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Oxygen transport in a matrix–fracture system under reactive conditions at pore-scale

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A B S T R A C T

In this work, the oxygen transport in a nitrogen saturated matrix–fracture system at pore-scale was modelled. The microstructure of the porous matrix was modelled as a medium composed of circular particles periodically arranged. We considered the oxygen–coke reaction on the particle surface in order to simulate the combustion reaction encountered in an in-situ combustion process. The gas, coke and oxygen mass balances, and the gas momentum balance (assuming Newtonian fluid) were solved using a finite element solver. The oxygen distribution, in the matrix–fracture system, was studied in terms of the oxygen flow rate, fracture width and combustion reaction rate. It was found that increasing the oxygen flow rate, fracture width and combustion reaction rate favours the coke consumption. Moreover, these parameters increase the oxygen transport from the fracture to the porous zone.

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1. Introduction

The in-situ combustion (ISC) is an advanced method to recover petroleum from reservoirs. Its application is primarily intended for heavy-oil or mature reservoirs where primary or secondary recovery techniques are no longer feasible. The ISC requires the injection of standard or oxygen-enriched air into the oil reservoir in order to promote the oil ignition and propagation of a combustion front through the reservoir. The high temperatures taking place improve the oil mobility due to the reduction of viscosity and the effects of fluid-(steam, combustion gases, water) flooding. In the ISC there are several complex mechanisms driving the momentum, energy and mass transport. The modelling of these mechanisms plays a crucial role for fundamental understandings of physics behind the process.

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Nomenclature

Latin letters

a	exponent for the viscosity model
a_v	specific surface area of solid particles, 1/m
A	pre-exponential factor, $m^3/(mole\ s)$
$\mathcal{A}$	integration area
b	exponent for the oxygen diffusion model
C	molar or surface molar concentration, $mole/m^3$ or $mole/m^2$
d	diameter, m
D	effective molecular diffusivity, m^2/s
E	energy activation for the combustion reaction, J/mole
F	mass flux, $kg/(m^2\ s)$
$\mathbf{I}$	identity tensor
K_r	reaction rate constant, $m^3/(mole\ s)$
l	line differential, m
L	line for integration
M	molecular weight, kg/mole
$\mathbf{n}$	unit normal vector pointing outside the domain
$\mathbf{N}$	total molar flux, $mole/(m^2\ s)$
p	pressure, Pa
R	ideal gas constant, J/(mole K)
t	time, s
T	temperature, K
u	element of the velocity vector, m/s
$\mathbf{u}$	velocity vector, m/s
W	width, m
x	molar fraction

Greek letters

η	stoichiometric factor between the coke and oxygen
μ	viscosity, Pa m
ρ	density, kg/m^3

Superscripts and subscripts

0	initial value
atm	atmospheric conditions
av	average value
coke	coke
f	fracture
inj	conditions in the injected fluid
N_2	nitrogen
oil	oil
O_2	oxygen
p	solid particle
ref	reference conditions
T	transposed
x	*x*-direction
y	*y*-direction

For sizing commercial ISC operations, information about air requirements, fuel availability, oil recovery and the combustion temperatures regime is needed. For many years, two main approaches have been used for preliminary design of ISC projects. These are that one of Nelson and McNeil (1961) and the so-called *oil-recovery/volume-burned* method (Gates and Ramey, 1980). Further, some improvements to engineer ISC were proposed modifying the mentioned methods (Moore et al., 1999). In these works, it is established that to estimate the size of compressor installation, the ratio of injected air to produced oil needs to be calculated. This quantity is intrinsically involved with the kinetic model quantifying the oxygen consumption rate, which takes place mainly from two exothermic oxidations regime. These are the *low-temperature* and *high-temperature oxidation* reactions (LTO and HTO, respectively) (Sarathi, 1999). The oxygen might react directly with some oil components, or with coke, which is produced by a pyrolysis reaction. Currently, the complete understanding of oxidation reactions is still an open matter of investigation (Kök and Acar, 2006; Cinar et al., 2009). It is assumed that the difference between the original oil in place and the produced oil is related to the fuel burned during the ISC process. Thus, the ratio air (or oxygen)/fuel is also an important parameter to design the total air required according to the whole size of the petroleum reservoir. The relation oxygen–coke is considered in this work when the kinetic modelling of their chemical reactions be stated.

Around the world, there is a large amount of petroleum in naturally fractured reservoirs which is an additional difficulty to the comprehension of the ISC. Since several decades ago, theoretical and experimental developments have been conducted for gaining knowledge about the effects of fractures over the thermal and hydrodynamical performance of ISC (Schulte and de Vries, 1985; Greaves et al., 1991; Awoleke et al., 2010). The most of these works agree that oxygen transport is one of the main features to sustain and propagate the combustion front. As fractures induce *channeling* effects, then the gas-phase, and consequently the oxygen, travels preferentially through the fracture network. Thus, the oxygen transport through the fracture–matrix boundary might play a crucial role for the ISC inside the porous medium. The modelling of oxygen transport, from fractures to the porous medium, can be carried out from two main observation scales. These are the macroscale and microscale. At the macroscale the results are in terms of average variables while at the microscale the results are in terms of point variables. At microscale the homogeneous phases composing the system are clearly identified. The relationships of information between both scales are often established using some up-scaling techniques as the volume averaging (Whitaker, 1999) and homogenization methods (Sanchez-Palencia, 1983). Whatever scale being used, the complexity for simulating the ISC comes from its multiphase and multicomponent nature.

In this work, we focus on the fundamental study of the oxygen transport from fractures to porous medium at pore-scale. The influence of the fracture width, Péclet number and oxygen–coke reaction rate were investigated. With these aims, we avoid the real complexity of an ISC process and we consider a two-phase (rock and gas), three-component (N_2, O_2 and coke), isothermal system. The porous medium has an idealized 2D microstructure, which is initially saturated with nitrogen. The theoretical model characteristics are given in Section 2. Our objective is to gain fundamental knowledge on the reactive transport of oxygen in heterogeneous domains, which is useful for understanding the ISC when it is applied to enhance the oil recovery in naturally fractured reservoirs.

2. Mathematical model

An ISC process involves several phenomena interacting simultaneously in a multiphase mixture at whatever scale of study (commercial-, pilot plant- or lab-scale). For instance, we can quote the existence of several chemical reactions, multicomponent and multiphase equilibrium, multiphase flow, capillary pressures, thermal expansion, etc. In order to study such phenomena at lab-scale, combustion tube experiments are carried out, capturing essential composition of a real oil reservoir (rock, gas, water and