Non-isothermal, multi-phase, multi-component flows through deformable methane hydrate reservoirs

Shubhangi Gupta · Rainer Helmig · Barbara Wohlmuth

Abstract We present a hydro-geomechanical model for subsurface methane hydrate systems. Our model considers kinetic hydrate phase change and non-isothermal, multi-phase, multi-component flow in elastically deforming soils. The model accounts for the effects of hydrate phase change and pore pressure changes on the mechanical properties of the soil. It also accounts for the effect of soil deformation on the fluid-solid interaction properties relevant to reaction and transport processes (e.g., permeability, capillary pressure, and reaction surface area). We discuss a 'cause-effect' based decoupling strategy for the model and present our numerical discretization and solution scheme. We then proceed to identify the important model components and couplings which are most vital for a hydro-geomechanical hydrate simulator, namely, (1) dissociation kinetics, (2) hydrate phase change coupled with non-isothermal two phase two component flow, (3) two phase flow coupled with linear elasticity (poroelasticity coupling), and finally (4) hydrate phase change coupled with poroelasticity (kinetics-poroelasticity coupling). To show the versatility of our hydrate model, we numerically simulate test problems where, for each problem, we methodically isolate one out of the four aforementioned model components or couplings. A special emphasis is laid on the kinetics-poroelasticity coupling for which we present a test problem where an axially loaded hydrate bearing sand sample experiences a spontaneous shift in the hydrate stability curve causing the hydrate to melt. For this problem, we present an analytical solution for pore-pressure, which we subsequently use to test the accuracy of the numerical scheme. Finally, we present a more complex 3D example where all the major model components are put together to give an idea of the model capabilities. The setting is based on a subsurface hydrate reservoir which is destabilized through depressurization using a low pressure gas well. In this example, we simulate the melting of hydrate, methane gas generation, and the resulting ground subsidence and stress build-up in the vicinity of the well.

Keywords Methane hydrate reservoir · Hydro-geomechanical model · Kinetics-poroelasticity coupling

Mathematics Subject Classifications (2010) 74F10 · 74F25 · 76S05 · 76V05

Nomenclature

χκα Mole fraction of component κ = CH₄, H₂O in phase α = g, w
γCH₄ CH₄ generation rate
γH₂O H₂O generation rate
−gHyd, −gh Hydrate consumption rate
Qh Heat of hydrate phase change
qm,u Volumetric injection rate for phase α = g, w
1 Introduction

Methane hydrates are formed when water molecules form a cage-like structure and trap a large number of methane molecules within, forming a crystalline solid similar to ice [40]. Methane hydrates are thermodynamically stable under conditions of low temperature and high pressure and occur naturally in permafrost regions or below ocean/sea floors [13]. If warmed or depressurized, methane hydrates destabilize and dissociate into water and methane gas. Methane hydrates are a very dense source of methane gas. One cubic meter of methane hydrate stores approximately 164 standard cubic meters of methane gas. Also, the energy content of methane occurring in hydrate form is immense, possibly even exceeding the combined energy content of all other conventional fossil fuels [29].

The research in methane hydrates stems from a 'three-fold' motivation driven by concerns of methane gas extraction and production feasibility, global warming potential and climate change concerns, and inherent geo-hazards of mining/drilling induced destabilization of methane hydrates in subsurface reservoirs. Phenomenological modeling and numerical simulation of these systems are thus vital (1) for optimizing recovery techniques for extracting methane from hydrate bearing sediments, (2) for conducting studies and making predictions for mitigating bore-hole, local and regional slope stability hazards, (3) for sequestering carbon-dioxide in gas hydrate, (4) for possible application in natural gas storage and transport, and (5) for evaluating the role of gas hydrate in global carbon cycle.

Methane hydrate formations are a fairly complex subsurface system characterized by a large number of highly interdependent physical phenomena. The typical physical processes occurring in a stimulated hydrate reservoir include (1) hydrate phase change, (2) non-isothermal multiphase, multi-component flow, (3) geomechanical deformation of the hydrate bearing sediment, and (4) change in the hydraulic as well as the mechanical properties of the hydrate bearing sediment. Thus, any detailed study of these reservoirs and their possible applications in energy, environment, and quantification of geo-hazards requires the development