Computers and Geotechnics 87 (2017) 49–61

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Parameters controlling pressure and fracture behaviors in field injectivity tests: A numerical investigation using coupled flow and geomechanics model

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ARTICLE INFO

Article history:
Received 19 November 2016
Received in revised form 6 January 2017
Accepted 7 February 2017

Keywords:
Field injectivity tests
Fracture modeling
Cohesive zone method
Parametric study

ABSTRACT

Field injectivity tests are widely used in the oil and gas industry to obtain key formation characteristics. The prevailing approaches for injectivity test interpretation rely on traditional analytical models. A number of parameters may affect the test results and lead to interpretation difficulties. Understanding their impacts on pressure response and fracture geometry of the test is essential for accurate test interpretation. In this work, a coupled flow and geomechanics model is developed for numerical simulation of field injectivity tests. The coupled model combines a cohesive zone model for simulating fluid-driven fracture and a poro-elastic/plastic model for simulating formation behavior. The model can capture fracture propagation, fluid flow within the fracture and formation, deformation of the formation, and evolution of pore pressure and stress around the wellbore and fracture during the tests. Numerical simulations are carried out to investigate the impacts of a multitude of parameters on test behaviors. The parameters include rock permeability, the leak-off coefficient of the fracture, rock stiffness, rock toughness, rock strength, plasticity deformation, and injection rate. The sensitivity of pressure response and fracture geometry on each parameter is reported and discussed. The coupled flow and geomechanics model provides additional advantages in the understanding of the fundamental mechanisms of field injectivity tests.

1. Introduction

Field injectivity test is a generic name for pressure tests conducted in drilling and completion phases of oil and gas wells. The tests may include leak-off test (LOT) or extended leak-off test (XLOT) commonly carried out during drilling, and mini-fracture test or diagnostic fracture injection test (DFIT) performed in completion operations. Petroleum engineers make critical decisions for drilling and stimulation operations based on interpretations of such tests. For instance, XLOTs are usually used to predict fracture pressures of the formation, i.e. formation breakdown pressure (FBP) or fracture propagation pressure (FPP), which are further used to design mud weight and casing setting depth for the drilling operation. DFITs are increasingly used for estimating reservoir permeability, original reservoir pressure, leak-off coefficient, and the least principal stress (in many cases the minimum horizontal stress), which are vital for stimulation design and post-stimulation production management.

Field injectivity tests can be performed in open-hole intervals or cased well intervals, depending on the types of the tests. Usually, a LOT or XLOT in drilling phase is carried out in a short open-hole interval below the casing shoe, while a mini-fracture test or DFIT in completion phase is conducted in a cased and perforated well section before the main hydraulic-fracturing operation. Incorrect interpretation of field injectivity tests can lead to serious consequences in oil and gas development. For example, misinterpretation of fracture pressure from LOT or XLOT may result in an unrealistic prediction of the mud-weight window, and consequent problems of wellbore instability, lost circulation, unnecessary squeeze job, or premature setting of the casing. These problems can severely jeopardize well progress [1,30,41]. For another instance, misinterpretation of mini-fracture test or DFIT can lead to inaccurate evaluations of field stresses and reservoir properties, consequently resulting in undesirable stimulation results and erroneous production forecast [4,3].

Difficulties often arise in the interpretations of field injectivity tests because pressure and fracture behavior during the tests are sensitive to a variety of factors. The factors include both operational parameters, e.g. injection rate and time, and formation parameters, e.g. rock permeability and strength. In addition, the

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http://dx.doi.org/10.1016/j.compgeo.2017.02.002
0266-352X/

test behaviors are highly dependent on the coupling between fluid flow, fracture mechanics, and geomechanics involved in the test system [5]. The impacts of various factors and the coupling effect are seldom considered in previous interpretations of field injectivity tests. For instance, interpretations of DFITs are commonly based on analytical models, such as Carter's leak-off model [15] and the G-function model [26]. The so-called pressure derivatives, log-log, and G-function plotting techniques are proposed based on these models [2,3,20,21,37]. However, they are based on the assumption of linearly elastic fracture mechanics and do not explicitly account for coupling between fluid flow and geomechanics, e.g. fluid flow into and within the reservoir and reservoir deformation.

Numerical models can be used to examine the effects of different operational and material parameters on the behaviors of field injectivity tests while considering the coupling between fluid flow and geomechanics. However, there are very few numerical studies on this topic. Lavrov et al. [18] presented a hydro-mechanically coupled model for XLOT simulation by connecting TOUGH2 reservoir simulator [31] and an in-house fracturing code. However the coupling is two-way, explicit, and sequential: (1) the deformation and failure of fracture elements are calculated by the fracturing code; (2) the permeability and porosity of the failed fracture elements are updated and passed to the TOUGH2 reservoir simulator; (3) fluid flow is calculated by TOUGH2 and the resulting pore pressure is passed to the fracturing code. The model is not fully-coupled. Another limitation of the model is that the wellbore is explicitly meshed and modeled as a solid part with very high permeability and low modulus; this is not really consistent with actual situation because the material within the wellbore is a liquid phase and there are no shear stresses on the wellbore wall. Similarly, Padmakar [29] proposed a numerical model for DFIT simulation using a two-way, sequential approach by connecting the commercial fracturing code MFrac and reservoir simulator GEM. Meng et al. [23] developed a fully coupled fluid flow and geomechanics model for DFIT analysis using the finite-element method. However, the fractures are represented by predefined narrow regions with high permeability, so it is not able to capture fracture propagation as well as the corresponding pressure response. The model was therefore only used to analyze pressure decline during the shut-in stage of DFIT.

To examine the impacts of different operational and material parameters on fracture and pressure behaviors of field injectivity tests, a fully coupled, implicit, hydro-mechanical model has been developed in the Wider Windows research program at The University of Texas at Austin, using the finite-element method. Instead of using a two-way coupling approach, the new model simultaneously simulates fluid injection into the well, fracture initiation and propagation, fracture fluid flow, fluid leak-off, pore fluid flow, and formation deformation. Fracture geometry and synthetic pressure response during the entire duration of simulated tests can be captured. The model provides a powerful new tool towards a better understanding of field injectivity tests and can be useful in aiding test design and interpretations.

2. Numerical method

2.1. The basics of field injectivity tests

Modeling field injectivity test is a fairly complicated endeavor. It involves several interacting components and coupled physical phenomena. Fig. 1 shows a generalized open-hole test configuration. There are three major components in the system, i.e. the well, the fracture, and the formation, interacting with each other. During the test, several coupled physical processes must be considered for successful modeling of the test, including: fluid flow in the injection pipe; fracture initiation and propagation; fracture fluid flow; fluid leak-off from fracture into formation; rock deformation; and pore fluid flow. In this work, the interacting components and coupled processes are modeled simultaneously using an integrated numerical model. The model was developed using the finite-element method on platform ABAQUS, a general-purpose finite-element code for solving linear and non-linear stress-analysis problems [36].

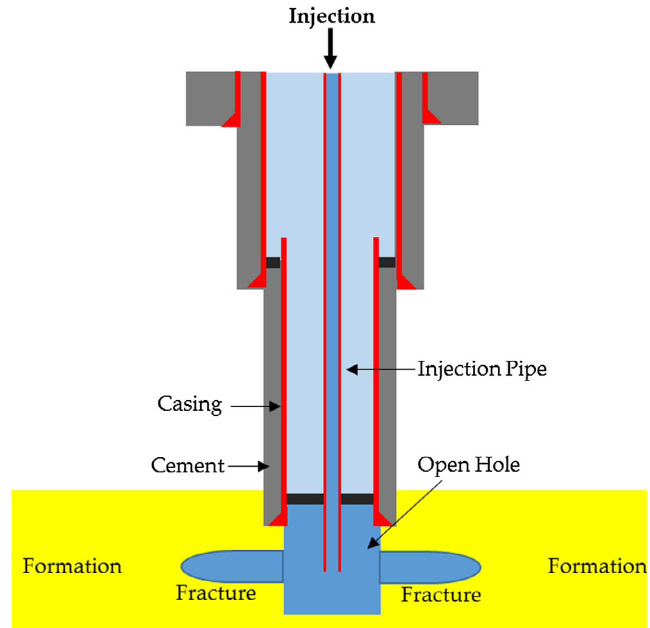

Fig. 1. The generalized configuration of field injectivity test.

2.2. The basic equations

2.2.1. Fluid flow in the injection pipe

The flow in the injection pipe is assumed to be a single-phase, steady-state flow. The fluid is incompressible. The injection pipe has a constant cross-sectional area and is fully filled with the injection fluid. Under these assumptions, the fluid flow in the injection pipe can be modeled using Bernoulli's equation, including both viscous and gravity pressure losses:

$$\Delta P - \rho g \Delta Z = \frac{fL}{D_h}\frac{\rho v^2}{2} \tag{1}$$

where ΔP and ΔZ are the changes of pressure and elevation respectively; ρ is fluid density; g is gravity acceleration factor; f is friction factor; L is pipe length; $D_h = 4A/P$ is the hydraulic diameter of the pipe; A and P are the cross-sectional area and wetted perimeter of the pipe, respectively; v is fluid velocity in the pipe.

2.2.2. Fluid-solid coupling in the formation

The formation is assumed to be a porous medium consisting of a solid skeleton and pores saturated with a single-phase fluid. The total stress $\boldsymbol{\sigma}$ within the formation is composed of two parts: the effective stresses $\boldsymbol{\sigma}'$ associated with the solid skeleton and the pore pressure p_p associated with the fluid [14]. The equilibrium equation for the porous medium is expressed using the principle of virtual work for the volume within the current configuration [42,44,46]:

$$\int_V (\boldsymbol{\sigma}' - p_p \mathbf{I}) : \delta\boldsymbol{\varepsilon} dV = \int_S \boldsymbol{t} \cdot \delta\boldsymbol{v} dS + \int_V \boldsymbol{f} \cdot \delta\boldsymbol{v} dV \tag{2}$$