Mathematical Modeling of Coal Seam Methane Drainage in Longwall Mining

Prof. Kazem Oraee, PhD
Professor, Stirling University, Stirling, UK, E-mail: sko1@stir.ac.uk

Arash Goodarzi, MSc
Research Fellow, Ministry of Labor and Social Affairs, Tehran, Iran, E-mail: arash_good@yahoo.com

ABSTRACT
Excessive emissions of methane from the coal seams can have a serious adverse effect on both safety and productivity of longwall coal faces. Mechanization of coal faces has increased production possibilities to the extent that normal ventilation systems may not be able to ventilate coal face areas in order to lower methane content in the air to within legal limits. Production increases may therefore be prohibited for this reason, especially in gassy seams. Methane drainage from the coal seam by means of long holes and before production starts can act as a useful remedial action.

In this paper a two dimensional mathematical model has been produced. The model that is based on finite elements, simulates a methane drainage system where the resultant risk is linked to the coefficient of diffusion, coal permeability, holes pattern and the duration for which the seam is subject to drainage. It is concluded that methane drainage of this type can assist in achieving production increases in many coals seems, especially where high gas content is a virtue of the seam.

INTRODUCTION
Coal seams were formed over millions of years ago as a result of biochemical decays and metamorphic transformations of plant materials. During coalification, large quantities of methane gas are generated as a by-product and stored within the coal on internal surfaces. The Earth’s crust contains huge amounts of methane. Methane is a chemical compound with the molecular formula of CH$_4$. It is the simplest alkane, and the principal component of natural gas. A part of this gas is retained in the coal and the rest is escaped to the atmosphere. Conservative estimates suggest that more than 900 trillion cubic meter of coal-bed methane exists in the world.

During coalification, large quantities of methane gas are generated and stored within the coal on internal surfaces. Because coal has such a large internal surface area, it can store surprisingly large volumes of methane. It can hold six or seven times as much gas as a conventional natural gas reservoir of equal rock volume. Methane produced during coal formation is absorbed onto its internal surfaces and it is notable that just 1 tone of coal will have an internal surface area of around 90 million m$^2$, onto which this and other gases can congregate in a molecule thin layer. Once there it is packed so that it is as dense as a liquid and volumes held this way can exceed 30 m$^3$ per tone of coal. Actual gas content of coal seams varies from 0-25 m$^3$ per ton of coal. Methane is released into coal mines from seams as mining proceeds. Methane is a combustible gas and can mix with air in a closed space such as the excavation to form an atmosphere that can explode when an unexpected ignition occurs. It makes an explosive mixture with mine air in concentration range of 5 to 15 percent by volume. The auto-ignition temperature of methane is 630°C in air. By law, methane concentrations must be below 1.0 percent in volume at the working faces. The frequent accidents occurring in mines are largely caused by the explosion of coal mine methane, which accumulates in the mining process. The history of coal mining is full with mine explosions and its result is loss of miners and properties.

Ventilation is the primary means of controlling methane. Ventilation dilutes incoming gas and removes it from the excavation, preventing it from forming a hazardous accumulation. However, ventilation is commonly not entirely effective. A rapid gas inflow can briefly overcome even the ventilation system performing as intended. The serious hazard of explosion is prevented by methane drainage from coal seams prior to and during mining.

MEHTANE DRAINAGE
Today, emissions of methane from coal mines have increased significantly because of higher productivity and the trend towards recovery from deeper coal seams; on the other hand, amount of methane must be controlled at the working faces and at other points in the mine layout. This has traditionally been performed using a well-designed ventilation system in years prior to mining, vertical or horizontal vent holes are drilled into the underground coal seam to drain the methane gas, prior to longwall mining (Fig. 1).
In order to improve mine safety, many mines are now using a degasification system to discharge much of the coalbed methane from their seams before or during mining. Methane drainage offers the added advantages of reducing the ventilation costs, reducing the development costs of the mine. The degasification methods, coupled with mine ventilation, may be the most economical method of keeping methane concentrations low in many mines. With increasing coal production and depth of coal mines, traditional ventilation methods are not always the most economical methods of handling methane in the coal seam. A systematic technique to reduce methane emissions in development headings is concluded by drilling in-seam horizontal long vent holes in the head and tail entries and discharging the produced gas into the mine air (Fig. 2).

This technique reduces methane emissions in the face area significantly if the vent holes are drilled ahead of the development of the heading at a suitable time and according to a proper layout. Horizontal methane drainage vent holes completion designs, drilling strategies, and degasification lead times may need to be adjusted for site specific conditions due to mine design, geology, and the gas content of the coalbed. The gas is diluted strongly by fresh air which is supplied by the ventilation system. Similarly, if vent holes capture gas and then methane is piped from holes to the surface area, mixing gas with the air mine will not occur and it causes to reduce the ventilation air requirement significantly. To enhance the flow of gas from a coalbed, both free surfaces of seam and vent holes are generally used. Vent holes are produced by drilling and are serviced by means of a perforated pipe through the seams to insure sufficient flow. Horizontal in-seam vent holes drain high-quantity gas from the coal seam and the surrounding strata. However, these holes generally do not seriously affect the mine-ability of the coal seams if the roof is competent. They can drain 50% to 90% of the gas content of the coal and are normally placed in operation two to seven years before mining begins.

This technique works very well for shallow or medium depth coal seams. Early vents holes were drilled to release gas as a safety measure prior to coal mining operations. Increase in natural gas prices in the 1970’s encouraged intensive research efforts and it led to the exploration and development of coalbed methane in order to maximise the profit.
In a more permeable coal, which has raised gas content, the pre-draining of the worked seam is perfected, drilling long horizontal holes into the coal. Low flows of high purity methane can be drained from the seam in this way over a number of months or years. In a coal that has raised gas content but is less permeable, gob wells drilled from the surface or underground cross measures boreholes can be employed.

**FORMULATION**

Gas occurs in coalbed in an absorbed and a free gas state. Absorbed gas is stored in the micro-pore structure and its transport is governed by diffusion theory. The free gas occurs in the fracture system and flows according to seepage theory. The absorbed gas constitutes about 90% of the total content of the coal typically (Fig. 3). The methane flow from seam is dependent upon the effective permeability of coal and the diffusion characteristics of coal. Although coal is a porous medium but its permeability is usually extremely low. The intact coal permeability is commonly accounted nearly micro Darcy. The coal seams with a less fractured structure show a degasification rate that is controlled by diffusive movement.

The diffusion theory of in-situ coal degasification is developed and a mathematical model is derived for the process. The major purpose of the theory is to provide a basis for quantitative understanding of in-situ coal degasification and to lead to important general conclusions concerning the nature of the process. The result of degasification of coal is the reduction of methane content of seams by drilling vent holes through coal strata. This process provides to move methane from the seam to atmosphere safely before mining. This transport process is modelled to accord diffusion theory. The diffusion is the process by which mass goes from a higher concentration to a lower concentration. Diffusion is caused by random molecular motion that leads to complete mixing.

The diffusive model based on Fick’s law has been commonly used for transport processes porous Medias. Adolf Fick proposed the quantitative laws of diffusion at 1886 on the basis of experimental investigations of Thomas Graham about diffusion fundamentals. A gas diffuses from a region of greater to one of less concentration (Fick’s first law) and Fick’s second law (Equation 1) predicts how diffusion causes the concentration field to change with time. Many phenomenon in nature can be described with the aid of the laws of physics in terms of differential equations relating various quantities of interest. A differential equation is a mathematical equation for an unknown function of one or several variables that relates the values of the function itself and its derivatives of various orders. The process responsible for the movement of the methane from coldbed to fresh air is diffusion. The diffusion governing equation is a second order partial differential equation which describes density fluctuations in a material undergoing diffusion. The model treats the changes of amount of concentration of methane in parallel with two independent system variables of time and space. Unsteady state (Transient) diffusion of methane from coalbed to atmosphere has been measured by solution of second Fick’s law for a concentration (C), under the boundary conditions imposed by the experimental technique.

\[
\frac{\partial c}{\partial t} = D \left( \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \quad (1)
\]

Where:
- c: is the concentration of amount of substance.
- t: is time.
- D: is the diffusion coefficient in dimensions of (length$^2$/time).

The diffusion coefficient is a constant that is dependent upon the nature of the substances. It is a function of the size of the diffusing molecules, the nature of medium and temperature. Solving this equation requires specifying one boundary condition for time and two for space. The second derivative of a concentration versus distance is not an easy quantity to measure with the required accuracy. The development of a mathematical model and then, numerical simulation methods of analysed phenomena based on that model, and computer software opens opportunities for carrying out initial evaluations of the process of methane drainage as well as for defining necessary time of drainage to reduce concentration of methane in coal. Diffusion coefficient of coal seam is the most important parameter needed for the evaluation of the emissions of methane through seams. In fact, the diffusivity property is presented by the coefficient of diffusion. Steady-state diffusion coefficient is on the order of $10^{-8}$ to $10^{-9}$ m$^2$s$^{-1}$ and transient diffusion coefficient ranges from 0.5 to 10 times the steady-state value. Based on these assumptions, the diffusion coefficient is estimated at about 6E-9 m$^2$s$^{-1}$ in this paper.
Contrary to the permeability, the diffusion coefficient can be measured in the laboratory. The methane content of coal panel is the most important of quantitative properties in the drainage process. With evaluation techniques and the numerical simulation of diffusion of methane from seam, it is possible to accurately predict the methane degasification performance on every point of panel.

SIMULATION
The simulation must determine many variables, such as:
Mathematical formulation of process and numerical analysis of mathematical formulation are different phases to solve a problem.
An effective computational method should have a sound mathematical as well as physical basis, flexible and be applicable to practical problems. It should not have limitations with regard to the geometry, boundary and initial conditions. The finite elements method is an ideal technique to solve a partial differential equation which has complex domain and conditions. Taking quantitative account of diffusive emission through a seam and a decrease in gas content in consequence is accomplished by numerical methods because a typical closed form solution does not exist.
The major steps in finite elements analysis are as follows:
- Discretisation of domain into a set of finite elements.
- Weak formulation of the governing differential equation.
- Derivation of finite element interpolation functions.
- Development of the finite element model using the week form.
- Assembly of finite elements to obtain the global system of algebraic equations.
- Imposition of boundary conditions.
- Solution of equations.
- Post computation of solution and quantities of interest.
The solution has basically been developed as two-dimensional, one-phase gas flow numerical model to simulate the diffusion of gas through partially coal seam. The governing system of fully coupled non-linear partial differential equations is solved spatially by the finite elements method. ANSYS software is used for modelling purposes as a computational fluid dynamics (CFD). CFD models are widely used to solve most complex problems involving the transport of mass. Before CFD, flow prediction was based on experiments with small geometrically similar physical models but it was unreliable.
CFD models are widely employed in mine ventilation projects recently. Transient diffusivities are determined for a coal panel by solving a model of second order partial differential equation with finite elements method. The changes of concentration of gaseous content are determined by 2D numerical simulations.
A longwall panel is blocked out by the panel entries that are excavated in-seam on both sides of the main entries. In a two dimensional model, coal block is considered as a rectangle which is surrounded by two immediate entries on both sides of the panel which are called head entry and tail entry (Fig. 2). The head entry is used for the passage of intake air while the tail entry is used for the passage of the return air.
When a coal block with high methane content is in contact with the surface of air, the amount of the methane which will go into air is proportional to the contact surface of that gas. A simple rationale for principles of physics of gases is that if the contact surface of a gas is twice as high, then on the average twice as many molecules will hit the air surface in a given time interval, and on the average twice as many will be captured and go into air.
The effective contact between air and coal is increased by the horizontal and vertical vent holes which are drilled through the coal bed for draining methane. Air displaces the methane adsorbed on the internal surface of the coal. The vent holes gather the methane as free gas and they release large accumulations of gas from coal beds. The diffusion coefficient of the methane in the coal varies with pressure and temperature, increasing as the coal loses gas.

COMPUTATION
Panel width and panel length are usually determined by experience, based on the size and shape of the coal seam and technical considerations. The panel width varies from 100 to 300 m and the panel length varies from 600 to
4,000 m in typical modern longwall faces. The numerical simulation results show that the change in coalbed gas content is extremely small relative to pass time without drilling vent holes. The rate of degasification is often accelerated by an increase in contact surfaces.

The fundamental simple assumptions in this study are that the average in-situ gas content of the coalbed is assumed to be 15 m$^3$/t. This study investigates different horizontal methane drainage vent holes patterns, vent holes lengths and degasification times prior to and during panel extraction to evaluate their effectiveness in reducing methane emissions using a 2D reservoir modelling of a 100 m wide longwall panel operating in the Kerman coal basin in Iran.

The changes of coalbed methane content were computed on the basis of the below assumptions.

Diffusion coefficient: $6 \times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1} = 0.01555 \text{ m}^2 \cdot \text{month}^{-1}$
Calculation time= 12, 36, and 72 months
Panel width = 100 m
Panel height = 2 m

A section of panel was considered to solve the problem (Fig. 4). As the panel was symmetrical, half of section (50 m) was modelled. Fig. 4a, 4b, and 4c show model geometry, meshed model, and loaded model respectively. The right wall of the model is contacted with fresh air (without methane). The Percentage of methane in fresh air was assumed 0%.

Figure 4: Model geometry, meshed model and loaded model

The total of all sections construct the whole panel. Since the model is considered homogeneous and isotropic, therefore, the behaviour of the panel is modelled according to the investigation of every section in the processes of drainage. The computed behaviour is repeated throughout the panel similarly. To reduce the computer time required to perform the simulation, a half of the panel (coal block) was modelled with finite element grid. The length of every element is considered 1 m.

A transient analysis is used to investigate the model. Transient analysis determines a quantity which varies over time. A transient analysis follows basically the same procedures as a steady-state analysis. The main difference is that conditions in a transient analysis are functions of time.

Fig. 5 presents the drainage results of a section of panel without any vent holes and Fig. 6 presents the drainage results of a section of panel where spacing of vent holes was 5 m after 72 months.
The results show that the quantity of methane concentration is quite sensitive to pass time and also the distance between the surface contacts with air and space where is investigated.

Based on data from the simulation, the maximum methane content of coalbeld was decreased from 0.453, 4.280, and 8.785 m³/t after 12, 36, and 72 months respectively (Fig. 7, 8, and 9).
Figure 7: Results for a model which vent holes spacing was 2.5 m after 12 months

Figure 8: Results for a model which vent holes spacing was 2.5 m after 36 months

Figure 9: Results for a model which vent holes spacing was 2.5 m after 72 months
The modelling results indicated that methane concentration reduction on the panel was more where the intervals between the holes were closed together. Decreasing the spacing of the vent holes from 5 m to 2.5 m caused the methane content to be approximately halved at a same period.

CONCLUSIONS
Results of this study showed that vent holes are effective in decreasing emissions. Modelling results showed that after 72 months of pre-mining methane drainage, the average longwall face emission rates can be reduced by as much as half using vent holes, where spacing was 2.5 m. It was also shown that if pre-mining methane drainage time is short, it is important to continue methane drainage during the panel extraction to maximise reductions in longwall face emissions since additional face emission reductions achieved during this period can be comparable to pre-mining degasification.

The trend of the changes of methane content for a space of panel where X=4, Y=0 and Z=0 is presented in Fig. 10. The gas content decreased from 15 m$^3$/ton to 3.75 m$^3$/ton after 72 months where vent holes were drilled 2.5 m each other.

![Figure 10](image.png)

Figure 10: The trend of the changes of methane content for a space (4,0,0) after 72 months where vent holes drilled 2.5 m each other

In longwall development mining of coal seams, providing adequate drainage system is very important to eliminate the accumulation of explosive methane air mixture in the working environment. The approach which was presented, can improve the fundamental principles of degasification. It has helped to improve in the development of control measures and practices through the effective use of in-seam horizontal vent holes and methane control in the development of mining. It is suitable in most cases of drainage. The model is able to compute the gas content of every space of coal panel at every time of drainage process.

BIBLIOGRAPHY