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Improved Prediction of Oil Recovery From Waterflooded Fractured Reservoirs

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Abstract
Simulations of waterflooding in fractured media are based on the Warren and Root (WR) approach, which uses an empirical transfer function between the fracture and matrix block. Arbogast used homogenization to formulate an improved flow model in fractured media, leading to an integro-differential equation; also called the boundary condition (BC) approach. A wellposed numerical 3D model for the BC approach has been formulated. This paper derives this numerical model to solve full 3D integro-differential equations. The results of this model are compared with the ECLIPSE results. For the interpretation it is useful to define three dimensionless parameters, which characterize the oil production in fractured media. The most important of these parameters is a Peclet number defined as the ratio between the time required to imbibe water into the matrix block and the travel-time of water in the fracture system. The results of the WR approach and the BC approach are in good agreement when the travel-time is longer than the imbibition time. However, for times with the same order of magnitude and for the travel time shorter than the imbibition time, the approaches give different results. The BC approach allows the use of transfer functions based on fundamental principles, e.g., the use of a rate dependent capillary pressure function. When implemented, it can be used to improve recovery predictions for waterflooded fractured reservoirs.

Introduction
Naturally fractured petroleum reservoirs (NFR's) represent over 20% of the world's oil and gas reserves (Saidi 1983), but are among the most complicated class of reservoirs to produce efficiently. NFR's comprise an interconnected fracture system that provides the main flow paths and the reservoir rock or matrix that acts as the main source of hydrocarbons.

From the geological point of view it is possible to distinguish between various types of fractured reservoirs (Nelson 1985; Stearns 1969; Stearns 1972). The most important aspect is whether the fracture network provides a continuous flow path (Saidi 1983) or whether it has regions with different fracture geometries or systems consisting of a hierarchy of fracture systems at different scales (multi-scale fractures) (Yu-Shu Wu 2004). When the fracture network is not continuous, the reservoir can be split up in fractured and non-fractured domains. Also in the fractured domains the reservoir is heterogeneous, with different fracture densities, fracture apertures, anisotropies etcetera. In some approximate sense the fractured reservoirs shows some repetition of fractured sub-domains. This aspect will be used for obtaining averaged properties of the subdomains. The same idea can also be used as a first guess to obtain the global flow field. Alternatively it is possible to use the global flow field to obtain boundary conditions at the local scale and repeat this procedure until convergence has been obtained.

Flow modeling in fractured reservoirs was greatly advanced by Barenblatt et al. (1960) who introduced the concept of dual porosity. In addition, he introduced the transfer function and shape factor. From the geometrical point of view, Barenblatt assumed that the fracture system is regular "to some extent". Warren and Root (1963) used the double porosity model and applied it to a well test analysis. They also introduced the sugar cube model, which has been the basis of many of the fractured reservoir simulators since that time. The double porosity model of Warren and Root for examining pressure drawdown and buildup phenomena in naturally fractured reservoirs was extended by Kazemi et al. (1969, 1992) to interpret interference test results. These ideas were extended with the introduction to the so-called dual permeability model, where the matrix blocks can also contribute to the global flow depending on the permeability ratio of fractures and matrix blocks.

The transfer function is semi-empirical. It relates the fluid flow at the interface between matrix and fracture to the driving force, e.g., average phase pressure difference between fracture and matrix. More recently the ideas were extended with the derivation of transfer functions based on fundamental transport modeling. Dutra and Aziz (1992) presented a model that takes into account the transient nature of the imbibition process and the effect of variation in fracture saturation. Sarma and Aziz