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Numerical studies of improved methane drainage technologies by stimulating coal seams in multi-seam mining layouts

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ABSTRACT

This paper presents procedures and results of the numerical modelling of different stimulation methods as applied to the specific conditions of a multi-seam mining layout at the Zofiówka Coal Mine operated by Jastrzębska Spółka Węglowa (JSW), Poland. Studies reported in this paper include constructions of three types of numerical models: (1) a geological model of the Zofiówka coal mine area based on large set of available data (structure maps, cross-sections, well logs, lithological profiles, laboratory measurements); (2) both large and small scale geomechanical models including the multi-seam mining layout and details of local geomechanical conditions resulting from the application of different stimulation technologies; (3) dynamic flow models including transport properties modified by the geomechanical state of the analysed seam and its surroundings. Resulting drainage process simulations were performed for three different technologies (hydraulic fracturing, high pressure jet slotting, and the use of explosives). Detailed analyses of the technologies pointed out the hydrofracturing and jet slotting as the stimulating methods that can potentially enhance methane drainage from the analysed seam. Quantitative results of the simulations estimate the dependence of the drainage process characteristics upon the basic technological parameters of the stimulation methods.

1. Introduction

It is a well-known observation that methane content in coal seams increases with depth. As coal mining in Poland is extended to ever deeper levels, high methane emissions are encountered.[1,2] This fact implies not only a serious safety risk but also significant problems for coal production by limiting the advance rates of longwalls and other mining activities. To conduct mining in such gaseous mines, it is therefore necessary to take special measures intended to prevent methane concentrations in mine air from exceeding safety limits.[3] The standard method to achieve that target is the use of ventilation systems that can ensure the required air streams.[4] However, ventilation systems may not be and are usually not sufficient to solve the problem, and it is necessary to drain methane from coal seams and surrounding rock strata.[5,6]

Methods of methane drainage prior to and during mining used in Polish coal mines involve drilling boreholes to unstressed zones in both roof and floor layers and in the mined seams.[7] The process of methane drainage has a complex character and is dominated by two basic phenomena: methane desorption and diffusion from the coal matrix and methane viscous flow through systems of macropores and fractures described by their permeability.[8] Both phenomena significantly depend on the stress state of the coal being drained. Seam destressing increases desorption/diffusion rates and effective coal permeabilities.[9–11] Due to the very limited extensions of the distressed zones produced by typical boreholes used in Polish mines and rather low original permeabilities of coal seams found in Polish mines, such drainage methods are not sufficiently effective.[12]

Consequently, the idea of using stimulated boreholes has been forwarded.[13] It consists in the investigation of the potential for the application of the following borehole stimulation techniques: (a) hydraulic fracturing, a method successfully used in the world wide oil and gas industry[14]; (b) open hole cavitation, a method that has proven effective in stimulating coalbed methane wells in low cohesion and soft coals[15]; (c) high pressure water jet slotting, a method successfully used in several Chinese coalfields to overcome gas outburst problem[16]; and (d) the use of explosives for the direct stimulation of coal seams around drainage wells.[17]

The objectives of the research reported in this paper was to study various improved methane drainage technologies realised by stimulated coal-seams under the specific conditions of the multi-seam mining layouts of the Zofiówka Coal Mine operated by Jastrzębska Spółka Węglowa (JSW), Poland. These objectives were obtained by procedures and results of the numerical modelling of the above methods as applied to the conditions of the multi-seam mining layout at the Zofiówka Coal Mine. The Zofiówka Coal Mine produces coking coal, whereas JSW

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operates both coking and steam coal mines and implements cross-measure borehole drainage to cope with methane problems. However, in-seam pre-drainage has not been used to date and standard, unstimulated drainage has been found ineffective in the coal seams characterized by low permeabilities.

Improving methane drainage from a coal seam by stimulating methods consists in modifying its geomechanical state in a way that enhances both methane release from coal matrix and gas migration to drainage boreholes. Therefore, to properly model the process it is necessary to apply both geomechanical and flow simulations. While the latter is basically limited to the seam and its nearest surroundings, the former requires modelling the analysed structure over the large scale to adequately reconstruct boundary geomechanical conditions. Furthermore, also local geomechanical models are necessary to obtain high-resolution distributions of modified stress and strain within the stimulated area that result in modifications of transport properties of flow models. In addition, such local geomechanical models determine main direction of maximum horizontal stress in the area subjected to stimulation and thus, imply optimal direction of the stimulated horizontal boreholes. The necessity of constructing both large and small scale geomechanical models also makes general-purpose, geological models for both scales indispensable.

The studies presented below were based on numerical simulations and used comprehensive numerical models of the multi-seam structure that included geological, geomechanical, and flow models. These models were constructed from prior laboratory and field studies undertaken to determine the geological, geomechanical and transport properties of the coal seam and surrounding rock strata. The paper is arranged into three major sections that are devoted to (i) geological modelling, (ii) geomechanical modelling and simulations, and (iii) flow modelling and simulations.

All the models used in this project were constructed with Petrel™ software.[18] The appropriate geomechanical simulations were performed with Visage™ simulator[19] and flow simulations with Eclipse™ simulator.[20]

2. Geological modelling

The Zofiówka coal mine is located in the south-western part of the Upper Silesian Coal Basin, which is among the major coal basins in Europe. The basin, which is filled with molassic sediments, is situated in the Variscan Upper Silesian intermountain depression. The coal-bearing sequence had a dual origin. The lower part, which is represented by the Paralic Series (Mississippian–Namurian A), was deposited in a paralic environment, whereas the upper part (Pennsylvanian–Namurian B to Westphalian D), which is represented by the Upper Silesian Sandstone Series, Mudstone Series and Cracow Sandstone Series, is of continental origin.[2,21,22]

The main focus of this study concerned an interval within the Upper Silesian Sandstone Series between the 409/3 coal seam, 413 coal seam, and in particular, the 412 coal seam, for which applications of varying methane drainage stimulation techniques were considered.

The geological model was developed at two scales to meet the requirements of the geomechanical and fluid flow modelling tasks: a large scale (global) model that covers the entire area of the Zofiówka coal mine and an entire geological profile (with a horizontal resolution equal to 25 × 25 m), whereas a second local model that represents only the D-2 part of the 412 coal seam subjected to the coal seam stimulation treatment was constructed with a 5 × 5 m horizontal resolution (Fig. 1A).

Property modelling was based on three main data sources: lithofacies well profiles, interpreted geophysical wellbore logging data disclosed by JSW operator of Zofiówka coal mine and the results of laboratory measurements carried out on coal samples collected from the 412 coal seam.[23] The property modelling was carried out at both model resolution scales; the model covering the entire geological profile up to the ground level was populated with lithofacies, total porosity and rock density values. The 3D distributions of those properties were used in the subsequent task of geomechanical modelling by defining the constraints for more reliable definitions of the mechanical properties of rocks that are strongly dependent on facies / lithology type. For the 3D property modelling, stochastic algorithms were applied (Sequential Indicator Simulation and Gaussian Random Function Simulation), which enabled the generation of multiple equally probable realizations of the property being modelled.[24] For the 3D property model application in the subsequent modelling tasks, the averages of the multiple realizations were calculated (Fig. 1B).

The other important part of the geological modelling workflow was focused on petrophysical properties modelling for the D2 part of the 412 coal seam, which is within an area of planned methane drainage activity. 3D models of porosity and permeability were elaborated, which were of the highest importance for the dynamic modelling of fluid flows to boreholes. Porosity reflects the volume of pore space within the reservoir (in this case, coal interval), whereas permeability defines the reservoir's capability to conduct fluid flow (methane and water). In unconventional formations such as coal seams, permeabilities are low or extremely low (from a fraction of mD to micro and nano darcys), and they therefore require stimulation treatments such as hydraulic fracturing to initiate gas flows through the reservoir and boreholes. 3D distributions of petrophysical properties were developed on the basis of laboratory measurements of porosity and permeability carried out on coal samples collected from the 412 coal seam, in the area where the enhanced methane drainage is being designed.

To characterize the D2 part of the 412 coal seam, a model with a 5 × 5 m horizontal resolution was populated with total and effective porosity values and horizontal and vertical coal permeabilities (Fig. 1.C). The modelling procedures were carried out using stochastic algorithms, but for the fluid flow modelling, averaged realizations were used.

Based on the geological model and the results of Langmuir's sorption measurements, the amount of in-place gas was calculated for the D2 part of the 412 coal seam for further analysis of the expected methane recovery factor for the various stimulation techniques under consideration.

3. Geomechanical modelling

A geomechanical model is a numerical representation of the mechanical state of a reservoir, field or sedimentary basin. To model the stress field and resulting deformations of rock requires information regarding the spatial variabilities of many physical properties of rock formations, including petrophysical, elastic and mechanical properties. The modelling was carried out using a geometry that reflected the elements of the structural geology of the modelled coal mine.

Based on delivered hard copy geological documentation of the Zofiówka coal mine, digital datasets were created that contained lithotype logs, bulk density, porosity, Young's modulus (E) and Unconfined Compression Strength (*UCS)* logs. Other properties crucial for geomechanical modelling, such as Poisson's ratio, friction angle and dilatation angle, were assumed based on the available literature.[25–27]

Apart from the reservoir zone, material properties in the overburden were also modelled primarily based on well log data and lithological profiles from the available boreholes. The advantage of this approach is a more accurate model of the density and porosity distributions that translates into a more accurate stress model.

The elastic and mechanical properties of rock are fundamental for conducting geomechanical analyses because they describe rock behaviour under applied stresses, including both reversible (elastic) and irreversible (plastic) deformations and indicate the level of stress needed to cause failure.

Because the distributions of the geomechanical properties strongly depend on the distribution of facies (lithotypes), applications of facies