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Efficient simulation of hydraulic fractured wells in unconventional reservoirs

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ABSTRACT

Reservoir simulators remain essential tools for improved reservoir management in order to optimize hydraulic fracturing design in unconventional low permeability reservoirs. However, the commonly-used simulator requires too much computational efforts for the description of local phenomena in the vicinity of the hydraulic fractures, and is practically infeasible for field applications, due to large number of gridblocks involved in a full-field simulation with many multi-fractured complex wells. Therefore, coarse grid simulations have been widely used, but the techniques for the coarse grid simulation of fractured wells need to be improved.

In this paper, we present efficient numerical methods to handle both long-term well performance and transient behavior simulations for hydraulic fractured wells in unconventional reservoirs with a coarse grid. To simulate correctly the long-term behavior, transmissibilities around the fracture and the connection factor between a fractured block and the fracture are computed, based on a (pseudo)-steady-state near-fracture solution. This approach provides not only an accurate long-term well production calculation, but also a correct pressure distribution in the near-fracture region. In unconventional reservoirs, the transient effects cannot be ignored, due to the very low reservoir permeability and near-well/near-fracture physical processes such as fracturing fluid induced formation damage. In order to handle the transient effect, the coupled modeling technique is used, and its efficiency is demonstrated with a tight-gas reservoir.

1. Introduction

With the increasing demand of hydrocarbon facing current energy shortage, the unconventional resources, such as tight gas and shale gas plays, are becoming more and more important. Significant progress has been made in the past decade for economic development of unconventional petroleum resources. Economic production from unconventional tight and shale gas reservoirs depends upon artificial well stimulation like hydraulic fracturing. Now, reservoir modeling and simulation become increasingly important in order to optimize and improve reservoir management of a tight or shale field by designing fracture length and spacing, and well spacing or infill well location or trajectory, etc.

From a numerical modeling point of view, a single hydraulic fracture can be handled for research purpose using a very refined grid for flow simulation. However, unconventional reservoir developments include many wells with multi-hydraulic fractures. These fractures are long with a length of several hundred meters and narrow with a width of only several millimeters. Besides, fracturing in unconventional reservoirs induces usually a complex fracture network by reactivating reservoir natural fractures (see, for example, Delorme et al., 2013; Norbeck et al., 2014). A fine grid numerical model to simulate these field cases requires too much CPU time and it is generally impractical or even impossible to perform fine grid simulations in field applications. So, there is a need to model hydraulically fractured reservoirs with coarse gridblocks.

To simulate hydraulic fractures with a reservoir simulator, some authors suggested using an equivalent wellbore radius or a negative skin factor with a coarse grid (see, for example, Lefevre et al., 1993). But this approach does not produce "elliptical shape" pressure distribution around the fracture and can generate a negative well connection factor for the reservoir simulator. Elahmady and Wattenberger (2006) proposed to use pseudo-permeabilities to simulate flow perpendicular and along the fracture directions. Zhou and King (2011) used an upscaling method to handle fractured wells in heterogeneous media. Many

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Nomenclature

C	a constant
C_f	dimensionless fracture conductivity
F	flow across a block edge
FCI	fracture connection index
K	permeability
P	pressure
P_0	pressure at a wellblock or a fracture block
Q	well flow rate
r_0	equivalent wellblock radius
r_w	wellbore radius
PI	(numerical) productivity index
S	skin
T	transmissibility
x	a 2D point with $x=(x_1, x_2)$
x_1	coordinates
x_2	coordinates
X_f	fracture half length
y	a 2D point with $y=(y_1, y_2)$
y_1	coordinates
y_2	coordinates
w	fracture width
W_0	wellblock
φ	potential
Γ	fracture boundary
Γ^+	fracture boundary outside the fracture
Γ^-	fracture boundary inside the fracture
Δx	gridblock size

Subscripts

f	fracture
i	gridblock i
j	gridblock j
res	reservoir
s	steady-state or pseudo-steady-state solution
w	well
0	wellblock or a fracture block

papers can be found in the literature to discuss the simulation of fractured wells with coarse grids and to propose some practical solutions (see, for example, Sadrpanah et al., 2006; Gataullin, 2008; Abacioglu et al., 2009; Burgoyne and Little, 2012).

The problem of well modeling has been discussed for a long time. Peaceman's (1978, 1983, 1993) model has been widely used for reservoir simulations. But that model has its limitations and cannot be used for the fractured well simulation. To improve the well modeling, Ding et al. (1995), Ding (1996) and Ding and Jeannin (2001) proposed to modify the near-well numerical scheme, based on a steady-state or a pseudo-steady-state flow regime, to adapt the singular flow behavior in the near-well region with coarse grid simulations. This concept was also extended for the modeling of fractured wells by Ding and Chaput (1999).

For unconventional reservoir simulations, it is essential to model correctly long conductive fractures such as hydraulic fractures. Li and Lee (2008) proposed to use a transport index (fracture connection index) between a matrix block and the fracture to handle embedded discrete fractures. They assumed that the pressure varies linearly in the normal direction to each fracture and they computed an average distance between a fractured block and the fracture for the transport index calculation. The same formula was used by Hajibeygi et al. (2011) in hierarchical fracture model for conductive fracture modeling and by Moinfar et al. (2013) for the simulation of hydraulically fractured unconventional reservoirs. In unconventional reservoir simulations, even with the presence of complex fracture networks, it is common to simulate large hydraulic fractures explicitly using a discrete fracture approach and homogenize short/diffused fractures for a single or dual continuum (see, for example, Moinfar et al., 2013; Wu et al., 2013). The flow transfer between a grid block and a hydraulic fracture as well as between grid blocks near a large fracture needs to be simulated with precisions. However, assuming linear pressure variation is not very accurate near the fracture extremities and in the zone where several fractures are intersected, especially on large gridblocks. In this paper, we propose to compute the fracture connection index (FCI) based on steady-state or pseudo steady-state pressure solution with integral representation. Our approach can handle complex cases like flow modeling near fracture extremities, and it can also be extended to compute flow transports between grid blocks near a fracture. Examples are presented to handle hydraulically fractured wells in unconventional reservoirs. Note that some formation damage issues can also be handled through the modification of connection factors (or skin) between a fractured block and the fracture.

Another issue related to the fractured well simulation in unconventional reservoirs is the modeling of transient flow behavior. In a conventional reservoir, the transient period is generally very short, and a pseudo-steady-state flow regime is quickly reached in the near-well/near-fracture region. The transient behavior can generally be neglected in conventional reservoir simulations, except for transient well testing. However, the transient behavior cannot be ignored in low permeability unconventional tight and shale gas reservoirs. Artus and Fructus (2012) used very fine meshes to simulate transient behavior in shale-gas reservoirs and they showed the necessity to improve transmissibility calculation even for very fine mesh connections around the fractures, especially near the fracture extremities.

Coarse gridblock is generally not adapted to the modeling of transient behavior (the size of the gridblock is too large compared to variation length of physical variables such as pressure, saturation) and the description of near-well/near-fracture physical processes. To simulate the transient behavior, Blanc et al. (1999) proposed a transient well index, based on an analytical solution, to handle well testing problem for vertical wells. Al-Mohannadi et al. (2007) and Aguilar et al. (2007) used time-dependent well index to simulate horizontal and multilateral wells. Archer (2010) also shows the necessity of transient well index for the coarse grid simulation. The transient effect becomes particularly important for fractured wells in the unconventional reservoir due to long fracture length and low reservoir permeability or long transient flow period (Medeiros et al. 2007; Ibrahim, 2013).

Transient effects associated with the near-well/near-fracture physical process are generally more complex. For a fractured well in an unconventional reservoir, the typical physical process is the fracturing fluid induced formation damage and cleanup (Bennion et al., 2000; Friedel, 2004; Ding and Renard, 2005; Cheng, 2012; Agrawal and Sharma, 2013; Bertoncello et al., 2014) or possible non-Darcy flow inside the fracture towards the well (Wu, 2002). All these studies require the use of very fine gridblocks around the fractures, and it is difficult to investigate well production behavior in a full-field context. Besides, a full-field reservoir simulator might not have all the options to simulate detailed near-well/near-fracture physical processes. In order to take into account the