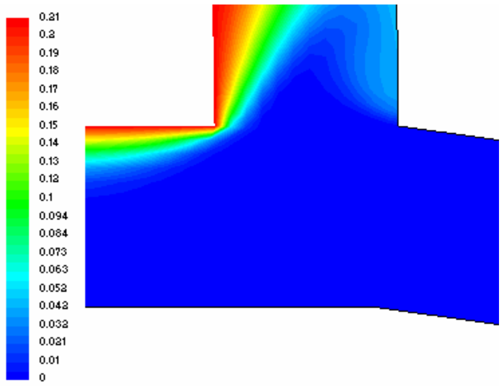
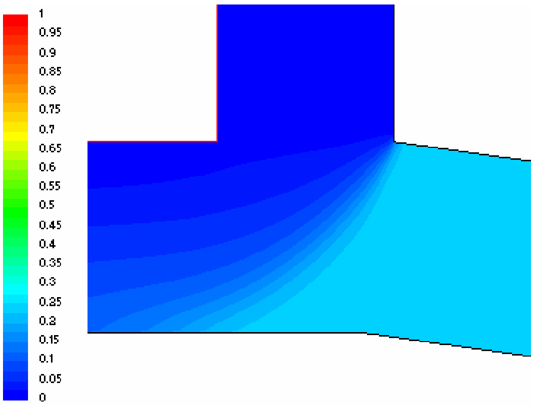


Figure E-8 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 0 degrees.







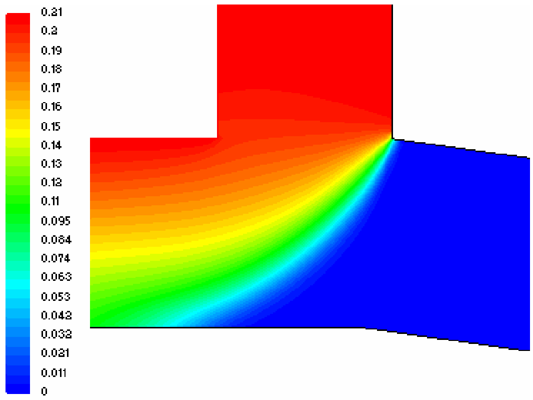


Figure E-9 Methane Concentration at 150m

Figure E-10 Oxygen Concentration at 150m

Figure E-11 Methane Concentration at 200m

Figure E-12 Oxygen Concentration at 200m

Figure E-13 Methane Concentration at 250m

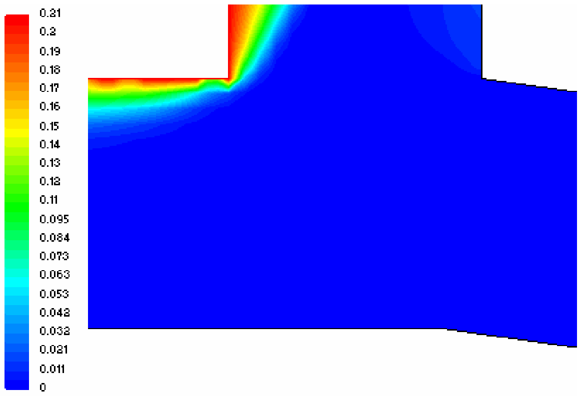


Figure E-14 Oxygen Concentration at 250m

Figure E-15 Methane Concentration at 300m

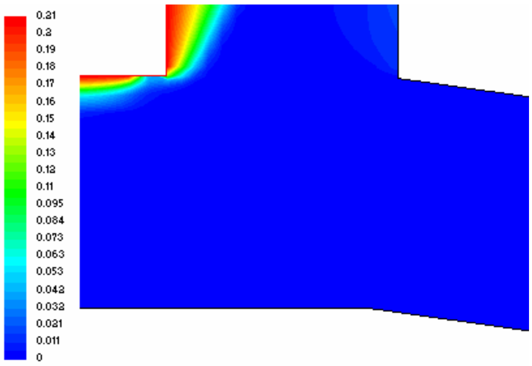


Figure E-16 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the carbon dioxide is injected at 0 degrees. Note that 0% oxygen concentration was indicated in this region.

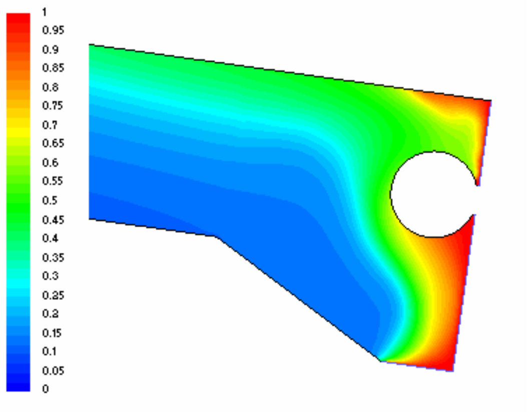


Figure E-17 Methane Mass Fraction at 150m

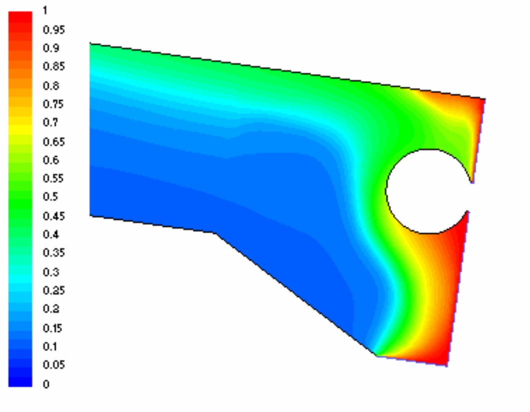


Figure E-18 Methane Mass Fraction at 200m

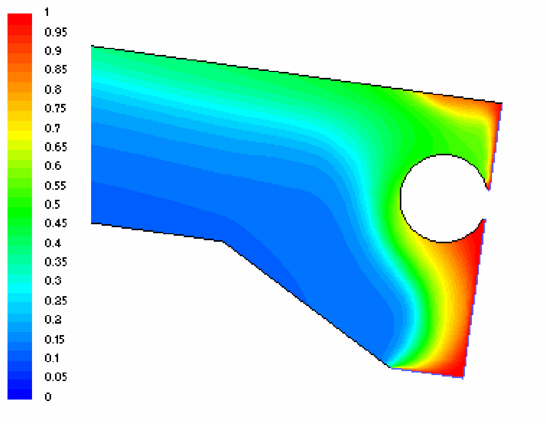


Figure E-19 Methane Mass Fraction at 250m

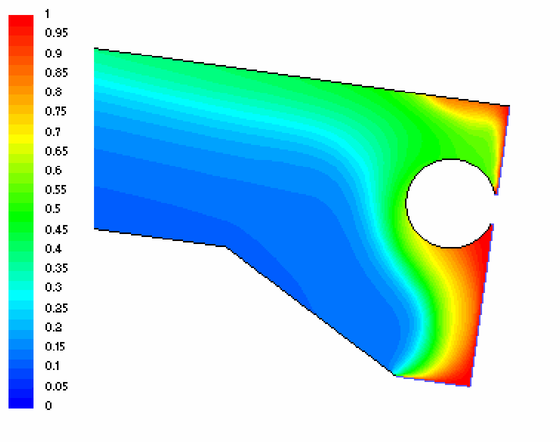


Figure E-20 Methane Mass Fraction at 300m

E.2. Gas Injected at 30 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the carbon dioxide is injected at 30 degrees.

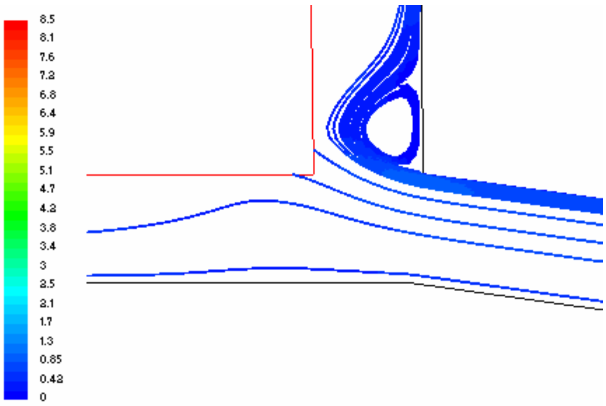


Figure E-21 Velocity Path Lines at 150m

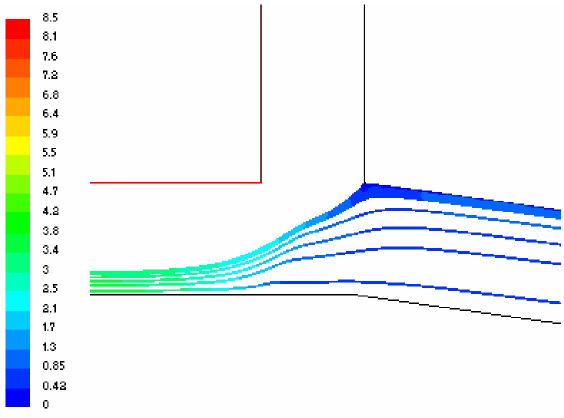


Figure E-22 Velocity Path Lines at 200m

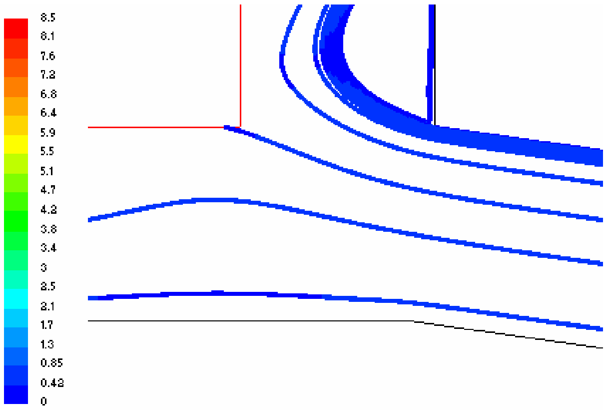


Figure E-23 Velocity Path Lines at 250m

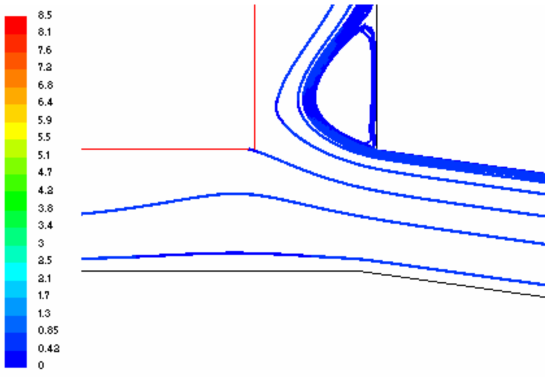


Figure E-24 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the carbon dioxide is injected at 30 degrees.

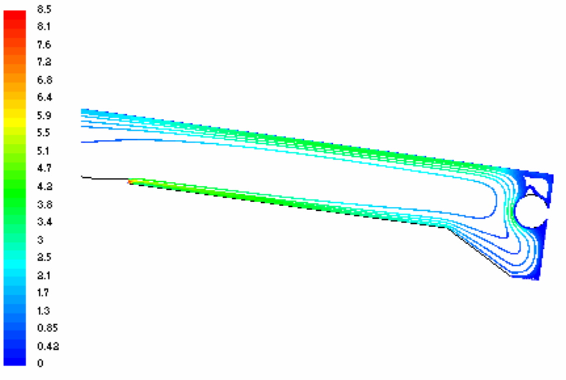


Figure E-25 Velocity Path Lines at 150m

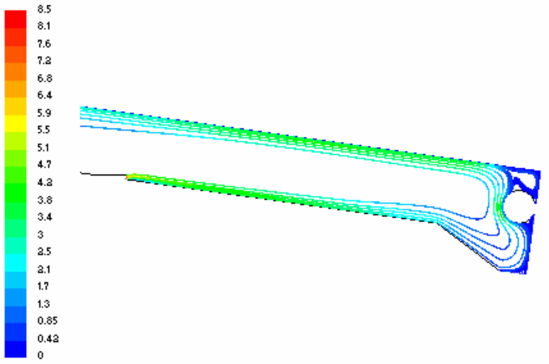


Figure E-26 Velocity Path Lines at 200m

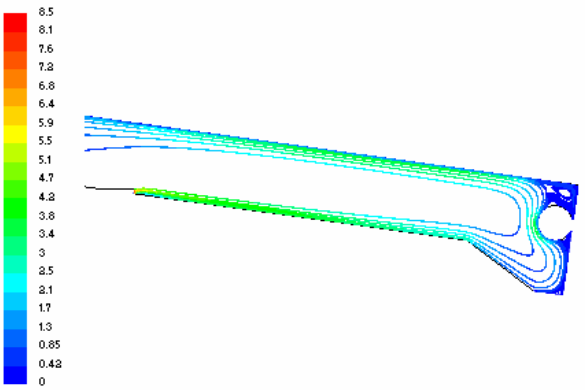


Figure E-27 Velocity Path Lines at 250m

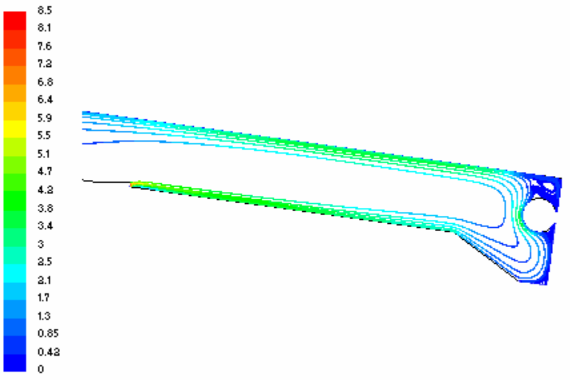


Figure E-28 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 30 degrees.

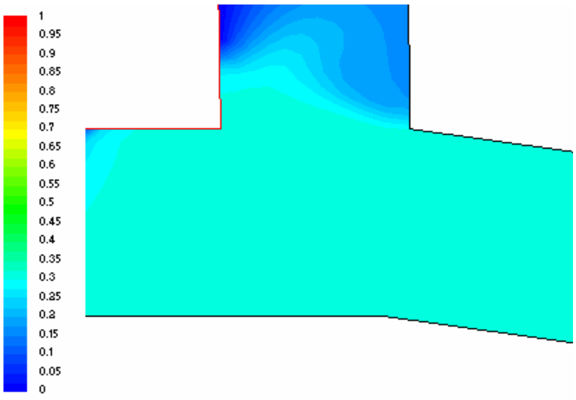


Figure E-29 Methane Concentration at 150m

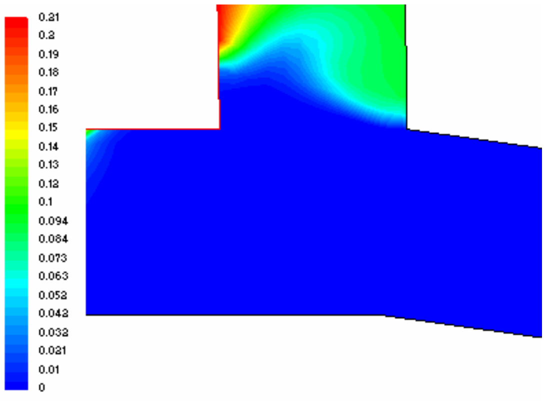


Figure E-30 Oxygen Concentration at 150m

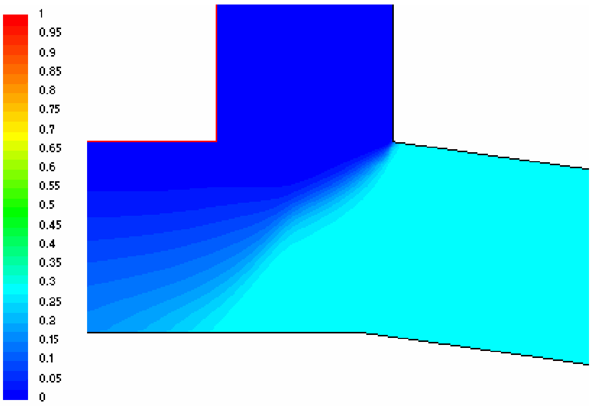


Figure E-31 Methane Concentration at 200m

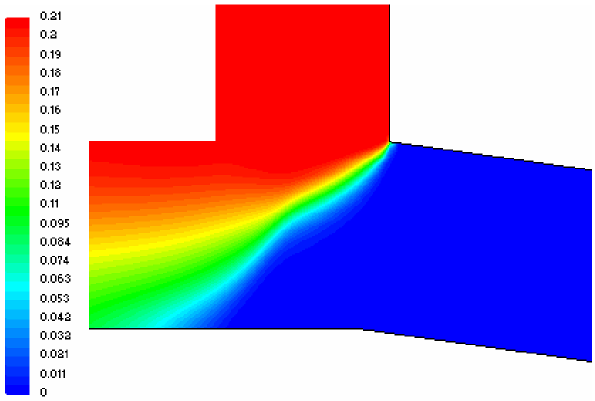


Figure E-32 Oxygen Concentration at 200m

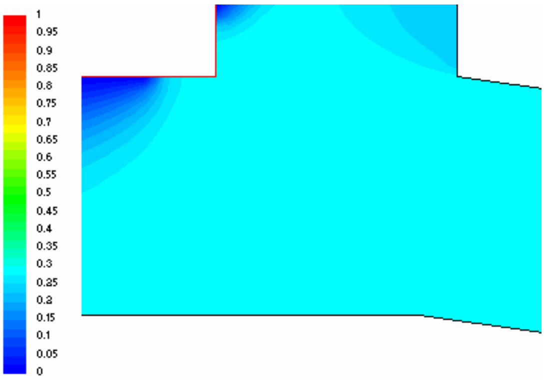


Figure E-33 Methane Concentration at 250m

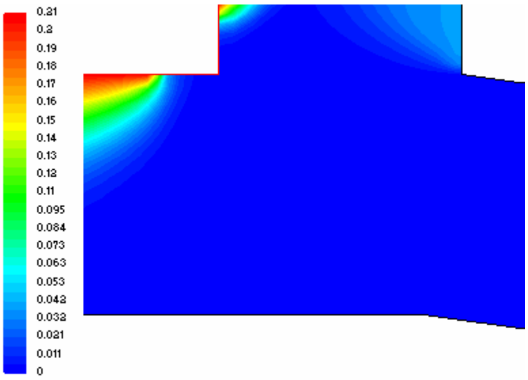


Figure E-34 Oxygen Concentration at 250m

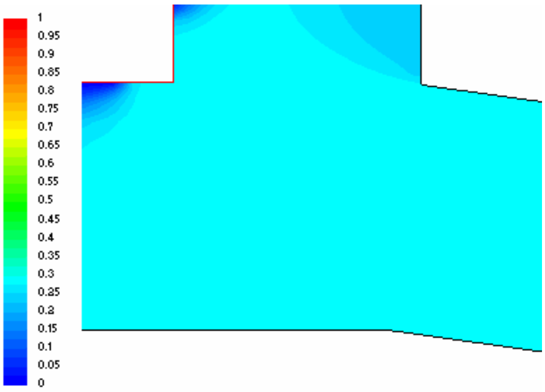


Figure E-35 Methane Concentration at 300m

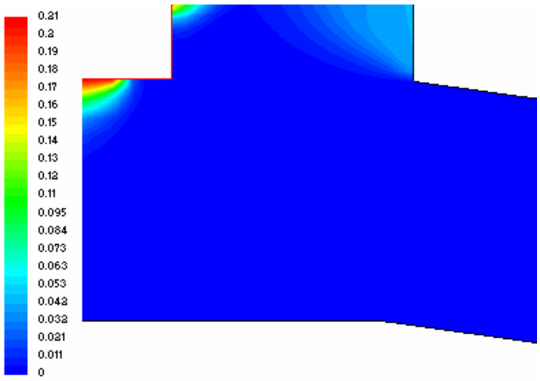


Figure E-36 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the carbon dioxide is injected at 30 degrees. Note that 0% oxygen concentration was indicated in this region.

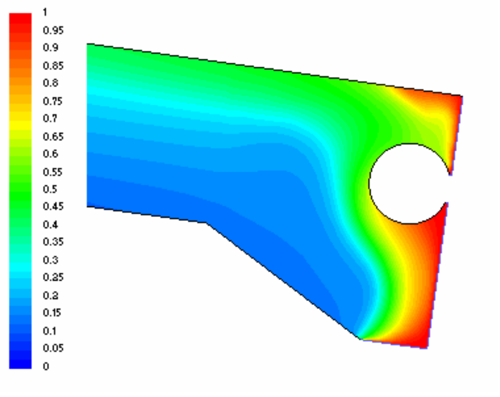


Figure E-37 Methane Mass Fraction at 150m

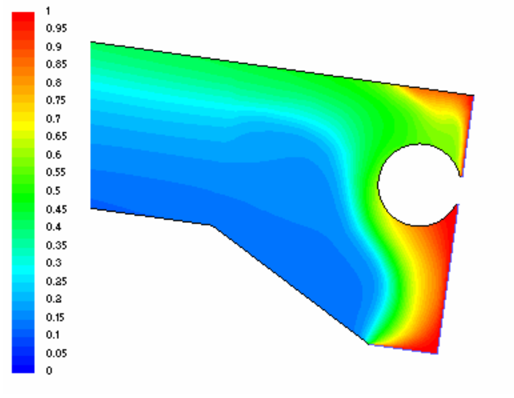


Figure E-38 Methane Mass Fraction at 200m

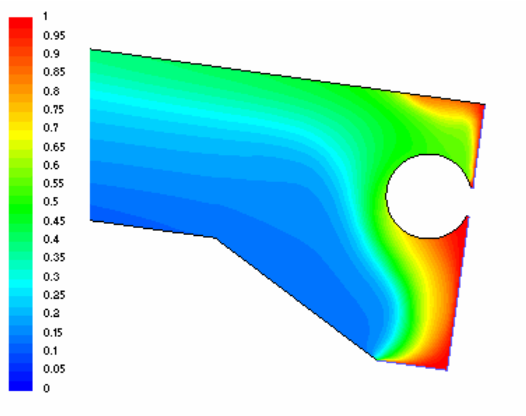


Figure E-39 Methane Mass Fraction at 250m

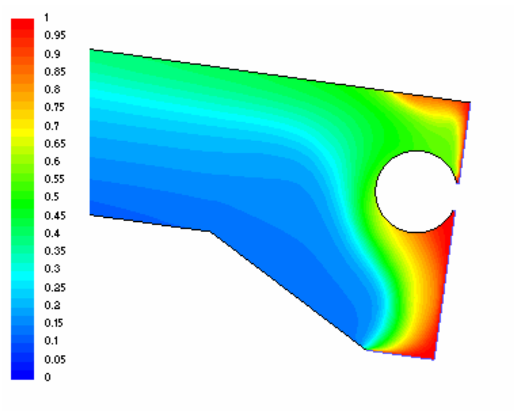


Figure E-40 Methane Mass Fraction at 300m

E.3. Gas Injected at 60 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the carbon dioxide is injected at 60 degrees.

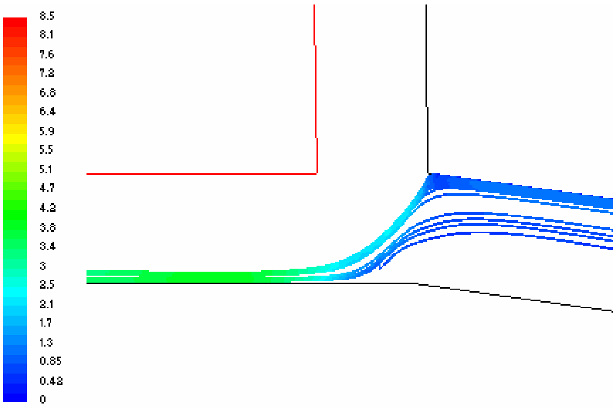


Figure E-41 Velocity Path Lines at 150m

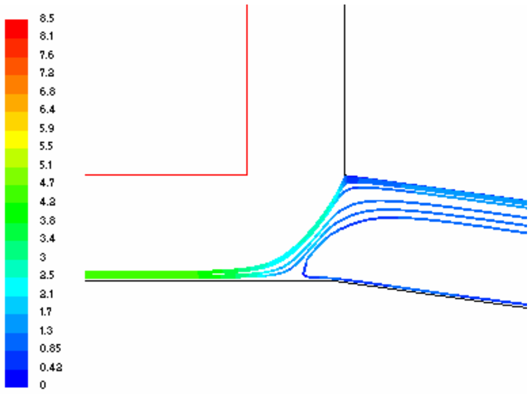


Figure E-42 Velocity Path Lines at 200m

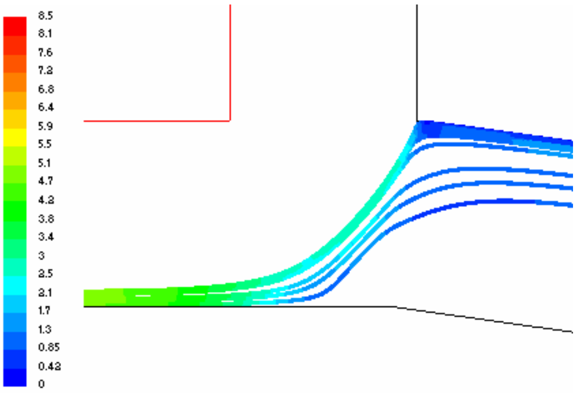


Figure E-43 Velocity Path Lines at 250m

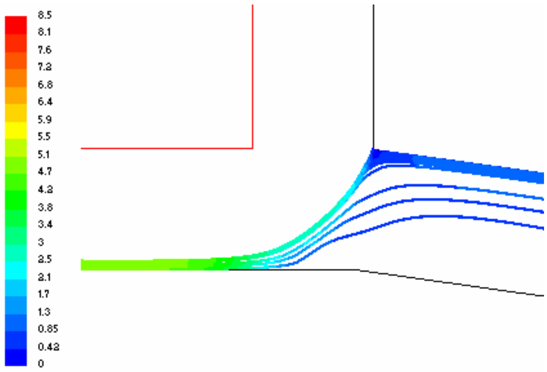


Figure E-44 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the carbon dioxide is injected at 60 degrees.

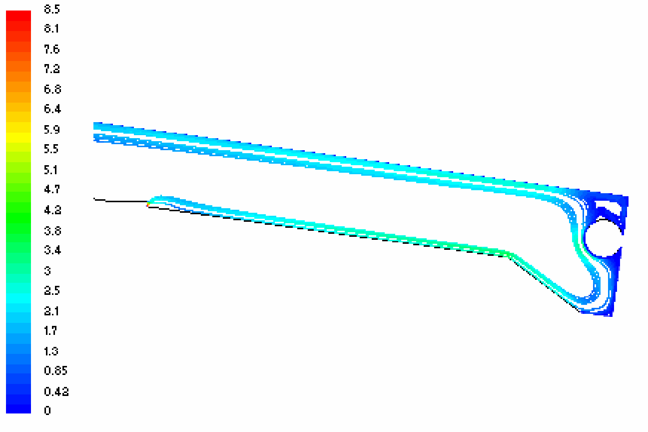


Figure E-45 Velocity Path Lines at 150m

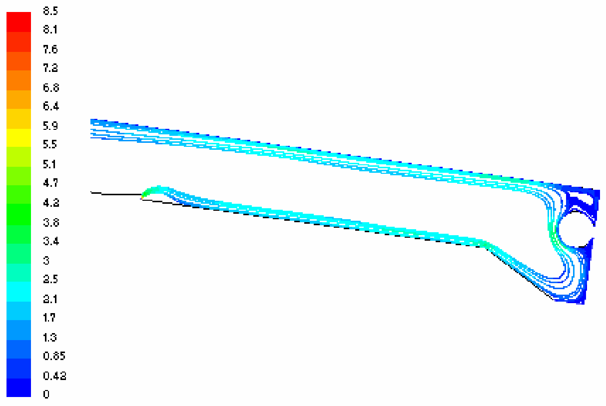


Figure E-46 Velocity Path Lines at 200m

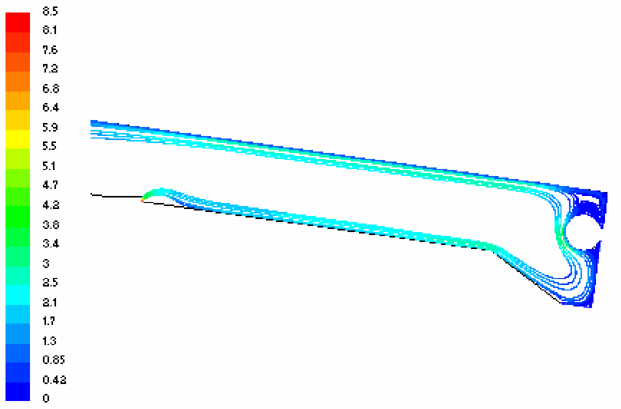


Figure E-47 Velocity Path Lines at 250m

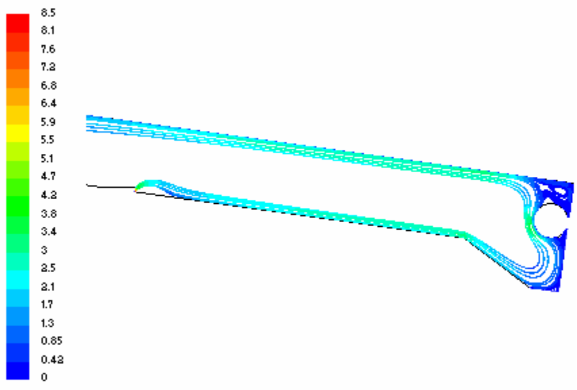


Figure E-48 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 60 degrees.

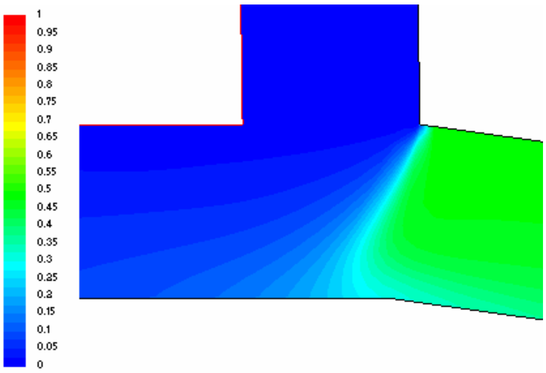


Figure E-49 Methane Concentration at 150m

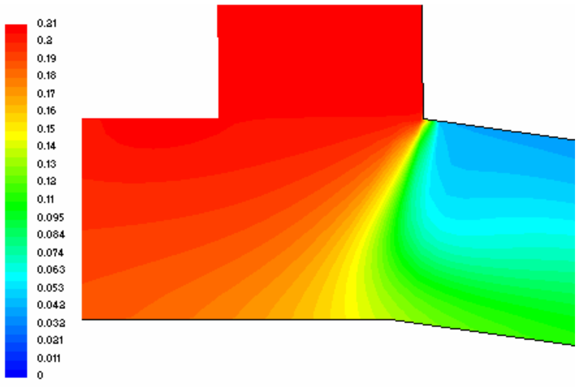


Figure E-50 Methane Concentration at 150m

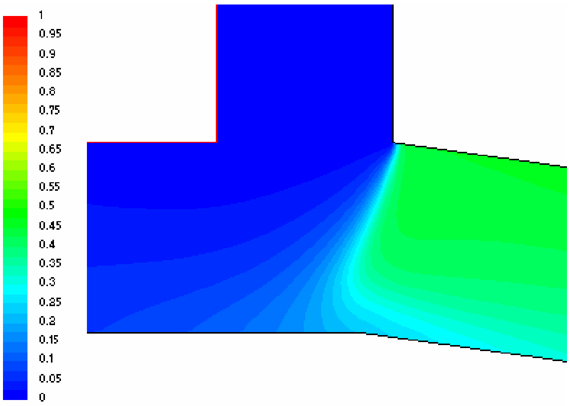


Figure E-51 Methane Concentration at 200m

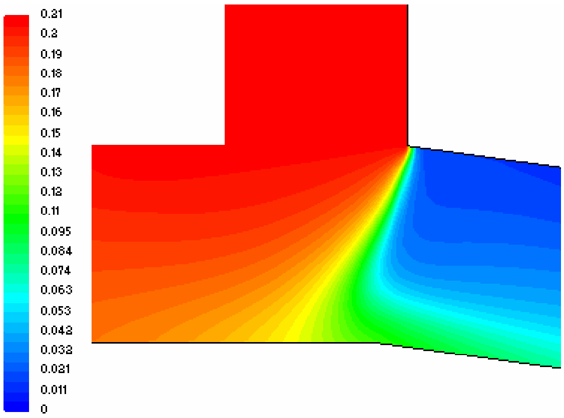


Figure E-52 Oxygen Concentration at 200m

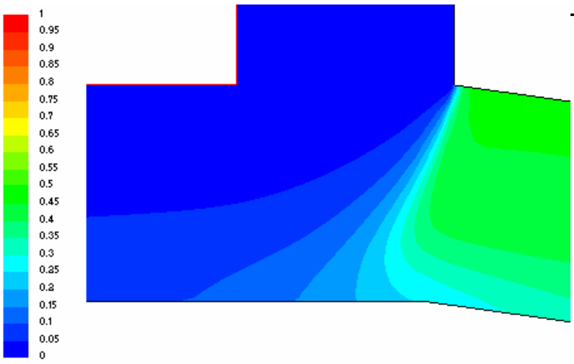


Figure E-53 Methane Concentration at 250m

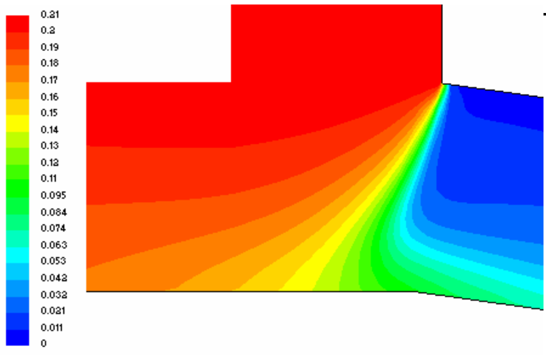


Figure E-54 Oxygen Concentration at 250m

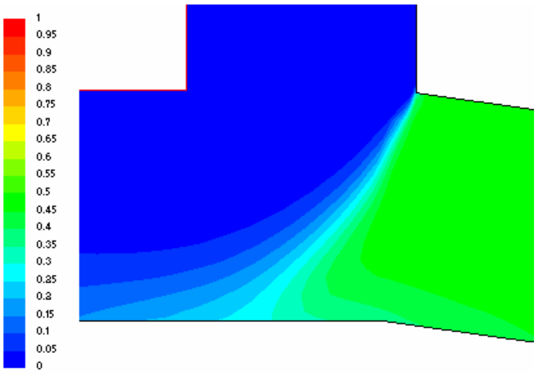


Figure E-55 Methane Concentration at 300m

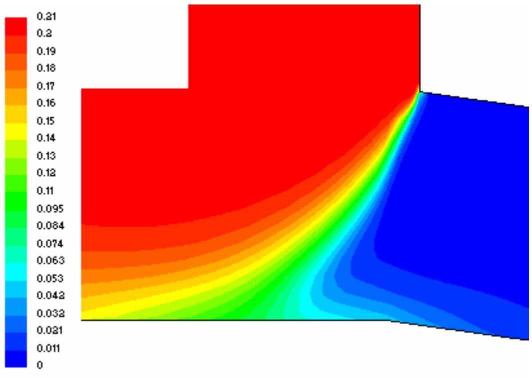
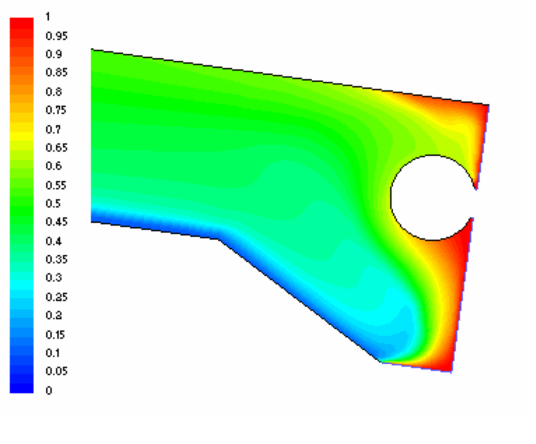


Figure E-56 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the carbon dioxide is injected at 60 degrees. Note that 0% oxygen concentration was indicated in this region.



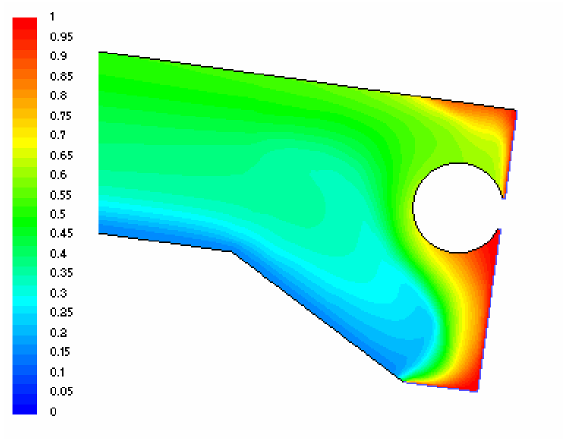
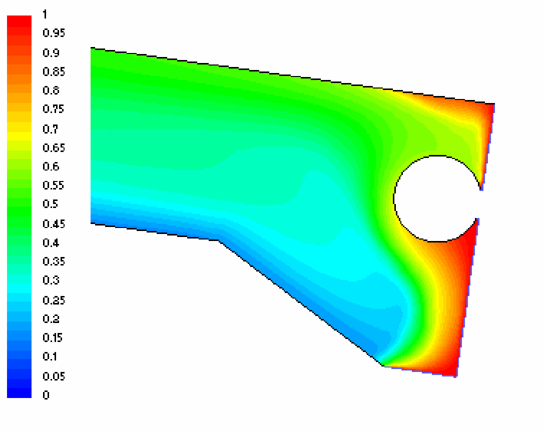


Figure E-57 Methane Mass Fraction at 150m

Figure E-58 Methane Mass Fraction at 200m



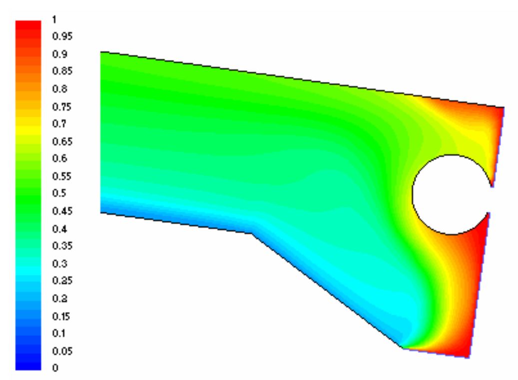


Figure E-59 Methane Mass Fraction at 250m

Figure E-60 Methane Mass Fraction at 300m

Appendix F: CFD Results for Nitrogen

F.1. Gas Injected at 0 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the nitrogen is injected at 0 degrees.

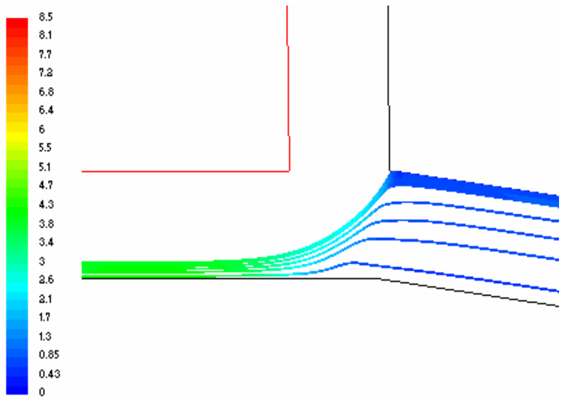


Figure F-1 Velocity Path Lines at 150m

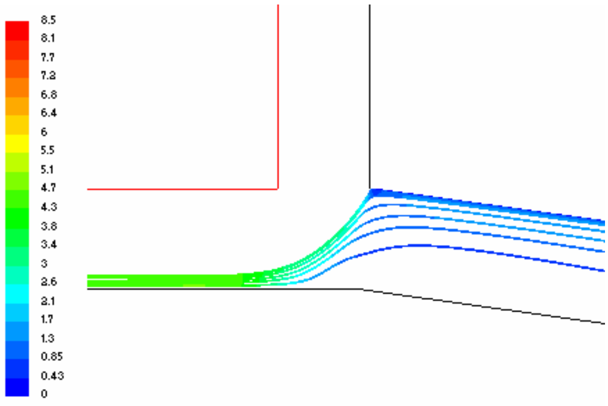


Figure F-2 Velocity Path Lines at 200m

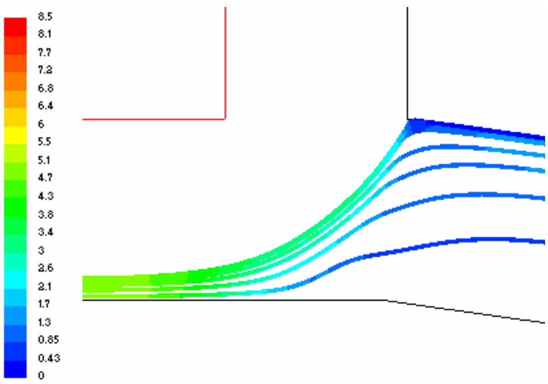


Figure F-3 Velocity Path Lines at 250m

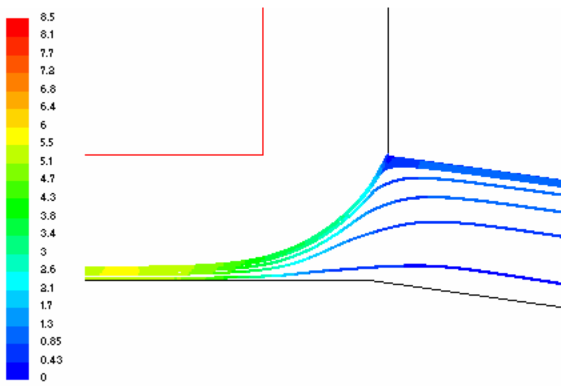


Figure F-4 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the nitrogen is injected at 0 degrees.

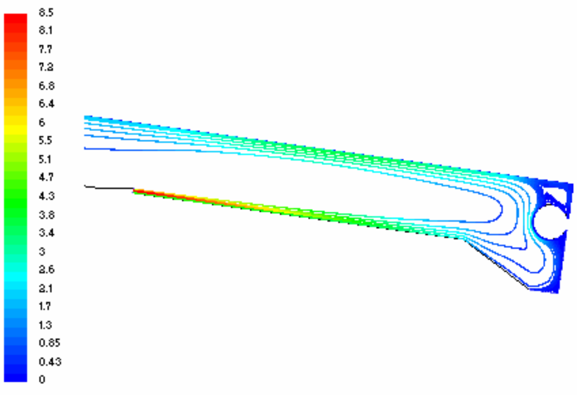


Figure F-5 Velocity Path Lines at 150m

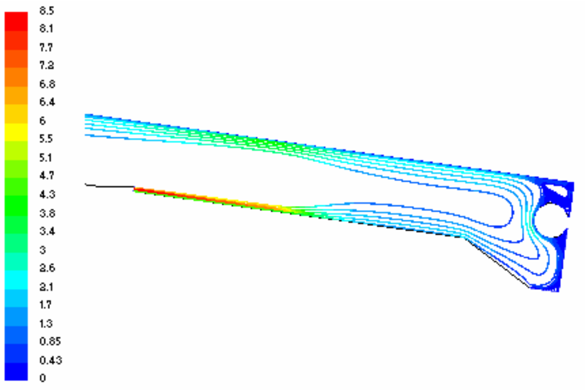


Figure F-6 Velocity Path Lines at 200m

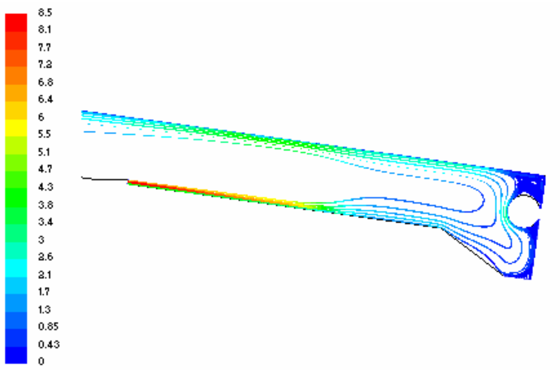


Figure F-7 Velocity Path Lines at 250m

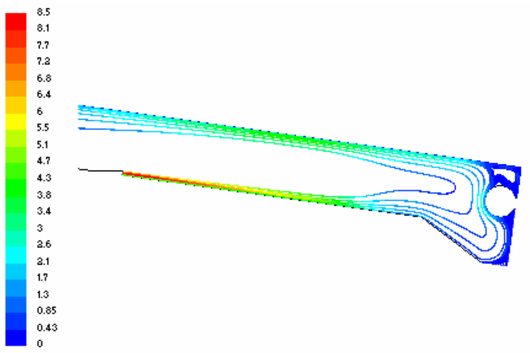


Figure F-8 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 0 degrees.

Figure F-9 Methane Concentration at 150m

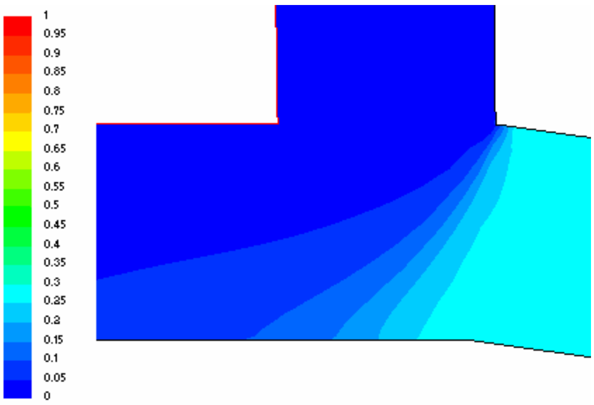
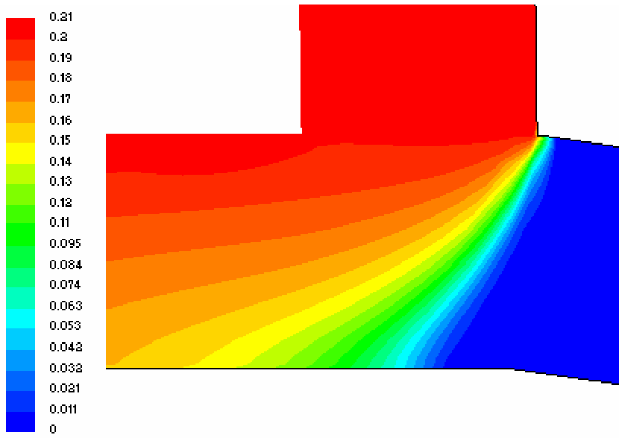


Figure F-10 Oxygen Concentration at 150m



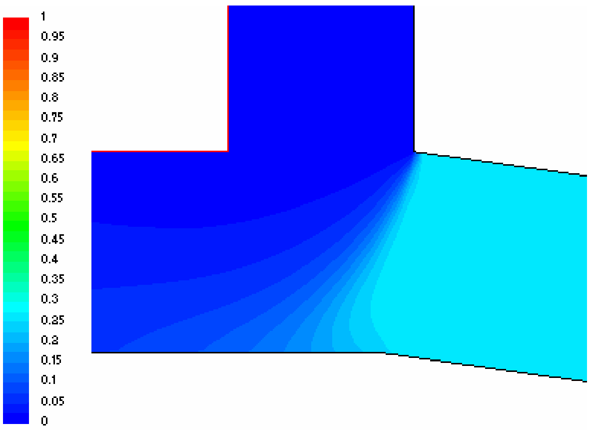


Figure F-11 Methane Concentration at 200m

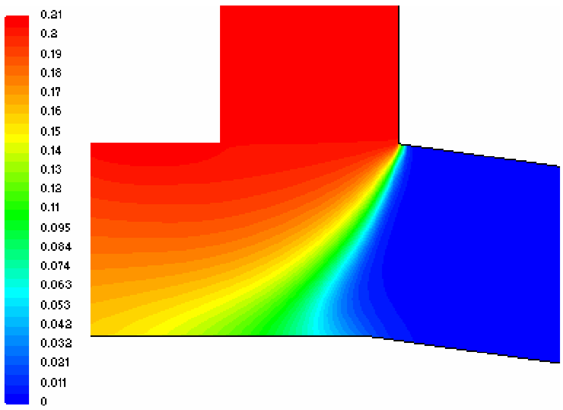


Figure F-12 Oxygen Concentration at 200m

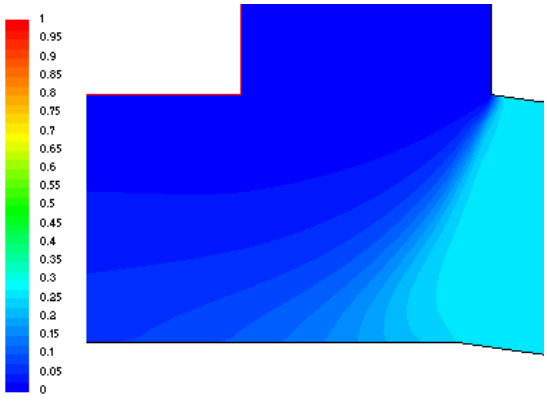


Figure F-13 Methane Concentration at 250m

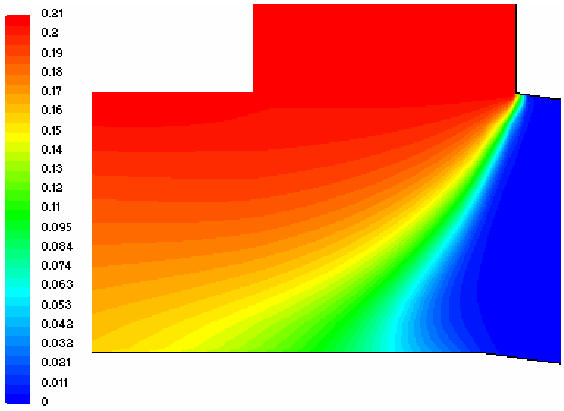


Figure F-14 Oxygen Concentration at 250m

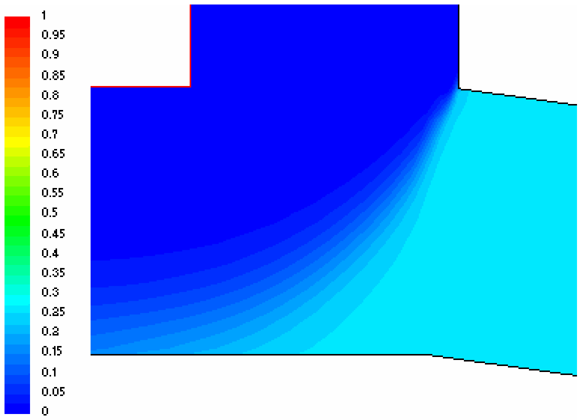


Figure F-15 Methane Concentration at 300m

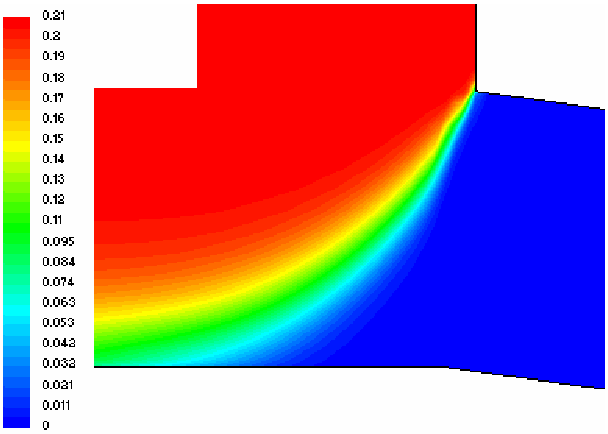
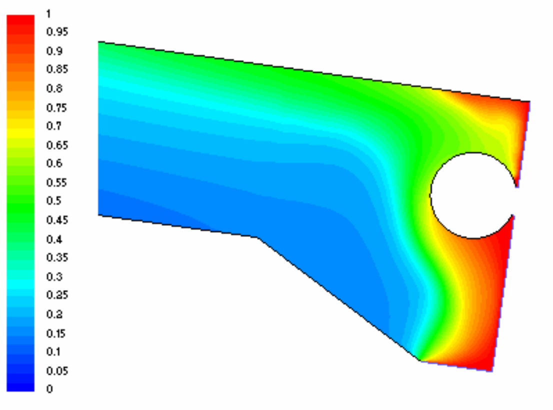


Figure F-16 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the nitrogen is injected at 0 degrees. Note that 0% oxygen concentration was indicated in this region.



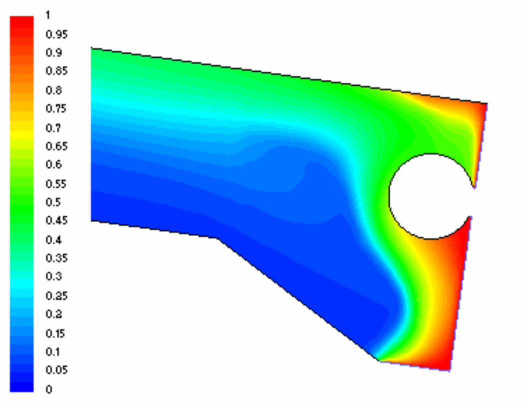
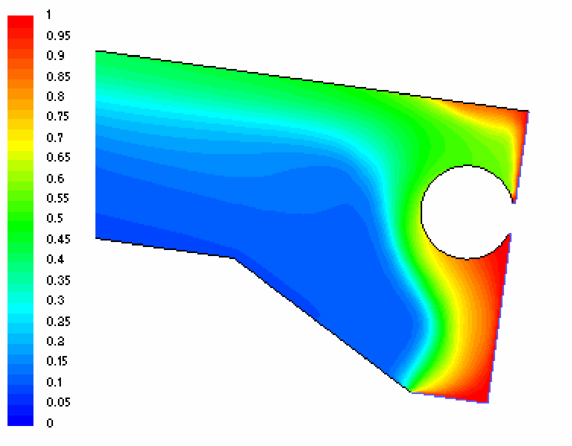


Figure F-17 Methane Mass Fraction at 150m

Figure F-18 Methane Mass Fraction at 200m



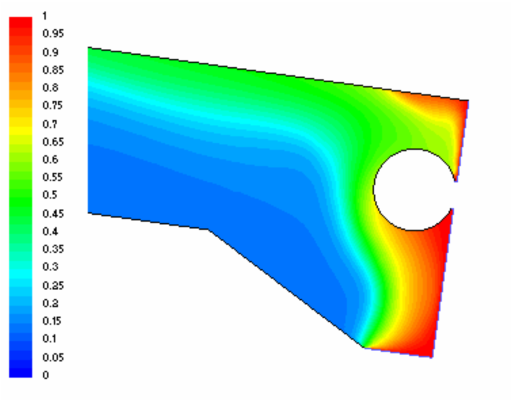


Figure F-19 Methane Mass Fraction at 250m

Figure F-20 Methane Mass Fraction at 300m

F.2. Gas Injected at 30 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the nitrogen is injected at 30 degrees.

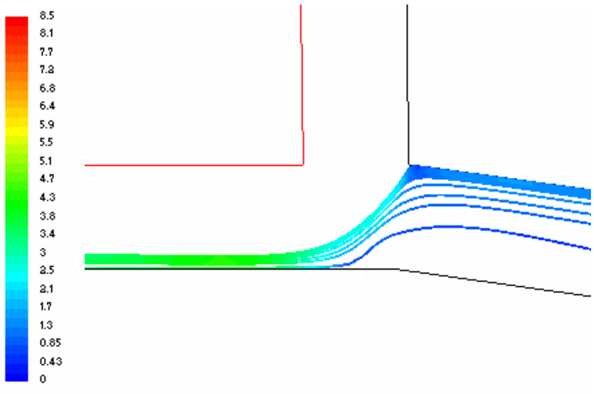


Figure F-21 Velocity Path Lines at 150m

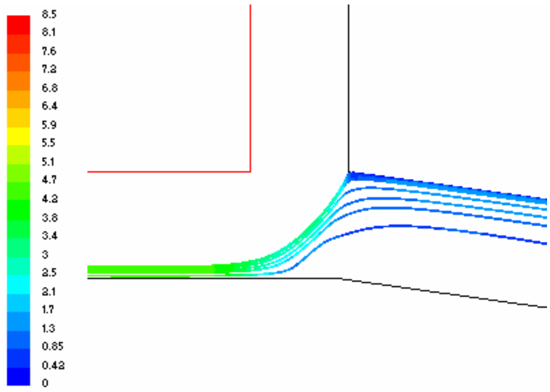


Figure F-22 Velocity Path Lines at 200m

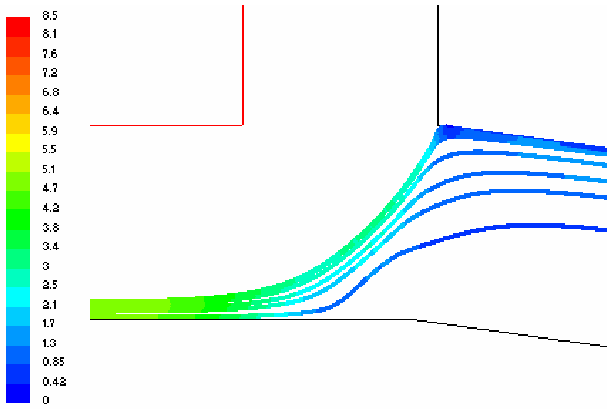


Figure F-23 Velocity Path Lines at 250m

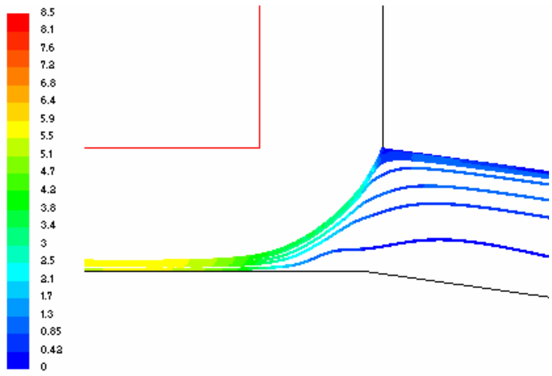


Figure F-24 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the nitrogen is injected at 30 degrees.

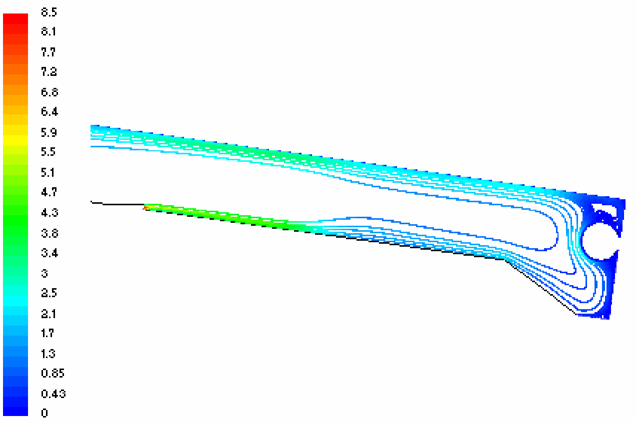


Figure F-25 Velocity Path Lines at 150m

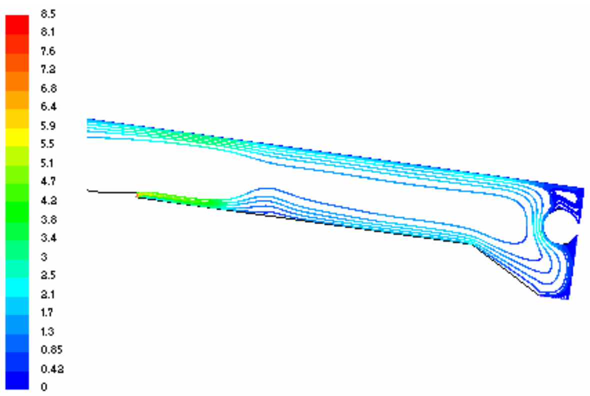


Figure F-26 Velocity Path Lines at 200m

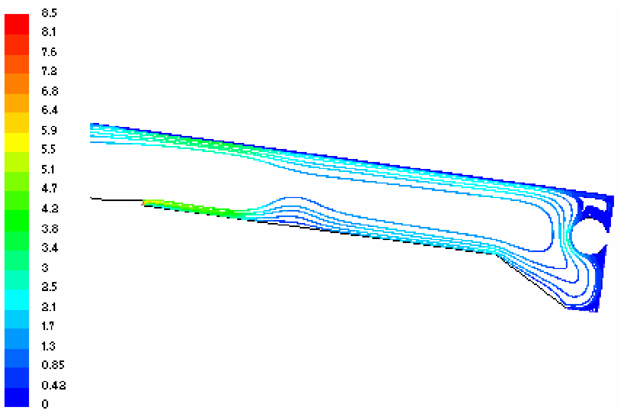


Figure F-27 Velocity Path Lines at 250m

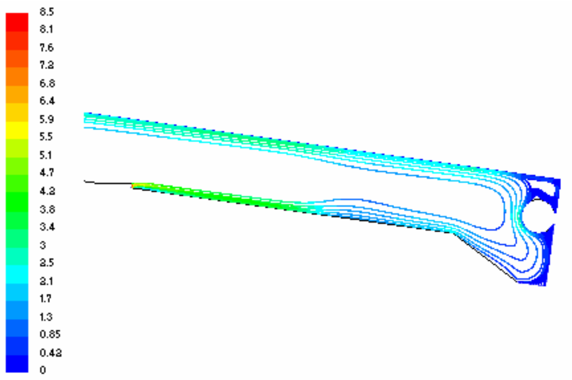


Figure F-28 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 30 degrees.

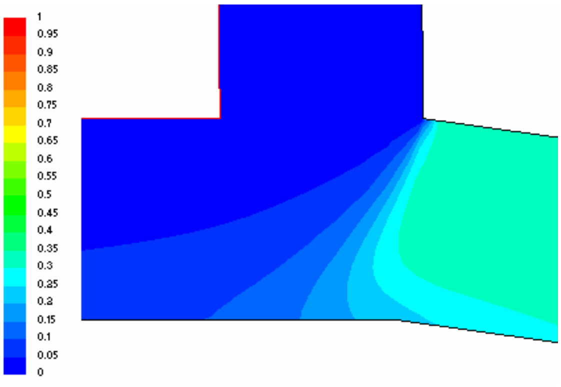


Figure F-29 Methane Concentration at 150m

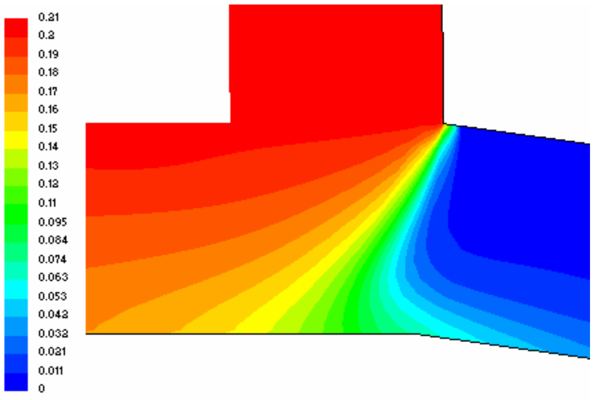


Figure F-30 Oxygen Concentration at 150m

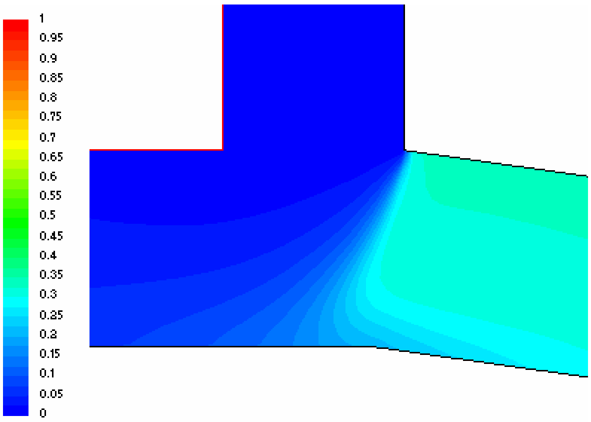


Figure F-31 Methane Concentration at 200m

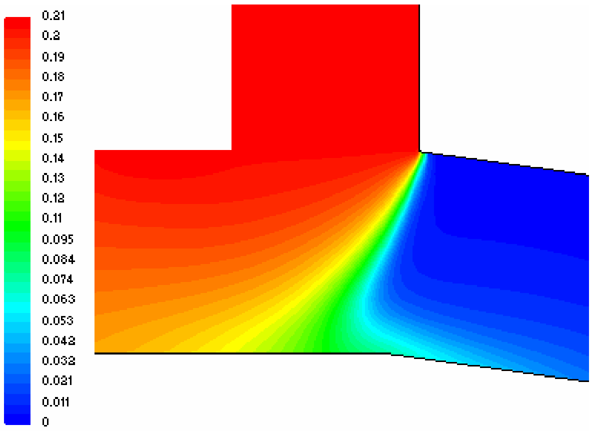


Figure F-32 Oxygen Concentration at 200m

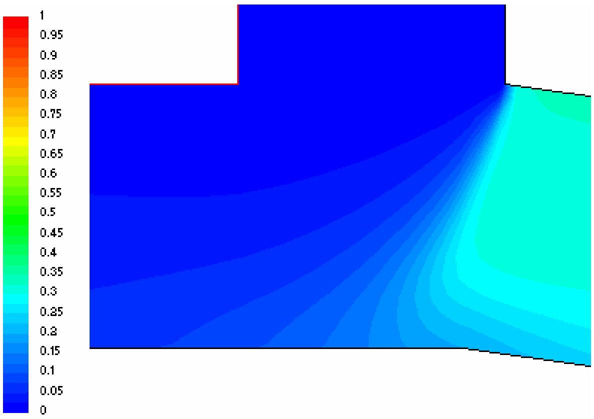


Figure F-33 Methane Concentration at 250m

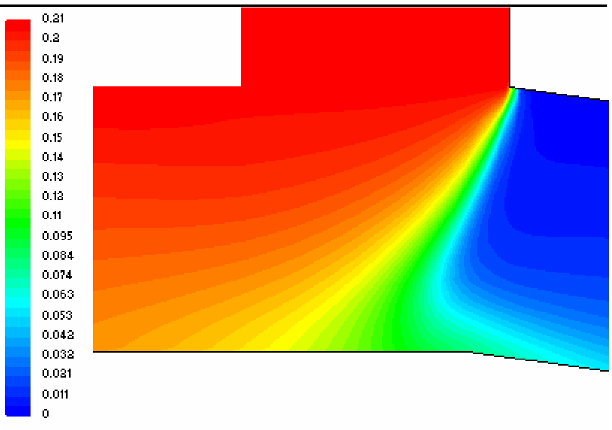


Figure F-34 Oxygen Concentration at 250m

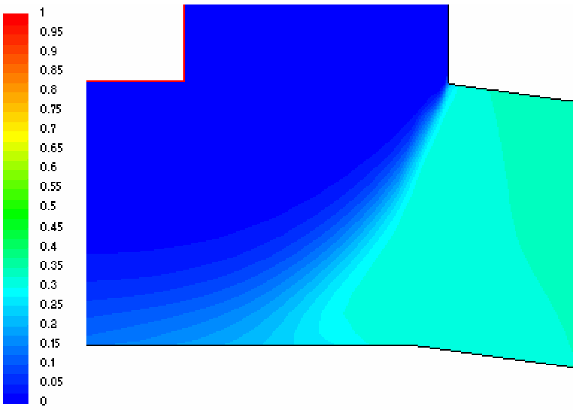


Figure F-35 Methane Concentration at 300m

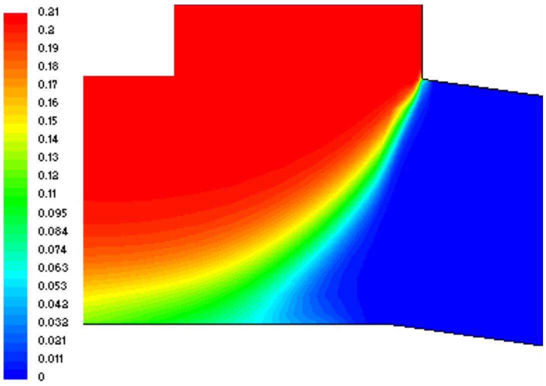


Figure F-36 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the nitrogen is injected at 30 degrees. Note that 0% oxygen concentration was indicated in this region.

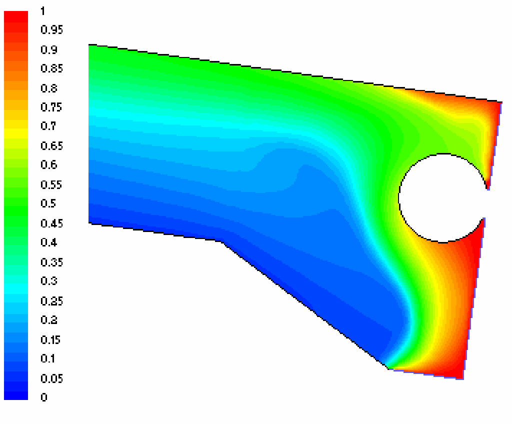


Figure F-37 Methane Mass Fraction at 150m

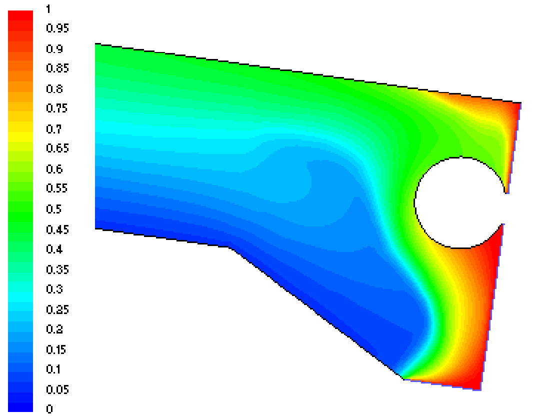


Figure F-38 Methane Mass Fraction at 200m

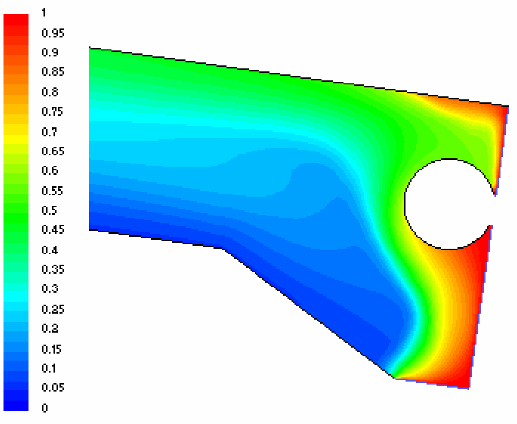


Figure F-39 Methane Mass Fraction at 250m

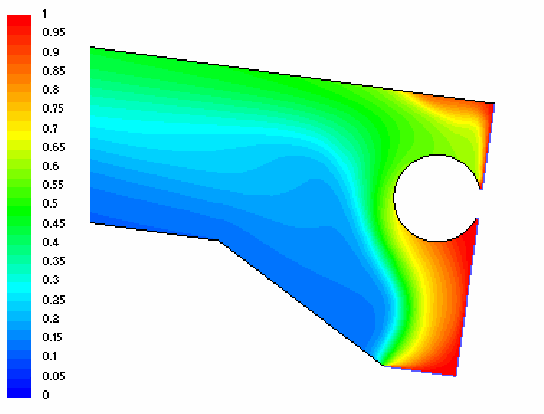


Figure F-40 Methane Mass Fraction at 300m

F.3. Gas Injected at 60 Degrees

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the base of the highwall for the various penetration depths when the nitrogen is injected at 60 degrees.

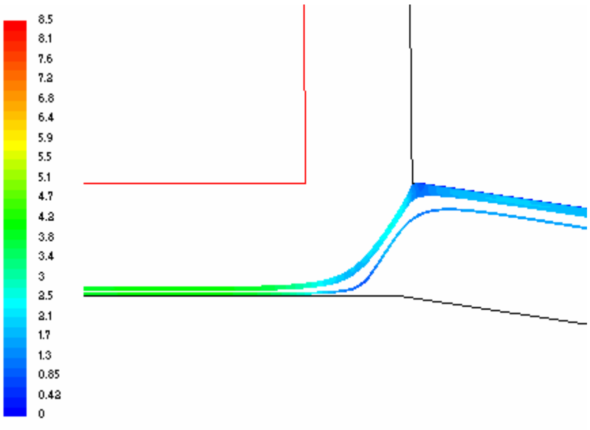


Figure F-41 Velocity Path Lines at 150m

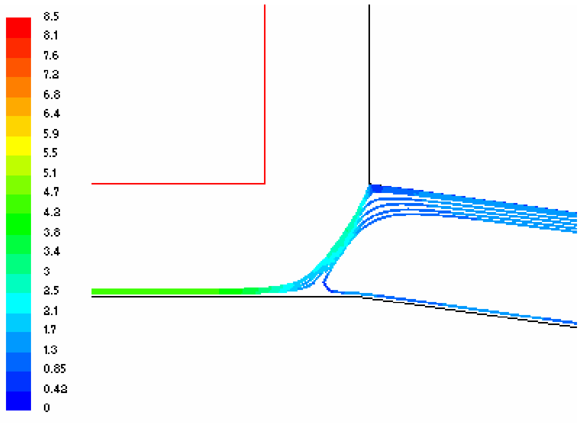


Figure F-42 Velocity Path Lines at 200m

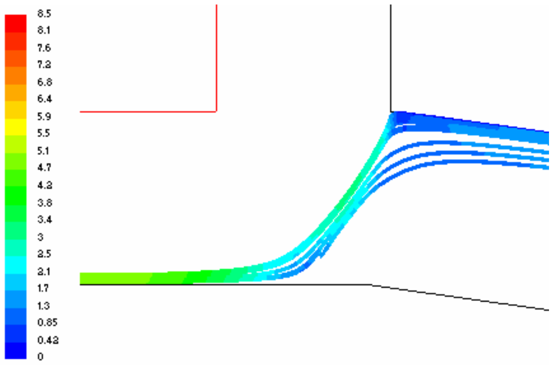


Figure F-43 Velocity Path Lines at 250m

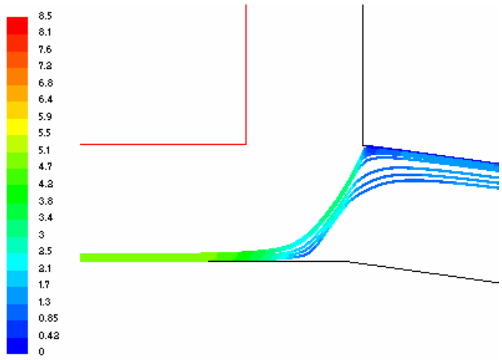


Figure F-44 Velocity Path Lines at 300m

The velocity (m/s) particle path lines from the inert gas injection point, coal face and floor shown at the coal face region for the various penetration depths when the nitrogen is injected at 60 degrees.

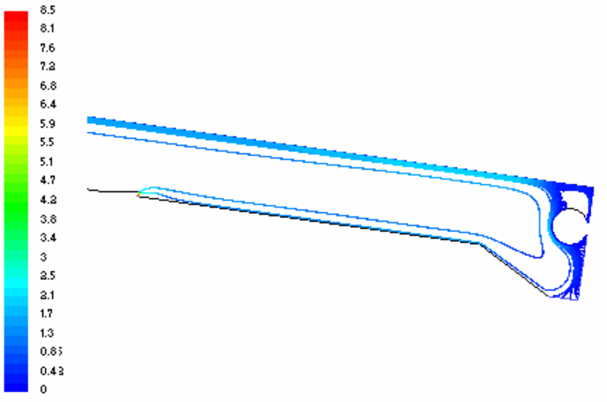


Figure F-45 Velocity Path Lines at 150m

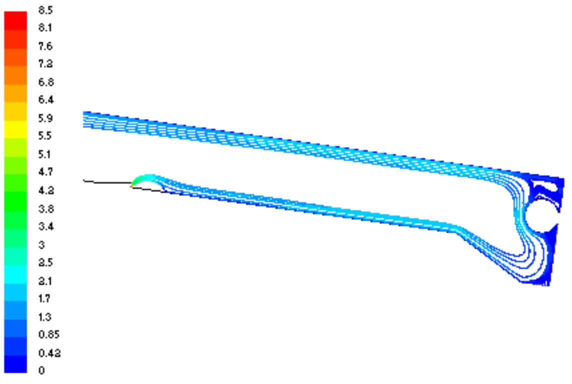


Figure F-46 Velocity Path Lines at 200m

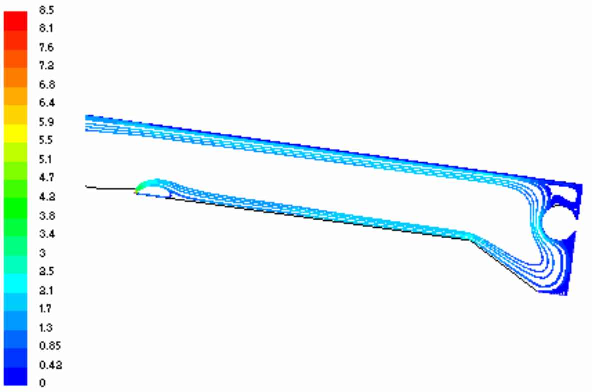


Figure F-47 Velocity Path Lines at 250m

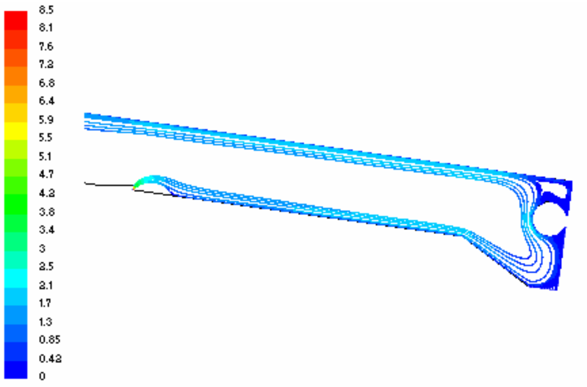


Figure F-48 Velocity Path Lines at 300m

The mass fractions (%) of the methane gas and oxygen at the base of the highwall are shown below for the various penetration depths when the boiler gas is injected at 60 degrees.

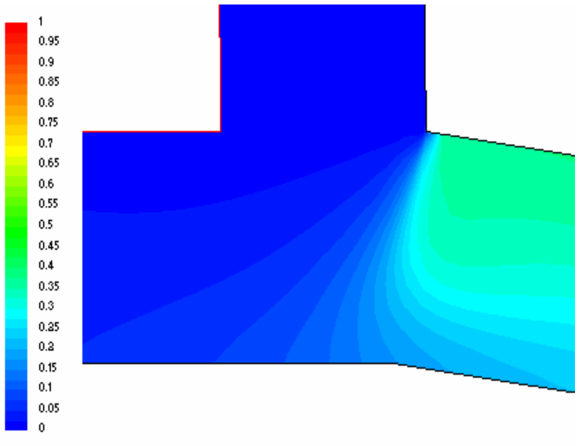


Figure F-49 Methane Concentration at 150m

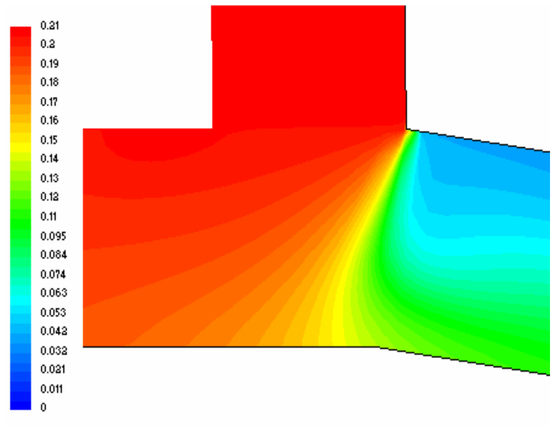


Figure F-50 Oxygen Concentration at 150m

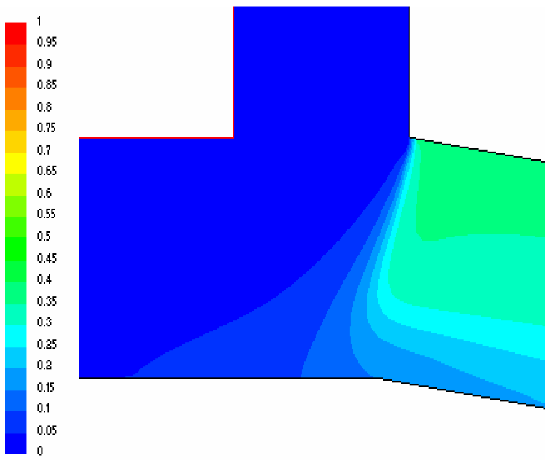


Figure F-51 Methane Concentration at 200m

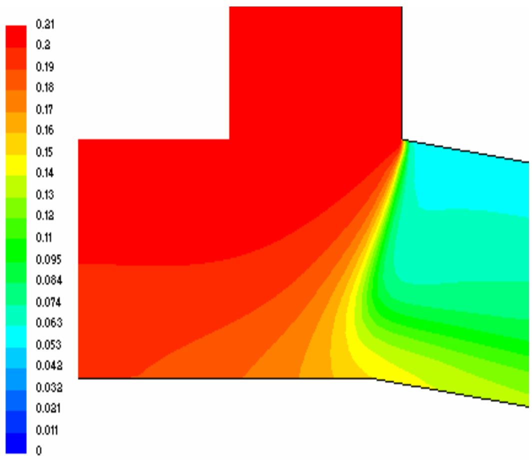


Figure F-52 Oxygen Concentration at 200m

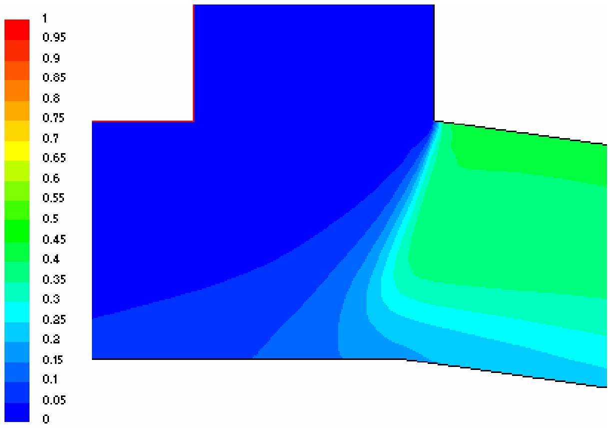


Figure F-53 Methane Concentration at 250m

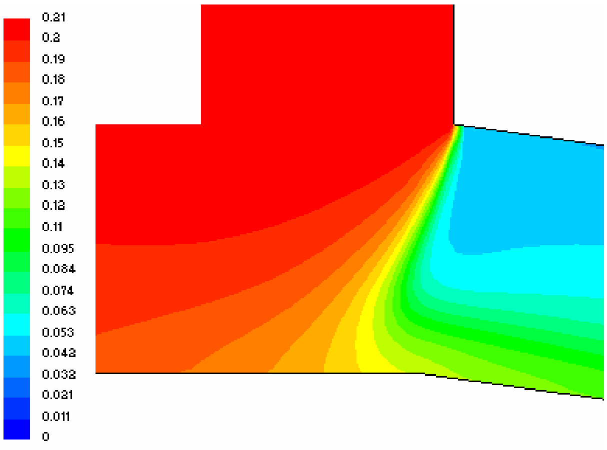


Figure F-54 Oxygen Concentration at 250m

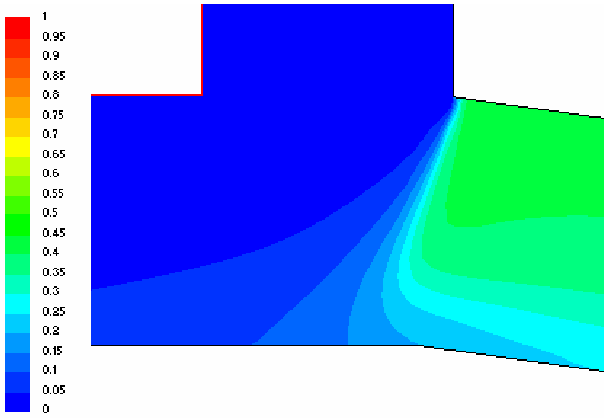


Figure F-55 Methane Concentration at 300m

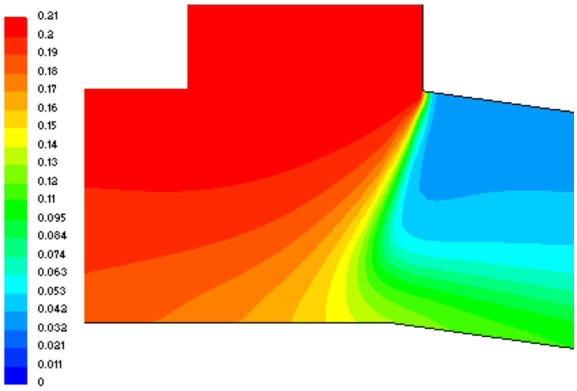


Figure F-56 Oxygen Concentration at 300m

The mass fractions (%) of the methane gas within the highwall drive at the coal face are shown below for the various penetration depths when the nitrogen is injected at 60 degrees. Note that 0% oxygen concentration was indicated in this region.

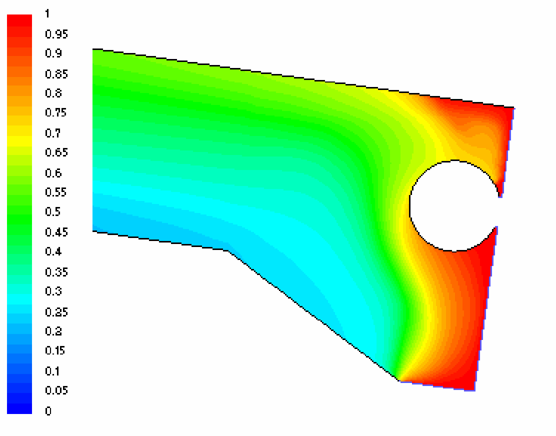


Figure F-57 Methane Mass Fraction at 150m

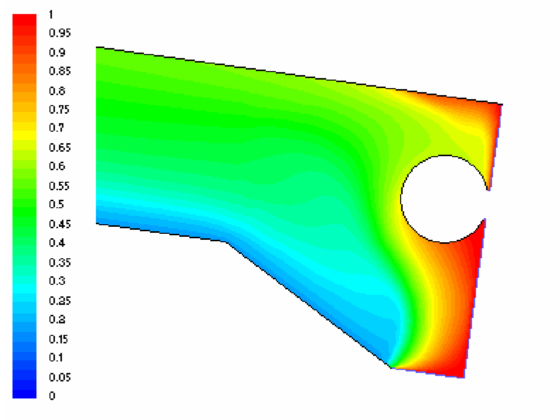


Figure F-58 Methane Mass Fraction at 200m

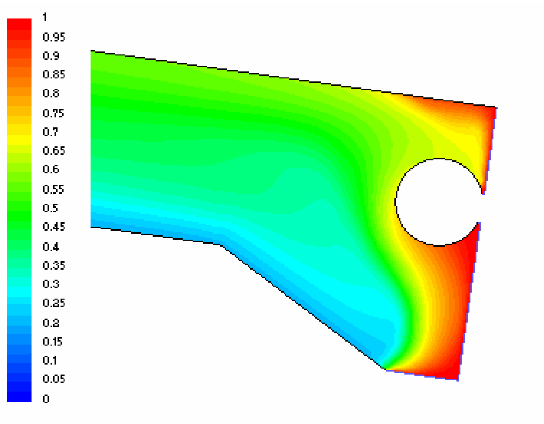


Figure F-59 Methane Mass Fraction at 250m

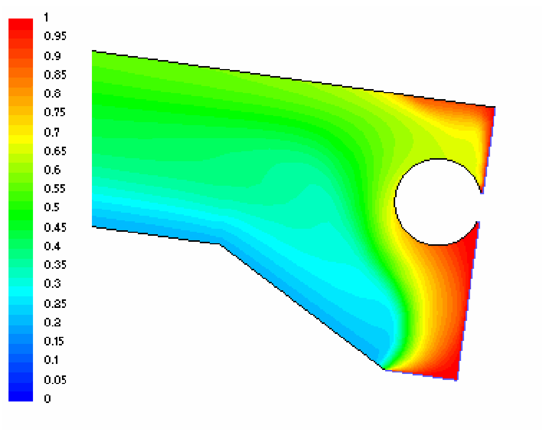


Figure F-60 Methane Mass Fraction at 300m