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Reinfiltration through liquid bridges formed between two matrix blocks in fractured rocks

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SUMMARY

Liquid reinfiltration is a significant process, which can considerably retard and slowdown the transport of oil, water and contaminants in fractured subsurface formations. However, accurate modeling of the reinfiltration via liquid bridges formed in a horizontal fracture or space between two rock porous blocks remains a controversial topic. In an attempt to improve an understanding of the problem, the reinfiltration from upper to lower matrix blocks through formation of liquid bridges is theoretically modeled by using generalization of the Lucas–Washburn theory for a porous medium, which takes into account pressure differences due to matrix capillary, gravity, inertia, viscous, and fracture capillary forces. The developed model results in a second-order nonlinear ordinary differential equation (ODE), which is solved numerically to obtain depth and rate of the reinfiltrated liquid versus time. The results showed that three reinfiltration regimes: including Early Time Regime (ETR) ($z \sim t$, $q = constant$), Middle Time Regime (MTR) ($z \sim \sqrt{t}$, $q \sim 1/\sqrt{t}$) and Late Time Regime (LTR) ($z \sim t$, $q = constant$) can be observed, where the inertia, viscous, and gravity forces are dominant, respectively. The results also indicated that by increasing the permeability of the porous medium, the durations of the ETR ($z \sim t$, $q = constant$) and the LTR ($z \sim t$, $q = constant$) are prolonged while the duration of the MTR ($z \sim \sqrt{t}$, $q \sim 1/\sqrt{t}$) is reduced. Moreover, the results revealed that by increasing the liquid viscosity, the durations of the ETR ($z \sim t$, $q = constant$) and LTR ($z \sim t$, $q = constant$) are reduced whereas the duration of the MTR ($z \sim \sqrt{t}$, $q \sim 1/\sqrt{t}$) is prolonged. In addition, the results showed that in the case of high permeability of the porous medium when the fracture capillary pressure is strong enough only the LTR ($z \sim t$, $q = constant$) can be observed. The MTR ($z \sim \sqrt{t}$, $q \sim 1/\sqrt{t}$) and the LTR ($z \sim t$, $q = constant$) scalings are of practical significance since the liquid reinfiltration in fractured rocks associated with gas–liquid drainage mechanism is a very slow process. These findings advance the understanding of the two-phase flow in fractured porous media.

1. Introduction

An understanding of fluid flow and transport through unsaturated fractured porous media is important in geohydrological sciences (Ghezzehei and Or, 2005; Singhal and Gupta, 2010), oil recovery from hydrocarbon reservoirs (Dindoruk and Firoozabadi, 1994; Hoteit and Firoozabadi, 2008; Dejam and Hassanzadeh, 2011; Mashayekhizadeh et al., 2011; Dejam et al., 2011), subsurface waste disposal management (Or and Ghezzehei, 2007), and wicking of liquids connected to porous materials in printing or coating processes as well as cleaning applications (Gat et al., 2012). A fractured porous medium is composed of porous matrix blocks, with low permeability and high storage capacity, and fractures, with high permeability and low storage capacity. In other words, the fractures provide the flow path for the liquid drained from the porous matrix blocks. However, the porous matrix blocks suck the drained liquid from the upper blocks and significantly affect the transport of liquid. The drained liquid may be the oil phase, which is drained from the upper rock matrix blocks, or a liquid carrying a contaminant. The process of reinfiltration of the drained liquid can significantly affect the transport of oil and contaminants in subsurface. For a gas–liquid drainage mechanism, the drained liquid from different porous matrix blocks may be quickly reinfiltrated to the lower porous matrix blocks (Saidi et al., 1979; Firoozabadi and Ishimoto, 1994; Sajjadian et al., 1999; Dejam et al., 2009). The interaction between the porous matrix blocks by reinfiltration was originally proposed by Saidi et al. (1979). They attributed the interaction between porous matrix blocks to the reinfiltration process between the upper and lower porous matrix blocks via liquid bridges. Fig. 1 illustrates a simple schematic of the reinfiltration from the upper to lower porous matrix blocks via formation of liquid bridges in a horizontal fracture between two por-

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Nomenclature

a	a parameter defined as $8\mu/r_0^2\rho$ in Bosanquet (1923) equation
b	a parameter defined as $(P_e r_0 + 2\sigma)/r_0\rho$ in Bosanquet (1923) equation
d	differential
dz/dt	front velocity in the lower porous matrix block (L/T)
d^2z/dt^2	front acceleration in the lower porous matrix block (L/T^2)
$(\Delta p)_g$	pressure difference due to gravity force (M/LT^2)
$(\Delta p)_i$	pressure difference due to inertia force (M/LT^2)
$(\Delta p)_v$	pressure difference due to viscous force (M/LT^2)
g	gravitational acceleration (L/T^2)
k	permeability of the porous medium (L^2)
m	fitting parameter in Eq. (28)
n	fitting parameter in Eq. (28)
p_{cf}	fracture capillary pressure (M/LT^2)
p_{cm}	gas-liquid matrix capillary pressure (M/LT^2)
P_e	pressure at the entrance of the capillary tube (M/LT^2)
p_{gf}	fracture gas pressure (M/LT^2)
p_{gm}	matrix gas pressure (M/LT^2)
p_{lf}	fracture liquid pressure (M/LT^2)
p_{lm}	matrix liquid pressure (M/LT^2)
P_o	fitting parameter in Eq. (28) (M/LT^2)
q	rate of the reinfiltrated liquid into the lower porous matrix block (L^3/T)
r_c	critical value for capillary radius (L)
r_0	the radius of each capillary in a bundle of tubes (L)
S_e	an effective saturation defined by Eq. (29)
S_{lf}	fracture liquid or wetting phase saturation
S_{lrf}	residual fracture liquid saturation
S_{lsf}	fracture liquid saturation at zero fracture capillary pressure
t	time (T)
t_1	crossover time between the ETR ($z \sim t$, q = *constant*) and the MTR ($z \sim \sqrt{t}$, $q \sim 1/\sqrt{t}$) (T)
t_2	crossover time between the MTR ($z \sim \sqrt{t}$, $q \sim 1/\sqrt{t}$) and the LTR ($z \sim t$, q = *constant*) (T)
x	distance traveled by the front in the horizontal capillary tube (L)
z	depth of the reinfiltrated liquid into the lower porous matrix block (L)

Greek symbols

σ	surface tension of the liquid–gas interface (M/T^2)
θ_e	static (equilibrium) contact angle
μ	liquid viscosity (M/LT)
ρ	liquid density (M/L^3)
δ	parameter defined as $\phi\mu/k\rho$ in Eq. (9)
λ	parameter defined as $\lambda = -p_{cf}/\rho + \sigma\cos\theta_e\sqrt{\phi/2k}/\rho$ in Eq. (9)
ϕ	porosity of the porous medium

Subscripts

cf	fracture capillary
cm	matrix capillary
e	equilibrium for contact angle or effective for S_e in Eqs. (28) and (29)
g	gravity
gf	fracture gas
gm	matrix gas
i	inertia
lf	fracture liquid
lm	matrix liquid
lrf	residual fracture liquid
lsf	fracture liquid at zero fracture capillary pressure
v	viscous
o	for P_o in Eq. (28)
0	for r_0

ous matrix blocks. The reinfiltration process can change the main flow path to be the porous matrix blocks, instead of the fractures, and, therefore, significantly affect the travel time for migration of the drained liquid and contaminants in fractured rocks. This phenomenon can also occur as an important vadose zone process, the so-called infiltration of a liquid into soil or porous medium (Green and Ampt, 1911; Philip, 1957; Barry et al., 1993; Kao and Hunt, 1996; Swartzendruber, 2000; Liu et al., 2008; Prevedello et al., 2009; Valiantzas, 2010; Ahuja et al., 2010; Corradini et al., 2011; Pellichero et al., 2012; Hilpert and Glantz, 2013). The reinfiltration process can significantly retard and slowdown the transport of oil, water and contaminants in the fractured subsurface formations.

Liquid reinfiltration into porous matrix blocks is a significant process, which can strongly influence the two-phase gas–liquid transport in fractured porous media. Therefore, a good understanding of this phenomenon is the key to the successful description of a number of processes such as underground water resources, contaminant transport, waste disposal management, vadose zone and oil recovery.

It is widely accepted to model liquid adsorption into a porous medium using the theory of fluid flow through a bundle of capillary tubes (Batten, 1984; Schoelkopf et al., 2000; Hamraoui and Nylander, 2002; Marmur, 2003; Lockington and Parlange, 2004; Fries and Dreyer, 2008). Several theoretical and experimental studies on the role of capillarity in porous media (Deinert et al., 2008; Shikhmurzaev and Sprittles, 2012; Gomez et al., 2013) and capillary tubes (Dimitrov et al., 2007; Fries and Dreyer, 2008; Masoodi et al., 2013) have been reported in the literature. In the following, a brief summary of the previous studies, which discuss different regimes for fluid flow through capillary tubes, is presented. A detailed review of related works to liquid flow in capillary tubes is presented elsewhere (Dreyer, 2007).

The mathematical modeling of the capillary rise in a tube, which is still applied in explaining the rate of uptake of liquid into porous systems, was first proposed by Bell and Cameron (1906), and later independently developed by Green and Ampt (1911), Lucas (1918), and Washburn (1921). They balanced the viscous force inside the horizontal tube, using Poiseuille law, and the static capillary force at the front. Their force balance resulted in $x = \sqrt{(r_0\sigma\cos\theta_e/2\mu)t}$, in which x is the distance traveled by the front, r_0 is the radius of the capillary tube, σ is the surface tension of the liquid–gas interface, θ_e is the static (equilibrium) contact angle, μ is the liquid viscosity and t is the time. This equation is commonly known as the Lucas–Washburn equation and shows that the distance traveled by the front is proportional to the square root of time ($x \sim \sqrt{t}$). When only the viscous and static capillary forces are in competition, it is expected to see the Lucas–Washburn regime. As it will be shown later in our study, this regime is identified as the Middle Time Regime (MTR), since it happens at the middle times of the process. Several studies have been performed to improve the Lucas–Washburn theory, some of which are reviewed as follows.

Rideal (1922) added the inertia force inside the horizontal tube. He did not consider the force required to impart momentum to the liquid entering the capillary tube, $\pi r_0^2\rho(dx/dt)^2$, in the inertia term and presented an analytical solution as given by