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Calculation of relative permeabilities from field data and comparison to laboratory measurements

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ABSTRACT

Relative permeabilities of water and steam were calculated, by applying the Shinohara method, using data from geothermal wells in Iceland. This method does not require that the local water saturation of the two phase mixture is known, but requires production history of mass flow and enthalpy from each well. The results were compared to relative permeability curves found in literature and to values from laboratory measurements and revealed that wells within the same field can follow different relative permeability curves. This method enabled us to get relative permeability values for geothermal wells with production history.

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1. Introduction

Fluid flow in geothermal systems usually occurs through fractures in the surrounding rocks (Grant and Bixley, 2011). When simulating such flow with numerical models, the system is considered as a porous medium either with homogeneous permeability or with a permeability tensor accounting for the anisotropy of the permeable matrix. For flow in fractures the porous media assumption is generally used (Chen et al., 2004; Chen and Horne, 2006). Some reservoir modelling tools like TOUGH2 allow double porosity and dual permeability definitions for the reservoir structure where relative permeability functions for both flow through the porous material as well as the fracture flow can be simulated simultaneously (Pruess et al., 1999). However, in such cases, the fracture permeability is normally dominant.

Flow in porous or fractured rocks in high temperature geothermal system occurs under different conditions. One is where recharge water flows into the system, and another case where geothermal fluid gains heat in the system due to conduction from the magmatic heat source below as reported by White (1967). This results in convection of the fluid, causing it to flow upwards against gravitational acceleration due to buoyancy. Another case is the flow of geothermal fluid towards wells which have been drilled into the liquid dominated geothermal system. At some point, boiling might occur in the reservoir, causing two phase flow of water and steam to occur. A representation of the two occurrences where two phase flow of water and steam might occur in geothermal reservoirs is shown in Fig. 1.

Darcy's law is normally used to evaluate mass flow and velocity of a fluid through porous media. It is applicable in its original form for single phase fluid, but if there are two or more phases flowing simultaneously through the permeable matrix the concept of relative permeability is introduced. In geothermal reservoir modelling, the relative permeabilities can be used to evaluate the mass flows and fluid mixture properties, such as the total viscosity and flowing enthalpy of the two phase fluid (Bodvarsson et al., 1980). They are also important parameters for determining how much steam vs. how much water a geothermal reservoir produces. The relative permeabilities can be determined from functions obtained from literature, but they require the water saturations to be known. There are various relative permeability relations that can be found in literature (Pruess et al., 1999). Many of them are gained from experiments using fluids other than water, like oil and gas (Corey, 1954) and much information gained from oil and gas research has been adopted to geothermal systems. However, using a different fluid for both of the vapour and liquid phases can give results that differ from systems in which the same fluid is used for both the vapour and liquid phases. That has been shown in the study of Chen (2005) where the phase transformation effect enhanced the relative permeabilities of water and steam compared to water and nitrogen flow.

Previous results from steam water experiments have shown that there is no set of relative permeability curves which is applicable for all flow cases (Verma, 1986; Sanchez and Schechter,

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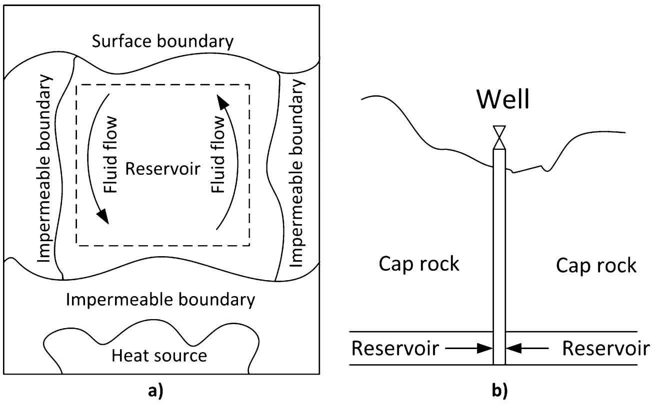

Fig. 1. (a) Convective system representing a convective volcanic geothermal reservoir. (b) A figure showing where a geothermal well is drilled into a reservoir, causing fluid to flow through the fractured reservoir into the well.

1990; Piquemal, 1994; Ambusso, 1996; Satik, 1998; Mahiya, 1999; O'Connor, 2001). An arbitrary relative permeability curve must be chosen when modelling the two phase flow of water and steam, which are available in tools like TOUGH2 and HYDROTHERM (Pruess et al., 1999; Kipp et al., 2008). Furthermore, the relative permeabilities cannot be determined directly since the water saturations are normally not known for the reservoirs. However, the relative permeabilities can be estimated by applying a method introduced by Shinohara (1978). That method uses the flow discharge and enthalpy from the production history of a specific well and the corresponding wellhead or downhole temperature to determine fluid properties that are used to evaluate the relative permeabilities for downhole two phase reservoir conditions. Another method by Grant (1977) was defined to determine the relative permeabilities from field data, using discharge and enthalpy measurements from the wellbores followed by an improved analysis by Horne and Ramey (1978).

Reyes et al. (2004) applied the Shinohara method on production data from two geothermal fields. They also used the method on laboratory results from Chen (2005) where the relative permeabilities for water and steam were calculated using two different methods. One where the water saturations were directly measured and the relative permeabilities calculated and the other where the Shinohara method was applied. There was a very small difference between the values calculated using the two different methods.

In this paper, the Shinohara method for quantifying relative permeabilities is derived from Darcy's law and then applied to well data from geothermal fields in Iceland. The purpose of this study is to use this method on field data and to derive the relative permeabilities of the reservoir fluid which flows to the wells located in the fields. The results are also compared to laboratory measurements. This method allows the relative permeabilities to be calculated without direct measurements of the water saturation. The results can be used for modelling the reservoir, using information about the resulting relative permeabilities for the wells that were calculated with this method.

2. Method

2.1. Darcy's law and relative permeabilities

Darcy's law was first discovered empirically by the French hydrologist Henry Darcy in 1856 (Darcy, 1856). It is applicable to laminar flow with low Reynolds numbers and is given by Eq. (1) for flow of a single phase fluid.

$$\vec{q} = -\frac{k}{\nu}(\nabla p - \rho\vec{g}) \quad (1)$$

where $\vec{q}$ is the mass flux (mass flow per area of the porous matrix), k is the intrinsic permeability of the porous matrix, ν is the fluid kinematic viscosity, ∇p is the pressure gradient of the fluid flow, ρ is the fluid density and $\vec{g}$ is the gravitational acceleration.

The intrinsic permeability is usually determined experimentally and then it can be more convenient to use the mass flow definition, $\dot{m}$, where Eq. (1) becomes:

$$\dot{m} = -\frac{k}{\nu}A\vec{n}\cdot(\nabla p - \rho\vec{g}) \quad (2)$$

where $\vec{n}$ is the unit normal to the cross sectional area A of the permeable flow channel.

When two phases are present and flowing simultaneously, as is the case of water and steam in high enthalpy geothermal reservoirs, the intrinsic permeability alone is not sufficient to describe the flow in the porous matrix. An area reduction factor is applied in the Darcy's law and Eq. (2) split into two equations, one for each phase. Then, the concept of relative permeabilities, k_r is introduced as shown in Eqs. (3) and (4):

$$\dot{m}_w = -\frac{kk_{rw}}{\nu_w}A\vec{n}\cdot(\nabla p - \rho_w\vec{g}) \quad (3)$$

$$\dot{m}_s = -\frac{kk_{rs}}{\nu_s}A\vec{n}\cdot(\nabla p - \rho_s\vec{g}) \quad (4)$$

where the subscripts w and s specify the water and steam phase respectively.

The relative permeabilities are usually presented as functions of local water saturations, which are defined as the following volume fraction in Eq. (5).

$$S_w = \frac{V_w}{V_w + V_s} \quad (5)$$

where V_w and V_s are the volumes occupied by water and steam respectively.

In real geothermal applications, it can be difficult to determine the local water saturation in the flow channel. Nevertheless, the flowing saturation, $S_{w,f}$, can be defined as in Eq. (6).

$$S_{w,f} = \frac{\dot{V}_w}{\dot{V}_w + \dot{V}_s} = \frac{(1-x)\nu_w}{(1-x)\nu_w + x\nu_s} \quad (6)$$

where $\dot{V}_w$ and $\dot{V}_s$ are the volumetric flow rates of water and steam respectively and ν_w and ν_s are the specific volumes of water and steam respectively and x is the steam fraction as defined in Eq. (7).

$$x = \frac{\dot{m}_s}{\dot{m}_s + \dot{m}_w} \quad (7)$$

The relative permeabilities can be determined in various ways. If the local water saturation in Eq. (5) is known, the relative permeabilities can be determined using one of the available relative permeability functions, f and g, of the water saturation as shown in Eqs. (8) and (9).

$$k_{rw} = f(S_w) \quad (8)$$

$$k_{rs} = g(S_w) \quad (9)$$

These functions can be selected from known relative permeability curves.

Widely used sets of relative permeability curves include the Corey curves (Corey, 1954) shown in Eqs. (10) and (11) and the Functions of Verma (Verma, 1986) shown in Eqs. (12) and (13).

$$k_{rw} = S_{wn}^4 \quad (10)$$

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