An Improved Void-Resistance Model for Abandoned Coal Mine Gas Reservoirs

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Abstract

Previous studies have shown that the gas pressure behaviour of some abandoned coal mines may be described with the aid of a simple conceptual model, the so called void-resistance model. In this study, an improved void-resistance model has been developed and validated using previously collected data. Two model parameters, i.e. an apparent source/sink pressure and a time constant, which control the gas pressure behaviour during recharge and under certain gas production conditions, are defined. It has been shown that the two parameters can be determined via linear regression through analysing the historical abandoned mine gas pressure data during recharge. The void-resistance model developed has been successfully applied to analyse the historical pressure data recorded at two abandoned coal mines in Europe.

Keywords: abandoned coal mine gas reservoir, conceptual model development, void-resistance model, methane extraction

1. Introduction

Coal has been used as an early source of heat for thousands of years; however, it was the energy requirements of the industrial revolution that expanded the coal mining industry into increasing production capabilities worldwide. First, coal fuelled the iron industry in the mid eighteenth century, then the steel industry of the nineteen century, and since, due to the energy consumption in an ever more industrialised society, it has supported the electric power
plants of the twentieth century, and still today, coal is the most utilised resource to produce electricity.

The environmental impacts associated with coal extraction and mine closures have different degrees of severity depending on the geological conditions, coal characteristics, mining method, depth and physical parameters of the workings. Some of the most prominent effects that may be associated with coalmine closures are subsidence, mine gas emissions, spontaneous combustion, and deterioration of the groundwater quality. Coal mining is associated with hazardous gases, particularly methane; therefore, different measures are put in place to prevent gas emissions from operating mines. Methane released during mining is either drained away or diluted into the mine ventilation system. However, when a mine is abandoned, methane stored in the remaining coal and gas bearing strata flows into the residual mine void creating an artificial gas reservoir.

A series of processes are associated with mine closures as water drainage and ventilation are stopped and the reservoir tends to stabilise at their new found natural conditions. Withdrawal of hundreds of litres per second of water, a common pumping rate for mining operations, results in an unnaturally rapid change in the groundwater system creating a cone of depression in the water table. Termination of dewatering results in water table recovery, which reduces the volume available for gases to accumulate and force the gas to migrate to shallower abandoned mine workings. Experience shows that the total rebound period may vary from a few months for relatively small mine systems to several decades for regionally interconnected coalfields such as the Durham Coalfield in England (Adams and Younger, 2001).

Mine gas builds up in the underground void left by the old workings and the residual empty space creates an underground reservoir with a volume that ranges from 25% to 35% of the volume of the total coal extracted (Sizer et al., 1996). The void volume of an abandoned mine consists of the residual volumes of the underground connections and the open fractures in the goaf and collapsed areas, as well as the cavities and spaces created due to the fracturing of the strata surrounding the workings. To account for void volume left in underground developments is an uncertain task. The degree to which these residual voids will shrink over time depends on the residual stress, the geometry of the openings, and the support methods used.
In the absence of gas drainage, and under the influence of a gas pressure gradient, mine gases accumulated in abandoned mines tend to migrate to areas of lower pressures (Tauziède et al., 2002). The pressure difference can be due to any of the following reasons:

- Increase in the pressure due to three main processes
  - Termination of dewatering results in water table recovery, which displaces the gas at a rate equivalent to the water inflow within the underground voids, compressing the gases.
  - Gas being supplied to the reservoir through desorption from the coal left in place.
  - Reduction in the volume of the void space caused by subsidence and the bulk of collapsed material increase the hydrostatic pressure.
- variations of pressure gradient between mine reservoir and outside atmosphere, which is one of the main forces driving fugitive emissions in leaky abandoned coal mines (Lagny, 2014).

Laboratory experiments and underground observations carried out during early and mid-1900s in Britain demonstrated the connection between barometric pressure and the emission of gases in mines (Carter and Durst, 1955; Durst 1956). Later studies by Cote (2000) have shown the relationship between fugitive emissions from abandoned mines and atmospheric pressure changes.

Largely flooded mines will have associated reduced gas reservoirs where small barometric pressure fluctuations can cause the mine to “breath”, which means air is flowing into the mine during periods of high barometric pressure. On the other hand, in dry gassy mines, substantial quantities of gas may be produced from the mine and barometric pressure changes cause only small variations in the emission rate (Coté, 2000).

Dry or partially flooded abandoned mines present an environmental hazard as they will continue to emit methane to the atmosphere at rates dependant on the amount of coal left in the mine and the gas content of coal and other strata above the water level. Sealing measures to prevent surface discharges into the atmosphere generally do not stop mine gas emission taking place through permeable or fractured strata, geological faults or faulty seals as most seals are known to leak (Coté, 2000). Other measures available to control methane emissions from abandoned mines are flaring and the extraction of gas for electricity generation or for injection into the natural gas grid. Therefore, the benefit of methane extraction from abandoned mines is twofold; firstly to generate energy from a low-polluting source and secondly to limit the emission of a greenhouse gas into the atmosphere. Another important
benefit is also to ensure safety for people living above former mining workings, by putting the mine reservoir in depression and so reducing risk of uncontrolled gas migration through former shafts/audits or cracks/fractures towards surface.

Over the past 50 years, there has been a significant reduction in coal mining activity in most Western European countries. Complete closure of the coal industries in the Netherlands and Belgium has been followed by progressive size reductions in Germany, the UK and Spain (Younger, 1993). In April 2004, France closed its last coal mine (Etext, 2005). In the US it is estimated that at least 7,500 underground coalmines have been abandoned since 1970 (MSHA, 1999). The UK has some 900 abandoned coal mines, some of which (around 400) leak methane into the atmosphere which represents approximately 0.17% of the total UK greenhouse gas emissions (DTI, 2004). Commercial Abandoned Mine Methane (AMM) extraction and utilisation schemes, which predominantly aim to generate electricity or provide fuel to industrial customers, have been practiced in the UK, Germany, France, Czech Republic, the USA and China. In the UK it was estimated that 52kt of methane were emitted annually from abandoned mine sites of which 31kt of methane emissions were captured and used by the Coal Mine Methane (CMM) industry (DTI, 2004).

Previous studies (Couillet et al., 1998; Burrell and Kershaw, 2000) have shown that the pressure behaviour of gases in some abandoned mines may be described with the aid of a simple conceptual model, the so called void-resistance model. The general model for an abandoned mine assumes that the flow behaviour can be represented with the inflows of methane and air into a void of a particular volume which is also connected to the surface through an extraction system. Simple conceptual models that consider extensively interconnected volumes of workings as individual ponds, which are connected to other ponds only at discrete overflow points, have also been developed to simulate ground water rebound in systems extending more than 100 to 3,000 km² (Adams and Younger, 2001).

Durucan et al. (2004) carried out detailed numerical modelling for the prediction of AMM recovery from the Saar Coalfield in Germany. More recently Palchik (2014) evaluated time-dependent changes in methane emissions from vertical exploration boreholes drilled to abandoned mines. Karacan (2015) reported a reservoir modelling study that characterises methane extraction from an abandoned room-and-pillar mine in the Springfield coal, Indiana through history matching of two AMM wells drilled into two sealed sections.
In the study reported here, an improved void-resistance model has been developed building upon the previous work reported by Couillet et al. (1998) and Burrell and Kershaw (2000). The model has been successfully applied to analyse the historical pressure data recorded at two abandoned coal mines in France and England.

2. Void resistance model representation of abandoned coal mine gas reservoirs

Couillet et al. (1998) developed a simple conceptual model, the first so called void-resistance model, to describe gas pressure variations in old mine workings during extraction of methane. In this conceptual model, the gas reservoir is assigned a volume \( V \), which corresponds to the residual volume of mining cavities and spaces due to fracturing of the neighbouring strata and porosity. The gas is stored in free form in this volume, and principally under an adsorbed form on the coal seams. This reservoir is connected to surface drainage installations through old shafts or drainage boreholes.

The pressure of this volume varies with the outgoing flow rate of mine drainage and the incoming gas flow rate. The latter is made up of two parts: firedamp desorption flow, \( q_d \), and leakage flow from atmospheric air, \( q_a \). Air leakage rate can be expressed as a function of the depression of the reservoir pressure \( p \) relative to the atmospheric pressure \( p_a \)

\[
p_a - p = R_B q_a^\chi
\]  

where \( R_B \) is the equivalent resistance to air leakage into the mine and \( \chi \) is the power coefficient, which equals 2 for turbulent flows and 1 for laminar flows. Introducing parameter \( C_B = 1/R_B \) as the atmospheric air inflow capacity of the reservoir and assuming laminar flow for air leakage, one obtains

\[
q_a = C_B (p_a - p)
\]  

Couillet et al. (1998) argued that, over a short period of time (days), \( q_d \) maybe expressed as a decreasing linear function of the reservoir pressure,

\[
q_d = \alpha(p_a - p) + \beta
\]  

where \( \alpha \) and \( \beta \) are firedamp desorption capacity constants. The total incoming flow of gas is expressed as:
\[ q_{in} = q_a + q_d = (\alpha + C_B)(p_a - p) + \beta \] (4)

The simple void-resistance model thus has four parameters, i.e., \( \alpha, \beta, C_B \) and \( V \), which need to be estimated through model calibration by matching the field pressure data in an iterative manner over a series of time steps. The model has been applied with good results on some abandoned mine reservoirs in the French coal basins (Couillet et al., 1998). In a separate study, Lagny et al. (2004) reported some examples of model application on the case of Saint-Charles reservoir in the Lorraine coal basin.

### 2.1 Tight reservoirs

Some abandoned mines where low mining activity has taken place and a good effective sealing is put in place constitute a special type of gas reservoir, so-called “tight reservoirs”. This type of reservoirs, which represent a special case of the general void-resistance model, has been considered by Burrell and Kershaw (2000). As illustrated in Figure 1, the conceptual model features three parameters, the effective connected void volume \( V \), the equivalent recharge flow resistance \( R_A \), and the average gas pressure in the surrounding strata \( p_s \). The strata pressure \( p_s \) may be viewed as the limit approached asymptotically by the reservoir pressure during a long-term shut-in.

![Figure 1 The conceptual model for tight reservoirs considered by Burrell and Kershaw (2000).](image-url)
Assuming laminar flow from strata to the void during recharges, the firedamp flow rate is expressed as

$$ q_m = (p_s - p) / R_A $$  \hspace{1cm} (5) $$

Burrell and Kershaw (2000) derived the following equation during recharge

$$ p = p_0 + (p_s - p_0) \left(1 - e^{-\frac{t}{t_c}}\right) $$  \hspace{1cm} (6) $$

where $p_0$ is the initial void pressure and $t_c$ is a time constant given by

$$ t_c = \frac{R_A V}{p_o} $$  \hspace{1cm} (7) $$

The time constant represents the time period over which 63.2% of the total pressure recovery has occurred. One shortcoming of this model formulation is that the strata pressure is treated as a constant during recharges. In reality, the strata pressure would increase over time with the recovery in the void pressure.

The exponential function for the pressure recovery curve has been evaluated using several sets of measurements confirming the validity of the model in tight reservoirs. Comparison between data and actual recharges using the above equations is reported to show good fits, in general.

3. An improved void resistance model for abandoned coal mine gas reservoirs

The conceptual model developed in this study represents an extension of the tight reservoir model by Burrell and Kershaw (2000). It consists of a connected void volume $V$ surrounded by the remaining coal seams at an average pressure of $p_s (> p)$ (Figure 2). The gas pressure $p$ in the void is affected by the gas inflow rate, which is made of two parts: $q_m$ from the source strata (mainly methane) and air leakage rate $q_a$ from the atmosphere during a recharging period, and also by the gas extraction rate $q_e$ (at void gas pressure) when in production. The inflow rates are controlled by the pressure difference between the void $(p)$ and source strata $(p_s)$ and the atmosphere $(p_a)$ and the resistances to gas flow ($R_A$ and $R_B$ in Figure 2).
Figure 2 The void-resistance conceptual model of an abandoned coal mine gas reservoir proposed in this study.

At pressure and temperature conditions of abandoned coal mines the gas behaviour can be described by the Ideal Gas Law $pV = mRT/M$, where $m$ and $T$ are mass and temperature of the void gas respectively, $M$ is the molecular weight of the gas and $R$ is the universal gas constant. The mass balance equation for the void-resistance model may be written as

$$\frac{dm}{dt} = \frac{d}{dt} \left( \frac{MpV}{RT} \right) = q_m\rho_m + q_a\rho_a - q_v\rho_v$$

(8)

Where $\rho_m$ and $\rho_a$ are the gas density for the two inflow rates at the mean gas pressure respectively, and $\rho_v$ is the void gas density given by

$$\rho_v = \frac{MPV}{RT}$$

Define an apparent mean gas density for the two incoming flows

$$\rho_{am} = \frac{q_m\rho_m + q_a\rho_a}{q_m + q_a}$$

As a first approximation, it is assumed that the difference between $\rho_{am}$ and $\rho_v$ can be neglected over a recharge/gas extraction period. This allows the density terms in Equation (8)
to be replaced with the corresponding pressures under constant void temperature conditions. Assuming that the void volume \( V \) remains unchanged, Equation (8) becomes

\[
\frac{V}{dt} \frac{dp}{dt} = q_m \frac{p_s + p}{2} + q_o \frac{p_o + p}{2} - q_e p
\]  

As with Burrell and Kershaw (2000), methane gas is assumed to flow from the surrounding strata with an average pressure of \( p_s(t) \) and mass inflow rate of methane into the mine void is expressed as

\[
q_m = \frac{p_s - p}{R_A}
\]  

where \( R_A \) is the equivalent recharge resistance coefficient. Note that unlike in Equations (5) and 6), here \( p_s \) may vary with time. Following Couillet et al. (1998), the incoming flow rate of air is given by

\[
q_m = \frac{p_a - p}{R_B}
\]  

where \( R_B \) is the equivalent leakage resistance coefficient.

Substituting Equations (10) and (11) into (9)

\[
\frac{V}{dt} \frac{dp}{dt} = \frac{p_s^2 - p^2}{2R_A} + \frac{p_a^2 - p^2}{2R_B} - q_e p
\]  

Or in terms of the flow capacity coefficients

\[
\frac{V}{dt} \frac{dp}{dt} = C_A(p_s^2 - p^2) + C_B(p_a^2 - p^2) - q_e p
\]  

where \( C_A = 1/(2R_A) \) and \( C_B = 1/(2R_B) \).

Rearranging Equation (12b)

\[
\frac{dp}{dt} = \frac{p(C_A + C_B)}{V} \left[ \frac{C_A p_s^2 + C_B p_a^2}{p(C_A + C_B)} - \frac{q_e}{C_A + C_B} - p \right]
\]

Defining
\[ p_s' = \frac{C_A p_s^2 + C_B p_s^2}{(C_A + C_B) p} - \frac{q_e}{C_A + C_B} \]  

Equation (13) then becomes

\[ \frac{dp}{dt} = \frac{p(C_A + C_B)}{V} (p_s' - p) \]  

Parameter \( p_s' \) may be considered as an apparent source/sink pressure. Note that during recharging periods \( (q_e = 0) \), Equation (14) reduces to

\[ p_s' = \frac{C_A p_s^2 + C_B p_s^2}{(C_A + C_B) p} \]  

During a recharge period the flow resistance coefficients \( R_A (C_A) \) and \( R_B (C_B) \) may be expected to remain largely unchanged. The atmospheric pressure may vary with time. The void pressure will increase, so is likely the strata pressure \( p_s \) (desorption/diffusion from the remaining coal seams). Thus \( p_s' \) in general would also vary with \( p \) and time. However, it is noted that \( p_s' \) is likely to be a weak function of \( p \). In this study, \( p_s' \) is treated as a time-invariant parameter over recharging periods so Equation (15) may be solved analytically.

Defining a time constant for the abandoned mine similar to that in Equation (7)

\[ \tau = \frac{V}{(C_A + C_B) p_s'} \]  

Equation (15) becomes

\[ \frac{dp}{dt} = \frac{p}{\tau} (p_s' - p) \]  

Equation (18) indicates that the gas pressure behaviour of an abandoned mine reservoir that conforms to the void-resistance model is controlled by the apparent source/sink pressure \( p_s' \) and the time constant \( \tau \) under recharge conditions. Furthermore, it can be shown that parameters \( p_s' \) and \( \tau \) may be determined by fitting the historical reservoir pressure data during recharging periods.

Equation (18) may be rearranged as
\[
\frac{d \ln p}{dt} = \frac{p - p_s'}{\tau} + \frac{p_s'}{\tau}
\]

There thus exists a linear correlation between the left-hand side of Equation (19) and the void pressure \( p \), which allows the estimation of \( p_s' \) and \( \tau \) through linear regression.

Under recharge conditions, Equation (18) may be solved to yield (Appendix A)

\[
p(t) = \frac{p_s'}{1 + \frac{p_s' - p_i}{p_i} \exp\left(-\frac{t - t_i}{\tau}\right)}
\]

where \( p_i \) is the void pressure at time \( t_i \)

Note that this solution to Equation (18) also holds under certain active gas extraction conditions when the apparent sink pressure in Equation (14) can also be treated as a constant.

3 Model implementation

The improved void-resistance model developed has been validated using the field pressure data monitored at the Peyerimhoff abandoned mine in the Loraine Basin, France and the Markham abandoned mine reservoir in Derbyshire, England.

3.1 Peyerimhoff abandoned mine, France

Abandoned mine methane production data at the Peyerimhoff abandoned mine from January 1995 to December 2002 have been made available to Imperial College by Candice Lagny of INERIS. The records included measured reservoir pressure, barometric/atmospheric pressure methane concentration and daily extraction rates of mine gas. Of particular interest here are the two well defined recharging periods in 1995 and 1997 and a 72-day production period immediately after the first recharging period, during which the production rate remained nearly constant (Figure 3).
Figure 3  Barometric (grey dots) and field reservoir pressures (blue dots) and gas extraction data (black dots) at the Peyerimhoff mine.

3.1.1 Recharging periods

It is noted that the abandoned mine gas pressure recovery behaved in a rather similar manner in the two recharging periods which are approximately two years apart (Figure 3), suggesting that the reservoir conditions remained largely unchanged during the intervening years. In particular, the abandoned mine gas pressure increased from 75 to 98 kPa over a period of 65 days in 1997.

Estimation of the model parameters involves two steps: 1) computing the rate of change of \( \ln p \); 2) plotting \( \frac{d\ln p}{dt} \) against \( p \) to obtain \( p_s \) and \( \tau \) by linear regression. To eliminate the oscillations experienced in the direct computation of \( \frac{d\ln p}{dt} \) using the raw data between two adjacent data points, the \( \ln p-t \) plot is first made and fitted using polynomials. The fitted
polynomial is then differentiated with respect to $t$ to obtain $\frac{d(lnp)}{dt}$ and plotted with respect to $p$. It was found that $\frac{d(lnp)}{dt} - p$ plot for the second recharge period in Figure 4 could be fitted well using a 3rd order polynomial (Figure 5). Differentiation of the polynomial and applying linear regression (Figure 6) yields a time constant $\tau$ of 40.4 days and an apparent source pressure $p_s'$ of 106.1 kPa. Using these values, good agreement between the analytical solution Equation (19) and the field pressure data is obtained (Figure 7).

**Figure 5**  The logarithmic pressure (in kPa) during the recharge period is fitted using a 3rd order polynomial of the recharge time (Peyerimhoff abandoned mine).

**Figure 6**  Application of linear regression to yield the two model parameters during recharge (Peyerimhoff abandoned mine).
3.1.2 Gas extraction at a near-constant rate

From 2nd October to 15th December 1995, an average extraction rate of 92,700 m³/day (at the atmospheric pressure) was maintained (Figure 8). During this period, the abandoned mine gas pressure dropped by approximately 10 kPa, from ~97 to ~87 kPa. An attempt has been made to apply the linear regression method to estimate the model parameters under this active mine gas extraction period.

Following the procedure detailed above, the logarithm of the mine pressure is first fitted using a 3rd order polynomial of the extraction time (Figure 9); its derivative with time $\frac{d\ln(p)}{dt}$ is then plotted as a function of the pressure $p$, from which the model parameters ($p_s'$ and $\tau$) are obtained through linear regression (Figure 10). Note that the linear regression is performed over the first part of the extraction period when the mine pressure remained above 90 kPa. An apparent sink pressure of 87.1 kPa and a time constant of 33.6 days are obtained for the extraction period. It can be seen that the model predictions compare reasonably well with the field pressure data throughout this period (Figure 11).
Figure 8  Decline in the abandoned mine gas pressure during the period where a near-constant extraction rate was maintained (Peyerimhoff abandoned mine).

Figure 9  The logarithmic pressure (in kPa) during the active gas extraction period is fitted using a 3rd order polynomial of the extraction time (Peyerimhoff abandoned mine).

Figure 10  Application of linear regression to yield the two model parameters during drawdown (Peyerimhoff abandoned mine).
Figure 11  Model predictions vs. field gas pressure data during the active extraction period where a near-constant rate was maintained (Peyerimhoff abandoned mine).

3.1.3 Estimation of the abandoned mine void volume

Based upon the above analysis, an attempt has been made to estimate the model constants, in particular the void volume. From Equation (19), one has

\[ \frac{V}{(C_A + C_B)} = \frac{1}{\tau} \]

It is noted that the ratio \( V/(C_A + C_B) \) computed for the recharge period at 4,286 kPa-days is significantly larger than that (2,927 kPa-days) for the production period. As the mine resistance to gas flow might be expected to remain largely unchanged, this result suggests that a significantly larger extent of the abandoned mine was accessed during the recharge. This may be attributed to the fact that the mine had undergone a deeper drawdown (~ 75 kPa) prior to the recharge period than that (90 kPa) during the production period considered in the analysis.

The sum \( C_A + C_B \) may be estimated from Equation (14), which can be expressed as

\[ p_s' = p_s \bigg|_{\text{recharge}} - \frac{q_e}{C_A + C_B} \]

Or
as the gas extraction rate is usually measured under the atmospheric pressure.

With \( p_s' = 87.1 \text{ kPa}, \quad p_s \big|_{\text{recharge}} = 106.1 \text{ kPa}, \quad q = 92,700 \text{ m}^3/\text{day}, \quad \bar{p} = (97 + 90)/2 = 93.5 \text{ kPa}, \quad \) and \( p_0 = 103 \text{ kPa}, \) \((C_A+C_B)\) is computed as 5,375 m\(^3\)/s kPa. This gives rise to a void volume between 15.7 and 23.0 million m\(^3\) for the production and the recharge periods respectively. The estimated void volume range is comparable with the figure of 17 million m\(^3\) reported by Couillet et al. (1998). The latter is said to be consistent with the extracted tonnage of coal during mining.

### 3.2 Markham abandoned mine, England

Markham colliery was in operation from 1882 until 1993, during which period nine coal seams have been mined. Initially, the mine was formed of three collieries, Markham No. 1, No. 2 and No. 4, which merged to form Markham colliery on 1 September 1967. Minable coal seams in the area have been extensively worked by Markham and nearby collieries, this has resulted in an extensive network of migration paths for gas and water to move within the abandoned mine complex.

Following the same procedure described for the Peyerimhoff mine, the void-resistance model has been successfully applied to the second recharge period during 2003-2004 at Markham colliery as shown in Figure 12. The abandoned mine pressure recovered from under 50 to approximately 102 kPa over a recharge period of around 200 days. The results are presented in Figures 13 to 15. Note that the linear regression is performed over the period when the abandoned mine pressure was recovered to above 60 kPa. The model parameters \( p_s' \) and \( \tau \) were found to be 109.5 kPa and 78.7 days respectively.

### 3.3 Discussion
The apparent source pressure of 109.5 kPa obtained for Markham colliery is slightly higher than that for Peyerimhoff mine (106.1 kPa). On the other hand, the recharge time constant of 78.7 days is almost double that for the Peyerimhoff mine (40.4 days). The latter suggests that the two mines have different characteristics in terms of void volume and the equivalent flow capacity for firedamp recharge and atmospheric air leakage (Equation (17)). And yet the recharge apparent source pressures for the two mines are very close to each other. Furthermore, they lie just above the normal atmospheric pressure, reflecting the important influence of the atmospheric pressure during abandoned mine recharges (Equation (16)). This finding supports the assertion that the apparent source pressure is a weak function of the void pressure and therefore its treatment of being considered as a constant in the void-resistant model is justified.

![Figure 12](image_url)

**Figure 12** Field reservoir pressure and gas extraction data at Markham abandoned mine.
Figure 13  The logarithmic pressure (in kPa) during the recharge period is fitted using a 3\textsuperscript{rd} order polynomial of the recharge time (Markham abandoned mine).

\[
y = -0.116x + 12.695 \\
R^2 = 0.9765
\]

Figure 14  Application of linear regression to yield the two model parameters during recharge (Markham abandoned mine).

\[
0 40 80 120 160 200 240 280 \\
\text{Recharge time (days)}
\]

\[
40 60 80 100 \\
\text{Abandoned mine pressure (KPa)}
\]

\[
\text{Field data} \\
\text{model } \tau = 78.7 \text{ days} \\
p_{s}' = 109.5 \text{ kPa}
\]

Figure 15  Model predictions vs. field pressure data during the 2003-04 recharge period (Markham abandoned mine).

4 Conclusions

The pressure and gas content of the strata surrounding old mine workings vary due to different stress conditions experienced in the collapsed, disturbed and un-mined seams. This study has demonstrated that the gas pressure behaviour of a complex abandoned coal mine reservoir during recharge periods, as well as under active gas extraction conditions, may be
described using a void-resistance model. Such a model has been successfully validated using data from two abandoned coal mines in France and England.

The analysis of the recharge pressure data at the two abandoned mines indicates that the abandoned mine gas pressure would eventually approach the apparent source pressure, which is slightly higher than the normal atmospheric pressure (103 kPa). This finding is consistent with the reported effects of barometric pressure changes on fugitive emissions from abandoned coal mines (Coté, 2000) and its influence on methane concentration in the cavities left behind (Hupp et al., 1999).

Nomenclature:

$C_A$: Equivalent recharge flow capacity coefficient, m$^3$/kPa-s

$C_B$: Equivalent air leakage flow capacity coefficient, m$^3$/kPa-s

$m$: Mass of gas in the void, kg

$p$: Void gas pressure, kPa

$p_0$: Initial void gas pressure in Equation (6), kPa

$p_a$: Atmospheric pressure, kPa

$p_s$: Average gas pressure in the surrounding strata, kPa

$p'_s$: An apparent source/sink pressure, kPa

$q_a$: Air leakage flow rate, m$^3$/s

$q_d$: Firedamp desorption flow rate, m$^3$/s

$q_e$: Firedamp gas extraction flow rate, m$^3$/s

$q_m$: Firedamp recharge flow rate, m$^3$/s

$R$: the universal gas constant

$R_A$: the equivalent recharge flow resistance, kPa-s/m$^3$
$R_t$: the equivalent resistance to air leakage into the void, kPa-s/m$^3$

$t$: time, day

$t_c$: A time constant in Equation (7), day

$V$: Void volume, m$^3$

$\alpha, \beta$: Void-resistance model parameters

$\chi$: Power coefficient in Equation (1)

$\rho_a$: Air leakage flow gas density, kg/m$^3$

$\rho_m$: Firedamp recharge flow gas density, kg/m$^3$

$\rho_v$: Void gas density, kg/m$^3$

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Appendix A

Equation (18) can be re-written in the following form

$$\frac{dp}{dt} = p - \frac{p^3}{\alpha p_s}$$

(A-1)
Equation (A-1) is a non-linear differential equation of the type

\[ y' + ay = by^n \]  
\[ \text{(A-2)} \]

This type of equation can be solved via a substitution, \( z = y^{1-n} \). In our case \( a = \frac{-1}{\tau}, \)

\[ b = -\frac{1}{\tau}, \]

and \( n = 2 \). With the new variable, Equation (A-2) becomes

\[ z' - az = -b \]  
\[ \text{(A-3)} \]

The general solution to Equation (A-3) is given by

\[ z = \frac{a}{(az_i - b)e^{a(t-t_i)} + b} \]  
\[ \text{(A-4)} \]

Or in terms of the original variable \( p \) after substituting for \( a \) and \( b \)

\[ p(t) = \frac{p_i}{1 + \frac{p_i - p_e}{p_i} \exp\left(-\frac{t-t_i}{\tau}\right)} \]  
\[ \text{(A-5)} \]

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