Numerical Modelling and Prediction of Abandoned Mine Methane Recovery: Field Application at the Saar Coalfield, Germany

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Outline

- Background on Imperial CBM simulator METSIM2
- Abandoned mines methane extraction in the Saar Coalfield
- Abandoned mine model development
- History matching of field production data (Hangard shaft)
- Production forecasts for two new boreholes
- Summary and conclusions
Coal as a Reservoir Rock

Uniform and orthogonal fracture (CLEAT) structure

- Macropores > 50 nm
- Mesopores 2 – 50 nm
- Micropores < 2 nm
- Cleat system (2mm - 25 mm)
- Pore surface area 20 – 200 m²/gm

Langmuir isotherm, $T = C$

$$V = \frac{V_L p}{R_L + p}$$

Gas content (m³/t)

Pressure (MPa)

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Permeability of coal is both Stress and Pore Pressure dependent.

\[ k = k_0 e^{-3c_f (\sigma - \sigma_0)} \]

- \( c_f \): cleat volume compressibility
- \( \sigma - \sigma_0 \): changes in effective horizontal stress

\[ \sigma - \sigma_0 = -\frac{\nu}{1-\nu} (p - p_0) + \frac{E\alpha_S (V - V_0)}{3(1-\nu)} \]

- compaction term
- shrinkage term

Shi and Durucan Permeability Model

\[ k = \frac{b^3}{12a} \]

\( b \): width
\( a \): length

Bundled matchstick model

\( E \): Young's modulus
\( \nu \): Poisson's ratio
\( \alpha_S \): shrinkage coefficient

Flow

(after Seidle et al., 1992)
Mining History in the Saar Basin

Upper Carboniferous age (formed 350-285 Million years ago)

- 1816 Mining activities began
- 1879/82 Construction of shafts Frankenholz 1 and 2 and later Frankenholz 3, 4 and 5 (5=Hangard)
- 1903 Start of production
- 1908 Known CH₄ gas explosions in Saarland workings
- 1930 2.822 workers produced 484.228 tons coal
- 1941 Greatest explosion and subsequent mine closure
- 1946 Reopening of Frankenholz colliery
- 1954 Opening of St. Barbara colliery
- 1960 Connection of St. Barbara and Frankenholz mines and upcast ventilation from the Hangard shaft
- 1984 Filling of Hangard shaft (= Frankenholz 5)
- 1992 Filling of Anna shafts 1 and 2, later known as Kohlwald

Frankenholz Colliery is known as one of the most gassy mines in Europe
Until 2002 DSK produced mine gas from 13 shafts, with methane concentrations in the produced gas varying from 30 to 90%.

In 2003 the gas production activities have been transferred to a regional energy producer, STEAG Saar Energie AG (now STEAG New Energies GmbH).
Up to 32 seams of varying thickness between 0.3 – 3 m in the Frankenholz - St. Barbara mining complex, dipping in Northwest direction.

Between levels 1 and 11 (-470 m), where the water level was before filling of the Hangard shaft in 1984, the total thickness of coal is calculated as 40 metres in 430 metres of coal measures strata.

The water level in the mining complex rose from level 11 (-470 m) to between levels 9 and 10 (-244 m) by 1984 and has remained at the same level since.

From 1833 to 1959, Frankenholz and St. Barbara Collieries jointly mined a total coal surface area of 4.5 km².
Gas extraction from the Hangard shaft reached over 26 million m$^3$ per annum with a methane concentration of over 57% in the first few years of production.

The back-filling of Hangard Shaft in 1984 resulted in an immediate recovery in both the gas rates and methane concentration, reaching approximately 20 million m$^3$ per annum and 55% respectively.

The produced gas quality was further boosted to a high of 90% methane following the filling of the Kohlwald Shaft in 1992.

Hangard has vented an average of 6 million m$^3$ of methane per annum between 1981 and 1984.

After the filling of Hangard shaft in 1984 the free methane gas in the mine air was also recovered.

Assuming that an average volume of 6 million m$^3$ methane was lost through ventilation in the period from 1960 to 1984, the total methane flow rates at the Hangard shaft were plotted.
An areal model with a uniform thickness of 40 m (the net thickness of all the seams down to -470 m) was built.

A uniform grid of 710 active gridblocks (100m x 100m) used.

5.0 million m² in the Northeast region (I) and 2.1 million m² in the Southwest region (II) yielding a net coal volume of 7.1 m² x 40 m = 284 million m³.
In situ gas content estimates at Frankenholz – St. Barbara Mining Complex

Düpre and Barth [1980] 2,700 million m$^3$ of methane in situ in virgin conditions and 15m$^3$/tonne for the Frankenholz – St Barbara mining area.

Kneuper and Muller [1971] 10.77 m$^3$/tonne for the coal seams in the Saar coalfield.

Hebel [1999] approximately 4,000 million m$^3$ gas in situ between levels 1 and 11 in the area defined as regions I and II in the areal model 10.8 m$^3$/t

Initial gas content:
- Zone I = 11.5 m$^3$/t
- Zone II = 9.7 m$^3$/t

Total initial methane in-place = 4,000 million m$^3$

Residual methane after abandonment = 1.800 million m$^3$
History Matching of Field Data at Hangard Shaft

**Enhanced permeability**

**Base Permeability 1 md**

**Annual methane rates (million m$^3$)**

- **1960**
  - Hypothetical shaft

- **1970**
  - Hangard shaft

- **1980**
  - Model
  - Field

- **1990**
  - Model
  - Field

- **2000**

**Suction pressure (mbar)**

- **1960**
  - Model
  - Field

**Year**

- 1960
- 1970
- 1980
- 1990
- 2000

**Annual methane rates**

- **50 md**
- **40 md**
- **30 md**
- **Field**
Frankenholz – St. Barbara Complex

Methane pressure distribution with production from Hangard shaft only

Methane production predictions from Hangard shaft only.

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Frankenholz – St. Barbara Complex

Residual methane contents with production from Hangard shaft only

- **2000**
  - Hangard Shaft
  - Allenfeld Shaft

- **2015**
  - Hangard Shaft

Annual methane production (million m³)

- 2001 to 2015
  - 2001: 9
  - 2002: 8.5
  - 2003: 8
  - 2004: 7.5
  - 2005: 7
  - 2006: 6.5
  - 2007: 6
  - 2008: 5.5
  - 2009: 5
  - 2010: 4.5
  - 2011: 4
  - 2012: 3.5
  - 2013: 3
  - 2014: 2.5
  - 2015: 2
  - 2016: 1.5
  - 2017: 1
  - 2018: 0.5

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Methane Production Predictions

Methane Production Forecast from the Allenfeld Shaft

Allenfeld shaft was seen to be emitting 5m³/min (2.6 million m³ per annum) CH₄.

Residual methane contents with production from both Hangard and Allenfeld shafts.
Methane Production Predictions

Methane Production Forecast from the Frankenholz Shaft

- Predicted annual methane production at Frankenholz

- Residual methane contents with production from Hangard, Allenfeld and Frankenholz shafts
Methane Production Predictions

Methane Production Forecast from the Frankenholz – St. Barbara Complex
3 Shafts Producing Simultaneously

Predicted annual methane production for the 3 shafts
Conclusions

- A general gas-water two-phase CBM simulator METSIM2 has been modified to simulate methane extraction from abandoned coal mines.
- Reservoir characterisation was carried out and abandoned mine models were developed for an abandoned coal mine complex in the Saar coalfield of Germany.
- A methodology for reservoir characterisation of abandoned mines has been formulated.
- An areal model to represent the lumped effect of all coal seams that contribute to methane production was developed and used in the predictions.
- Predictions carried out at Imperial College involved the assessment of potential gas production from additional boreholes at the Allenfeld and Frankenholz sectors for the future.
The authors wish to thank Mr Hans-Jurgen Kaltwang, Mr Gerhard Hebel and Mr Jörg Lehmann of former Saarberg (later DSK-Saar) who have contributed to the work carried out at Imperial College at the time of the project described here.

STEAG New Energies GmbH’s permission to reproduce some of the figures and data included in this presentation is also acknowledged.

The funding provided by DG-TREN of the European Commission for the project METSIM at the time is also gratefully acknowledged.