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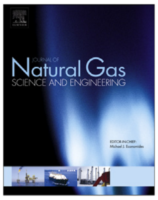

Designing shale-well proxy models for field development and production optimization problems

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ABSTRACT

The surge to maintain a high and sustainable gas supply causes shale-gas fields to be developed with a high number of wells and an extensive infrastructure. This may result in large and complex optimization problems in order to utilize shared infrastructure, optimize the field design, and improve the recovery of the natural-gas resource. Solving large-scale, field-wide shale-gas optimization problems put different requirements on the well and reservoir models than conventional history matching, as it is crucial that the models are low ordered, numerically efficient and adaptable to changing operating conditions. To this end, using appropriately designed proxy models is critical. In this paper, we construct a dynamic shale-well proxy model based on the first principles for gas flow in dry shale-gas reservoirs, rendering a semi-physical modeling approach between purely data-driven black-box models and detailed numerical models. To tune proxy models, we propose a parameter-estimation scheme that incorporates prefiltering of prediction errors between the proxy model and reference data. The prefiltering approach provides a means for emphasizing certain ranges of the dynamics in the model, and thus constitutes a structured approach for defining weights in the accompanying weighted least-squares problem. Further, we show how the proposed approach allows for considering the model tuning and spatial grid design as a joint problem with respect to the purpose of the proxy model.

1. Introduction

The rapid increase in exploitation of unconventional gas resources has reshaped the global natural-gas market. Shale gas and tight gas sands constitute the main sources of unconventional gas supply, with shale-gas alone estimated at 67% of the share of the total global technical recoverable unconventional gas resources (McGlade et al., 2013). The US shale-gas boom has increased the interest and activity in the natural-gas based chemical industries (Siirola, 2014), both as a fuel in itself and as feedstock in production of chemicals, while also having a significant influence on electric power production (Knudsen et al., 2014c; MIT Energy Initiative, 2011). Shale-gas, being a land-based resource, is tightly connected to the natural-gas value chain, and has as a such substantial impact on the economics of all industries engaged in transport, processing and storage of natural gas.

Economic development of shale-gas assets involve complex planning and decision making. Due to the characteristic early decline in well productivity and the sustained low gas price, the focus in the shale-gas industry has been on maintaining a high drilling and completion frequency to offset the decline in total field production. This field-development strategy has caused a high number of wells and a comprehensive surface network in order to share equipment and reduce costs, and thereby large and complex production optimization problems. These inherently challenging problems, together with the observation of the enormous impact shale gas has on industries and economics, have generated an interest for structured model-based techniques to optimize both field development and production, including strategic planning and design (Cafaro and Grossmann, 2014; Grossmann et al., 2014; Wilson and Durlofsky, 2013; Yu and Sepehrnoori, 2014), water handling (Yang et al., 2014), intermittent, shut-in based production optimization (Knudsen and Foss, 2013; Knudsen et al., 2014a; Tang, 2009), and integration of shale gas and electricity generation (Knudsen et al., 2014c).

All of the above design and production problems involve modeling of gas well production, the major well-pad equipment, and possibly partial or complete modeling of the surface pipeline network. Common for all these problems, however, is the need to

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construct and apply a suitable and sufficiently accurate shale-well model. A shale-well model of this kind comprises a near-wellbore or reservoir model, and a tubing or wellbore model to connect the subsurface flow to the surface production facilities. Although the integration of subsurface and surface models is challenging in conventional petroleum production due to the complexity of a model composed of reservoir and topside models, it is perhaps even more challenging in shale-gas applications due to the reservoir dynamics, in particular the fact that shale-gas reservoir dynamics are fast. Thus, the dynamic interactions between reservoir dynamics and production systems are tighter than for conventional reservoirs.

Numerical shale-gas reservoir models are generally constructed either as variants of the dual-porosity model for naturally fractured reservoirs, e.g. (Carlson and Mercer, 1991; Medeiros et al., 2010; Ozkan et al., 2011), or as fully discretized single-porosity dual-permeability models (Cipolla et al., 2010). Dual-porosity like models intuitively fit the matrix-fracture system of shale-gas reservoirs, but are based on an idealized cube-based geometry and require the definition of reservoir-specific coefficients such as matrix storativity and interporosity flow. The latter approach, based on treating the shale matrix blocks and fracture network as *one* continuum, renders a high modeling flexibility, but often at the cost of large and complex models with poor numerical efficiency. Hence upscaling techniques are frequently applied (Cipolla et al., 2010; Knudsen et al., 2014b; Wilson and Durlofsky, 2013). Another widespread technique for rate forecasting from shale-gas wells is the use of static, semi-analytical or empirical models (Al Ahmadi et al., 2010; Bello and Wattenbarger, 2010; El-Banbi, 1998; Ilk et al., 2008; Nobakht et al., 2012). Although these models may be sufficiently accurate and good in matching well production data, they all assume operation at constant bottomhole pressure or constant rate, and are therefore not suited for optimization of multi-well shale-gas systems with changing operating conditions.

Proxy modeling constitutes a viable modeling approach for a wide range of shale-gas design and production optimization problems. Proxy-modeling techniques apply either a black-box or generic model structure, or a model based on first-principle physical properties, with parameter tuning. In this paper, we present and analyze a dynamic dry-gas shale proxy model constructed from the properties of linear flow in shale matrix blocks, assembled with a static tubing model. We then formulate a tuning scheme in order to fit the proxy to production data. Compared to the conventional separation of parameter estimation and spatial grid construction, we show in this paper how these two problems are intimately related and may benefit from being considered together. To this end we use frequency-dependent filters in the parameter estimation to construct fit-for-purpose reduced-sized proxy models.

The remaining of the paper is organized as follows: In Section 2 we describe general proxy-modeling techniques to motivate and categorize our proposed shale-well proxy model. Section 3 presents the proxy model, with a subsequent description of the tuning scheme in Section 4. In Section 5 we analyze and demonstrate properties of the proxy modeling scheme using a numerical case study, with concluding remarks in Section 6 ending the paper.

2. Reduced-order proxy modeling

Proxy models are used to model systems where a rigorous, detailed model is difficult to obtain or numerically too expensive for simulation or optimization purposes. Proxy modeling, which is also referred to as surrogate modeling, is used within a variety of applications in statistics and engineering, including many contexts of reservoir management and analysis, e.g. Awasthi et al. (2007), Onwunalu et al. (2008), Saputelli et al. (2005), Schiozer et al. (2008). The definition of a proxy model is somewhat vague, however, common for all types of proxy models is the attempt to replace a complex model or system description with a simpler and more efficient model, while still retaining sufficient accuracy for the given application.

Within reservoir modeling and petroleum production optimization, commonly applied proxy-modeling techniques include polynomial regression, response-surface models and artificial neural networks (Bieker et al., 2007). Each of these schemes are examples of nonlinear *black-box* model structures used within system identification in control engineering (Ljung, 1999). Proxy modeling with these types of model structures may be applied with very little a priori knowledge of the system, with an acceptable model fit often obtained in a trial-and-error fashion with parameter estimation and testing of different model structures. Although such black-box modeling approaches may be very efficient and in fact highly suitable for many applications, their intrinsic disadvantage lie in not considering the relevant underlying physics of the system. System behavior that is not inherit in input and output data may hence be left out in the model, thus limiting the operating range in which the model is valid.

Compared to the aforementioned, data-driven modeling approaches, semi-physical or *gray-box* modeling approaches seek to combine physical insight and prior knowledge of a process or system in the selection of a model structure and set of parameters to tune to achieve required performance (Sjöberg et al., 1995; Thompson and Kramer, 1994; Tulleken, 1993). The model structure applied in semi-physical approaches are often mainly mechanistic, but may be augmented with stochastic elements, empirical relations and parameters that are not necessarily physically interpretable (Johansen and Foss, 1997). Gray-box modeling often provides a good compromise for constructing small sized and sufficiently accurate proxy models, compared to rigorous physical modeling, which may be expensive to construct and render prohibitive large problem sizes, and black-box models that are not compatible with physical reality (Tulleken, 1993). As shown in Fig. 1, gray-box models may be constructed directly from physical insight and available production data, or via a high-fidelity simulator model to support the choice of model structure. Depending on the size of the model and level of complexity of the physics included, a gray-box shale-well model may be sufficiently accurate also for longer prediction horizons, hence being a viable alternative to

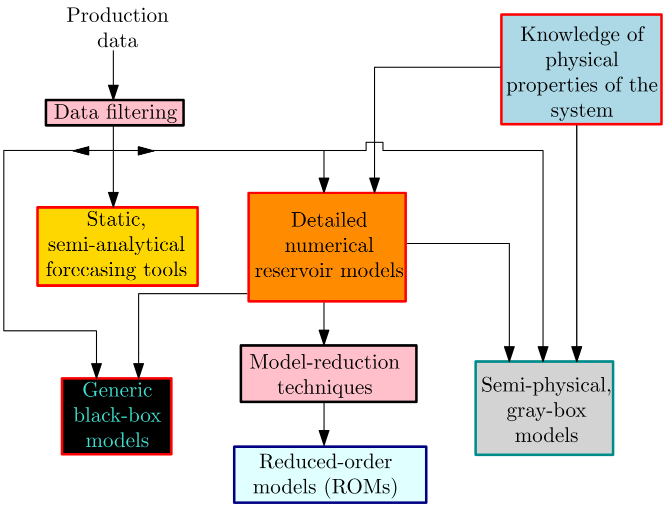

Fig. 1. Connections between different modeling approaches for shale-gas wells.