An experimentally-based in-situ combustion model with adaptive meshing

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ABSTRACT

This work considers a detailed model for compositional flow in porous media, applied to the modelling of in-situ combustion of heavy oil. An experimentally-derived phase and chemical equilibrium model is used, and the combined fluid-reaction system validated against combustion tube experiments. Several one-dimensional simulation studies are carried out. An ignition mode via low-temperature oxidation, and an unsteady propagation mode, are demonstrated by perturbing the reaction parameters governing fuel formation and combustion. An adaptive mesh refinement method is successfully applied to this problem, and detailed simulations in two dimensions demonstrate multi-dimensional dynamics of a propagating combustion front. These include a viscous instability, non-uniform propagation, and local extinction of the front.

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1. Introduction

Heavy oil is a major unconventional oil resource. This type of oil has a very low mobility within the reservoir and is therefore not amenable to conventional extraction, instead being extracted by mining (for shallower deposits) or thermal methods. When the oil-bearing formation is loosely consolidated and the oil extremely heavy (bituminous), these reserves are called oil sands or tar sands. Particularly large heavy oil reserves and oil sands exist in Canada and Venezuela. The area north of the Orinoco river in Venezuela is estimated to contain over 1 trillion barrels of oil, with 513 billion barrels technically recoverable [1]. The size of reserves such as these is what motivates research into technologies for extracting heavy oil.

This paper is concerned with in-situ combustion (ISC), a thermal method of extraction applicable to heavy oil. The idea behind ISC is to propagate a smouldering fire-front through the reservoir, using the heavier components of the oil to form fuel in-situ. The combustion is sustained by air injection. This produces high temperatures which aid mobilisation of the oil. Only a small fraction (a few percent to ten percent) of the oil is burned, and it is mostly the less economically-desirable heavy components. Since the fuel for the combustion is generated within the solid matrix, heat losses to wells are minimised. For these reasons ISC is an attractive process for extracting heavy oils. The process is discussed in more detail in Section 3.

Modelling ISC is particularly challenging because of the physical complexity of the process. The details of the process depend on the thermodynamics and other physical properties of the oil, as well as the fluid-mechanical behaviour of the oil-rock system. In multiple dimensions, the fluid system may exhibit instabilities or other dynamic behaviours, and cannot in general be decoupled from the reactive system. The oil itself is composed of many complex, unknown long-chain hydrocarbons and must be characterised experimentally. The pyrolysis and combustion of the oil is again a complex process involving multiple reactions, and must also be characterised experimentally.

The disparate scales involved in ISC also present a challenge. The combustion front is very narrow ($\sim$ cm), and the high-temperature oxidation reactions which produce much of the heat of the combustion can occur on short reaction kinetic time-scales ($\sim$ s). However the propagation speed of the front in the field is very low ($\sim$ cm/day) and the typical length scale between wells is large ($\sim$10–100 m), meaning that long simulation time scales are often required ($\sim$1 year or more). This poses a challenge for simulation methods, which must be able to bridge these scales somehow.

This work attempts to bridge the scale gap using an adaptive mesh refinement (AMR) approach [2]. This makes it possible to resolve the fine scales where needed (at the combustion front), while coarsening the grid elsewhere to reduce computational

expense. This method works well and obtains good solutions on domains of 10 m × 5 m in two dimensions, using the same detailed model that is used at the lab scale and for one-dimensional tests. Resolved three-dimensional simulation at the field scale is still out of reach. However the problem sizes considered here in two dimensions allow the examination of some important essentially-multi-dimensional aspects of combustion front dynamics, namely viscous fingering and local front extinction and bypass.

1.1. Structure and contents of the paper

The next section gives an overview of a model for thermal flow in porous media, and the numerical approach used for the problem. This is a sequential time stepping method using a primitive-variable shock-capturing scheme for advection, together with an AMR method.

In Section 3 a model for in-situ combustion of heavy oil is considered, and coupled with the thermal flow solver. The model is compared against experimental combustion tube studies in Section 4, and in Section 5 one-dimensional simulations are used to examine sensitivities of the fluid-reaction model. Section 6 contains two-dimensional simulations. Finally Section 7 gives conclusions and directions for further work.

2. Fluid model and discretisation

In [3] a model for thermal, multiphase, multicomponent flow in heterogeneous porous media was developed. This model describes the flow of N_C fluid components in an arbitrary mixture of phases; the current work uses a two-phase model with liquid (l) and vapour (v) phases. Define $\mathbf{n}_\alpha$ to be the vector of moles of each component in phase α divided by the pore volume. The quantity $\sum_\alpha \mathbf{n}_\alpha \equiv \mathbf{n}$ is the total component-wise molar density for the combined fluid system. The fluids flow within a porous medium with porosity denoted by ϕ. Table 1 summarises the main physical variables of importance for this model, together with their units.

Table 1
Main physical variables of importance. Quantities typeset in boldface (e.g., $\mathbf{n}$) have dimensions N_C, where N_C is the number of components in the model. Quantities typeset with an over-line (e.g., $\vec{v}_T$) are spatial vectors.

c_p: Overall scaled heat capacity at constant pressure [J K^{-1} cm^{-3}]

c_p^f: Scaled heat capacity of the fluid at constant pressure [J K^{-1} cm^{-3}]

c_p^r: Scaled heat capacity of the porous medium at constant pressure [J K^{-1} cm^{-3}]

$\vec{g}$: Gravity [cm s^{-2}]

$\mathbf{h}_\alpha$: Phase partial enthalpy [J mol^{-1}]

H_r: Enthalpy of the porous medium [J kg^{-1}]

H_t: Total enthalpy [J cm^{-3}]

k: Effective thermal conductivity coefficient [W cm^{-1} K^{-1}]

k_α: Phase thermal conductivity coefficient [W cm^{-1} K^{-1}]

$k_{r,\alpha}$: Phase relative permeability [between 0 and 1]

K: Absolute permeability [cm^2]

$\mathbf{n}$: Component mole densities [mol cm^{-3}]

p: Reference pressure [Pa]

p_α: Phase pressure [Pa]

s_α: Phase saturation [between 0 and 1]

T: Temperature [K]

u_α: Phase volume/pore volume [cm^3/cm^3]

U: $\sum_\alpha u_\alpha$ [cm^3/cm^3]

$\vec{v}_\alpha$: Volumetric flow rate of phase α [cm s^{-1}]

$\vec{v}_T$: Total velocity [cm s^{-1}]

$\mathbf{x}_\alpha$: Phase mole fractions [mol/mol]

η_α: Phase viscosity [Pa s]

λ_α: Phase mobility [cm^2 Pa^{-1} s^{-1}]

λ_T: Total mobility [cm^2 Pa^{-1} s^{-1}]

ρ_α: Phase density [kg cm^{-3}]

ρ_r: Density of the porous medium [kg cm^{-3}]

ϕ: Porosity [between 0 and 1]

2.1. Flow equations

The flow is governed by the equations of mass and energy conservation and by Darcy's law. Capillary pressure terms are neglected; the effects are small for larger-scale two-phase simulations in a sandstone material [4]. Similar arguments apply for the larger-scale simulations in this paper which are the main focus of interest, although for smaller-scale simulation with mesh sizes <1 cm capillary effects may become significant.

The volumetric flow rate $\vec{v}_\alpha$ of each phase in terms of the pressure p as

$$\vec{v}_\alpha = -\frac{Kk_{r,\alpha}}{\eta_\alpha}(\nabla p - \rho_\alpha \vec{g}) \equiv -\lambda_\alpha(\nabla p - \rho_\alpha \vec{g}), \tag{1}$$

where K is the permeability of the medium, $k_{r,\alpha}$ is the relative permeability of phase α, η_α and ρ_α are respectively the phase viscosity and density, and $\vec{g}$ is the acceleration due to gravity. Here $\lambda_\alpha \equiv Kk_{r,\alpha}/\eta_\alpha$ is the phase mobility.

Conservation of mass for each component is given by

$$\frac{\partial(\phi \mathbf{n})}{\partial t} + \nabla \cdot \sum_\alpha \frac{\mathbf{n}_\alpha}{u_\alpha}\vec{v}_\alpha = \mathbf{R}_n, \tag{2}$$

where u_α is the volume occupied by phase α divided by the pore volume at thermodynamic equilibrium. The term $\mathbf{R}_n$ is a reaction source term. Molecular diffusion and dispersion effects are neglected; this is reasonable due to the dominance of the convective and reactive terms. The Péclet number based on an oxygen mass diffusion coefficient of 0.667×10^{-5} is O(10) for the tests considered in this paper. However in other cases, particularly fractured media, mass diffusion effects may become significant [5].

An energy conservation equation is necessary for non-isothermal flows and includes energy in the solid phase. We assume that the porous medium and the fluid are in thermal equilibrium. The total energy balance is of the form

$$\frac{\partial H_t}{\partial t} + \nabla \cdot \sum_\alpha \frac{\vec{v}_\alpha}{u_\alpha}\mathbf{n}_\alpha^T\mathbf{h}_\alpha = \nabla \cdot (k\nabla T) + R_H, \tag{3}$$

where $H_t = (1-\phi)\rho_r H_r + \phi\sum_\alpha \mathbf{n}_\alpha^T\mathbf{h}_\alpha$ is the total enthalpy of the system, $\mathbf{h}_\alpha$ the partial molar phase enthalpies, H_r the enthalpy of the medium and ρ_r the density of the medium. Here, k is a heat conduction term and R_H represents energy changes from reactions and external heating.

2.2. Phase behaviour

As described in [3], the local phase equilibrium occurs at a phase composition of maximum entropy. The phase equilibrium problem is to determine the composition of the phases $\mathbf{n}_\alpha$ given the total moles $\mathbf{n}$, pressure p and total enthalpy H_t, subject to the constraints

$$\mathbf{n} = \mathbf{n}_l + \mathbf{n}_v \tag{4}$$

and

$$H_t = (1-\phi)\rho_r H_r + \phi(\mathbf{n}_l^T\mathbf{h}_l + \mathbf{n}_v^T\mathbf{h}_v). \tag{5}$$

The final constraint on the fluid behaviour comes from the requirement that the sum of the phase volumes match the available pore volume. This is represented as the constraint

$$1 = U(p, T, \mathbf{n}) \equiv \sum_\alpha u_\alpha(p_\alpha, T, \mathbf{n}_\alpha). \tag{6}$$

2.3. Numerical solution

The solution of the model uses a decoupled sequential formulation. This is combined with an explicit shock-capturing approach