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A crossflow model for an interacting capillary bundle: Development and application for waterflooding in tight oil reservoirs

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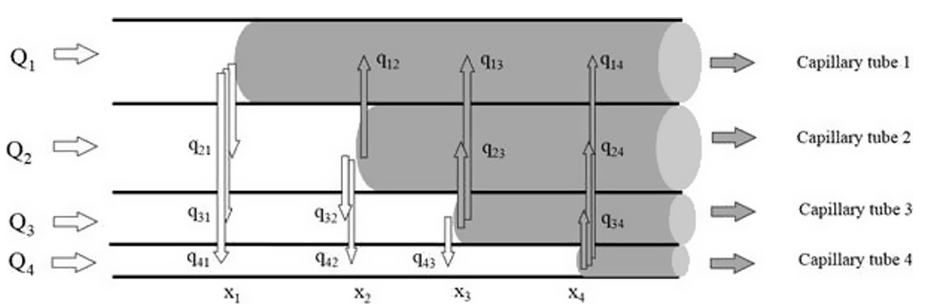
HIGHLIGHTS

- An new analytical solution was developed for a capillary bundle model.
- Cross-flows and flow rates were solved before and after water breakthrough.
- Narrow pore size distribution and high flow rate increase sweep efficiency.
- Low IFT greatly helps reach stable displacement front in tight oil reservoirs.

GRAPHICAL ABSTRACT



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ABSTRACT

A new analytical method to calculate crossflow in an interacting capillary bundle has been proposed to analyze immiscible displacement processes in porous media. Capillary force, pressure equilibrium and mass balance were incorporated to develop algebraic equations for crossflow within the interacting bundle respectively before and after water breakthrough. By solving the equations analytically, flow rate in each capillary tube and crossflows among different tubes in the bundle were obtained as a function of water/oil interface positions at different times. The model was then applied to analyze the fluid dynamics of immiscible displacements. The whole process was modelled, from water first entering into the bundle to the moment that no more oil could be further produced. Eight water-displacing-oil cases, including specifically designed scenarios representing a tight reservoir, were modelled in an imbibition process to investigate the effects of pore size distribution, injection rate, and interfacial tension (IFT). The model successfully predicted fingering effect for a tight oil reservoir and even displacement front that could only be achieved by ultra-low IFT. The modelling results are highly consistent with previous experimental and simulation results in the literature. The theoretical model can be used to investigate the effects of different reservoir parameters in immiscible displacement process, such as permeability, wettability, and interfacial tension. The proposed interacting capillary bundle model leads to the pore network simulation in its simplicity as pore connection and topology information is not required.

1. Introduction

Immiscible two-phase fluid flow in various porous media is of special importance to soil science, environmental engineering, construction, and petroleum industries. In particular, injection of water into oil flowing through porous materials is an important process involved in oil recovery. Extensive theoretical modelling and experimental techniques have been used to investigate the fluids flow in porous media (Purcell, 1949; Yortsos and Fokas, 1983).

Although many studies have aimed at experimentally modelling the actual flow path of fluid in sand or rock, the other main stream of fluid flow researches has tried to establish an abstract

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Nomenclature

$A(R_i)$	abbreviated term. $A(R_i) = \frac{\pi R_i^4}{8\mu \sum_{k=1}^{n} R_k^4}$
i	the indicator of the tube number
j	the indicator of the interface number
L	total length of the bundle
m	the number of the tubes which have water breakthrough already
n	the number of the tubes in the bundle
Pc_i	the capillary pressure in the ith tube
Q	total flow rate to the interacting capillary bundle
$Q_{i,in}$	the inlet flow rate to the ith tube
$Q_{i,out}$	the outlet flow rate from the ith tube
$Q_{i,j}$	flow rate in the ith tube at the jth segment
Q_{in}	total inlet flow rate to the interacting capillary bundle
Q_{out}	total outlet flow rate from the interacting capillary bundle
$q_{i,j}$	the crossflow from the jth tube to the ith tube
$q'_{i,j}$	the partial crossflow from the jth tube to the ith tube, which only includes the term with $(Pc_2 - Pc_1)$
$q''_{i,j}$	the partial crossflow from the jth tube to the ith tube, which only includes the term with $(Pc_3 - Pc_2)$
$q'''_{i,j}$	the partial crossflow from the jth tube to the ith tube, which only includes the term with $(Pc_4 - Pc_3)$
R_i	the radius for the ith tube
S	the distance of water in the smaller tube before water invades to the neighbouring larger tube
T_i	the flow rate which pushes the interface in the ith tube
t_s	the sth timestep
Δt	interval of each timestep
μ	the viscosity of the fluid, for both oil and water
x_i	the interface position in the ith tube
$x_{i,s}$	the interfaces position for the ith tube at the sth timestep

model to mimic flow mechanisms. A tube-bundle model with a set of parallel-placed capillary tubes is one of the most important ones that represent the pore space in porous media (Yuster, 1951; Scheidegger, 1953; Bartley and Ruth, 1999). A limitation of this model is that it does not account for crossflow and pressure equilibrium, and that fluid flow in an individual tube is independent of that in the other tubes. However, due to the existence of a 3-D network of connected voids, pores, and capillaries in a real porous medium, crossflow would occur between adjacent flow channels (Dullien, 1992). As a result, the fluid flow profile in a traditional tube-bundle model contradicts physical observation, and the suitability of using such a model to represent real porous media needs to be re-examined (Dong et al., 2005, 2006).

With the aim of overcoming this limitation, interacting capillary-bundle models with pressure equilibrium have been developed. For example, Dong et al. (1998) developed a modified tube-bundle model with pressure equilibration at every distance x along the axis of the core, wherever it is single phase flow. The assumptions behind that were tube-to-tube flow resistance and tube-to-tube fluid invasion was excluded. They claimed that the model accounted for the physical reality that water was imbibed first into the smallest tube when displacing oil, which was entirely different from the original tube-bundle model. Based on the same assumptions, Ruth and Bartley (2002) developed a "perfect-crossflow model" for which there was no resistance between any tubes that contained the same phase (either oil or water) at a given segment. They also provided a solution for interacting capillary bundle model after water was imbibed into all the tubes and compared the solution with modified Darcy's law (Ruth and Bartley, 2011). The interacting tube bundle model was also successfully used as a history matching tool to determine relative permeability curves from displacement experiments (Wang et al., 2012). Relative permeability curves were tuned by adjusting the model parameters to match the production histories of laboratory displacement experiments. Some researcheres extended their study to the resistance in the interacting capillary bundle: Wang et al. (2008) considered the pressure differences between two tubes when transverse flow happened. The so-called "uniform resistance-type" model required extensive numerical calculation, but the results indicated that it only has negligible effect on the rate of advance of the interfaces. Furthermore, trapping of oil in waterflooding was studied by Wang and Dong (2011) using interacting-serial type triangular tube bundle models. Simulation results were in qualitative agreement with those obtained from laboratory experiments in the actual porous media reported in the literature. However, numerical approximation was adopted when considering the resistance.

On the other hand, the limitations of previous research on interacting capillary bundle models are as follows: the previous simulation studies aimed to solve the interface positions in each tube, x, whereas few research investigated the fluid flow behavior after water breakthrough, which would change the direction and amount of crossflow due to the sudden disappearance of the interface. And there has been a lack of study focused on linking microscopic menisci positions to macroscopic concepts in petroleum engineering, such as fluid flow in tight reservoirs, surfactants flood performance, and existence of fractures.

The research described in this paper addressed these several aspects: (1) we developed separate interacting capillary bundle models and applied them before and after water breakthrough; (2) we obtained the analytical solution of flow rate according to the positions of menisci in each tube, by solving the crossflow of oil and water at each segment in an imbibition process; (3) general solution was obtained when the number of tube increases to n. Under these circumstances, the solved cross-flows and flow rates formed a two-dimensional matrix, which makes the model useful for the pore network simulation in the future; (4) we tracked the oil and water occupying varying portions of separate tubes over the entire course of an imbibition process, which began at the time water entered the smallest tube and ended when there was no interface in the tube, by solving a model with 20 tubes; and (5) we did scenario analysis for important parameters, such as pore size and distribution, injection rate, and interfacial tension.

2. Model development

2.1. Background

Idorenyin and Shirif (2012) stated these following assumptions when developing a tube-bundle model, and they are also adopted in the current study: (1) fluids are Newtonian and incompressible; (2) fluids are non-reactive; (3) isothermal condition for displacement; (4) porous medium is isotropic; (5) the porous media is considered as water-wet by default; and (6) there is no residual oil left after the displacement front in circular tubes, indicating displacement efficiency is 100%, i.e., perfect displacement. As a result, the residual oil was represented by unswept oil in the larger tubes. Oil and water viscosities are known parameters and input to the