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Virtual special issue: Advanced theoretical and numerical approaches and applications to enhanced gas recovery

Introduction to special issue

Natural gas resources, a vital and relatively clean component to world energy supply, are consumed as both gases and as liquids extracted from the gas across all sectors of the economy. The substantial reserves of unconventional fuels have spurred energy production and supplemented the existing supply from conventional sources. This significant trend in energy production from conventional towards unconventional resources, including tight gas, shale gas, liquids-rich shales, coal-bed methane, and gas hydrate reservoirs, is a consequence of innovative new techniques applied to their recovery. These techniques are complemented by advanced theoretical and numerical approaches, including fractal analysis and microscopic/mesoscopic modelling, applied to predict gas production and to enhance recovery from in-place resources.

This special issue bridges the gap between theory and field practice to understand process-based mechanisms and their applications as advanced techniques employed to improve recovery. The topics addressed include innovative techniques for stimulation, production enhancement, flow assurance, reservoir characterization, and other approaches. The following summarizes the scope of this special issue, divided into six broad topical fields:

1. Fractal-based approaches to flow and transport in complex reservoirs
2. Novel numerical methods and modelling to enhance gas recovery
3. Fracture characterization and hydraulic fracturing
4. Transport properties in single- and dual-porosity tight-gas reservoirs
5. Capillarity in enhanced gas recovery
6. Geochemical, geophysical and microbial approaches to unconventional gas reservoir characterization and recovery

1. Fractal-based approaches to flow and transport in complex reservoirs

In natural gas and oil reservoirs, fracture networks and pore space possess a hierarchical structure and may be represented as fractals. Where this is the case, the transport properties may be characterized by fractal-based approaches. Given that geometric properties of fractures exert a significant influence on the directional permeability of fracture networks, Liu et al. (2016, JNGSE, 33: 1330–1341) present a numerical study to analyse response where fracture length follows a fractal power-law distribution. The fracture networks contain two sets of fractures with different distributions of length, aperture and orientation. Their results show that the directionality of the permeability is significantly influenced by the ratios of fractal dimensions, fracture apertures, fracture intersection angles, and the orientations of the two fracture sets. The direction of the maximum permeability is always identified to be closer to the orientation of fractures with larger fractal dimension or aperture.

Gas diffusion and flow in fractal porous media has also received much attention. Xiao et al. (2016, JNGSE, 33: 1324–1329) derive a fractal analytical model to quantify gas diffusion across fibrous porous media composed of nanofibers. The proposed model is expressed in terms of porosity, pore area fractal dimension, fractal dimensions representing average tortuosity, and geometrical structures of the porous nanofibers. Zheng et al. (2016, JNGSE, 34: 1446–1452) develop a pore-scale model of gas flow through a porous medium represented by a Sierpinski fractal. Velocity distributions inside the porous medium are analysed, and effects of the porous structure and rarefaction effect on gas permeability are investigated numerically. Based on a micro-model for flow and a fractal capillary model, Li et al. (2016, JNGSE, 34: 534–540) present a fractal model for gas effective permeability of micro- and nanoscale porous media over the entire Knudsen number range. The analytical expression for gas effective permeability together with the Klinkenberg effect is stated in terms of structural parameters of the porous medium and properties of the gas.

Recently, a new fractal approach, namely the “Intermingled Fractal Units” (IFU) model, is formalised to predict numerous characteristics of porous media. This procedure allows the simulation of the porous microstructure in terms of pore size distributions. Pia (2016, JNGSE, 35: 283–290) develops this IFU model to predict the water vapour permeability characteristics of porous media. The reservoir rocks studied include limestones from South Sardinia, which have similar characteristics of those observed in tight gas reservoirs. The ability to predict water vapour permeability and resulting fluxes for similar microstructures should assist in the exploitation of certain tight gas resources.

2. Novel numerical methods and modelling to enhance gas recovery

During active underground coal mining operations, it is essential to maintain safe working conditions including the development of an effective gas recovery strategy of methane released from the

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mining face. Kurnia et al. (2016, JNGSE, 35: 661–672) investigate the air flow and methane dispersion at the mining face and suggest strategies to mitigate and enhance methane gas recovery using a computational fluid dynamics approach.

Coal seam gas productivity is generally affected by coal properties, gas content and wellbore geometry. A full understanding of fluid flow and transfer through the reservoir and wellbore is critical for analysing reservoir behaviour. Azadi et al. (2016, JNGSE, 35: 320–330) develop a large-scale three-dimensional model for the simulation of an integrated reservoir-wellbore flow system to study the effect of wellbore geometry on flow characteristics and wellbore productivity.

Accurate description and quantitative estimation of permeability of fractured rock masses have attracted substantial attention. Hydraulic properties of fractured rock masses are commonly estimated from 2-D fracture network models. However, the geometric simplification associated with 2-D models commonly results in a significant underestimation of fracture network permeability. Huang et al. (2016, JNGSE, 33: 1271–1281) present a numerical procedure to address flow mechanisms in 3-D discrete fracture networks in which the fractures are modelled as circular discs of arbitrary size.

Based on the “interMixingfoam” solver in OpenFOAM, Xu et al. (2016, JNGSE, 35: 1270–1276) analyse water propagation and silt spreading over a silty seabed. The influence of different silts on water over a shoreline was investigated with different parameters such as silt viscosity, silt density, and inlet-water velocity. The developed numerical model can also be used to examine the response of low permeability reservoirs such as gas-bearing shales.

Accurate prediction of gas permeability in shale is an important challenge due to geometrical complexity and heterogeneity at the pore scale. In addition, the application of conventional- Darcy's-law approaches to shale usually fail due to the predominance of slip and Knudsen flow. Wang et al. (2016, JNGSE, 34: 948–957) study the influence of pore-scale anisotropy and heterogeneity of shale microstructures on gas permeability focusing on the high Knudsen number regimes.

3. Fracture characterization and hydraulic fracturing

Unconventional gas reservoirs exhibit composite and heterogeneous microstructures including organic patches and inorganic materials. This heterogeneity exerts a significant influence on the initiation and propagation of hydraulic fractures. By coupling finite and discrete element methods, Ju et al. (2016, JNGSE, 35: 614–623) numerically investigate the process of initiation and propagation of hydraulic fractures in a heterogeneous medium based on the continuum-based discrete element method (CDEM) algorithm. They present a numerical model to represent the actual heterogeneous structure of a physical specimen. They also discuss the location of initiation and the process of fracture propagation as influenced by differences in geostress and heterogeneity. The veracity of the simulations is identified by comparing 3-D reconstructions of the models with experimental results.

Generally, gas recovery from unconventional reservoirs has a low production rate and unsatisfactorily ultimate recovery. This is because gas remains trapped in the ultra-tight formation and conventional methods of exploitation are unable to release this residual gas. Hydraulic fracturing is an effective approach to obtain economic gas production rates. A proper evaluation of the effectiveness of the fracturing process is essential in designing and optimizing future-stimulation operations. Li et al. (2016, JNGSE, 35: 873–881) propose a hybrid model to simulate the evolution of complex multi-scale fracture networks in a very efficient way. This can serve as a reliable tool to rapidly evaluate different plans for enhanced gas recovery, especially when multiple realizations are required for uncertainty analysis.

Efficient extraction from gas-rich but low-permeability coal seams is a pressing practical problem. There are two main technologies applied in attempts to increase permeability: deep hole blasting; and, hydraulic coal seam fracturing. To optimize permeability enhancement for coal seams, Lei et al. (2016, JNGSE, 33: 1282–1290) conduct a shaped-charge-blasting-comparison test of different radial-decoupling-charging coefficients and a hydraulic-fracturing-comparison test of different injection pressures and fracturing durations. Contrasting tests show that the effective range of permeability improvement by hydraulic fracturing is much greater than that achieved by shaped-charge blasting. In addition, although shaped-charge blasting provides a higher initial peak of the gas-volume fraction recovered in the extraction boreholes, the gas-volume fraction recovered associated with hydraulic fracturing has a lower decline rate.

Roughness of fractures plays a crucial role on proppant transport affecting the maintenance of aperture and conductivity of hydraulic fractures. Raimbay et al. (2016, JNGSE, 33: 1291–1307) present an experimental scheme and analysis to fundamentally understand the transport of proppant in a single fracture penetrating different rock types. Change in fracture conductivity due to roughness is quantitatively described for fractures of different lithologies. Fracture conductivity and proppant distribution are correlated to three fractal methods (variogram, power spectral density, and triangular prism) and the ratio of total and planar fracture surface areas.

Natural fractures are commonly filled, in addition to fluids, with solid and plastic infill materials including sheared-off or broken rock fragments and clays. In order to understand the effects of fracture infill on mechanical properties and crack propagation behaviour of pre-fractured rocks, Zhao and Zhou (2016, JNGSE, 34: 702–715) conduct a large number of numerical uniaxial compression tests for rock samples with single or double flaws which are either open or infilled, using a particle mechanics method. Results show that infill plays a significant role in improving the mechanical properties of pre-fractured rock samples.

Since hydraulic fracturing may cause significant environmental issues in shale gas recovery, the substitution of supercritical carbon dioxide (SC-CO_2) for water as a fracturing agent is proposed. To investigate the use of an SC-CO_2 jet on wellbore pressure and temperature, Hu et al. (2016, JNGSE, 36: 108–116) conduct a series of experiments based on the theory of an impinging jet. Their results help to optimize parameters for the application of SC-CO_2 jets and promote the application of fluid-driven fracturing involving SC-CO_2.

4. Transport properties in single- and dual-porosity tight-gas reservoirs

Gas migration and accumulation in low-permeability (tight) sandstone reservoirs are among the most important issues in resource evaluation and in enhancing gas recovery. Zeng et al. (2016, JNGSE, 33: 1308–1315) design and implement experiments on gas migration and accumulation in natural tight sandstone cores. The properties of steady gas migration, apparent permeability, minimum migration pressure gradient and terminal gas saturation of tight cores are discussed based on their experiments.

Porosity, permeability and elastic parameters are important in the design and engineering of tight-gas sandstone wells. Li et al. (2016, JNGSE 35: 362–371) present a fundamental investigation into behaviours of physical parameters under different stresses by considering: 1) a combination of static and dynamic elastic parameters under different stresses; 2) a systematic analysis of tight gas sandstone parameters; and 3) controlling effect of rock composition and depth on physical parameters. Results yield an improved understanding of tight-gas sandstone properties that are useful in gas reservoir engineering and well design.

Apparent gas permeability of shale is determined by intrinsic permeability as well as gas slip flow and Knudsen diffusion mechanisms. Wei et al. (2016, JNGSE, 34: 1453–1460) introduce an intrinsic permeability model under variable stress conditions and including the impact of the adsorbed layer thickness into a typical apparent permeability model. The apparent permeability model is applied to evaluate the evolution of shale permeability under a spectrum of boundary conditions from stress-controlled to displacement-controlled. Their results show that the evolution of gas permeability is controlled under high pressure by the change in intrinsic permeability and at low pressure by the flow regimes.

Modelling and prediction of flow in naturally- and hydraulically-fractured porous media with low initial permeability has received much attention. Fan and Ettehadtavakkol (2016, JNGSE, 33: 1353–1363) develop a new transient shale-gas-flow model specifically tuned for hydraulically-fractured horizontal gas wells. The model addresses the role of fracture-network conductivity in the evaluation of unconventional reservoir performance and reveals the effects of desorption on the primary depletion phase in shale gas reservoirs.

Multi-stage fracturing in unconventional shale gas reservoirs typically creates a complex fracture network around the horizontal wellbore. Therefore, the stimulated reservoir volume has a significant impact on the performance of fractured horizontal wells. Guo et al. (2016, JNGSE, 35: 425–443) extend previous work and present a more comprehensive model to simulate the performance of multi-stage fractured horizontal wells in shale-gas reservoirs. More specifically, the model takes into account the influences of fracture conductivity, multiple flow mechanisms (desorption, transient state and pseudo-steady state viscous flow and diffusion) in the shale matrix, as well as the effects of a non-uniform fracture distribution.

Deployment of multiply-fractured horizontal wells (MFHW) has recently become an effective technique to develop ultralow permeability unconventional shale gas reservoirs. The complex fracture network created both around the well and during hydraulic fracturing makes the well-testing model of MFHWs more complex. By dividing the stimulated reservoir into five regions with different formation properties and taking into account the multiple seepage mechanisms in shale formations, Zhang et al. (2016, JNGSE, 33: 1316–1323) propose a five-region linear flow model to analyse the transient-well-pressure responses of MFHWs. The model is used to better understand gas flow mechanisms and pressure response dynamics of MFHWs in shale gas reservoirs.

Using a modified pseudo-function approach, Xu et al. (2016, JNGSE, 35: 1129–1138) study the effect of stress sensitivity on transient flow behaviour for fractured wells in gas reservoirs. This study provides a comprehensive analysis of stress sensitivity for fractured gas wells and new insight into investigating production performance in stress-sensitive gas reservoirs. This is examined for the most-widely used interior conditions: constant flow rate and constant bottom-hole pressure. Furthermore, type curves are generated to investigate the effects of stress sensitivity, reservoir size, and fracture properties.

5. Capillarity in enhanced gas recovery

Spontaneous imbibition is regarded as a crucial driving mechanism for enhancing gas/oil recovery from naturally fractured reservoirs, especially those with low permeability. Shen et al. (2016, JNGSE, 35:1121–1128) study the spontaneous imbibition of water into marine shale samples from the Sichuan Basin and continental shale samples from the Erdos Basin to explore fluid imbibition characteristics and permeability alteration during water imbibition.

Ren et al. (2016, JNGSE, 34: 925–933) present an analytical model for spontaneous imbibition including a hysteretic relative permeability-saturation-capillary pressure relation and investigate the influence of hysteretic processes via fracturing-fluid-imbibition modelling. Gao and Hu (2016, JNGSE, 34: 541–551) further study the effects of initial water saturation and imbibed fluid on spontaneous imbibition in Barnett shale core samples taken from three different depths. This study addresses mechanisms controlling fluid loss and ultimate gas/oil recovery in unconventional hydrocarbon reservoirs. The information provided is vital for optimizing the hydraulics of fracturing and treatment fluids to enhance recovery rate. Singh (2016, JNGSE, 34: 751–766) provides a critical review of experimental observations, mechanisms behind those observations, and models to mimic the imbibition behaviour of shales. This, includes the history of imbibition in shales, laboratory observations, field observations, mechanisms of water imbibition in shales, and simulation models. Furthermore, the evaporation of water in shale as an additional mechanism that has not been previously proposed, but that may contribute to the loss of water from shale formations is discussed.

Information about the capillary pressure-saturation curve for each wetting phase is needed to simulate leak-off using numerical reservoir models. By replacing traditional methods measuring capillary pressure-saturation curves with a new technique, Donnelly et al. (2016, JNGSE, 33: 1342–1352) utilize a water-activity meter to measure air-water capillary pressures at various water saturation levels in both wetting and drying. Data for six of seven shale types are successfully fitted by the Brooks-Corey relation, which indicates that this may be a viable method for parameterizing capillary pressure-saturation relationships for inclusion in numerical reservoir models.

6. Geochemical, geophysical and microbial approaches to unconventional gas reservoir characterization and recovery

Location and accessibility of hydrocarbons are key points to understand in order to improve the recovery of hydrocarbons by hydraulic fracturing. To understand how native organics are distributed with respect to pore size and to determine the relationship between hydrocarbon chemistry and pore structure in shales, DiStefano et al. (2016, JNGSE, 35: 646–660) use neutron scattering to complement conventional methods of geochemical analysis. These are used to investigate the link between type of extractable organic material present in shales and the porosity of the shale reservoirs. Their experimental results show that the amount of native organic material extracted directly relates to the percentage of clay in the shale. Toluene, dichloromethane, and hexane were the best solvents for extraction because they are chemically compatible with the paraffinic hydrocarbons in shales.

Based on X-ray diffraction, organic geochemical measurements, nitrogen adsorption measurements and tests of rock electrical parameters, with examples from the Longmaxi organic shale in Sichuan province of China, Wang et al. (2016, JNGSE, 36: 573–585) discuss the experimental relationships between electrical properties and geological parameters, such as brittle mineral content, total organic carbon content and microscopic pore structure. Their study provides a series of basic parameters for shale gas exploration and recovery, and discusses the geological features of significance for shale gas development in this area. In addition, during the process of monitoring hydraulic fracturing, electrical characteristics of the low-resistivity anomaly are shown to correspond with the possible existence of a fracture or fracture zone, potentially providing useful information in the exploitation of shale gas.

Up to now, the Muli area, Qinghai province of China, is the only region where gas hydrate has been found in the mid-latitude permafrost regions of the world. Certain geophysical characteristics are key parameters for identifying gas hydrates, and for optimizing effective gas-hydrate-detection methods in hard-rock permafrost areas. Fang et al. (2017, JNGSE) perform a series of tests in this region, including seismic reflection and electromagnetic surveys, and integrated geophysical well logging. Three types of gas hydrate reservoirs are distinguished: sandstone-pore; mudstone-fracture; and, shale-fracture types. The gas hydrates in the Muli area have complex and particular geophysical characteristics. These characteristics can be used to estimate the type and the distribution of the gas hydrate reservoirs, and potentially improve the gas recovery rate by targeting exploitation in specific types of reservoir.

Coal biodegradation by microbes forms methane and can both improve the yield of coal-bed methane and reduce the environmental hazard of coal mining. Microbially enhanced coal-bed methane generation is also an environment-friendly approach to potentially improving coal-bed methane production. Based on available data. Bao et al. (2016, JNGSE, 35: 68–78) summarize and analyse the biogenic methane yield, coal intrinsic characteristics and incubation conditions to understand the potential of biogenic methane generation and factors controlling the process.

Separating CO_2 from natural gas and re-injecting it into reservoirs is one possible solution to enhance gas recovery and to sequester CO_2. Membrane-based natural gas pre-treatment processes are able to efficiently recover hydrocarbons and separate CO_2 at low cost. The dual-membrane module (DMM) is an enhanced module configuration for membrane gas separation, which synchronously recovers CO_2 and hydrocarbons by housing CO_2-selective and hydrocarbon-selective membranes in the same module. Chen et al. (2016, JNGSE, 34: 563–574) propose two DMM processes to quantify the effects of DMM for enhancing separation and optimizing the separation sequence. Their results show that condensation-DMM is the optimal process design, and employing DMM is an effective CO_2-separation method with currently-available and advanced membrane materials.

Summary and acknowledgments

This special issue presents and highlights recent advanced theoretical and numerical approaches and their application to enhanced gas recovery. The assembled papers cover broad fields of fractal-based approaches, novel numerical methods and modelling techniques, fracture characterization and hydraulic fracturing, transport mechanisms in single and dual porosity media, capillarity, and geochemical, geophysical and microbial approaches to unconventional gas reservoir characterization and recovery. This compilation of research provides a valuable scientific resource to further advance this multidisciplinary endeavour.

The Guest Editors would like to acknowledge all authors of this special issue for their inspiring contributions, as well as the many anonymous referees for their diligent work and valuable insight. Both authors and reviewers have ensured the high quality of this issue. The Guest Editors also thank the Editor-in-Chief, David Wood, and the Editorial Supervisor, Zhien Zhang, for their invaluable help and continuous support during the compilation of this volume.

Contributions to the special issue-listing of articles arranged by category

1. Fractal-based approaches to flow and transport in complex reservoirs

Li, C., Xu, P., Qiu, S., Zhou, Y., 2016a. The gas effective permeability of porous media with Klinkenberg effect. J. Nat. Gas. Sci. Eng. 34, 534–540.
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2. Novel numerical methods and modelling to enhance gas recovery

Azadi, M., Aminossadati, S.M., Chen, Z., 2016. Large-scale study of the effect of well-bore geometry on integrated reservoir-wellbore flow. J. Nat. Gas. Sci. Eng. 35, 320–330.
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6. Geochemical, geophysical and microbial approaches to unconventional gas reservoir characterization and recovery

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