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Uncertainty quantification of coal seam gas production prediction using Polynomial Chaos

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ABSTRACT

A surrogate model approximates a computationally expensive solver. Polynomial Chaos is a method used to construct surrogate models by summing combinations of carefully chosen polynomials. The polynomials are chosen to respect the probability distributions of the uncertain input variables (parameters); this allows for both uncertainty quantification and global sensitivity analysis.

In this paper we apply these techniques to a commercial solver for the estimation of peak gas rate and cumulative gas extraction from a coal seam gas well. The polynomial expansion is shown to honour the underlying geophysics with low error when compared to a much more complex and computationally slower commercial solver. We make use of advanced numerical integration techniques to achieve this accuracy using relatively small amounts of training data.

1. Introduction

In coal seam gas production reservoir simulations play an important role in estimating extraction rates and associated economic forecasting (Aminian and Ameri, 2009; Scott, 2008; Zhou, 2014). Under appropriate pressure and temperature conditions buried peat, gas is generated by thermal or biogenic processes, and a network of fractures (face and butt cleats) is formed (Levine, 1996).

Prior to production, most of the coal seam gas (CSG, predominantly methane) exists as adsorbate in the micro-pores (Gray, 1987) while cleats are fully or partially saturated with water. Dewatering is used to decrease the pressure in the cleats and when this pressure is less than the critical desorption pressure the gas desorbs from the matrix into the cleats (Seidle, 2011). Once the gas saturation exceeds the residual gas saturation, gas begins to flow along with water to a producer. This process is assumed to obey Darcy's Law (Aminian and Ameri, 2009; Zhou, 2014) and is simulated numerically to predict gas and water production for CSG wells. The gas and water production increases until the production rates reach a peak (not simultaneous for water and gas) and decline thereafter. Over time a reduction in the gas content and pressure in the matrix results in a decline in gas production rates.

Key indicators are used to predict the gas production curve, for instance: peak gas production rate, the time to peak gas rate, and other production decline coefficients (Aminian and Ameri, 2009; Keim, 2011). Aminian and Ameri (2009) derived a formula for calculating the peak gas rate based on the fluid radial flow equation. Bhavsar (2005) estimated the dimensionless peak gas rate using a regression equation with critical gas desorption pressure, skin factor, porosity, Langmuir volume and Langmuir pressure. Zhou (2014) developed equations to predict the peak gas rate, peak gas rate arrival time and decline rate by multiple regression of 200 simulations. Those simulations were based on a static model with varied skin factor, porosity, permeability, model geometry, desorption time, Langmuir volume and pressure, thickness, dewatering pressure, and critical desorption pressure.

For the operation of a CSG field, peak gas and the cumulative gas production over a period of time are important measures of field performance and aid in field management decisions. Uncertainty in these model results has significant impact on economic and budgeting considerations.

Sophisticated simulation packages have been developed to capture the complicated nature of the pressure changes and fluid flow regimes in hydrocarbon reservoirs. Techniques such as experimental design and

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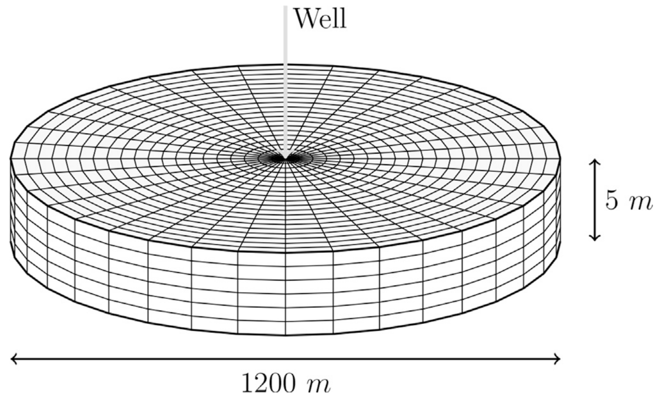

Fig. 1. Illustration of the grid system with radial distance plotted on a logarithmic scale.

Monte Carlo simulations have been incorporated into some of the commercial simulation packages and applied across various industries; see for instance (Collins and Badessich, 2015; Yeten et al., 2005) for studies on petroleum recovery. Li et al. (2011) used probabilistic collocation methods to quantify uncertainty in petroleum reservoirs and then compared these techniques with the more traditional experimental design approach. A key disadvantage of the experimental design approach is that the stochastic nature of the problem may not be captured as the probability distributions of the parameters are ignored. While Monte Carlo simulations can overcome this problem, they can be time consuming and expensive, especially for production optimisation and uncertainty quantification. In addition, the complexity of these simulation packages renders them virtual 'black-boxes' in the sense that modifications to their inner workings are not possible. In this setting techniques that reduce computational cost, while at the same time deliver additional statistical information, are invaluable.

As an alternative Sarma and Xie (2011) proposed the use of Polynomial Chaos Expansions (PCEs) to develop simulations for forecasting oil reservoir performance. Sarma and Xie treated the reservoir simulation as a black-box, approximating it with a PCE.

Polynomial Chaos Expansion (PCE) is a mathematical technique for taking very complex models and constructing *surrogate* models that take the same inputs and accurately and more efficiently approximate the outputs. *Non-intrusive polynomial chaos* is a variation of this technique that requires no modification of the original model, but can replace a virtual 'black-box' with a simple surrogate that behaves similarly in terms of its inputs and outputs. This much simpler model can then be evaluated very quickly, allowing for better exploration of the parameter space, uncertainty quantification, and, potentially, better forecasting tools and new work-flows that take advantage of the significant reduction in computational time. Moreover, it enables the ready extraction of Sobol' indices and hence provides a global sensitivity analysis for the surrogate, which in turn approximates the equivalent analysis for the original model.

Further examples of the application of PCEs in the study of subsurface oil reservoirs can be found in (Alkhatib and King, 2014) and (Jansen et al., 2008) where PCEs are used to study surfactant-polymer flooding for oil recovery processes. The application PCEs are also applied to subsurface oil reservoir models in (Bazargan et al., 2013) and (Dai et al., 2014); indeed (Dai et al., 2014) uses the constructed PCEs to perform global sensitivity analysis in a similar manner to that used later in this paper for coal seam gas models. The literature also documents the use of PCEs in many other applications, for instance, to study the trapping of CO_2 (Babaei et al., 2015b; Oladyshkin et al., 2011), flow in porous media (Fajraoui et al., 2011), and subsurface flows (Babaei et al., 2015a; Elsheik et al., 2014). Applications of PCE techniques to CSG modelling have recently begun to be addressed in the literature (Senthamaraikkannan et al., 2016), but are not used in the conventional CSG industry, supporting the argument of a need to study and apply PCE to problems unique to CSG.

In the current paper we wish to take advantage of the power of PCE and use it to emulate a commercial simulation package for the estimation of peak and total gas production for a single well tapping water and gas from a single coal seam. The production forecasts for coal seam gas are heavily dependent on the time of peak gas arrival, a problem somewhat unique to coal seam gas. The two phase flow of gas and water behaves differently from two phase flow of oil and water, with the peak rates occurring at different times for water and gas with the gas flowing after the water is much diminished, as demonstrated in Fig. 2. As evidenced by current industry practices, there is a need to investigate models developed specifically for CSG; a need that indicates the timeliness of and

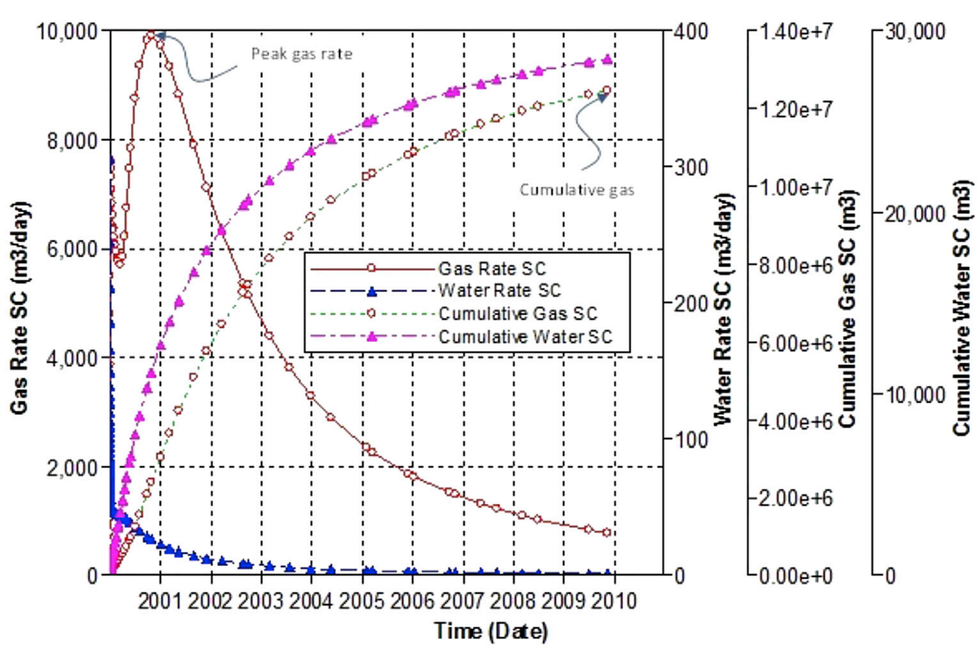

Fig. 2. Simulated gas and water production rates and cumulative gas and water production for one run of the model. The permeability, porosity, Langmuir volume and pressure for this case are 43 mD, 0.7%, 0.255 mol/kg, and 5882 kPa, respectively. This case was simulated with well bottom-hole pressure at 300 kPa as the constraint.