GOB VENTILATION BOREHOLE DESIGN AND PERFORMANCE OPTIMIZATION FOR LONGWALL COAL MINING USING COMPUTATIONAL FLUID DYNAMICS

by

Saqib Ahmad Saki
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Golden, Colorado School of Mines

Date__________________________ Signed__________________________

Saqib Ahmad Saki

Signed__________________________

Dr. Jürgen Brune
Thesis Advisor

Signed__________________________

Dr. Gregory Bogin
Thesis Advisor

Golden, Colorado School of Mines

Date__________________________ Signed__________________________

Dr. Priscilla Nelson
Professor and Head
Department of Mining Engineeri
ABSTRACT

Longwall mining is a method used in underground coal mining, which is preferred by mine operators due to increased productivity and lower overall injury rates. Coal mines may be considered gassy based on the presence of hazardous gases like, methane, CO and CO$_2$. In the United States, the Mine Safety and Health Administration (MSHA) considers all coal mines to be gassy as a safety measure. In longwall mines, gases from rider coal seams or the floor can migrate into the gob, which has the higher permeability, and then move forward to the working space and areas. The accumulation of methane gas is a safety hazard to the working environment as it can be explosive when mixed with oxygen and exposed to an ignition source. Coal bed degasification, ventilation, nitrogen injection, and gob ventilation boreholes (GVBs) are some of the methods used to control methane hazards.

A well designed mine ventilation system, alone, is limited in its ability to manage methane emissions. When methane emissions are beyond the level that ventilation can handle, additional measures are required, like drilling vertical methane drainage holes, or GVBs, from the surface into the gob area to extract the methane gas; these boreholes are drilled from the surface, above the panel ahead of the mining activity. When the advancing face intercepts the GVBs, the boreholes begin producing methane. It is important to predict the performance of GVBs to ensure a safer working environment in longwall coal mining. The performance of GVBs depends on multiple factors, including; borehole locations, number of boreholes, length of slotted casing, diameter of casing, setting depth of casing above the panel, overburden strata,
wellhead vacuum pressure, permeability of caved and fractured zones, and the area of influence of GVBs.

GVBs are widely used in United States (U.S.) underground coal mines for longwall gob degasification. GVBs can recover 30 to 70% of methane emissions from the longwall gob depending on geologic conditions (Mutmansky, 1999). Generally, they are considered useful for reducing methane concentrations in working areas, thereby reducing explosion hazards and creating safer working conditions for a longwall section. The computational fluid dynamics (CFD) modeling work in this dissertation confirms that GVBs are helpful to reduce the methane concentrations at the face. However, they may also draw fresh air from the face into the gob; increasing oxygen ingress into the gob creates explosive gas zones (EGZs) within the gob. It is important to identify the locations for gob ventilation borehole placement to maximize methane extraction and minimize any explosion hazards.

CFD models were developed for this dissertation to analyze the effects of GVB design and operating parameters for methane extraction, the formation of explosive gas zones in the gob and methane concentrations at the longwall face and tailgate. Parameters such as the distance of GVBs from the tailgate and the working face, the borehole diameter, the distance from the top of the coal seam being mined, the wellhead vacuum pressure and the number of GVBs operating on the panel, all have a significant effect on methane extraction, explosive gas mixtures volume and methane concentration in working areas. The CFD studies in this research identified optimal GVB design and operating parameters to maximize benefits and minimize risks. This research used the CFD modeling software package ANSYS® Fluent® along with the
output of geomechanical modeling for permeability and porosity input into the CFD models. Earlier research at Colorado School of Mines developed the geomechanical models of the case study mines based on data received from cooperating mines, using the geomechanical software package FLAC$^{3D}$ to determine the permeability of the gob and fractured zone (Marts et al., 2014a; Wachel, 2012; Worrall, 2012).

The main purpose of mine ventilation design is to provide sufficient quantity and quality of air to the workers, and to dilute the concentration of methane and other contaminants. A common perception among mining engineers is that additional air along the longwall face will improve methane dilution on the face and in the tailgate. In this dissertation, a parametric study is presented to discuss the effect of face air quantity on methane concentrations in the tailgate and formation of EGZs in the gob. Counter to conventional wisdom, increased longwall face air quantities may increase the explosion hazard as they result in higher EGZ volumes in the gob and increased methane quantities in the tailgate return. The results have been validated against the data provided by cooperating mines and also compared with published data.

This dissertation provides the industry with a methodology to predict the optimal GVB design and operating parameters and their importance in creating a safe working environment. It will also contribute to the body of knowledge of the effects of face ventilation air quantity changes and how they affect the gob environment and methane dilution in working areas.
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. iii
LIST OF TABLES .......................................................................................................................... x
LIST OF FIGURES ....................................................................................................................... xii
LIST OF ABBREVIATIONS ......................................................................................................... xvi
ACKNOWLEDGEMENTS ........................................................................................................ xviii
DEDICATION .............................................................................................................................. xix

## CHAPTER 1 INTRODUCTION ............................................................................................. 1

1.1 Introduction to Longwall Mining .................................................................................... 2
1.2 Longwall Ventilation ....................................................................................................... 7
1.3 Gob Ventilation Boreholes ........................................................................................... 11

## CHAPTER 2 RESEARCH METHODS ............................................................................... 13

2.1 Motivation for Research ............................................................................................... 13
2.2 Research Objective and Hypothesis ............................................................................ 15
2.3 Research Questions ........................................................................................................ 16
2.4 Specific Aims and Research Tasks ................................................................................ 17
   2.4.1 Permeability and Porosity fits for CFD Modeling ................................................ 18
   2.4.2 Computational Fluid Dynamic Model (CFD Model) ........................................... 19
   2.4.3 Summary of Research Tasks ............................................................................. 20
2.5 Cooperating Mine C ....................................................................................................... 21
2.6 Expected Research Outcomes ...................................................................................... 22
2.7 Original Contributions to Science ................................................................................ 22

## CHAPTER 3 BACKGROUND ............................................................................................ 24
8.2 CFD Model Description ........................................................................................................ 116
8.3 Ventilation Layout ................................................................................................................ 116
8.4 Boundary Conditions ............................................................................................................. 118
8.5 Modeling Results and Discussion .......................................................................................... 118
8.6 Explosive Gas Zones (EGZs) and Methane in Tailgate Returns ........................................ 120
8.7 Gob Communication with Face and Tailgate Return .............................................................. 122
8.8 Impact of Face Ventilation on GVB Performance ................................................................. 124

CHAPTER 9 CONCLUSIONS ...................................................................................................... 126

CHAPTER 10 IMPLICATIONS FOR FUTURE RESEARCH ...................................................... 128

REFERENCES CITED ............................................................................................................ 130
LIST OF TABLES

Table 2.1: Methane accidents in underground coal mines ............................................... 13
Table 3.1: Gas sensor technologies (Cliff et al., 1999; Grubb, 2008) ................................. 29
Table 4.1: Properties of rock types used in model (Mine C) ............................................. 65
Table 4.2: In situ permeabilities of fractured zone rock layers ........................................ 70
Table 4.3: Permeabilities of strata layers for the studied mine ......................................... 71
Table 5.1: General Solver Settings .................................................................................. 75
Table 5.2: Turbulence model settings .............................................................................. 75
Table 5.3: The methane-air mixture and properties ......................................................... 76
Table 5.4: Solution settings ............................................................................................ 77
Table 5.5: Overall mass balance of model ....................................................................... 78
Table 5.6: Iteration based convergence criteria evaluation ............................................. 79
Table 5.7: The residual convergence .............................................................................. 79
Table 5.8: GVBs wellhead vacuum pressure used by different operations ...................... 81
Table 5.9: GVB wellhead vacuum pressure ..................................................................... 81
Table 6.1: Validation runs results .................................................................................... 84
Table 6.2: Diameter variation of GVBs results comparison with Karacan (2006) .......... 86
Table 6.3: Setting depth study results comparison with Karacan (2006) ......................... 86
Table 6.4: Gob Mesh Controls ....................................................................................... 87
Table 6.5: Fractured Zone Mesh Controls ...................................................................... 88
Table 6.6: Fractured Zone Mesh Refinement ................................................................... 88
Table 6.7: Mesh Independence Study Results ................................................................. 89
Table 7.1: GVBs locations in CFD model for location optimization study ...................... 94
Table 7.2: Methane quantity variation in the model................................. 108
Table 7.3: Methane variation effects on solution (20 cm diameter GVBs).......... 108
Table 7.4: Methane variation effects on solution (30 cm diameter GVBs)......... 109
Table 7.5: Methane variation effects on solution (30 cm diameter GVBs)........... 110
Table 7.6: Estimated radius of influence for different diameter GVBs .............. 113
LIST OF FIGURES

Figure 1.1: Coal share in U.S. electricity generation .............................................................. 1
Figure 1.2: Coal production and use in U.S. ........................................................................ 2
Figure 1.3: Depiction of longwall coal mining method operations ........................................ 3
Figure 1.4: Longwall miner layout ...................................................................................... 4
Figure 1.5: Complete longwall system ............................................................................... 6
Figure 1.6: Longwall shields and shearer on face ............................................................... 6
Figure 1.7: Longwall shearer ............................................................................................ 7
Figure 1.8: Bleeder ventilation plan (Grubb, 2008) .............................................................. 8
Figure 1.9: U-System of Bleederless Ventilation (Grubb, 2008) ....................................... 9
Figure 1.10: Progressively sealed Y ventilation system (Grubb, 2008) ............................ 10
Figure 1.11: Y-System with a Back Return (Grubb, 2008) ............................................. 11
Figure 1.12: A schematic representation of longwall mining ........................................... 12
Figure 3.1: A typical gas chromatograph installation (Mason, 2012) ............................... 26
Figure 3.2: Typical tube bundle system flow diagram ....................................................... 27
Figure 3.3: Tube bundle data ........................................................................................... 28
Figure 3.4: Graphical representation of avoiding an explosive atmosphere ................. 31
Figure 3.5: Different gob gas recovery methods (Brunner, 2000) .................................... 32
Figure 3.6: Superjacent borehole drilled into overlying an underlying coal bed .......... 33
Figure 3.7: Schematic of gob ventilation borehole (Xue and Balusu, 2002) ................. 34
Figure 3.8: Map of study area. (Moore et al., 1976) ....................................................... 36
Figure 3.9: GVB 20 effectiveness in reducing methane in underground entries ........... 37
Figure 3.10: Depiction of Gob vent holes positions and their production ..................... 38
Figure 3.11: Schematic diagram of a typical subsidence profile ........................................ 38
Figure 3.12: Gas flow rate from GVBs (Balusu et al., 2005) ............................................. 40
Figure 3.13: Gas compositions from GVBs (Balusu et al., 2005) ................................. 40
Figure 3.14: GVBs configurations and locations for the cases tested ................................ 44
Figure 3.15: Generalized subsidence profile (Campoli et al., 1993) ............................... 46
Figure 3.16: Modeled method of extraction’s effect on gob compaction ........................... 47
Figure 4.1: Progressively sealed, U-type ventilation .................................................... 50
Figure 4.2: Gob geometry in CFD model ....................................................................... 52
Figure 4.3: Photograph of void observed on both sides of gob (Worrall, 2012) ............... 53
Figure 4.4: Void geometry in ANSYS Design Modelar ................................................. 54
Figure 4.5: Face geometry with shields gaps ................................................................. 55
Figure 4.6: Headgate and tailgate entry ........................................................................ 56
Figure 4.7: Vertical cross section showing zones of disturbance .................................... 57
Figure 4.8: Geometry of fractured zone in the CFD model ............................................ 57
Figure 4.9: Gob mesh .................................................................................................... 59
Figure 4.10: Quality of gob mesh .................................................................................. 60
Figure 4.11: Skewness of gob mesh ................................................................................ 60
Figure 4.12: Fractured zone mesh ................................................................................ 62
Figure 4.13: Fractured zone mesh skewness matric ...................................................... 63
Figure 4.14: Fractured zone mesh quality matric .......................................................... 63
Figure 4.15: Full CFD model mesh ................................................................................ 64
Figure 4.16: Dynamic subsidence data comparison with model prediction .................... 66
Figure 4.17: Shield loading comparison (Mine C), (Marts et al., 2014). .......................... 66
Figure 4.18: Gob VSI curve fitting approach ................................................................. 68
Figure 4.19: Mine C porosity contours........................................................................... 69
Figure 4.20: Mine C permeability contours.................................................................... 69
Figure 4.21: Color coded Coward’s triangle (Worrall, 2012)......................................... 72
Figure 6.1: Oxygen measurements from mine (a) comparison with CFD model .......... 85
Figure 6.2: Increased permeability contour plots in the gob.......................................... 90
Figure 6.3: Decreased permeability contour plots in the gob ........................................ 90
Figure 6.4: Change in normalized EGZ by changing the permeability ......................... 91
Figure 6.5: Oxygen contour plots with changed permeabilities in the gob................. 92
Figure 6.6: GVB flow change with change of permeability in the model.................... 92
Figure 7.1: GVBs Flow with respect to location ............................................................. 94
Figure 7.2: Normalized EGZs comparison with respect to GVBs location ................. 95
Figure 7.3: EGZs contour plot comparison .................................................................... 96
Figure 7.4: Oxygen ingress contour plots ...................................................................... 97
Figure 7.5: Oxygen ingress contour plots ...................................................................... 97
Figure 7.6: Tailgate methane comparison with respect to GVBs location .............. 98
Figure 7.7: GVBs flow vs. setting depth above coal seam ........................................... 100
Figure 7.8: Methane concentration in GVBs exhaust vs. setting depth ..................... 101
Figure 7.9: Normalized EGZ volumes and CH_4 with respect to setting depth ......... 102
Figure 7.10: EGZs location vs. setting depth ............................................................... 103
Figure 7.11: EGZs location vs. setting depth ............................................................... 103
Figure 7.12: GVBs flow vs. diameter ........................................................................... 105
Figure 7.13: GVB methane concentration vs. diameter .............................................. 105
Figure 7.14: GVBs diameter vs. normalized EGZ volume and CH₄ in returns............. 106
Figure 7.15: Oxygen contour plots comparison for different GVBs diameter............. 107
Figure 7.16: Normalized EGZ volume and TG methane comparison...................... 110
Figure 7.17: GVB and methane inlet pressure contours in gob and fractured zone.... 111
Figure 7.18: Pressure profile of a GVB (20 cm diameter)........................................ 112
Figure 7.19: GVB radius of influence..................................................................... 113
Figure 8.1: Vertical cross-section of model geometry ............................................. 117
Figure 8.2: Progressively sealed, U-type ventilation design................................. 117
Figure 8.3: Contour Plots of Explosive Gas Zone .................................................. 119
Figure 8.4: Oxygen Ingress Plots ............................................................................ 120
Figure 8.5: Normalized EGZ volume and CH₄ concentration plots....................... 121
Figure 8.6: Flow from face to gob and gob to face ................................................... 123
Figure 8.7: Flow pathlines in the gob....................................................................... 124
Figure 8.8: GVB Methane Concentration ................................................................ 125
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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</thead>
<tbody>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CFR</td>
<td>Code of Federal Regulations</td>
</tr>
<tr>
<td>CDC</td>
<td>Center for Disease Control</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>CSM</td>
<td>Colorado School of Mines</td>
</tr>
<tr>
<td>EGZ</td>
<td>Explosive Gas Zone</td>
</tr>
<tr>
<td>GC</td>
<td>Gas Chromatograph</td>
</tr>
<tr>
<td>HG</td>
<td>Headgate</td>
</tr>
<tr>
<td>MSHA</td>
<td>Mine Safety and Health Administration</td>
</tr>
<tr>
<td>NIOSH</td>
<td>National Institute for Occupational Safety and Health</td>
</tr>
<tr>
<td>OMSHR</td>
<td>Office of Mine Safety and Health Research</td>
</tr>
<tr>
<td>PRESTO</td>
<td>PREssure STaggering Option</td>
</tr>
<tr>
<td>RNG</td>
<td>Renormalization Group Theory</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>Semi-Implicit Method for Pressure-Linkage Equations</td>
</tr>
<tr>
<td>TG</td>
<td>Tailgate</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States</td>
</tr>
<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
</tr>
<tr>
<td>UBB</td>
<td>Upper Big Branch</td>
</tr>
<tr>
<td>UBJ</td>
<td>Ubiquitous Joint</td>
</tr>
<tr>
<td>USBM</td>
<td>U.S. Bureau of Mines</td>
</tr>
<tr>
<td>UDF</td>
<td>User Defined Function</td>
</tr>
</tbody>
</table>
U.S. Environmental Protection Agency .................................................USEPA
Volumetric Strain Increment ..............................................................VSI
Ventilation Air Methane .................................................................VAM
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To my late father, Ahmad Bukhsh
CHAPTER 1

INTRODUCTION

Coal mining continues to be an important component in U.S. economic activity, accounting for over 18% of total U.S. energy consumption and almost 39% of U.S. electricity generation is produced by coal, as shown in Figure 1.1. Figure 1.2 illustrates the coal production and coal usage by different business sectors in the U.S.

![Coal share in U.S. electricity generation. Source: EIA, Monthly Energy Review (March 2015)](image-url)
1.1 Introduction to Longwall Mining

In the United States, there are two primary techniques of coal mining: underground mining and surface mining. About 69% of U.S. coal comes from surface mines, while the remaining 31% comes from underground mines. The underground mining methods are the room and pillar (including conventional and continuous mining) and longwall. Longwall mining accounts for approximately 49.5% of underground coal produced (Humphries et al., 2013). Wider panels of longwall mining, combined with improved equipment lead to increased coal production. However, greater production of coal may lead to higher methane emissions and other gases (Tanguturi et al., 2012).

In the western U.S., the majority of coal mined underground is produced through longwall mining. Longwall mining maximizes coal production in underground beds that
do not have strong geological discontinuities, like faults or undulations. The initial step in developing a longwall mine is driving entries from the surface to the desired location of the longwall panel. A series of entries are then mined around the panel using continuous miners, leaving behind a solid block of coal, usually ranging from 900 m – 6000 m long and 240 m – 450 m wide. Once the development is complete, longwall machinery including shield support, face conveyor, stage loader and shearer is placed along the face and longwall mining begins. Fresh air is provided to the face and working sites by the mine ventilation system in a continuous flow. The intake side of the face is referred to as the headgate (HG), and the ventilation return is named as the tailgate (TG). A layout of longwall mining operations is shown in Figure 1.3.

Figure 1.3: Depiction of longwall coal mining method operations. (http://coalminingandgeology.com/coal-mining-2014/images-coal-mining-methods/, last accessed July 25, 2014)
A vertical, longitudinal cross section of a longwall is shown in Figure 1.4. Major longwall machinery includes the shearer, conveyer and longwall shields. When one cut is complete, the hydraulic shield supports advance and the roof collapses behind them; this forms the gob, sometimes known as the goaf.

Figure 1.4: Longwall miner layout. 
(A) Plan view, (B) Section view, (C) Shearer (Karacan, 2008a)
The longwall roof support, shown in Figure 1.5, consists of approximately 150 to 250 shields. The number of shields can vary depending on the length of the face and the width of the individual shields. The shields have a roof support canopy held up by hydraulic jacks. Hydraulic relay bars to advance the shields, as seen in Figure 1.6. The shearer, shown in Figure 1.7, cuts the coal while traversing the face of the longwall panel. The cutting drums break the coal and load it on an armored face conveyer.

The longwall eventually reaches the end of the panel, after having excavated nearly all of the coal in place. The strata above the coal collapses into the excavated space as the coal is removed. The collapsed material is compacted by the weight of the overlying strata, and forms the gob. Longwall coal mining results in large scale disturbance of the overlying rock mass; the fracturing and the caving of the mine roof take place behind the shields as the face advances. The resulting gob is a highly fragmented and fractured area.

The overlying rock layers fall into the mined-out space and break into irregular shapes of various sizes. The gob initially exhibits a high void volume due to the fragmented rock pieces and may provide high-permeability flow paths for gases flowing from surrounding formations into the mining environment.

Methane gas emissions from longwall gobs are one of the major problems in gassy coal mines. Longwall gobs gas emissions have increased substantially over the years and are set to increase with higher production rates, the increasing depth of mine workings, and the industry's trend towards wider and longer longwall panels in the future (Tanguturi et al., 2012).
Figure 1.5: Complete longwall system

Figure 1.6: Longwall shields and shearer on face
1.2 Longwall Ventilation

The major functions of ventilation in a longwall mine are to supply fresh air to the face and to dilute and remove gases and dust coming from the coal, equipment, and the mining environment. Concentrations of hazardous gases must be reduced to an acceptable level for the safety of miners. Both the safety and the productivity of the underground coal mines are affected by methane emissions. Up to a certain amount, methane emissions can be managed with an efficient ventilation design (Thakur, 2006). The main two types of ventilation designs are bleeder ventilation and progressively sealed gobs. In the United States, regulations require the use of a bleeder system. Exceptions are granted only if the mine has a demonstrated spontaneous combustion problem (30 CFR §75.334 (f)). In a bleeder design, fresh air is provided from the main
entries as shown in Figure 1.8, it then splits in three directions, towards the face, returns with the conveyer belt and inby the face to the bleeder fan. The face air goes in two directions, inby the face, deep into the mine, where it is exhausted to the surface by the fan via the bleeder shaft and tailgate return. Air from bleeder entries enters the gob to dilute the methane below the explosive limit and exhaust the methane to the surface.

Figure 1.8: Bleeder ventilation plan (Grubb, 2008)

The progressively sealed gob design must include methods to control spontaneous combustion and accumulations of methane–air mixtures in the worked out areas (Smith, 1994). Bleederless designs are used for longwall systems in other
countries with different regulations. They are the basis for the development of bleederless and modified bleederless systems in the United States (Grubb, 2008).

Both types of these ventilation systems are usually assisted by gob ventilation boreholes, which are drilled from the surface ahead of the mining to help reduce the methane in the gob area. The U type ventilation (bleederless), as illustrated in Figure 1.9, is used for progressively sealed gobs; the gob area is sealed progressively by building seals in the crosscuts along the headgate entries. In this ventilation design, the gob is inertized by nitrogen injection and GBV holes are used to reduce the methane in sealed gob area.

Figure 1.9: U-System of Bleederless Ventilation (Grubb, 2008)
The Y-system, shown in Figure 1.10, keeps the headgate ventilated for utilization as the tailgate on the next panel. The seals in the headgate are accessible for inspection and maintenance, but are more exposed to leakage and differential pressures (Smith et al., 1994). The U and Y systems can be altered with a back return, as shown in Figure 1.11. The back return allows a sweep of methane and oxygen deficient air from the tailgate corner of the gob (Smith et al., 1994). The back return design assists with compliance to the air quality requirements of 30 CFR §75.321 through §75.323, particularly in achieving concentrations of 19.5% oxygen, 0.5% carbon dioxide and 1.5% methane (30 CFR §75.321 to 30 CFR §75.323). This design also allows a high volume of air to be directed into the gob area and can result in high pressure differentials across the sealed gob and the flow of oxygen into the critical velocity zone (Koenning, 1994; Derick, 2007).
1.3 Gob Ventilation Boreholes

In longwall mines where methane emissions are higher, supplementary methane control measures are required. Methane emissions can originate from upper or lower unmined coal seams, longwall face, ribs, floor, coal on the conveyer belt, fractured sandstone, and the remaining coal in the gob area. To control the methane emissions in gassy coal mines, several techniques or the combinations of techniques are adopted.

Before mining begins in a longwall panel, vertical holes are drilled from the surface into the coal bed to extract methane from the coal bed reservoir. In addition, horizontal drill holes may be drilled from the entries around the panel to exhaust additional methane from coal bed.
Gob vent boreholes, or GVBs, are drilled into the gob area from the surface to remove the methane from the gob area while the longwall is operating. GVBs are generally drilled within 10 to 30 m (30 to 100 ft.) above the top of the coal bed into the fractured zone, but not into the caved zone. They are usually completed with a 18 cm (7-in.) casing and 60 m (200 ft.) of slotted pipe at the bottom (Karacan, 2007a). Vacuum pumps, referred to as blowers, are installed on the pipe to exhaust the methane from the vent holes. This suction creates a pressure sink to capture gas emissions before they can enter the underground workplace. For the GVBs to work effectively, they must be drilled near enough to the mined horizon to capture methane from the fractured zone above the gob. The setting depth should be sufficiently elevated above the caved zone to minimize the amount of ventilation air that is drawn into the vent holes. A schematic representation of a GVB operation is shown in Figure 1.12.

Figure 1.12: A schematic representation of longwall mining with shearer, fractures extending the overlying strata, bedding plane separation, possible methane flow paths (red arrows), air leakage from the face, and GVB (Karacan, 2009a)
CHAPTER 2

RESEARCH METHODS

This chapter outlines the research methodology used to complete the research presented in this dissertation. The description of the research motivation, objectives, tasks, questions and expected outcomes of the research follow.

2.1 Motivation for Research

The innovation and advancement in roof support and coal cutting machinery have led to the increased production of coal, but not without complications. The rapid rate of coal extraction results in increased gas emissions that require more ventilation air and well planned airway designs to dilute the resulting gases. Two of the most dangerous hazards in underground mining are explosions caused by methane and coal dust; these both have been responsible for huge losses of human life as well as property loss. Injuries and fatalities in underground coal mines in the U.S. from 2000 to 2010 are shown in Table 2.1.

Table 2.1: Methane accidents in underground coal mines between 2000 and 2010. (Source: MSHA)

<table>
<thead>
<tr>
<th>Year</th>
<th>Underground Coal Mine</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Willow Creek Mine</td>
<td>2</td>
</tr>
<tr>
<td>2001</td>
<td>Jim Walter Resources, No.5 Mine</td>
<td>13</td>
</tr>
<tr>
<td>2003</td>
<td>McElroy Mine</td>
<td>3</td>
</tr>
<tr>
<td>2006</td>
<td>Sago and Darby Mine</td>
<td>17</td>
</tr>
<tr>
<td>2010</td>
<td>Upper Big Branch Mine</td>
<td>29</td>
</tr>
</tbody>
</table>
Gob gas may constitute 40%-70% of the total gas emissions in coal mines (Jiachen et al., 2012). As a result, gob gas constitutes a major risk factor in gas explosions that must be mitigated. In the past 17 years, mine methane hazards have played a large role in the loss of life; some of these are directly attributable to gas escaping from the gob. In 1998, ignition of methane in the gob at the Willow Creek mine required sealing the mine, resulting in the loss of the mine (Goodman et al., 2007). In July 2000, a methane gas explosion originating in a gob at Willow Creek mine caused 2 worker deaths and 8 injuries. In 2006, an explosion in a sealed, mined-out area at the Sago Mine in West Virginia caused 12 fatalities and 1 injury. In Kentucky, May 2006, a similar accident at the Darby Mine resulted in 5 deaths. The most recent incident, in 2010 at the Upper Big Branch mine in West Virginia killed 29 miners and was attributed to explosive methane migrating from the gob into the tailgate area.

When ventilation alone cannot sufficiently dilute the methane, additional methane management techniques must be applied to bring methane concentrations to the acceptable levels. Degasification and methane control with GVBs are important to assist ventilation in controlling the methane levels, and to prevent methane and dust explosions in underground longwall coal mines.

In order to maximize GVBs effectiveness, it is important to understand the fundamental engineering and scientific principles in the design of gob ventilation boreholes such as well design, completion and operating parameters, spacing, diameter, setting depth and the number of boreholes required for different scenarios. As the GVBs extract methane, they draw air from face into the gob area. This air ingress into the gob can mix with oxygen and form hazardous methane-air explosive mixtures or
explosive gas zones (EGZs) within the gob. The identification of optimal GVB locations, well design, completion and operating parameters are necessary to minimize the explosion and spontaneous combustion hazard. Advanced computational fluid dynamics models and simulation techniques have the potential to offer the optimized methane control solutions for methane related safety problems. Several researchers have developed and used CFD models to analyze the gob environment and to predict related explosion and spontaneous combustion issues, as will be discussed in the literature review.

This research seeks to understand and investigate the role of gob ventilation borehole completion/operating parameters on GVB effectiveness and performance. This dissertation identified the optimal locations for GVBs to minimize EGZ formation and to effectively reduce methane levels in the working areas. This work also examined the effects of changes in ventilation design on the quality and quantity of GVB exhaust, using the commercial CFD code FLUENT, which is a finite volume computational fluid dynamics code that solves the Navier-Stokes equations for both incompressible and compressible flows.

2.2 Research Objective and Hypothesis

The mining industry is moving toward a zero harm policy for worker health and safety. Methane, one of the most serious hazards in underground coal mining, causes deadly explosions and has taken the valuable lives of miners. Most recently, the Upper Big Branch (UBB) mine explosion took the lives of 29 mine workers, and the company experienced severe economic losses while criminal prosecution of individual executives is ongoing. This research into improving and optimizing the GVBs will help to reduce the
risk of deadly methane explosions. It will give mine management a predictive tool to select GVBs locations. Mine operators will better understand how much total methane to expect in the gob, how much gas will be removed by GVBs, and how much will remain in the gob, possibly requiring inertization by nitrogen injection.

The role of GVBs in mine risk mitigation was examined, along with the individual design and operating parameters of GVBs in an effort to find the optimum design for each parameter. The results chapters discusses design guidelines for placement of GVBs to maximize their performance and reduce risk.

This research is based on the following hypothesis:

“EGZ hazards in longwall gobs can be minimized through suitable design, placement and operation of GVBs”.

2.3 Research Questions

This dissertation seeks to answer the following questions: what is the optimal GVB setting depth, what should be the diameter, what will be the effects of different ventilation designs on gob vent boreholes, and how many GVBs will be required to handle certain volumes of gas emissions. Additionally, this work will help the operators find the correlations between the ventilation plans and gob vent boreholes performance, and the explosion hazard in the gob.

Specific questions to be explored in this work are:

- What are the optimum locations of GVBs on a longwall panel?
- What is the area of influence of a GVB?
What are the effects of drilling and completion parameters of GVBs on EGZs in the gob and on methane exhaust quality?

How do drilling and completion parameters and operation of GVBs interact with mine ventilation?

2.4 Specific Aims and Research Tasks

The overarching aim of this research is to create safer working conditions for underground longwall coal mining. The research provides an overview of the GVBs’ role in reducing the risk of methane fires and explosions. It also identifies the optimal location, placement and operating parameters for GVBs, which minimize EGZs. Although the industry has a good understanding of GVB design and placement parameters, the effects of design, placement and operating parameters on EGZ formation are not clearly understood. This research addresses these issues.

Miners generally perceive that additional ventilation air on the longwall face will improve methane dilution on the face and in the tailgate. In contrast, CFD modeling studies reveal that increasing longwall face air quantities may increase the gob explosion hazard as they result in increased EGZ volumes in the gob. Additional face ventilation may also create increased methane quantities in the tailgate return as additional methane is flushed out of the gob. A face ventilation study is presented and discussed in this dissertation.

As it is impossible to take manual air quality readings from within the gob, CFD modeling becomes an indispensable tool to analyze the role of GVBs on the internal gob atmosphere. Mines take gob gas samples at certain points along the periphery of the gob through seals, using a tube bundle system. These readings can only reveal gas
composition in the fringes around the gob, not from deep within the gob. This research identifies variations in explosive mixtures found within the gob along with changes in the performance of GVBs.

Achieving a better understanding of gob and gob gas characteristics and their behavior in the longwall mine environment will aid the industry in approaching the zero accident goal by giving mine operators better tools to manage potentially explosive atmospheres within the mine. By employing CFD modeling, this research is more accurately able to simulate the gob atmosphere and understanding the impacts of how methane and ventilation air interact inside the gob. This creates a clearer picture of how strategic deployment and operation of GVBs will reduce explosion hazards and create a safer working environment.

2.4.1 Permeability and Porosity fits for CFD Modeling

Marts et al. (2014a) generated a geomechanical model from the stratigraphy of a cooperating mine to determine porosity and permeability values for the longwall gob used in this study. The volumetric strain increment (VSI) output of the geomechanical model was converted into porosity and permeability values and used as input as piecewise equation fits for different parts of the gob in the CFD model. As the overburden collapses behind the longwall shields and the gob forms, initial porosity and permeability are high. As the face moves forward, over time, the gob increasingly compacts and its porosity and permeability decrease.

Researchers at CSM have employed the geomechanical model (Marts et al., 2014a; Wachel, 2012) using FLAC3D software to simulate different aspects of the longwall mining and overburden subsidence process. Wachel simulated an active face
removing the coal and replacing it with the gob in a single step extraction. A Mohr-Coulomb failure criterion was used as an assumption of the elastic behavior of gob material, and a double yield model was developed and used for the study of gob compaction behavior. The porosity of the gob was calculated from the void volume and the volumetric strain increment values. The permeability was calculated from the porosity values using the Carman-Kozeny relationship (Marts et al., 2014a). The overburden was simulated using the ubiquitous joint (UBJ) model available in FLAC3D. The implementation of the UBJ model allows for sliding along failure planes due to the inclusion of joints giving the rock mass an anisotropic response (Marts et al., 2014). The properties of the UBJ model for friction angle, cohesion, and tensile strength were taken from a paper by Esterhuizen et al., (2010). A stepped extraction technique was used in the model where coal was removed in small steps and subsequently replaced by gob material. The geomechanical model was allowed to reach equilibrium after each step to allow the time for rock failure, compaction and stress redistribution before executing the next step.

2.4.2 Computational Fluid Dynamic Model (CFD Model)

The CFD models were developed using ANSYS® FLUENT®. The numerical model incorporated strata layers, the gob, GVBs and mine workings including headgate, tailgate, headgate void, tailgate void, longwall face with shields and orifices, crosscuts, and entries. A modular meshing approach, developed by Gilmore et al., (2015), was used to combine the mesh modules into the full CFD model mesh. In this approach, all basic mesh modules of the CFD model were created and combined into a library of mesh files. A journal file of FLUENT® commands was written to assemble the mesh
files. These mesh modules were created following the guidelines provided by ANSYS® for high cell quality and low skewness. Where required, inflation layers were included to refine the mesh near walls. The ventilation airways that usually experience turbulent flow were modeled with a combination of inflation layers and tetrahedral mesh elements. The porous regions of the gob that dominate the flow contain hexahedral elements only. These elements are better suited for modeling slow moving flow. Another advantage of the modular meshing technique is that users can make small changes to the mesh files without having to rebuild the entire model. This method minimizes the introduction of errors and maintains the greatest possible consistency between model variants.

Initially, a base case CFD model of a progressively sealed gob was created with GVBs at the same locations and same design parameters as they are on Mine C (the cooperating mine that provided calibration data). Once the model was validated, then changes were made in the location of boreholes, the number of boreholes, setting depth, length of slotted casing, diameter of GVBs, well head suction pressure, spacing, and the distance from the face. Each parameter value was optimized independently of each other. GVBs and ventilation interference was also analyzed. The GVBs were examined under varying amounts of methane emissions.

2.4.3 Summary of Research Tasks

The following tasks are completed in this dissertation:

- Development of permeability and porosity values for different rock layers of fractured zone or strata.
- Development of strata layer mesh modules with varying GVBs parameters.
• Using the CFD model to simulate changing GVB design and completion parameters, and optimizing each one of them such as diameter, slotted casing length, setting depth, spacing, distance from gateroads, and suction head.
• Estimating the area of influence of each GVB.
• Studying the face ventilation air and GVBs interference, and optimizing both of them.

2.5 Cooperating Mine C

The data to build the geometry and layout of the models used in this research were provided by a partner western U.S. longwall coal mine, identified as “Mine C”. The data was also used to validate the model. The extraction height of the coal seam is 11 feet (3.4 m) with a depth of cover of 450 ft. (140 m). Mine C is immediately overlain by weaker mudstone and shale, forming the gob. The reported average subsidence value for this mine is 77% of the coal seam height. The mine uses nitrogen injection and a tube bundle monitoring system to evaluate ventilation changes. Mine C, like many other underground coal mines, is considered gassy and must deal with methane emissions from the mined coal and the disturbed, surrounding strata. Using GVBs to capture the methane before it reaches the active mining face reduces methane emissions. Mine C is the prime focus for GVB research in this proposed research as Mine C has provided useful GVB operating data for validation and calibration of CFD models. Once validated, current modeling approach may be applied to other mine strata and geometries as well.
2.6 Expected Research Outcomes

The models developed in this dissertation can be used to improve the safety of longwall mines by giving mine management predictive tools for GVB placement and reducing the risk of methane explosions in mine. From current research, mine operators will better understand the design of GVBs and the role they play in reducing methane concentrations in the gob and minimizing the formation of EGZs.

This research informs the optimization of GVB placement, drilling and completion parameters, as well as the number of GVBs necessary to handle the methane found in the gob area. The research will help to optimize the longwall face quantity of air.

2.7 Original Contributions to Science

The research presented in this dissertation on GVBs completion and operating parameters optimization and face ventilation air quantity optimization for has following contributions to the field of science:

1. The GVBs completion and operating parameters have been optimized in reducing the explosion hazard, methane in the working areas and spontaneous combustion hazard rather than maximizing methane extraction. Research on GVBs done in the past has focused on cumulative methane production and GVBs exhaust methane quality, which may not result in a reduction of explosion hazards.

2. The area of influence of GVBs has been determined and it has taken into account the interaction between multiple GVBs operation and with the face ventilation.
3. The face ventilation quantity has been optimized. It was found that, counter to
general perception in the mining industry; higher air flow quantities on the face may
increase the explosion and spontaneous combustion hazards.
CHAPTER 3

BACKGROUND

This chapter discusses methane hazards, and reviews the current industry standard methane monitoring and safety practices. Also, previously published work on gob ventilation boreholes is examined, relative to expected improvements resulting from this research.

3.1 Methane

Methane is a gas generated during the coal formation process, called "coalification". When coal is mined, methane is released from the coal seam and the surrounding disturbed rock strata. The mining of a coal seam leads to the release of methane trapped within the coal seam. Due to the changes in strata stresses, gas from surrounding strata may move towards the mining area which acts as a pressure sink.

The methane content in coal depends on number of factors, the most important of which are coal rank, coal seam depth. As the depth of the coal seam increases, the overburden stresses and gas pressures also increase, resulting in a tighter capture of gas inside the pores of coal and strata. Methane gas is released when a coal seam is mined. The methane entering the working environment is normally diluted by ventilation air and is termed as Ventilation Air Methane (VAM). Methane released from the worked coal face is diluted and removed by large ventilation systems designed to move air through the mine workings. Methane may also be released into and trapped in the gob. Bleeder ventilation systems aim to dilute methane within the gob to concentrations
below the explosive range of 5-15%, with a target for methane concentrations of less than 2% in the return (30 CFR §75.323(e)).

3.2 Methane Hazard Mitigation

Mine operators have various tools to monitor the mine environment for hazardous gases and to mitigate the risk of methane ignitions and explosions, enabling them to maintain a safe working environment. These technologies include air quality monitoring systems, degasification, gob vent boreholes, and the injection of nitrogen to inertize an explosive mixture of methane and oxygen, if present. A review of all these practices is described below.

3.2.1 Air Quality Monitoring Systems

Different types of monitoring systems are used in underground coal mines to monitor gases like methane, carbon dioxide and carbon monoxide, among others. Operators choose one or a combination of several monitoring systems. Common monitoring systems include:

- Hand held gas detection devices used in spot inspections
- Gas bag sampling and gas chromatographic systems
- Telemetric, continuously monitoring, fixed sensor systems
- Tube bundle systems
The handheld devices carried by mine personals, measure concentrations of gases at the points of interest. Such devices can measure gases like methane, oxygen, hydrogen sulfide, and carbon monoxide. These hand held devices are normally set with an alarm if gas concentrations exceed a given threshold value.

Gas bag samples are collected manually from different points of the mine, and are analyzed for different gases including hydrogen, methane, oxygen, nitrogen, carbon dioxide, carbon monoxide, ethylene, and acetylene using gas chromatography. The analysis of the samples usually takes place at the surface. Gas chromatographs (GCs) have been used for the past few decades. Samples are passed through a column of the inert carrier gas like helium and are identified electronically as they are emitted in sequence as relegated by their retention properties (Grubb, 2008). The invention of ultra-fast gas chromatographic systems, shown in Figure 3.1, has resulted in wide acceptance and use of these systems.

Figure 3.1: A typical gas chromatograph installation (Mason, 2012)
Tube bundle systems are used for gas sampling in situ underground. A pump draws in the sample through a long tube connected to the underground sampling location and sends it to an online analyzer at the surface. A typical tube bundle system flow diagram is shown in Figure 3.2. Tubes for collecting samples can be several kilometers long.

Analyzers for a tube bundle system typically measure concentrations of methane, carbon monoxide, carbon dioxide and oxygen. Other gases like hydrogen, ethylene, and acetylene can be analyzed using a GC. A sample of measurement data of a tube bundle system in the gob is shown in Figure 3.3.

The tube bundle system has several advantages over other monitoring systems. The system can draw samples from behind seals and from other inaccessible areas. The analyzers operate at high resolution over a wide range of gas content values. Also, the tube bundle system does not depend on underground power or fan systems. However, tube bundle system response is not immediate because samples have to travel several kilometers from sampling point underground to the surface, so a delay time can last from several minutes up to an hour. The tubes can have problems leaking, so inspection and surety that samples are not polluted by leakage is necessary. Freezing and condensation of water in the tubes can cause problems in colder climates. The accuracy of measurement of more reactive gases such as sulfur dioxide and oxides of nitrogen may decrease in the plastic tubes during transport. Also, a back-up analyzer is recommended to ensure continuing analyses in the event of a failure of the system analyzer (Cliff et al., 1999).

Figure 3.3: Tube bundle data
Telemetric systems use real time sensors to measure methane, carbon dioxide, carbon monoxide and oxygen in the underground environment. These sensors are installed at strategic locations such as intakes, returns, belt conveyer, and other locations of interest (Cliff and Bofinger, 1998). These systems give real time warnings, and are best for reporting sudden events such as belt fires (Brady, 2008). Telemetric sensors have a limited range of measurement with high accuracy; they can measure up to 50ppm carbon monoxide, 5% methane, and carbon dioxide up to a few percent. Common gas sensor technologies are presented in Table 3.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Gases</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid state semiconductor</td>
<td>Wide-range with varying sensitivity</td>
<td>Cheap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Used in electronic noses</td>
</tr>
<tr>
<td>Catalytic combustion - includes Pellistor</td>
<td>Combustible gases particularly hydrocarbons</td>
<td>Subject to inhibition by sulfur gases and poisoning by silicones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Requires oxygen for combustion</td>
</tr>
<tr>
<td>Solid electrolytes</td>
<td>Oxygen</td>
<td>High temperature of sensor will combust any flammable gas present causing false reading</td>
</tr>
<tr>
<td>Aqueous electrochemical gas sensors</td>
<td>Oxygen, carbon dioxide, carbon monoxide, hydrogen</td>
<td>Acidic background gases can interfere with the electrolytes</td>
</tr>
<tr>
<td>Paramagnetic gas sensors</td>
<td>Oxygen, nitrogen oxides</td>
<td>Sensitive and gas specific</td>
</tr>
<tr>
<td>Photometric gas sensors (spectroscopic)</td>
<td>Wide range of gases</td>
<td>Non-intrusive</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Wide range of gases</td>
<td>Non-specific</td>
</tr>
<tr>
<td>Fiber optic gas sensors</td>
<td>Wide range of gases</td>
<td>Spectroscopic and also optrode linked to electrochemical</td>
</tr>
</tbody>
</table>

3.2.2 Inertization of the Gob

To render the gob atmosphere inert and prevent fires and explosions, inertization is used. Self inertization occurs when the gob is isolated from oxygen or sealed, allowing the atmosphere to fill with methane. Induced inertization describes the
introduction of an inert gas into the gob atmosphere to achieve an overall inert atmosphere. This can be done by using exhaust from jet engines or Tomlinson boilers or by injecting an inert gas like CO$_2$ or nitrogen. Induced inertization replaces or facilitates the natural inertization process. Inert gases like CO$_2$ or N$_2$ can also be used to inertize the area, but CO$_2$ is the more expensive option (Grubb 2008). CO$_2$ has been successfully applied to several operations. Carbon dioxide enriched combustion gases are more manageable agents for inertization than carbon dioxide alone (Cliff et al., 2004).

Nitrogen is also used in some underground coal mines to inertize the gob. It can be used to diminish the hazard of spontaneous combustion and reduce or eliminate explosive gas zones developed in the gob. There are two methods of nitrogen injection. Either boreholes are drilled from the surface and nitrogen is injected through them, or it is transported via pipes and injected through the cross cuts behind the longwall face. Nitrogen for inert gas injection is often produced on the mine site. It can be produced by air cryogenic separation, which results in high quality (99.9%) nitrogen. A less expensive method of producing nitrogen on site is via membrane plants; however, this is lower quality at 95 - 98% nitrogen. Nitrogen injection inertizes the explosive volume, bringing the gas mixture to the green area of the Coward triangle (Grubb, 2008) as shown in Figure 3.4, where it is no longer explosive. Self-inertization is a natural process where a mine area is sealed, allowing the atmosphere to come to an inert level. Methane continues to migrate into the gob, displacing other gases. In addition, coal oxidation processes consume the oxygen from the area (Grubb, 2008).
3.2.3 Coal Seam and Gob Degasification

When the mine ventilation system alone cannot handle the methane problem and emissions are high, additional measures, such as degasification, can be used to remove the methane. There are three main types of degasification systems as shown in Figure 3.5 and 3.6: cross measure boreholes, the superjacent method, and gob ventilation boreholes. These can be used singly or in combination.
Cross measure boreholes are often used in Europe; some of U.S. mines have tested this method as well. This method can be effective where operators cannot implement vertical gob wells because of surface constraints (Cervik and King, 1983). Holes are drilled from gateroads into the overlying or underlying strata; they are usually 50 to 100 mm in diameter. Their length and spacing is dependent on the stratigraphy and other geomechanical properties of the site (Brunner, 2000). To avoid the interference of ventilation air, the initial part of the borehole is cased. Boreholes are operated under vacuum to exhaust the methane from the strata. Reported efficiency of the cross measure boreholes is from 20% to 70% of total gas emissions (McPherson, 1993). These boreholes create low pressure above and below the coal seam so that emissions can travel towards them.

![Figure 3.5: Different gob gas recovery methods (Brunner, 2000)](image)

The superjacent method is shown in Figure 3.6. Galleries or entries are driven above and below the longwall panel, and can be into strata or coal. The entries above
the longwall panel are subject to subsidence. The purpose of such galleries is to provide access and long-term stability of boreholes. This method is used in highly gassy mines. Boreholes are drilled into the fractured strata from galleries. The method uses in-mine directional drilling equipment to develop 75mm to 100 mm diameter boreholes with lengths in excess of 1000 m. The method provides immediate access to overlying and underlying strata. The efficiency of this method is reported to capture from 80% to 90% of total methane emissions (Liu and Bai, 1997).

![Figure 3.6: Superjacent borehole drilled into overlying an underlying coal bed (Brunner et al, 2005).](image)

The gob ventilation borehole (GVB) technique is the dominant degasification method used in U.S. longwall coal mines. The boreholes are drilled from the surface in advance of the longwall face, normally 10 to 30 m above the seam. Boreholes have a casing and some portion of it is cemented. A schematic cross section of GVB is shown in Figure 3.7.
Figure 3.7: Schematic of gob ventilation borehole (Xue and Balusu, 2002)
3.3 Previous Gob Ventilation Borehole Research

Several experimental and numerical studies have been conducted for design, and to evaluate and optimize the performance of gob vent boreholes. These studies have been funded by U.S. agencies such as the U.S. Bureau of Mines, the CDC NIOSH Office of Mine Safety and Health Research (OMSHR), as well as by nongovernmental sources. An experimental study for evaluating the use of vertical boreholes to assist the ventilation of a longwall gob area was conducted by the U.S. Bureau of Mines (Elder, 1969) in the Kittanning coal bed at Bethlehem Mines Corporation mine no. 33. 61 million cubic feet of methane was captured by surface borehole using head vacuum pump. An increase in daily production was reported because of lowered methane concentrations in the return airways.

Another study for longwall gob degasification was conducted by the U.S. Bureau of Mines, using surface ventilation boreholes at the Lower Kittanning coal bed in central Pennsylvania (Moore et al., 1976). The study was carried out on a 3,200 ft. long, 570 ft. wide and 58 inches thick longwall panel. Two boreholes were drilled and monitored, as shown in Figure 3.8. The first borehole (No. 20) was 500 feet from the start of the panel and was drilled to a depth of 783 ft. before the panel started. It was completed with 8-inch steel casing down to a depth of 760 ft. The bottom 119 ft. of casing remained ungrouted and slotted to provide access for methane migration. The second hole (No. 21) was drilled 2,200 ft. from the start end and was 565 ft. in depth. During the development period, low methane emissions were recorded (23 cfm). Methane flow dropped 75% in the return entries after borehole 20 began production. When the longwall mining began, methane emissions rose to 1,500 cfm. Researchers monitored
borehole 20 for five days prior to, and then for three days following the borehole intersection. Figure 3.9 shows how the methane flow rate increased as the longwall panel advanced. When borehole 20 began production, the methane flow dropped significantly.

Figure 3.8: Map of study area. (Moore et al., 1976)

The U.S. Bureau of Mines conducted an experimental study to improve the performance of gob vent boreholes (Diamond et al., 1995). Researchers monitored 61 GVBs over a period of seven months at five longwall panels in the Lower Kittanning coal bed. The mine operator placed five holes near the centerline on a 216 meter wide panel and seven near margins of the panel located between 16.8 and 59.4 meters from the panel gateroads.
After seven months of monitoring, Diamond et al. (1995) reported that the near-margin holes produced 80% more methane than centerline holes, as shown in Figure 3.10. Diamond et al. reported higher permeability near the margins of panel, as shown in Figure 3.11. Near the margins, the strata are in tension and supported by pillars. They concluded that increased permeability was the reason for higher methane production of near-margins holes. The centerline strata were in compression, reducing the permeability of the gob over time, and most GVBs ceased production even before the completion of the monitoring period because of low permeability.
Figure 3.10: Depiction of Gob vent holes positions and their production over 7 month experimental study (Diamond et al., 1995)

Figure 3.11: Schematic diagram of a typical subsidence profile over an extracted longwall panel (Diamond et al., 1995)
Another study of gas capture from the longwall gobs was conducted in one of the gassiest mines in Australia (Balusu et al., 2005). This study entailed real time monitoring of mine methane and CFD modeling of the gob area. The mine had a two-entry gateroad system. The face was 200 m wide, and the length of panels varied from 1,000 m to 2,500 m. One longwall face and three continuous miner sections were in operation.

Two surface exhaust fans supplied 46,000 cfm of air at 2.1 kPa pressure. The active coal seam was at a depth of 420 m and had a gas content of 15 m3/t. Three rider seams were within 100 m and one rider seam was 30 m below the panel, significantly contributing to the methane emissions. The gas content was reduced with in-seam predrainage. Design parameters such as location, spacing of holes, diameter of the holes, slotted casing length, gob plant suction pressure, flow capacity, and number of holes in operation were studied.

Other elements of the study included field investigations, gob gas distribution monitoring, tracer gas studies, face gas profile monitoring, surface gob hole tests, CFD modeling studies, and caving modeling studies. The gas emissions from the longwall panel were reduced to 375 l/s, which could be diluted by ventilation. The average methane flow from surface GVBs was around 1.25 m3/s, with 75% methane as shown in Figures 3.12 and 3.13. Balusu et al., (2005) recommended near margin GVB drilling but at a sufficient distance from the gateroads that holes did not draw ventilation air and cause the spontaneous combustion problem. It was also reported that near margin gob ventilation boreholes produced more methane as compared to the holes near center of panel.
Figure 3.12: Gas flow rate from GVBs (Balusu et al., 2005)

Figure 3.13: Gas compositions from GVBs (Balusu et al., 2005)
A CFD study of gas drainage for gob gas capture was done on the Huang Sha coal mine in Hebei province (Jiachen and Hongbao, 2012). Total gas emissions were 0.2 m$^3$/s. The length of the model gob was 200 m. The results show the presence of a pressure sink because of gob vent borehole suction. The negative pressure region was sensitive to face ventilation. The presence of GVBs changed the characteristics of the gob gas concentration by exhausting the methane out of the gob. Jiachen and Hongbao concluded that, in order to improve the efficiency of gas drainage and to increase the gas drainage concentration, the location of drainage boreholes is important.

The mines in the Pittsburgh coalbed in the eastern United States have been the subject of extensive study for methane drainage, geomechanical modeling, and GVB research. Karacan (2009a) study examines the system of degasification selection for U.S. longwall mines using an artificial neural network (ANN) structure. It discusses the development of an expert classification system that can be used as a decision making tool to select the best degasification system for gassy coal mines based on the particular conditions of U.S. longwall operations. Results from ANN analysis suggest that the model can be used for different mines by changing the variables according to the conditions of a particular mine. The ANN modeling results can also be used as starting point for further optimization studies of GVBs and gas emissions (Karacan, 2008a).

Karacan (2008b) developed a method for calculating the permeability of the gob for air leakage calculations and improvements in methane control. The method is based on the principles of scaling and a fractal porous medium. This approach can predict the
porosity and permeability of the gob, which is helpful for prediction of flow amounts and flow patterns in the gob.

Karacan (2009b) also conducted a study to reconcile longwall gob gas reservoirs and gob venthole production performances using a multiple rate drawdown well test analysis. During this study, wellhead gas production rates and pressures were monitored for six GVBs on adjacent longwall panels during and after mining. This study shows a well test analysis method that can be used to calculate the permeability of the gob and around the GVBs, radius of investigation, total and mechanical skin around the GVBs, GVBs flow efficiencies, and damage ratios.

The impact of longwall panel width on the methane emissions and the performance of GVBs were studied by Karacan et al. (2007a). Reservoir modeling predicts increasing methane emissions due to the increase in longwall panel width. Optimizing GVB completion practices can capture more methane in the subsided strata above longwall panels. A 380 m (1,250 ft.) wide panel in the Pittsburgh coalbed provided the base case data and calibration; and a 440 m (1,450 ft.) wide panel was modeled for the simulations. Different GVB placement configurations were modeled to investigate the options for optimizing methane capture. The results show that increasing panel width may increase methane emissions due to the exposure of the gob environment to a larger area of fractured, gas-bearing strata. The results also show that the performance of the GVBs does not change with an increase in panel width unless there is a change in the permeability and saturation fields. The simulation results present optimal well completion configurations of GVBs, as shown in Figure 3.14. They
also show that moving the location of the GVB towards the centerline and away from the tailgate will reduce the gas drainage capability of the GVBs.

Karacan et al., (2006) examined the development and application of reservoir models for the evaluation and optimization of longwall methane control systems. Their results indicate that, by increasing the casing diameter of GVBs, the cumulative methane production increases, although methane concentrations in the GVBs decrease slightly. The results also demonstrate that longer slotted casing lengths produce more methane, and that the setting depth for the casing plays an important role relative to the concentration and volume of methane captured. If setting depth reaches into the estimated caved zone, the methane concentration of GVB exhaust decreases by approximately 30%.

Esterhuizen and Karacan (2005) conducted a study to determine the impact of gob permeability distributions. FLAC\textsuperscript{3D®} was used for geomechanical modeling, using a two stage approach to combine the output of geomechanical models with reservoir models. Esterhuizen and Karacan demonstrate that the approach can simulate the complex process of methane emission and flow around longwall panels in coal mines. Balusu et al. (2005) developed longwall gob gas drainage and control strategies for highly gassy mines, and concluded that GVBs provide the highest capacity and lowest cost option for gob gas drainage. Their results show that the GVBs should be drilled at 30 to 70 m from the gate roads depending on the longwall caving characteristics. The authors of this study recommend that the ventilation system should be designed to minimize the oxygen ingress into the goaf, including the immediate sealing-off all the cut-throughs behind the face, in order to improve overall gas drainage efficiency.
Figure 3.14: GVBs configurations and locations for the cases tested (Karacan et al., 2007a).
Schatzel et al., (2006) examined the prediction of methane emissions from wider longwall faces by analyzing the emission contributors. Results indicate that coal production and transportation factors have a dynamic effect on methane emissions on longwall face. Field measurements indicate that increases in methane emissions for wider longwall panels result primarily from the coal transported on the face conveyor and from direct emissions from the exposed coal on the face.

3.4 Improvements over Previous Research

This dissertation addresses two specific aspects of improvement in GVB research: improvement of permeability and porosity values of fractured zone and CFD modeling improvement. It is impossible to directly measure gob porosity and permeability in the gob and fractured zone. As a result, geomechanical modeling efforts become invaluable in order to define the values of porosity and permeability. More accurate CFD results can be obtained with more actual values of porosity and permeability as input. Researchers have previously modeled underground longwall gobs to derive porosity and permeability values using numerical models, such as Yavuz (2004), Esterhuizen et al. (2010), Esterhuizen and Karacan (2005), and Wachel (2012) and many others using the single step extraction method in FLAC$^{3D}$ to simulate the gob compaction, their results indicate the symmetric distribution of the subsidence profile from startup room to recovery room. Work done by the U.S. Bureau of Mines, shown in Figure 3.15, confirms that this is not an accurate representation as subsidence changes over time and along the length of panel so subsidence can not be symmetric along the length of panel.
An effort to refine the results of geomechanical modeling was carried out by Marts et al., (2014a). Sequential extraction of coal was used to record the effects of dynamic gob compaction. The FLAC\textsuperscript{3D} model was allowed to equilibrate before the each extraction step. The overburden was modeled using FLAC’s built in Ubiquitous Joint (UBJ) model to simulate anisotropic gob compaction. Marts et al., (2014a) models results are more realistic as stepped extraction was used and resultant subsidence profile was similar as depicted by Campoli et al., (1993). The models were validated against Mine C subsidence and shield loading data. From volumetric strain increments shown in Figure 3.16, porosity and permeability values were calculated and used as input into the CFD model in the form of a written FLUENT\textsuperscript{®} user defined function (UDF). This UDF is used in the CFD model for the gob vent borehole studies, a more realistic representation of an actual scenario.
In previous GVBs studies, the fractured zone permeability and porosity was simplified and did not take the variation in horizontal (X,Y) direction into account. This project uses the stress-permeability relationships (Kelsey et al., 2003) to calculate the fracture zone flow parameters, developing 3-D permeability and porosity fits to use in the CFD model.

Figure 3.16: Modeled method of extraction’s effect on gob compaction (volumetric strain) (Marts at el., 2014a)

Karacan (2006, 2007a, 2007b, 2009a, 2009b) conducted numerical modeling efforts for gob ventilation borehole studies using reservoir models to simulate design and operating parameters to predict performance of gob vent boreholes. Since reservoir modeling tools are not built to simulate flow in open spaces like the headgate, tailgate, and face openings, Karacan’s early modeling assumed simplifications, such as assigning 100% porosity and negligible resistance to openings (Esterhuizen & Karacan, 2007). Also, in previous modeling, mine entries were modeled as fractures. When
porosity is set to 100%, the governing equations simplify to laminar flow. Actual flow in mine openings is predominantly turbulent, skewing the results (Worrall, 2012). Researchers also observed the presence of an open void adjacent to the gateroads behind the shields (Worrall, 2012). Shield leakage into the gob and from the gob to the face and tailgate is modeled by inserting small openings in the interface between the gob and face to permit air leakage.

This project documents the impact of GVB design and operating parameters on the volume of explosive gas zones (EGZs) in the gob. The work presented in this dissertation optimizes the GVBs placement and operating parameters both with respect to methane extraction and with respect to minimizing EGZ hazards.
CHAPTER 4

CFD MODELING ENVIRONMENT

The building of CFD models for this research involved a number of steps. The geometries of the model parts were created using the ANSYS Design Modeler. The geometry pieces were meshed using the ANSYS meshing module, and assembled together into single model in FLUENT®. Gilmore (2015) discussed the details about geometry and mesh creation. A more detailed description of approach to assemble the mesh modules into model and creation of porosity and permeability fits and UDF can be found in Gilmore (2015) dissertation.

This chapter discusses the ventilation scheme used in the modeling and simulation process. The meshing approach and mesh quality parameters are discussed in the meshing section. Finally, it describes the simplifications and assumptions used during the modeling process.

4.1 Longwall Mine Ventilation Layout

There are two types of ventilation systems used in underground longwall coal mining operations: bleedered ventilation and bleederless, or progressively sealed, ventilation, sometimes called a U ventilation system. The bleedered ventilation is used primarily in the United States; it functions by sweeping fresh air into the development entries surrounding the gob in order to ventilate the gob area. The purpose of this process is to dilute the methane inside the gob to a concentration below the explosive range. The bleederless ventilation method uses progressive sealing of cross cuts surrounding the gob. The model developed for this project is constructed of data from a
cooperating partner mine, Mine C, which uses progressively sealed, or bleederless, ventilation.

The CFD models constructed for this dissertation used a U ventilation design for a progressively sealed panel, as shown in Figure 4.1. The fresh intake air enters the longwall face through the headgate, travels across the face and leaves through the tailgate. Concrete seals are constructed in the cross cuts, and the gateroads are progressively sealed as the panel advances. Nitrogen injection is used to inertize the gob if the mine has identified spontaneous combustion problems. GVBs are used to extract methane from the gob to assist methane dilution in the ventilation process. Gilmore et al. (2014) concluded that U-ventilation is an effective method to limit oxygen ingress into the gob to prevent spontaneous combustion.

![Figure 4.1: Progressively sealed, U-type ventilation](image)

Figure 4.1: Progressively sealed, U-type ventilation
4.2 CFD Model Geometry

The CFD models were developed based on actual mine maps and represent the geometry and stratigraphy of Mine C. The mine data included information about gas monitoring, methane drainage, and lithology of the overburden. Development of the model geometry and mesh creation required some simplification of the mine geometry, while preserving the actual conditions as much as possible. The ANSYS Design Modeler platform was used to create the model geometry.

The study used a panel length shortened to 460 m. The findings by Worrall (2012) demonstrated that it is not necessary to model the entire length of the gob when studying progressively sealed panels. Worrall (2012) stated that modeling results do not change after first 300 m of gob in bleederless type gob. Also the prime focus for the hazard assessment and mitigation is near the face, where explosive mixture can get ignition source. Detailed descriptions of each modeling element part are found in the following sections.

4.2.1 Gob Model

The gob in the CFD model used a full panel width of 305 m and 4560 m in length, as shown in Figure 4.2. The height of the caved gob or rubble zone was 13 m based on the data from Mine C. The gob was assigned permeability and porosity equation fits in FLUENT®, using the porous media model developed by Marts (2015). The gob itself was divided into several compartments to have good meshing control near the longwall face to improve the capture of detailed flow features.
4.2.2 Voids along the Gob Fringes

During several visits to cooperating mines, investigators on this project observed a void on the headgate and tailgate side of the gob. Mine C has a continuous open void along both sides of the caved gob. A photograph of the void is shown in Figure 4.3,
The length of these open voids cannot be determined visually. High levels of oxygen were measured behind the seals for several hundred feet in by the face (Worrall et al., 2012). This suggests that an open air passage exists that allows fresh air to flow along the fringes of the gob. The presence of this void has a significant effect on the flow characteristics in the gob (Worrall, 2012); hence this void is included in the model.

The geometry of the void developed in ANSYS Design Modelar is shown in Figure 4.4. The bottom width of the void is 0.9 m (3 ft.); the top width is 0.3 m (1 ft.) and it is 12.8 m (42 ft.) in height. The top edge has an offset-x of 4.7 m (16 ft.) to fit with the gob. The length of the void is equal to the length of the gob, 457 m (1,500 ft.).
4.2.3 Coal Face and Longwall Shield geometry

The section of the longwall face in the CFD model is represented in Figure 4.5. The width of the face is 293 m. When the headgate and tailgate are added to the face, the total width becomes 305 m. The height of the face is 3.3 m and its depth is 6 m. Air can flow from the face to the gob through gaps between the shields. These gaps are
modeled by placing a window in the center of the face approximately every 9.1 m (30 ft.). This approach to visually represent shield leakage was first employed by Worrall (2012). Worrall assumed, based on field measurements, that the average gap area between each pair of shields is 0.23 m$^2$ for every five shields. The shields gaps have model dimensions of 0.3 m by 0.76 m, as shown in Figure 4.5. The model headgate entry is 29 m long, 6 m wide and 3.3 m in height as shown in Figure 4.6. The same geometry is used for the tailgate. The cross cuts are 15 m long, 6 m wide and 3.3 m in height.

Figure 4.5: Face geometry with shields gaps
4.2.4 Fractured Zone Geometry with GVBs

During an active longwall mining operation, the coal is continuously cut by the shearer and extracted. Following extraction, the shield supports are advanced. As the shields move forward along the panel, the immediate roof is allowed to collapse into the void behind the shields. The collapse of roof rock forms a pile of rock fragments known as the gob. The passing longwall face also disturbs the strata overlying the gob,
referred to as the fractured zone, shown in Figure 4.7. The fractured zone is represented as layers in the geometry of the model. The height of the layers is determined from the stratigraphic column provided by Mine C. The modeled fractured zone was divided into five layers based on rock type, as shown in Figure 4.8.

Figure 4.7: Vertical cross section showing zones of disturbance above a longwall panel (Esterhuizen and Karacan, 2005)

<table>
<thead>
<tr>
<th>Fractured zone layer 5</th>
<th>8.8 m thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractured zone layer 4</td>
<td>8.8 m thick</td>
</tr>
<tr>
<td>Fractured zone layer 3</td>
<td>3 m thick</td>
</tr>
<tr>
<td>Fractured zone layer 2</td>
<td>3 m thick</td>
</tr>
<tr>
<td>Fractured zone layer 1</td>
<td>3 m thick</td>
</tr>
<tr>
<td>Gob</td>
<td>13 m in height</td>
</tr>
</tbody>
</table>

Figure 4.8: Geometry of fractured zone in the CFD model
The total height of strata is 135 m to the surface. Only the 27 m immediately above the gob are represented in the CFD model. The mining induced stresses are used to calculate the permeability of the fractured zone. The geomechanical analysis showed that above 25 m there is no significant change in the roof rock permeability. At Mine C, above the fractured zone, there is a rider coal seam, which has been identified as the source of methane seeping into the gob. The model includes GVBs within the fractured zone. The number of GVBs modeled on the panel varies by modeling case. The maximum numbers of GVBs over a panel were seven.

4.3 Meshing

The geometry parts of the model have been meshed in the ANSYS meshing module. Cut cell meshing is used in the gob and fractured zone meshing. Other sections are meshed using edge and face sizing controls, mapped face controls, and where applicable, inflation layers, for smooth transitions. The details about meshing approach can be found in Gilmore (2015) Ph.D. dissertation. The minimum mesh quality of 0.25 and a maximum skewness of 0.85 were achieved while meshing all parts of the model. The gob was divided into compartments as shown in Figure 4.2, and meshes controls were applied near the face and center of the gob to obtain a highly refined mesh. The near face 30 m of gob was meshed with element size of 0.2 m (0.6 ft.). The center of gob was 182 m in length after the first 30 m was meshed with 0.4 m (1.2 ft.) cell size. The back of gob after first 212 m, which was 245 m long has been meshed with cell size is 1.8 m (6 ft.) as shown in Figure 4.9. There are 3.76 million total cells in the gob area. The hexahedron elements were used to mesh the gob since they solve more efficiently and are more representative for the gob areas, which demonstrate
laminar flow. The minimum elemental quality of mesh is 0.72 with maximum quality of 0.99, as shown in Figure 4.10. The skewness metric for the gob mesh is shown in Figure 4.11, which demonstrates excellent quality gob mesh. In addition to mesh controls, the inflation options were used for a smooth transition, using 5 inflation layers with 1.2 growth rate.

Figure 4.9: Gob mesh
Figure 4.10: Quality of gob mesh

Figure 4.11: Skewness of gob mesh
The fractured zone was meshed using the cut-cell method along with other mesh generation control options. The presence of gob ventilation borehole geometries in fractured zone, which were 20 cm (8 in), 30 cm (12 in) and 40 cm (16 in) in diameter, presented a challenge for meshing. The GVBs were very small compared to the fractured zone domain, making it challenging to generate high quality mesh. The fractured zone mesh is shown in Figure 4.12.

The face sizing function was used to mesh the faces with local minimum size of 0.006 m. The minimum mesh quality of 0.35 and maximum skewness of 0.6 were maintained in the fractured zone mesh, as shown in Figure 4.13 and 4.14. The body sizing function was used to mesh GVB geometries with an element size of 0.05 m (0.16 ft.). The edge of GVB geometry was divided into at least three divisions. The 30 cm diameter GVB polygon has 15 cm of edge length and is divided into three elements of 5cm size. The minimum size of element in GVB meshing changes as the GVB diameter changes.

The transition of GVB small mesh into the coarse mesh of the fractured zone was achieved by applying transition and inflation functions. The maximum size of element in the fractured zone was 1.5 m. A total of 24 fractured zone mesh modules were created and meshed with varying diameters, settling depths and other location parameters. The number of elements in each module varied as per sizing requirement of each module and its subgeometries. One module, with GVBs of 30 cm (12 in) diameter, has 6 million cells. The range of elements in fractured zone modules varied from 5 to 7 million cells depending on required sizing functions. The smaller the GVB diameter, smaller mesh sizing is required to get the good quality mesh.
Figure 4.12: Fractured zone mesh
Figure 4.13: Fractured zone mesh skewness matric

Figure 4.14: Fractured zone mesh quality matric
The headgate entry was meshed with the cut cell method using a 3.8 cm (0.125 ft.) cell size. The headgate mesh minimum quality was 0.40 with maximum skewness of 0.72. The void was meshed with a maximum of 0.3 m (1 ft.) cell size and has a minimum quality of 0.28 and a maximum skewness of 0.52. The longwall face used the cut-cell method, with 0.03 m (0.125 ft.) face sizing controls, with the maximum size cell set to 0.3 m (1 ft.). The face mesh module has a total of 460,000 cells. The minimum quality was 0.40 and the maximum skewness was 0.72. The crosscut mesh used the mapped face controls on the walls and inflation. The total number of cells is 8,500 with a minimum quality of 0.20 and a maximum skewness of 0.86. Once all geometry parts were meshed, they were assembled into the final CFD model using modular meshing approach developed by Gilmore et al., (2015). The final CFD model developed by assembling mesh modules is shown in Figure 4.15.

Figure 4.15: Full CFD model mesh
4.4 Porosity and Permeability Assumptions

The permeability and porosity values in the gob and fractured zone are critical to accurately determining the flow characteristics and GVB performance. The CFD models require the permeability and porosity input in the form of UDF.

Researchers have used different approaches to define the permeability of the gob and fractured zone including direct measurement, numerical modeling and empirical derivations. In this research, the gob permeability and porosity was calculated from the geomechanical models developed by Marts et al. (2014a). The permeability and porosity of the fractured zone layers have been calculated using mining induced stress data from geomechanical modeling based on stress-permeability relationships (Kelsey et al., 2003). The rock strength parameters used in the geomechanical modeling were from Mine C. The properties of the UBJ model for friction angle, cohesion and tensile strength were taken from Esterhuizen et al. (2010), as shown in Table 4.1.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Bulk Modulus</th>
<th>Shear Modulus</th>
<th>Density</th>
<th>Cohesion</th>
<th>Friction Angle</th>
<th>Dilation Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>1,940 MPa</td>
<td>1,460 MPa</td>
<td>2,400 kg/m³</td>
<td>1.2 MPa</td>
<td>42 Degrees</td>
<td>15 Degrees</td>
</tr>
<tr>
<td>Mudstone</td>
<td>850 MPa</td>
<td>510 MPa</td>
<td>2,380 MPa</td>
<td>0.4 MPa</td>
<td>38 Degrees</td>
<td>10 Degrees</td>
</tr>
<tr>
<td>Shale</td>
<td>690 MPa</td>
<td>520 MPa</td>
<td>2,550 MPa</td>
<td>0.8 MPa</td>
<td>27 Degrees</td>
<td>15 Degrees</td>
</tr>
<tr>
<td>Coal</td>
<td>580 MPa</td>
<td>440 MPa</td>
<td>1,330 MPa</td>
<td>0.4 MPa</td>
<td>48 Degrees</td>
<td>10 Degrees</td>
</tr>
</tbody>
</table>

Marts (2015) validated the geo-mechanical model against the subsidence and shield loading data provided by Mine C. The subsidence prediction from the
A geomechanical model is quite close to the actual field measurements provided by Mine C, as shown in Figure 4.16. Also, shield loading data provided by Mine C agrees with the model’s predicted load supported by the gob elements, as seen in Figure 4.17.

Figure 4.16: Dynamic subsidence data comparison with model prediction (Mine C), (Marts et al., 2014).

Figure 4.17: Shield loading comparison (Mine C), (Marts et al., 2014).
4.4.1 Gob Porosity and Permeability

The output of the geomechanical FLAC$^{3D}$ model is in the form of volumetric strain increments, or VSI, which are translated into porosities using Equation 4.1.

\[
\text{Porosity} = \text{initial porosity} - \text{VSI} \quad \text{or} \quad \eta = \eta_0 - \epsilon_v \tag{4.1}
\]

Where $\eta_0$ is the initial porosity of the rock, $\eta$ is the resultant value of porosity and $\epsilon_v$ is volumetric strain increment, output from geo-mechanical model. The initial porosity is defined as the void volume, and is calculated from the caved zone height, extraction height of the panel, and the inherent porosity of the immediate overburden comprising the gob. The CFD model requires VSI distribution input in the form of smooth curve fits. Gilmore (2015) determined that piece-wise equation fits would best suit the distribution of VSI throughout the gob. The gob was broken down into nine segments to capture the areas of high gradients of porosity and permeability as shown in Figure 4.18.

The value of 0.4 (40\%) has been used as initial porosity of gob for mine C. An empirical relationship between permeability and porosity, the Carmen-Kozeny relationship given in Equation 4.2 is used to get the permeability values from porosity. $K_0$ is the base permeability ($m^2$) of the rock and $n$ is the porosity (fraction). The diameter of mean particles “d” value of 0.2 m is used as recommended by Pappas and Mark (1993). The final form of Carmen-Kozeny relationship is given in Equation 4.3, where $K$ is permeability ($m^2$).

\[
K_0 = \frac{n^3}{(180 \times (1-n)^2)} d^2 \tag{4.2}
\]
\[
K = \frac{K_0}{0.241 \left(\frac{n^3}{(1-n)^2}\right)} \quad (4.3)
\]

The porosity in Mine C ranges from 40% to 14%; the contour plot is shown in Figure 4.19. The roof rock of Mine C is a mixture of shale and mudstone with a low initial porosity and a low resistance toward compaction. Mine C subsides 77% of the extracted seam height. The calculated permeability contour plots are shown in Figure 4.20. The values are plotted on a logarithmic scale. The permeability ranges from \(5.1 \times 10^{-6}\) to \(2.0 \times 10^{-7}\) \(\text{m}^2\) for Mine C. The cell values of permeability are in the form of resistance, as shown in Equation 4.4.

\[
\text{Cell Resistance} = \frac{1}{K} \quad (4.4)
\]
4.4.2 Fractured Zone Porosity and Permeability

GVB design, placement and performance depend on permeability distribution in the fractured zone above the caved zone, where the GVBs are terminated (Diamond, 1995). In earlier research (Karacan; 2006, 2007a, 2007b, 2008a, 2008b, 2009a, 2009b, Marts; 2015, Gilmore; 2014, Worrall; 2012) the permeability in the fractured zone has been simplified by using uniform values in horizontal and vertical direction, which is not the actual case. The Mine C fractured zone is composed of sandstone, mudstone, limestone, coal and shale. The permeability of coal-measure rocks is highly dependent
on stress and stress redistribution after mining (Lowndes et al., 2002). In situ permeabilities depend on the stratigraphy, but they are modified by stress changes after mining. A typical range of permeability for fractured zone layers is given in Table 4.2. The initial, or in situ, permeabilities of different rocks are based on published sources (Esterhuizen et al., 2005; Marts et al., 2014; Lowndes et al., 2002; Kelsey et al., 2003 and Lewis et al., 2006).

**Table 4.2: In situ permeabilities of fractured zone rock layers**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Permeability ($\text{m}^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Sandstone</td>
<td>$9.87 \times 10^{-13}$</td>
</tr>
<tr>
<td>mudstone</td>
<td>$9.87 \times 10^{-14}$</td>
</tr>
<tr>
<td>limestone</td>
<td>$9.87 \times 10^{-14}$</td>
</tr>
<tr>
<td>siltstone</td>
<td>$9.87 \times 10^{-13}$</td>
</tr>
<tr>
<td>Coal</td>
<td>$9.87 \times 10^{-14}$</td>
</tr>
<tr>
<td>shale</td>
<td>$9.87 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

Durucan (1981) presented the following relationship for permeability, as seen in Equation 4.5, where $k$ is the permeability, $a$ and $b$ are constants and $\sigma$ is the applied stress.

$$k = ae^{-b\sigma}$$  \hspace{1cm} (4.5)

Kelsey et al. (2003) developed stress-permeability relationships with laboratory tests. These relationships are used to calculate the horizontal and vertical permeabilities of different rock layers in the fractured zone based on the predicted mining induced stresses from the geomechanical modeling. The equations used to calculate the horizontal and vertical permeabilities are below:

$$k_h = k_{ho} \times e^{-0.25(\sigma_{yy}-\sigma_{yyo})}$$  \hspace{1cm} (4.6)
\[ k_v = k_{v0} \times e^{-0.25(\sigma_{xx}-\sigma_{xx0})} \]  

(4.7)

Where \( k_h \) and \( k_v \) are modified horizontal and vertical permeabilities after mining induced stresses. The \( \sigma_{xx} \) and \( \sigma_{yy} \) are horizontal and vertical stresses, while \( 0 \) indicates initial conditions. The Carmen-Kozeny equation was used to calculate porosity as shown below. The porosity in fractured zone is used to calculate the volume of EGZ, if present.

\[ k \sim d^2 n^3 \]  

(4.8)

Where \( n \) denotes the porosity and \( d \) is the mean particle diameter, in this case, 0.25 m. The permeabilities of fractured zone layers were calculated using the geomechanical data and curve fitted the data in Matlab. The permeabilities and porosities of the strata layers are given in Table 4.3.

<table>
<thead>
<tr>
<th>Strata Layers</th>
<th>Thickness (m)</th>
<th>Horizontal k (m(^2))</th>
<th>Vertical k (m(^2))</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1.1x10(^{-12})</td>
<td>1.4x10(^{-12})</td>
<td>1.3x10(^{-12})</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>5.7x10(^{-13})</td>
<td>6.8x10(^{-13})</td>
<td>6.7x10(^{-13})</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3.8x10(^{-13})</td>
<td>4.5x10(^{-13})</td>
<td>4.4x10(^{-13})</td>
</tr>
<tr>
<td>4</td>
<td>8.8</td>
<td>2.8x10(^{-13})</td>
<td>3.4x10(^{-13})</td>
<td>3.3x10(^{-13})</td>
</tr>
<tr>
<td>5</td>
<td>8.8</td>
<td>1.8x10(^{-13})</td>
<td>2.1x10(^{-13})</td>
<td>2.1x10(^{-13})</td>
</tr>
</tbody>
</table>

4.5 Post Processing and Data Analysis

The explosive potential for the mixtures of methane and air is illustrated using a color scheme based on Coward’s triangle (Coward and Jones, 1952) in Figure 4.21. There are four distinct regions: the explosive region (red), a fuel-rich inert region that
can become explosive when fresh air or oxygen is added (yellow), an inert region where no explosive composition is possible (green) and a fuel-lean inert, near fresh air region (blue). An arbitrary orange fringe zone is added to denote atmospheres that are close to explosive. Worrall (2012) developed an algorithm, which is used as a UDF in FLUENT® to correlate the methane-air mixtures in the CFD output plots with these colors. The contour plots for the plan view of the model are used in order to visualize the EGZs, typically shown in a plane at a height of 1.5 m (5 ft.) above the mine floor, which is approximately in the middle of the coal seam height. A detailed discussion on post processing and data analysis is presented by Gilmore (2015).

![Coward's Triangle](image)

Figure 4.21: Color coded Coward’s triangle (Worrall, 2012)
4.6 Modeling Assumptions

Several assumptions were made regarding the complex mine geometry, during CFD modeling process, as listed below.

- The shield leakage into gob was represented by gaps in the model face.
- There is no leakage through the seals
- The three headgate and tailgate development entries were modeled as a single entry.
- The only methane source was the top rider coal seam.
- The methane gas that flows into the models was uniformly distributed over the top of the fractured zone. The methane source was continuous and did not deplete over time.
- The barometric pressure was considered constant over the period of panel mining.
CHAPTER 5

FLUENT® SET UP

This chapter details the FLUENT® model setup, solver settings, boundary conditions, wall functions and results validation. It also discusses the convergence criteria and studies, mesh independent studies, gravity treatment, Darcy law validity and porous media assumptions.

5.1 FLUENT® Solvers and Model Setup

The FLUENT® solver and model settings are based on the recommendation of Gilmore (2015) and Worral (2012). The detailed background on solver and model setting is discussed by Gilmore (2015).

5.1.1 General Solver Settings

The general solver settings for the model are given in Table 5.1. The solver settings are based on the recommendations of FLUENT® and the parametric runs done by Worral (2012). The pressure based solver type is chosen due to the large domain of model contains low speed incompressible flows as in gob and fractured zone (Worrall, 2012). FLUENT® also recommends using an absolute velocity formulation for low speed flows. Models are assumed to be steady state. Gravity is turned off since gravity would not have significant effect on results and would have localized effect near the top of the gob, which is not area of concern with respect to explosion hazard (Gilmore, 2015).
5.1.2 Model Settings

The FLUENT® viscous model settings are shown in Table 5.2. The settings were parametrically determined by Worrall (2012) to produce the best results after studying the effect of different k-ε turbulent sub model settings on the solution results, and concluded that the choice of the RNG k-ε turbulent model made little difference over the standard k-ε model. The RNG k-ε is considered more accurate in a wide range of applications (FLUENT® theory guide). Standard wall functions are used for the headgate, tailgate, face, and gob void surface roughness. The differential viscosity model is used in the RNG turbulence model to account for the low Reynolds number effects in the gob and fractured zone. The full multicomponent diffusion option enables the full multicomponent diffusion model, which is important in diffusion dominated laminar flows as in a gob and a fractured zone (Gilmore, 2015).

Table 5.2: Turbulence model settings

<table>
<thead>
<tr>
<th>ANSYS Fluent® Energy</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscous</td>
<td>RNG k-ε, Standard Wall Function, Differential Viscosity Model</td>
</tr>
<tr>
<td>Species Transport</td>
<td>CH₄, O₂, N₂, Full Multicomponent diffusion, Diffusion Energy Source</td>
</tr>
<tr>
<td>Porous Media Model</td>
<td>Gob and Strata Layers</td>
</tr>
</tbody>
</table>
5.1.3 Materials Settings

The methane-air mixture species consists of five species: oxygen, nitrogen, methane, carbon dioxide and water vapors. Carbon dioxide and water are not included in the model. This is the equivalent of modeling dry-air with the assumption of no carbon dioxide addition during mining. The three modeled species are methane, oxygen and nitrogen, which require only the solution for two species transport equations as the remainder is considered the third species. The methane air mixture properties are given in the Table 5.3.

Table 5.3: The methane-air mixture and properties

<table>
<thead>
<tr>
<th>Materials (Mixture)</th>
<th>Methane-Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane-Air</td>
<td>Methane, Oxygen, Nitrogen</td>
</tr>
<tr>
<td>Density</td>
<td>Incompressible Ideal Gas</td>
</tr>
<tr>
<td>Specific heat</td>
<td>Mixing Law</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.0454 W/m-K</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Ideal-gas-mixing-law</td>
</tr>
<tr>
<td>Mass Diffusivity</td>
<td>Kinetic Theory</td>
</tr>
</tbody>
</table>

5.1.4 Solution Methods

The FLUENT® solution settings are shown in Table 5.4. The default pressure-velocity coupling scheme, SIMPLE, is used in simulations for this project. The SIMPLE algorithm uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. The least squares gradient interpolation option in FLUENT® is the default method used in spatial discretization. The least squares gradient method is the least computationally intensive and performs well using structured meshes. It involves linearly interpolating the value at the center of
the cell to the cell faces. Worrall (2012) studied the effects of gradient schemes, reporting that the gradient settings have little impact on a longwall model solution. The PRESTO scheme is valid for all types of meshes. PRESTO is used in this simulation since ANSYS recommends it for porous media flow. Worrall (2012) compared linear, standard and PRESTO schemes and recommended PRESTO for use on longwall CFD models.

Table 5.4: Solution settings

<table>
<thead>
<tr>
<th>ANSYS Fluent®</th>
<th>Solution Method or Discretization Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure-Velocity Coupling</td>
<td>SIMPLE</td>
</tr>
<tr>
<td>Gradient</td>
<td>Least Squares Cell Based</td>
</tr>
<tr>
<td>Pressure</td>
<td>PRESTO!</td>
</tr>
<tr>
<td>Momentum</td>
<td>1\textsuperscript{st} Order Upwind</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>1\textsuperscript{st} Order Upwind</td>
</tr>
<tr>
<td>Turbulent Dissipation Rate</td>
<td>1\textsuperscript{st} Order Upwind</td>
</tr>
<tr>
<td>Species</td>
<td>2\textsuperscript{nd} Order Upwind</td>
</tr>
<tr>
<td>Energy</td>
<td>1\textsuperscript{st} Order Upwind</td>
</tr>
</tbody>
</table>

5.1.5 First Order vs. Second Order Accuracy

Worrall (2012) compared the first order and second order solutions for longwall model. The results for second order solution did not changed from the first order solutions in a significant manner to justify the additional computational cost (Worrall, 2012). Although a first order upwind scheme has low solution accuracy, the error can be reduced by using good convergence criteria and a refined mesh in longwall CFD modeling (Gilmore, 2015).
5.1.6 Solution Convergence Approach

In this dissertation, steady state cases are used for longwall panel CFD simulations. A steady state case implies that the solution no longer changes with further iterations. ANSYS FLUENT® recommendations for convergence criteria follow:

- Discrete conservation equations are solved to a specific tolerance.
- Overall mass, momentum, energy and scalar balance.
- Decrease in residuals by at least three orders of magnitude.
- Energy residual decrease by six orders of magnitude.
- Species residual decrease by five orders of magnitude.

The momentum and energy balance is not crucial in these simulations since temperature boundary conditions are uniform and momentum transfers to a fixed geometry (Gilmore, 2015). The overall mass balance for all inlets and outlets of model is shown in Table 5.5. The net mass imbalance is $1.4 \times 10^{-5}$ kg/s, which is four orders of magnitude less than the smallest mass inlet quantity.

Table 5.5: Overall mass balance of model

<table>
<thead>
<tr>
<th>Mass Flow Rate</th>
<th>kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headgate inflow</td>
<td>38.71</td>
</tr>
<tr>
<td>GVBs Outflow</td>
<td>-0.25</td>
</tr>
<tr>
<td>Methane Inflow</td>
<td>0.33</td>
</tr>
<tr>
<td>Tailgate Outflow</td>
<td>-38.79</td>
</tr>
<tr>
<td>Net</td>
<td>$1.42 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

A detailed study was conducted to evaluate the convergence criteria. The residual convergence criterion is usually met at fewer than 1,000 iterations. Elevating the residual convergence criteria iterates the solution further. Changes in the variables,
GVB flow, GVB methane concentration, EGZ volume and tailgate methane concentration were documented with an increase in iterations. The results of study are shown in Table 5.6. The iterations study results show no significant changes in variables with continued iterations. After 1,600 iterations, there is no significant further change in the variables. The solution is proved to be converged by iteration study.

Table 5.6: Iteration based convergence criteria evaluation

<table>
<thead>
<tr>
<th>No of Iterations</th>
<th>GVB Flow</th>
<th>GVB-CH₄</th>
<th>Explosive Volume</th>
<th>TG CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>Δ%</td>
<td>Δ%</td>
<td>Δ%</td>
<td>Δ%</td>
</tr>
<tr>
<td>1600</td>
<td>0.01%</td>
<td>0.23%</td>
<td>-2.12%</td>
<td>-0.55%</td>
</tr>
<tr>
<td>2600</td>
<td>-0.02%</td>
<td>-0.01%</td>
<td>0.03%</td>
<td>0.03%</td>
</tr>
<tr>
<td>3600</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.01%</td>
<td>-0.01%</td>
</tr>
<tr>
<td>5600</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total</td>
<td>-0.02%</td>
<td>0.22%</td>
<td>-2.08%</td>
<td>-0.52%</td>
</tr>
</tbody>
</table>

The residual convergence is shown in Table 5.7. The residual convergence shows that the criteria meet the all recommendations from FLUENT® for convergence, as mentioned above. Finally, it may be stated that the solutions in this project are converged with respect to mass balance, number of iterations, and residual convergence.

Table 5.7: The residual convergence

<table>
<thead>
<tr>
<th>Iterations</th>
<th>Continuity</th>
<th>X-Velocity</th>
<th>Y-Velocity</th>
<th>Z-Velocity</th>
<th>Energy</th>
<th>k</th>
<th>Epsilon</th>
<th>CH₄</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>997</td>
<td>6.1x10⁻⁶</td>
<td>1.6x10⁻⁶</td>
<td>1.3x10⁻⁶</td>
<td>4.2x10⁻⁶</td>
<td>8.9x10⁻¹¹</td>
<td>2.4x10⁵</td>
<td>1.0x10⁻⁴</td>
<td>4.1x10⁵</td>
<td>4.2x10⁻⁷</td>
</tr>
<tr>
<td>998</td>
<td>4.3x10⁻⁶</td>
<td>1.5x10⁻⁶</td>
<td>1.3x10⁻⁶</td>
<td>4.2x10⁻⁶</td>
<td>8.1x10⁻¹¹</td>
<td>2.4x10⁵</td>
<td>9.9x10⁻⁵</td>
<td>4.1x10⁵</td>
<td>4.2x10⁻⁷</td>
</tr>
<tr>
<td>Solution is converged</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

79
5.2 Turbulence Modeling

There are three types of k-ε turbulent model options in FLUENT®: standard, RNG, and realizable. Worrall (2012) recommended the RNG model in longwall gob CFD simulations as a realizable model was facing the stability and convergence issues. The remaining two models did not show significantly different results (Worrall, 2012). FLUENT® recommends the RNG model over the standard k-ε model, where both turbulent and laminar flow conditions exist within the same simulation (ANSYS, 2014).

5.2.1 Boundary Conditions

There are two inlets in the model, the methane inlet and the headgate inlet. Methane inlet boundary conditions are discussed in the methane source (section 5.2.2). The headgate inlet is source of ventilation air on the longwall face. The headgate inlet is modeled as a velocity inlet, as recommended by Worrall (2012). The magnitude and normal to the boundary velocity specification method is used.

The velocity magnitude of 1.6 m/s is used, which provides the 33 m3/s (70,000 cfm) of air on longwall face. Most longwall mines use 33 m3/sec of air on the face with a U-Type ventilation scheme. The GVB outlets are modeled as negative pressure outlets based on literature values and Mine C observations. A negative pressure of -30 to -40kPa is applied to the GVB outlets for different cases. The GVBs suction pressure values published by researchers and on different mines data are shown in table 5.8 and 5.9.
### Table 5.8: GVBs wellhead vacuum pressure used by different operations
(Source: USEPA, 2011)

<table>
<thead>
<tr>
<th>Mine</th>
<th>Country</th>
<th>Wellhead Vacuum (kPa)</th>
<th>CH₄ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambria 33 Mine</td>
<td>USA</td>
<td>20</td>
<td>40-90</td>
</tr>
<tr>
<td>Daxing Mine</td>
<td>China</td>
<td>13</td>
<td>35-90</td>
</tr>
<tr>
<td>Warndt Luisenthal Mine</td>
<td>Germany</td>
<td>20</td>
<td>70-80</td>
</tr>
<tr>
<td>Willow Creek Mine</td>
<td>USA</td>
<td>24</td>
<td>50-60</td>
</tr>
<tr>
<td>Belozyorskaya Mine</td>
<td>Ukraine</td>
<td>30</td>
<td>30-75</td>
</tr>
</tbody>
</table>

### Table 5.9: GVB wellhead vacuum pressure

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Wellhead Vacuum (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karacan (2006)</td>
<td>18</td>
</tr>
<tr>
<td>Schatzel (1979)</td>
<td>13</td>
</tr>
<tr>
<td>Loj and Laskuda (2013)</td>
<td>30-35</td>
</tr>
</tbody>
</table>

#### 5.2.2 Methane Source

The methane source in the model is the top coal seam, or rider coal seam, above the longwall panel. The other sources of methane in the longwall panel are neglected for modeling simplification. The top of fractured zone or strata is modeled as the velocity inlet. The use of a velocity inlet is based on the study done by Worrall (2012), who conducted a parametric study, which produced the value of velocity for velocity inlet. Worrall derived the amount of methane to match the mine measurements at GVBs and tailgate and calibrated it. Using this approach, the velocity of the inlet and the methane liberation rate are calculated for the 457 m (1500ft.) panel length to be 0.5 m³/s (1060 cfm) to match the mine readings at GVBs outlets and tailgate. The details of the methane source can be found in Worrall’s (2012) Ph.D. dissertation.
The velocity inlet produced the area weighted average pressure of 5000 Pa at the top of fractured zone. The pressure produced by the velocity inlet is in the same order of magnitude as reported by Karacan (2006) and Diamond et al. (1999). Karacan reported a shut-in pressure of 2500 Pa and 3000 Pa for two different boreholes. Diamond et al. (1999) reported a shut-in pressure of 2000 Pa, using these values for comparison, the pressure value produced by the methane velocity inlet is reasonable.

5.3 Gravity

The gravity option in current models is turned off. The inclusion of gravity causes instability and convergence problems to the models as reported by Worrall (2012) and Gilmore (2015). The current models have a 5000 Pa pressure boundary at the top of fractured zone, and GVB pressure outlets are at -30 to -40 kPa, which renders the effect of gravity negligible. Worrall (2012) and Gilmore (2015) both reported that the effect of gravity would be localized near the top of the gob, which is not a point of much concern with respect to the explosion hazard.
CHAPTER 6

MODEL VALIDATION

This chapter describes the validation of modeling results. The modeling results were validated with the mine measurements provided by Mine C. The methane concentrations at the GVB exhaust areas and at the tailgate were used to calibrate the simulation results. Also, the tube bundle system readings were compared with the CFD model’s predicted values. The CFD results were also compared with published results on GVB performance. The discussion on mesh independent study and model sensitivity to the permeability values is presented.

6.1 Validation of CFD Models with Mine Measurements

Mines monitor methane concentrations at the tailgate and in the exhaust of GVBs. The methane concentration at the tailgate fluctuates, but must be kept below 1.0%. Maintaining the tailgate methane concentration at or below 0.5% is a good practice. The methane concentrations in the GVB exhausts also vary over time as they depend on the level of methane emissions in the mine as well as multiple design and operating factors. If the exhausters are methane powered, the engines will stop when concentrations drop below 25% methane. The GVB methane exhaust concentrations at Mine C range between 50% and 80%.

The results of validation runs with varying GVB diameters are shown in Table 6.1. Increasing the diameter of GVBs results in an increase in total methane production, and it decreases the methane in GVBs exhaust and tailgate.
6.2 CFD Model Validation with Tube Bundle System Measurements

The CFD modeling results were also validated with the gob gas measurements made at the mine. Mine C uses a tube bundle gas analyzer system that measures atmospheric gas concentrations behind the seals along the fringes of the gob. Mine C also provided the data from manual measurements of gases through seal sampling tubes and from manual readings at the face. Oxygen ingress in the model was compared with the mine operating conditions, as shown in Figure 6.1. Figure 6.1 (a) shows the 12% oxygen contour plot from mine data. Figure 6.1 (b) shows the oxygen contour plots from the model that appear to be in good agreement.

6.3 Comparison of CFD Models with Published Results

The model results were compared with the published results on GVBs. Karacan (2006) employed reservoir modeling to predict the performance of GVBs, studying the effect of GVB diameter variation on the flow and methane concentration of GVB exhaust. He also presented the GVB interaction with mine ventilation, and explored the effect of setting depth variation on exhaust gas quality.
Table 6.2 presents a comparison of current CFD modeling results with Karacan's diameter variation study. Since there are some fundamental differences between models, the comparison is relative. The comparison shows that an increase in the diameter of GVBs pulls more ventilation air into the gob and the exhaust quality decreases in terms of methane concentration and air drawn through the GVB. The increase in diameter adds air into the exhaust more than it increases the methane exhaust quantity.
Table 6.2: Diameter variation of GVBs results comparison with Karacan (2006)

<table>
<thead>
<tr>
<th>GVBs Diameter</th>
<th>∆ GVB Flow (%)</th>
<th>∆ GVB Air (%)</th>
<th>∆CH$_4$ (%)</th>
<th>GVBs Diameter</th>
<th>∆ GVB Flow (%)</th>
<th>∆ GVB Air (%)</th>
<th>∆CH$_4$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4&quot; (10 cm)</td>
<td>-11</td>
<td>-15</td>
<td>-6.7</td>
<td>8&quot; (20 cm)</td>
<td>-13.2</td>
<td>-17.5</td>
<td>-11.6</td>
</tr>
<tr>
<td>7&quot; (18 cm)</td>
<td></td>
<td>Base Case</td>
<td></td>
<td>12&quot; (30 cm)</td>
<td></td>
<td>Base Case</td>
<td></td>
</tr>
<tr>
<td>10&quot; (25 cm)</td>
<td>7.1</td>
<td>12</td>
<td>4.9</td>
<td>16&quot; (40 cm)</td>
<td>9.9</td>
<td>14</td>
<td>8.4</td>
</tr>
</tbody>
</table>

The GVB setting depth is the distance between the coal seam and the bottom of the slotted casing where GVBs are terminated. The results of a setting depth study in this investigation are compared with Karacan’s research in Table 6.3. The current model’s results show similar trends with Karacan study. If the GVB setting depth is close to the gob, it draws more air and the exhaust quality drops.

Table 6.3: Setting depth study results comparison with Karacan (2006)

<table>
<thead>
<tr>
<th>Setting Depth (m)</th>
<th>∆ GVB Air (%)</th>
<th>∆CH$_4$ (%)</th>
<th>Setting Depth (m)</th>
<th>∆ GVB Air (%)</th>
<th>∆CH$_4$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6</td>
<td>74</td>
<td>-29</td>
<td>9.5</td>
<td>77</td>
<td>-23</td>
</tr>
<tr>
<td>7.6</td>
<td>-5</td>
<td></td>
<td>15.2</td>
<td>-68</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>Base Case</td>
<td></td>
<td>12.2</td>
<td>Base case</td>
<td></td>
</tr>
<tr>
<td>19.3</td>
<td>4</td>
<td></td>
<td>18.3</td>
<td>-93</td>
<td>8</td>
</tr>
</tbody>
</table>

6.4 Mesh-Independence Study

A CFD model is considered to be mesh-independent if solution no longer changes when the mesh size is decreased. The gob mesh controls are presented in Table 6.4. Initially, a minimum element size of 0.2 m and maximum element size of 3.2 m were used. The base mesh consists of 3.8 million cells. In refinement step 1, the
maximum size of the element was reduced in half and the maximum face element size was also cut in half. The resulting gob mesh had 5.8 million cells. In refinement step 2, the maximum face element size was reduced from 0.4 m to 0.2 m and the center gob element size was reduced from 0.8 m to 0.4 m. The refinement 2 mesh results in 24 million cells. When combined with other mesh parts of model, the total number of cells rises to 37 million.

Table 6.4: Gob Mesh Controls

<table>
<thead>
<tr>
<th>Mesh Refinement</th>
<th>Global Element Sizing (m)</th>
<th>Edge Sizing (m)</th>
<th>Middle of Gob Sizing (m)</th>
<th>Face Sizing (m)</th>
<th>Elements (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Original Mesh</td>
<td>0.2</td>
<td>3.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Refinement 1</td>
<td>0.2</td>
<td>1.6</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Refinement 2</td>
<td>0.2</td>
<td>1.6</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The mesh creation controls for the fractured zone are shown in Table 6.5. The minimum element size is related to the diameter of the GVBs in the fractured zone. The mesh body control is applied to mesh GVB bodies in the fractured zone domain.

The GVBs are in the form of polygons, and each side of polygon contains at least two elements in the mesh. FLUENT® recommends using at least 2 cells to mesh the edges of the outlet orifices in the model. It is evident from Table 6.5, that by reducing the GVB diameter, the number of cells in the fractured zone increases.

The fractured zone mesh with 20 cm diameter GVBs contains the maximum number of cells, 8.6 million. The fractured zone mesh with 30 cm GVBs contains 6 million cells, and with 40 cm GVBs, the mesh contains 2.7 million cells. The number of
cells in the fractured zone meshes increases as the diameter of GVBs in mesh module decreases.

Table 6.5: Fractured Zone Mesh Controls

<table>
<thead>
<tr>
<th>GVBs diameter (cm)</th>
<th>Global Element Sizing (m)</th>
<th>Face Sizing (m)</th>
<th>Body Sizing (m)</th>
<th>Elements (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>3.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>30</td>
<td>0.06</td>
<td>3.2</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>40</td>
<td>0.1</td>
<td>3.2</td>
<td>0.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The strata mesh module with 40 cm GVB diameter was selected for mesh independence study as it has increased capacity for mesh refinement compared to the other strata mesh modules with smaller diameter GVBs. The fractured zone mesh was refined by reducing all mesh controls in half, as shown in Table 6.6. In the refined mesh, the maximum size of an element was 1.6 m. The number of cells in the mesh increases from 2.7 million to 9.6 million.

Table 6.6: Fractured Zone Mesh Refinement

<table>
<thead>
<tr>
<th>Fractured Zone Mesh (40 cm GVBs diameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh Refinement</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Original Mesh</td>
</tr>
<tr>
<td>Refinement</td>
</tr>
</tbody>
</table>

The simulation cases were run, combining the refined mesh modules of the gob and the fractured zone with 40 cm GVBs. The GVB flow, GVB methane, EGZ volume and tailgate methane were documented to compare with the original mesh results. The
results are presented in the Table 6.7. The total change in GVB flow is 1.3%, and the change in methane concentration in the GVBs exhaust is 2.28%. The explosive volume is reduced by 3%, and the tailgate methane concentration is reduced by 4%. The results confirm mesh independence as there is no significant difference in the solution variables as a result of refining the mesh.

Table 6.7: Mesh Independence Study Results

<table>
<thead>
<tr>
<th>Gob</th>
<th>Fractured Zone</th>
<th>GVB Flow</th>
<th>GVB-CH₄</th>
<th>Explosive Volume</th>
<th>TG CH₄</th>
<th>TG CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>cells (millions)</td>
<td>cells (millions)</td>
<td>∆%</td>
<td>∆%</td>
<td>∆%</td>
<td>Base Case</td>
<td>0.49%</td>
</tr>
<tr>
<td>3.8</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.8</td>
<td>9.6</td>
<td>1.07%</td>
<td>1.58%</td>
<td>-1.56%</td>
<td>-1.19%</td>
<td>0.49%</td>
</tr>
<tr>
<td>5.8</td>
<td>9.6</td>
<td>0.13%</td>
<td>-0.13%</td>
<td>-1.19%</td>
<td>-1.17%</td>
<td>0.47%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.30%</td>
<td>2.28%</td>
<td>-3.03%</td>
<td>-4.22%</td>
<td></td>
</tr>
</tbody>
</table>

6.5 Model Sensitivity to Permeability Input

One of the major uncertainties in longwall CFD modeling is the permeability input. A sensitivity study was conducted to examine the solution changes by altering the permeability in the gob and fractured zone. The permeabilities in the gob and fractured zone were varied by 10% and 20%, and the resulting changes in EGZ volume and GVB flow were documented and analyzed. The contour plots of increased permeability are presented in Figure 6.2 and are compared with the original permeability contour plot of the gob. The contour plots of decreased permeability are shown in Figure 6.3 and are compared with the original permeability contours plot of the gob.
Figure 6.2: Increased permeability contour plots in the gob

Figure 6.3: Decreased permeability contour plots in the gob

Modifications in the permeability lead to observable changes in the EGZ volumes as shown in Figure 6.4. A 20% decrease in permeability in the model results in a 23%
decrease in the EGZ volume. A 20% increase in the model permeability results in a 36% increase in the EGZ volume.

![Graph showing change in normalized EGZ by changing permeability]

Figure 6.4: Change in normalized EGZ by changing the permeability

This phenomenon can be explained with the help of oxygen contour plots as shown in Figure 6.5. The left image in Figure 6.5 shows that when permeability is increased in the model, the oxygen ingress increases as well. Therefore, there is more oxygen available deep inside the gob to form a larger EGZ. The right image in Figure 6.5 reveals that, when there is a lower permeability, less oxygen penetrates into the gob, and hence, a smaller EGZ is formed. Figures 6.6 demonstrate how GVB exhaust flow quantity changed as permeability in the model changed. The 20% decrease in permeability resulted in 16% less flow through the GVB, while a 20% increase in permeability resulted in a 24% increase in the GVB flow.
Figure 6.5: Oxygen contour plots with changed permeabilities in the gob

Figure 6.6: GVB flow change with change of permeability in the model
CHAPTER 7

OPTIMIZING GOB VENTILATION BOREHOLE LOCATIONS

This chapter presents a study to optimize the locations for GVB placement, along with modeling the impact of setting depth and GVB diameter and other operating parameters.

7.1 GVB Location Optimization

In experimental field studies, Diamond (1995) demonstrated that the location of GVBs on a longwall panel is important for optimal gob degasification effectiveness, reducing methane concentrations in the working areas.

In this study, optimization refers to the GVB location with respect to maximizing methane reduction. In GVB location optimization study, the GVBs were operated independently of each other. The distance of the GVBs from the gateroads and from the face was varied. The diameter of GVBs used in location optimization studies is 0.3 m; they terminate 9 m above the top of the mined coal seam.

The distances of GVBs from the longwall face and the tailgate, respectively, were varied as shown in Table 7.1. The location study results, in Figure 7.1, illustrate that the GVB flow is maximized at a distance of approximately 18 m (60 ft.) from the tailgate and 44-88 m (100-200 ft.) inby the face. GVBs operating closer to the face pose a risk of drawing fresh air from the face into the gob, which may support spontaneous combustion and/or the formation of EGZs.
Table 7.1: GVBs locations in CFD model for location optimization study

<table>
<thead>
<tr>
<th>Distance of GVBs from Tailgate (m)</th>
<th>Distance of GVBs from Face in CFD Model (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>37</td>
<td>6</td>
</tr>
<tr>
<td>73</td>
<td>6</td>
</tr>
<tr>
<td>146</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 7.1: GVBs Flow with respect to location
A second series of studies was conducted to analyze which GVB location is optimal to minimize EGZ volume and to reduce the tailgate methane concentration. Figure 7.2 shows relative EGZ volume as a function of the GVB location. Coincidentally, the EGZ volume is also minimized at a distance of approximately 18 m (60 ft.) from the tailgate. GVBs near the center of the panel cause more fresh air ingress from headgate side, forming larger EGZs. Figure 7.2 also shows that GVBs far inby the face may contribute to the formation of larger EGZs by pulling fresh air deeper inside the gob. As the face advances, these far inby GVBs may need to be shut down to prevent them from drawing fresh air into the gob.

Figure 7.2: Normalized EGZs comparison with respect to GVBs location
Figure 7.3 compares the contour plots of EGZs for two different GVB locations. The image on the left side shows the EGZ for a GVB operating at 18 m (60 ft.) from the tailgate. The image on the right is for a GVB operating in the center of panel at a distance of 146 m (480 ft.) from tailgate, creating a larger EGZ volume. The larger EGZs volume is the result of increasing air ingress into the gob, as shown in Figure 7.4. Another oxygen ingress comparison is shown in Figure 7.5. In this scenario, both GVBs are at the same distance of 146 m from the tailgate, but one is located 60m from the face, while the other is 427m from the face. This comparison confirms that the GVBs located further from the face result in greater air ingress deep into the gob and consequently form larger EGZs as the interface zone between high concentration methane and fresh air becomes wider.
Figure 7.4: Oxygen ingress contour plots

Figure 7.5: Oxygen ingress contour plots
Figure 7.6 shows a comparison of GVB effectiveness in reducing the methane concentration in the tailgate return air course. The difference in the tailgate methane concentration for comparative cases is relatively small. This CFD study was conducted while operating GVBs one by one, independently of each other. One GVB operating over the entire model is not sufficient to drop the methane concentration to 0.5% in the returns – thus, for this parametric study, higher tailgate methane concentrations resulted. This study confirms again that GVBs at the distance of 18 m from the tailgate are the most efficient at reducing methane concentrations in the tailgate return.

Figure 7.6: Tailgate methane comparison with respect to GVBs location
7.2 Setting Depth Analysis

Setting depth plays an important role relative to the quantity and quality of methane exhaust from GVBs, as reported by Karacan (2006). Another important factor related to setting depth is the development of shear bands or shear zones. Horizontal shearing can damage the casing and can partially or completely block the GVB’s flow. Initial predictions forecast the development of horizontal shear planes within the immediate roof of a mined coal seam (Lowndes et al., 2002). To avoid shearing the GVBs, the setting depth should be above the caved zone. The permeability in or near the caved zone is higher than in the fractured zone as it ascends. If the GVB setting depth is within a caved zone, it will draw ventilation air into gob and the GVB exhaust will have reduced methane concentrations.

A parametric CFD study was conducted by changing the GVB setting depth above the top of coal seam being mined. Seven GVBs with 20 cm (8 in) diameters were modeled with -40 kPa wellhead vacuum pressure. The first GVB’s distance from the face was 30 m and the distance between the GVBs was 60 m. A diameter of 20 cm was chosen for the setting depth optimization study. The optimized distance, 18 m from the tailgate, was derived from the location optimization study. Figure 7.7 show the GVBs flow at different setting depth from the top of coal seam and caved zone. GVBs set at a depth of 9 m (30 ft.) above the top of coal seam have maximum flow compared to setting depths of 12, 15 and 18 m (39, 49 and 59 ft.) above the top of coal seam. When the setting depth was increased, the length of the GVB slotted casing inside the fractured zone was reduced, which is the main cause of the significant drop in GVB flow quantity.
Figure 7.7 shows the methane concentration in the GVB exhaust at different setting depths. The methane concentration in the GVB exhaust drops as the setting depth approaches the caved zone. At 9 m (30 ft.) setting depth, GVBs are at the top of caved zone and the methane concentration has dropped 25% for near face GVBs compared to 18 m (60 ft.) setting depth, the results match already published studies (Karacan, 2006). Closer to the gob, GVBs start pulling more fresh air from the ventilation system and the spontaneous combustion risk increases. This also increases EGZ volume.
Figure 7.8: Methane concentration in GVBs exhaust vs. setting depth

Figure 7.9 shows the comparison of normalized EGZ volumes for GVBs operating at different setting depths, and compares their ability to reduce the methane concentration in working areas. Changing the setting depth of GVBs from 9 m (30 ft.) to 18 m (60 ft.) above top of coal seam reduces the EGZ size by 30%; it also increases the methane concentration in the tailgate entry from 0.5 % to 1.1 %. The increased setting depth reduces the GVB’s efficiency to dilute the tailgate methane concentration.
Figure 7.9: Normalized EGZ volumes and CH₄ with respect to setting depth

Figure 7.10 demonstrates a reduction in the size of EGZs as a result of increasing setting depth. It also shows that, if the setting depth is closer to the caved zone, the GVBs will draw higher quantities of ventilation air into the gob and form larger EGZs. If the coal is prone to spontaneously combust, it also increases the risk of spontaneous combustion. Figure 7.11 is a comparison of two setting depth cases and the EGZs. The EGZ plot on left features GVBs at a setting depth of 18 m, while in the right image, an EGZ is formed by GVBs at setting depth of 9 m. These cases show how the setting depth impacts the formation of EGZs.
Figure 7.10: EGZs location vs. setting depth

Figure 7.11: EGZs location vs. setting depth
7.3 GVB Diameter Optimization

The diameter of GVBs plays a significant role in the quantity and quality of exhaust methane. The GVB diameter also has significant effect on the size of EGZs and air ingress into the gob. A study on GVB diameter was conducted for diameters of 20 cm (8 in), 30 cm (12 in) and 41 cm (16 in). Six GVBs were used with -40 kPa well-head vacuum pressure. GVB-1 is at a distance of 30 m (100 ft.) from the face and the other GVBs are modeled at 60 m (200 ft.) spacing. In the diameter optimization study, the GVBs terminated 9 m above the top of coal seam being mined. The optimized distance, 18 m from the tailgate, was derived from the location optimization study. Changing the diameter from 20 cm (8 in) to 30 cm (12 in) increases the exhaust quantity by 13%. Further expansion of the diameter from 30 cm (12 in) to 41 cm (16 in) increases the exhaust flow by 10%. The flow does not change in proportion to GVB diameter change at the same suction pressure, as the flow velocities in larger diameter GVBs are lower than in smaller diameter GVBs. Figure 7.12 shows the GVB flow under varying diameters. Although an increase in diameter increases the flow amount, it also decreases the concentration of methane in the exhaust, as shown in figure 7.13. The methane concentration drops more for near-face GVBs as compared to the GVBs operating far inby the face. GVBs near the face pull more ventilation air as compared to GVBs further from the face. The methane concentration in the GVB-1 exhaust dropped from 81% to 78% by changing the diameter from 20 (8 in) cm to 30 cm (12 in). By changing the diameter of GVB-1 from 30 cm (12 in) to 41 cm (16 in) the CH4 concentration decreased to 73% in the GVB-1 exhaust. Figure 7.13 show that GVBs deep in the gob have higher concentrations of methane in their exhaust quality.
Figure 7.12: GVBs flow vs. diameter

Figure 7.13: GVB methane concentration vs. diameter
The increase in diameter of the GVBs decreases the methane concentration in the GVBs exhaust because GVBs near the face start pulling ventilation air from the face into the gob. The increase in air ingress into gob can support spontaneous combustion. Mixing air with methane in the gob can also form larger EGZs, as shown in figure 7.14. Increased diameter of GVBs may help to reduce the methane concentration in the working areas with fewer GVBs operating on the panel, reducing the drilling cost.

![Figure 7.14: GVBs diameter vs. normalized EGZ volume and CH$_4$ in returns](image)

Figure 7.14: GVBs diameter vs. normalized EGZ volume and CH$_4$ in returns

Figure 7.15 shows the oxygen contour plots of two cases with different GVB diameters. Both cases have six GVBs operating at -40kPa pressure. The image on left has GVBs with 20 cm diameter, while the image on right has the GVBs with 41 cm diameter. The figure shows that the 41 cm diameter GVBs have more oxygen ingress into the gob and forms larger volume EGZs.
7.4 Methane Parametric Study

The effect of the methane quantity injected into the model from the rider seam was studied via a parametric evaluation. The methane inlet velocity was adjusted to change the quantity of methane flowing into the model. The methane quantity variation effects were analyzed for GVB exhaust quality, normalized EGZ volume and tailgate methane concentration. Table 7.2 shows the methane quantity in the model and methane inlet velocity under five different cases. The number of 20 cm diameter GVBs necessary to bring the methane concentration to 0.5% in the returns, normalized EGZ...
volumes, GVB methane concentrations and TG methane concentrations are presented in Table 7.3.

Table 7.2: Methane quantity variation in the model

<table>
<thead>
<tr>
<th>CH$_4$ inlet (m$^3$/s)</th>
<th>CH$_4$ inlet (cfm)</th>
<th>CH$_4$ inlet velocity (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1060</td>
<td>3.7x10$^{-6}$</td>
</tr>
<tr>
<td>0.4</td>
<td>850</td>
<td>3.0x10$^{-6}$</td>
</tr>
<tr>
<td>0.3</td>
<td>630</td>
<td>2.2x10$^{-6}$</td>
</tr>
<tr>
<td>0.2</td>
<td>420</td>
<td>1.5x10$^{-6}$</td>
</tr>
<tr>
<td>0.1</td>
<td>210</td>
<td>7.5x10$^{-7}$</td>
</tr>
</tbody>
</table>

Table 7.3: Methane variation effects on solution (20 cm diameter GVBs)

<table>
<thead>
<tr>
<th>CH$_4$ in Model (cfm)</th>
<th>No of GVBs</th>
<th>GVBs Vacumm head (kPa)</th>
<th>Normalized EGZs</th>
<th>GVBs CH$_4$ conc. %</th>
<th>TG CH$_4$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1060</td>
<td>7</td>
<td>40</td>
<td>1</td>
<td>98</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>50</td>
<td>1.2</td>
<td>82</td>
<td>0.51</td>
</tr>
<tr>
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<td>6</td>
<td>40</td>
<td>1.7</td>
<td>80</td>
<td>0.62</td>
</tr>
<tr>
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<td>7</td>
<td>40</td>
<td>1.8</td>
<td>73</td>
<td>0.48</td>
</tr>
<tr>
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<td>40</td>
<td>2.5</td>
<td>74</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>40</td>
<td>2.6</td>
<td>66</td>
<td>0.47</td>
</tr>
<tr>
<td>420</td>
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<td>40</td>
<td>4.2</td>
<td>65</td>
<td>0.52</td>
</tr>
<tr>
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<td>40</td>
<td>4.3</td>
<td>58</td>
<td>0.43</td>
</tr>
<tr>
<td>210</td>
<td>0</td>
<td>40</td>
<td>10.2</td>
<td>42</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>40</td>
<td>10.5</td>
<td>42</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 7.3 shows that fewer GVBs are needed to handle a reduced amount of methane coming to the model, but at the same time, there is greater air ingress into the gob, forming larger EGZs when the air mixes with the methane. Seven GVBs are
operating over the panel to reduce the methane to 0.5% in the TG return in case of 850 cfm of methane in the model. When the methane in the model is reduced to 640 cfm, five GVBs can reduce the methane in the returns to 0.5%. The higher air ingress is confirmed by low methane concentration in the GVB exhaust. It is also evident from the data that multiple GVBs will help to drop the TG methane concentration below the mandated levels, but at the same time, they pull more air into the gob and the EGZs increases in volume. Tables 7.4 and 7.5 show the similar results as Table 7.3, instead using 30 cm and 41 cm diameter GVBs on the longwall panels. The results also reveal that, although larger diameter GVBs are more effective in methane extraction and reducing the methane in the returns, they tend to form larger EGZs in the gob as they draw more ventilation air into the gob, as shown in Figure 7.16. This figure shows the results of methane entering the model at the rate of 0.5 m$^3$/s with seven GVBs operating over the panel.

Table 7.4: Methane variation effects on solution (30 cm diameter GVBs)

<table>
<thead>
<tr>
<th>CH$_4$ in Model (cfm)</th>
<th>No of GVBs</th>
<th>GVBs Vaccumm head (kPa)</th>
<th>Normalized EGZs</th>
<th>GVBs CH$_4$ conc. %</th>
<th>TG CH$_4$ %</th>
</tr>
</thead>
<tbody>
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<td>40</td>
<td>1.0</td>
<td>95</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>45</td>
<td>1.1</td>
<td>86</td>
<td>0.46</td>
</tr>
<tr>
<td>848</td>
<td>5</td>
<td>40</td>
<td>1.5</td>
<td>85</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>40</td>
<td>1.6</td>
<td>78</td>
<td>0.49</td>
</tr>
<tr>
<td>636</td>
<td>4</td>
<td>40</td>
<td>2.4</td>
<td>74</td>
<td>0.50</td>
</tr>
<tr>
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<td>40</td>
<td>2.6</td>
<td>65</td>
<td>0.38</td>
</tr>
<tr>
<td>424</td>
<td>2</td>
<td>40</td>
<td>3.9</td>
<td>64</td>
<td>0.49</td>
</tr>
<tr>
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<td>40</td>
<td>4.1</td>
<td>60</td>
<td>0.37</td>
</tr>
<tr>
<td>212</td>
<td>0</td>
<td>40</td>
<td>9.6</td>
<td></td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>40</td>
<td>10.0</td>
<td>42</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Table 7.5: Methane variation effects on solution (30 cm diameter GVBs)

<table>
<thead>
<tr>
<th>CH₄ in Model (cfm)</th>
<th>No of GVBs</th>
<th>GVBs Vacuum head (kPa)</th>
<th>Normalized EGZs</th>
<th>GVBs CH₄ conc. %</th>
<th>TG CH₄ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1059</td>
<td>6</td>
<td>40</td>
<td>1.0</td>
<td>97</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>40</td>
<td>1.2</td>
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<tr>
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<td>0.57</td>
</tr>
<tr>
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<td>40</td>
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</tr>
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<td>72</td>
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<tr>
<td>424</td>
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<td>40</td>
<td>4.1</td>
<td>71</td>
<td>0.60</td>
</tr>
<tr>
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<td>40</td>
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</tr>
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<td>40</td>
<td>10.4</td>
<td>41</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>40</td>
<td>10.8</td>
<td></td>
<td>0.29</td>
</tr>
</tbody>
</table>

Figure 7.16: Normalized EGZ volume and TG methane comparison for different diameter GVBs operating in the model
7.5 Gob Ventilation Borehole Radius of Influence

The information about the GVB radius of influence can help to determine the minimum spacing between the boreholes and to determine the proper distance from the face so that the GVB don’t draw as much ventilation air into the gob. This study discusses the radius of influence for GVBs with diameters of 20 cm, 30 cm and 41 cm.

Figure 7.17 shows the pressure contour plot of a 41 cm diameter GVB in operation at -40 kPa suction pressure. The positive pressure contours of the methane inlet can also be seen in the figure. The minimum pressure value is -40 kPa, applied to the GVB outlet. The maximum value of pressure is 5500 Pa, which is the methane inlet pressure.

![GVB and methane inlet pressure contours in gob and fractured zone](image)

Figure 7.17: GVB and methane inlet pressure contours in gob and fractured zone

The zone of influence is determined from the pressure values as shown in Figure 7.18. This figure shows that after a certain distance, the effect of suction pressure
fades, and the pressure values no longer change due to the wellhead vacuum pressure of the GVB. The positive pressure value following the suction pressure fade away is the methane inlet pressure, which is applied uniformly across the top of the panel.

![Pressure profile of GVB (20 cm diameter) 91 m behind the face](image)

Figure 7.18: Pressure profile of a GVB (20 cm diameter)

The Figure 7.19 shows the radius of influence for a 20 cm diameter GVB, which is 89 m. The radius of influence is calculated from the pressure profile, assuming the end of influence where suction pressure effect fades away as shown in Figure 7.19. Similarly, the radii for 30 cm and 41 cm diameter GVBs are calculated and presented in Table 7.6. This table demonstrates the change in flow and radius of influence by the alteration of the diameter of the GVBs.
Table 7.6: Estimated radius of influence for different diameter GVBs

<table>
<thead>
<tr>
<th>GVBs Diameter (cm)</th>
<th>GVBs Flow (cfm)</th>
<th>GVB Radius of Influence (m)</th>
<th>GVB Radius of Influence (ft)</th>
<th>∆ GVB Flow (%)</th>
<th>∆ GVB Radius of Influence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>99</td>
<td>45</td>
<td>148</td>
<td>-12</td>
<td>-6</td>
</tr>
<tr>
<td>30</td>
<td>112</td>
<td>48</td>
<td>157</td>
<td>Base Case</td>
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</tr>
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<td>41</td>
<td>123</td>
<td>50</td>
<td>164</td>
<td>10</td>
<td>4</td>
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</tbody>
</table>
CHAPTER 8

FACE VENTILATION EFFECT ON GVBs AND TAILGATE METHANE

The main purpose of mine ventilation design is to provide sufficient quantity and quality of air to the workers and to dilute methane and other contaminants. It is generally perceived that additional air along the longwall face will improve methane dilution on the face and in the tailgate. However, investigations conducted with computational fluid dynamics modeling in this research have found that higher flow velocities along the longwall face increase the pressure differential between the gob and longwall face, allowing more methane to be entrained in the active face and tailgate area, thereby negating the desired dilution effect.

The increased face ventilation leads to an increase in pressure along the headgate side, which allows more oxygen to ingress into the gob area, thereby increasing the formation of explosive methane air mixtures in the gob and increasing the potential for spontaneous combustion of the coal. Two effects are happening at two different locations along the longwall face. The airflow enters the active area causing an increase in pressure, which forces more oxygen into the gob. However, as the flow develops along the longwall face, the increasing velocities cause a greater pressure drop, allowing methane to enter the active face further downstream from the headgate towards the tailgate side.

This work presents a parametric study to discuss the effects that varying the face air quantity has on methane concentrations in the tailgate and formation of explosive gas zones in the gob. Counter to conventional wisdom, increased longwall face air
quantities may increase the explosion hazard as they result in increased EGZ volumes in the gob, along with increased methane quantities in the tailgate return.

8.1 Previous Research on Face Ventilation

Researchers have previously used CFD modeling to model gas flows in longwall gobs under various ventilation schemes. Ren and Balusu (2005) used CFD modeling of longwall gobs and concluded that reduction in the face air velocity on the intake side of the goaf, or gob, will help to reduce the risk of spontaneous combustion. Tanguturi et al. (2012) used CFD to study the effect of buoyancy on methane gas distribution in the tailgate region, concluding that a back return system is helpful in reducing the tailgate methane concentration level to below 1%. Brune and Sapko (2012) applied CFD to analyze ventilation, and the potential methane accumulation and mixing patterns in the tailgate corner area and recommended keeping the immediate longwall tailgate entry open at least to the nearest inby crosscut so that positive ventilation is maintained inby the face to dilute and carry away any methane released behind the shields.

Researchers at the Colorado School of Mines have modeled various longwall panels and ventilation configurations using the CFD software FLUENT® by ANSYS, Inc., under a project funded by the National Institute for Occupational Safety and Health. Marts et al. (2013) determined that a higher volume of face ventilation increases the size of EGZs in longwall gobs. Marts et al. (2014b) recommended a back return arrangement on the tailgate side, which is effective in pushing the tailgate EGZ away from face and reducing the likelihood of ignitions at the face. They also reported that the nitrogen injection and reduction in the face air velocity can effectively control risk in the sealed gobs of spontaneous combustion.
The CFD models in this investigation simulate varying the quantities of air at the face to dilute the tailgate methane. Models also analyze the communication of gob gases with the face air and TG return, as well as looking at the performance of gob ventilation boreholes (GVBs) under varying face air quantities.

8.2 CFD Model Description

The CFD model used to study the face ventilation varies from the models used for GVB study. The CFD model grid was created using ventilation and air quality data collected from cooperating Mine C. The collected data consists of mine layouts, geometric dimensions, lithology, overburden caving characteristics, ventilation operating conditions and gas concentration measurements. The panel for this CFD model is 314 m (1030 ft.) in width and 39 m (128 ft.) in height to account for the caved and fractured zone above the coal seam. The fractured zone is in the form of single layer rather than multiple rock layers as used in the GVB analysis. GVBs extend into the fractured zone and terminate at a setting depth of 18 m (60 ft.) above the top of the gob. GVBs are 18 m (60 ft.) away from the gateroads with the first GVB being located about 66 m (220 ft.) inby the face, and there is a 60 m (200 ft.) spacing between the GVBs. A vertical cross section of the model geometry is shown in Figure 8.1. The communication of leakage flow between the gob and the face occurs through openings between the shields.

8.3 Ventilation Layout

The CFD model is a U ventilation design for a progressively sealed panel, as shown in Figure 8.2. Fresh intake air enters the longwall face through the headgate, travels across the face and exhausts through the tailgate.
Figure 8.1: Vertical cross-section of model geometry

Figure 8.2: Progressively sealed, U-type ventilation design
8.4 Boundary Conditions

The face ventilation air quantity was varied from 23 m$^3$/s (50,000 cfm) to 61 m$^3$/s (130,000 cfm), with nitrogen injection on both the headgate and tailgate of 0.19 m$^3$/s (400 cfm). The two GVBs are operated at a 0.17 m$^3$/s (350 cfm). The methane liberation rate used for the 460 m (1,500 ft.) panel length is 0.5 m$^3$/s (1,040 cfm). The gob permeability is in the range of $2.0 \times 10^{-7}$ m$^2$ to $5.1 \times 10^{-6}$ m$^2$ and the porosity is 14% to 40%, based on geomechanical modeling of actual mine lithology, shield loading information, as well as the final and dynamic subsidence data (Marts et al. 2014a).

8.5 Modeling Results and Discussion

Figure 8.3 shows the explosive mixture plots. Figure 8.3(a) shows gas mixtures at a face air quantity of 33 m$^3$/s (70,000 cfm), and Figure 8.3(b) shows the results for a face air quantity of 61 m$^3$/s (130,000 cfm). In Figure 8.3(a), a fuel rich, oxygen deficient zone is visible behind the shields near the tailgate corner. If this yellow zone increases in oxygen content, it may transition to an explosive mixture. Figure 8.3(a) also shows that the nitrogen injection from the headgate (dark green) forms a separation between the oxygen rich zone near the face and the methane rich zone in the center of the gob. Figure 8.3(b) shows that, with a higher quantity of air on the face of 61 m$^3$/s (130,000 cfm), more face air ingresses into the gob and forms a larger explosive mixture, visible as a narrow red fringe between the green and yellow areas.

The explosive zone extends behind the shields and presents an immediate fire and explosion hazard. The oxygen plots, Figure 8.4(a) and Figure 8.4(b), demonstrate that, with 33 m$^3$/s (70,000 cfm) of air on the face, oxygen ingress into the gob is low;
and with 61 m³/s (130,000 cfm) of air flow on the face, the oxygen ingresses much deeper into the gob.

If the coal is present and has the propensity to spontaneously combust, such deep oxygen ingress could cause a fire, also presenting an ignition source for an EGZ. In all cases of face air variation from 23 m³/s (50,000 cfm) to 61 m³/s (130,000 cfm), the total EGZ volume increases linearly, as shown in Figure 8.5. It should be noted that the yellow zone, while not explosive, still presents a risk of fire; fuel-rich mixtures of methane and air can burn with a diffusion flame (Gilmore et al., 2014). Most of the deeper gobs contain little or no oxygen, as shown in the oxygen contour plots in Figure 8.4(a) and Figure 8.4(b).

![Figure 8.3: Contour Plots of Explosive Gas Zone](image)
8.6 Explosive Gas Zones (EGZs) and Methane in Tailgate Returns

This project also examined the relative volume of explosive mixtures and the concentrations of methane in the tailgate return as a function of varying the face air quantities. Normally, a linear dilution of the tailgate and face methane concentrations with increased face air quantities is expected. However, Figure 8.5 shows that there is no significant reduction of the tailgate methane concentration (red line) above approximately 70,000 cfm face air quantity. Figure 8.5 shows that the EGZ volume (blue line) in the gob increases with increasing the face air quantity. This phenomenon can
be explained as follows: as the face ventilation quantity is increased, a higher pressure differential is created between the face and the gob and more air (oxygen) migrates into the gob through the gaps between the shields.

![Figure 8.5: Normalized EGZ volume and CH₄ concentration plots with varying face air quantities](image)

Oxygen ingress into the gob enables the formation of the explosive mixtures. Where the coal has a high propensity for it, the oxygen ingress may increase the
spontaneous combustion potential. As shown in Figure 8.3(b), if the EGZ is located just behind the face, small changes to the gob atmospheric pressure such as a drop in barometric pressure or a roof fall could push the EGZ into the face area.

8.7 Gob Communication with Face and Tailgate Return

The increased face air flow along the longwall face will not lead to a proportional dilution in tailgate methane concentrations, as shown in Figure 8.5. There are two related phenomena occurring at two different locations along the longwall face. An increase in pressure as the flow enters the active area forces more oxygen into the gob, but as the flow develops along the longwall face, the higher velocity creates a greater pressure drop, allowing methane to enter the active face further downstream from the headgate towards the tailgate side.

Figure 8.6 shows that increasing the face air quantity increases the volumetric flow of fresh air into the gob on the headgate side (blue line). This air ingress, or leakage flow, sweeps increasing amounts of methane from the gob towards the face and into the tailgate. The red line shows the concentration of methane in the flow from the gob towards the face.

The trend lines show a near linear relationship between the face air quantity and the air and gas exchange phenomena in the gob. This trend provides insights as to why the concentration of methane does not drop further after reaching approximately 70,000 cfm of face air. The path lines of air flow in the gob are seen in Figure 8.7, confirming the flow into and out of the gob towards the tailgate.
Figure 8.6: Flow from face to gob and gob to face
8.8 Impact of Face Ventilation on GVB Performance

The model contains two GVBs on the tailgate side, which operate at 0.17 m$^3$/s (350 cfm) flow. The concentration of methane in the GVB exhaust, predicted by the model, is plotted in Figure 8.8. The methane concentration in both GVBs is near 100% at face air quantities of 33 m$^3$/s (70,000 cfm) or below. Since GVB-1 (red line) is located...
near the nitrogen injection point on the tailgate side crosscut, some of the nitrogen ends up in the GVB, reducing the methane concentration slightly. As the face air quantity is increased above $33\text{ m}^3/\text{s}$ (70,000 cfm), the methane concentration in the GVBs decreases due to the face air ingress into the gob and, subsequently, into the GVBs. As the face air quantity is increased, the GVBs start exhausting more air, and the methane concentration in this exhaust decreases apace. GVB performance studies provide additional evidence that higher face air quantities lead to deeper oxygen penetration into the gob.

![Figure 8.8: GVB Methane Concentration](image)

Figure 8.8: GVB Methane Concentration
CHAPTER 9
CONCLUSIONS

The following summarizes the findings based on trends observed in the results of the CFD parametric studies on gob ventilation boreholes and face ventilation.

➢ The optimal GVB location is near the tailgate where the upper gob retains sufficient permeability. For the specific conditions at Mine C, the optimum is at a distance of 18 m from the tailgate. This location is optimal with respect to GVB flow, Explosive Gas Zone (EGZ) formation in the gob and reducing the methane concentration in the longwall working areas.

➢ GVBs operating close to the face draw more fresh air into the gob compared to GVBs operating at a greater distance from the face.

➢ The setting depth of GVBs is an important factor as it governs the methane concentration of the GVB exhaust, as well as the amount of fresh air ingress into the gob. In the case of Mine C, a setting depth of 9 m is optimal in reducing the TG methane concentration while 18 m is optimal in reducing the size of EGZ. Optimum conditions for other mines may vary depending on the strata properties above the coal seam.

➢ The GVB setting depth also plays an important role in controlling EGZ formation. If the setting depth is closer to the caved zone, it increases the risk of spontaneous combustion and may form larger EGZs.

➢ Larger diameter GVBs may help reduce the methane concentration in the longwall face working areas, but they also reduce the methane concentration level in the GVB exhaust, decreasing the effectiveness of gob degasification.
Larger diameter GVBs may form larger EGZs, and may increase the air ingress into the gob that can promote spontaneous combustion.

By increasing the ventilation airflow quantity on the longwall face, additional air from the face may be pushed into the gob near the headgate side. In progressively sealed gob panels, this fresh air ingress tends to sweep methane from the gob into the tailgate. Due to this mechanism, an increase in face air quantity does not result in proportional dilution of methane on the face. As the face air quantity is increased, a point is reached where further increase of the face quantity will not result in additional dilution of tailgate methane concentrations anymore.

As fresh air from the face ingresses into the gob, the volume of EGZs and the explosion hazards tend to increase.

More air and oxygen ingress from face into the gob may increase spontaneous combustion hazards.

Fresh air ingress into the gob may decrease the effectiveness of gob ventilation boreholes.
CHAPTER 10

IMPLICATIONS FOR FUTURE RESEARCH

Implications of this research for future work include further refining the model geometry, meshing improvements along with an advanced study of boundary conditions.

- The longwall face model used for this research is in the form of a panel wide, long entry, and ventilation leakage into the gob is represented by gaps in the face. The face model is simplified. The inclusion of more realistic shields, armored face conveyor, tailgate and headgate drives, and the crusher would be a more accurate model of the face and would better represent flow patterns and pressure drops across the longwall face.

- In current modeling efforts, methane gas uniformly enters the models, distributed over the top of fractured zone as the velocity inlet. The methane reservoir is assumed to be non-depleting, and the methane supply into model does not decline under the current modeling assumptions. Two things need to be clarified and refined: whether a methane inlet should be used as a velocity inlet or pressure inlet, and whether it should be uniformly distributed over the top of fractured zone or used as profile declining over the length of model?

- The amount of methane used in the model is estimated from the methane concentration of fan exhaust and GVBs exhaust using inlet and exhaust methane balance approach. The methane quantity coming into an actual mine varies with time. Although a parametric study is conducted to look into the effects of methane variation into the model, as discussed in section 7.5, a more accurate
estimation of methane emissions into the mine using coal analysis and extensive measurement from the mine over a longer period of time would give a better estimate of methane emissions. This can be also be used as a boundary condition in the modeling process.

➢ The only methane source in current modeling is the rider seam, which is modeled at the top of fractured zone. The inclusion of other methane sources like face emissions, the coal on a belt conveyer, left over coal in the gob and floor coal seams should also be included into model.

➢ The effects of barometric pressure fluctuation are neglected in this research. Pressure is considered to be constant over the period of panel mining. However, mine personnel report that there are significant changes in methane concentrations in the returns during periods of barometric pressure fluctuation. Including barometric fluctuation in the model and analyzing its effects on explosion hazards would be a step further toward more representative models for coal mining safety research.

➢ For the purpose of this research, the mining process is assumed to be static instead of dynamic to consider steady state simulation as a good approximation. Transient studies can add further to the ongoing efforts to understand the explosion hazards in longwall coal mining.

➢ The modeling results are validated against actual mine measurements, but collecting additional data onsite at the mine would improve model validity.
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