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EFFECT OF FLOW CONFIGURATION ON THE RELATIVE PERMEABILITIES OF WATER AND STEAM IN TWO PHASE FLOW IN GEOTHERMAL RESERVOIRS

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ABSTRACT

In geothermal reservoirs water and steam can flow simultaneously through the porous and permeable medium which the reservoirs consist of. Darcy's Law is the traditional relation used to describe flow through the reservoir, where the concept of relative permeability is used for multiphase flow. In this paper we assess the effects of both the initial condition of the fluid and of its flow direction on the relative permeabilities for a steady, one dimensional two phase flow of water and steam. The results show that for different types of relative permeability relations these conditions can have a significant effect. Even when the mass fractions and conditions are identical for horizontal and vertical flow, the water saturation and consequently the relative permeabilities can vary significantly with flow direction and initial condition of the fluid.

It is of great importance to perform further research in this field since there may be a discrepancy between the relations commonly used and actual flow behavior. This paper also describes a large scale experiment being performed in a laboratory in Iceland. The anticipated outcome of this experiment, combined with model calculations, is improved flow relations that can be used in more advanced modeling tools.

INTRODUCTION

In geothermal reservoirs the geothermal fluid often exists as a two phase mixture of water and steam flowing through the reservoir. This flow occurs either because of internal conditions or as flow to a production well during utilization. The understanding of two phase flow of water and steam through porous media, like geothermal systems consist of, is therefore a very important topic in geothermal reservoir science. Even though considerable research has already been conducted in this field, an accurate general description and understanding of geothermal reservoirs is far from being available.

Geothermal reservoirs are explored to gain an idea of their condition, capacity and response and the behavior of the system is usually simulated by using numerical reservoir models. These models use state of the art relations to describe the geothermal reservoir and to predict future condition of the reservoir for different parameters. For simultaneous two phase flow of water and steam through a porous geothermal reservoir, the traditional Darcy´s Law is used to describe the flow. The concept of relative permeability is used as an area reduction factor for each phase. Previous research in this field has shown that the relative permeabilities do not follow the phase saturation (the portion of the flow area that the phase is occupying) linearly, but that they show behavior which can be fitted to a curve proportional to the saturation to a power greater than one. Several known relations, gained from experiments, are used in geothermal reservoir models which deviate from the linear dependency (Pruess et al. 1999).

Many of the widely used relations assume that the relative permeabilities are functions of saturation only since the effects of other fluid conditions, reservoir conditions, flow direction and phase interaction on the relative permeabilities are not well known. It is especially important to know the effects of flow direction since the fluid can normally flow in different directions in the reservoirs.

The relative permeabilities of the water and the steam are an important tool in defining the mass flow of the two phases and the flowing conditions of the two phase fluid. The fluid conditions like total kinematic viscosity and the flowing enthalpy of the fluid can be determined from Darcy´s Law and the relative permeabilities. The sensitivity of these parameters to relative permeability is large (Bodvarsson et al., 1980) and therefore the relative permeabilities should be determined carefully. Thus the relative permeabilities are important parameters when describing two phase flow of water and steam in geothermal reservoirs.

In this paper, the relative permeability theory is used on uniform two phase flow cases of water and steam, one horizontal and one vertical. In both cases, the two phase fluid flows through an identical permeable matrix. The objective was to assess the effect of flow direction on the relative permeabilities of water and steam. The results show this effect where the relative permeabilities are demonstrated as function of the steam fraction of the flow for both flow cases.

THEORY

Darcy´s Law

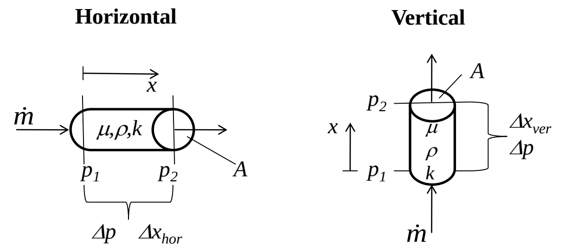
When a fluid is flowing through a porous media the fluid superficial velocity v, is described with the Darcy´s Law (or the Darcy Equation) shown in Eq. (1) for a one dimensional one phase flow.

$$v = -\frac{k}{\mu}\left(\frac{dp}{dx} + \rho g \sin\alpha\right) \tag{1}$$

where k is the intrinsic permeability (also called absolute permeability) of the surrounding porous media that the fluid flows through, μ is the fluids dynamic viscosity, dp/dx is the pressure gradient of the flow, ρ is the fluid density and g is gravitational acceleration. In addition, α denotes the inclination of the flow channel with respect to a horizontal plane, (α = 0° and $\sin\alpha = 0$ for horizontal flow and α = 90° and $\sin\alpha = 1$ for vertical flow). The Darcy´s Law can also be written for the mass flow of the fluid using the fluids kinematic viscosity $\nu=\mu/\rho$ and the relation between the mass flow and the superficial velocity $\dot{m} = \rho v A$ where A is the cross sectional area of the permeable matrix. The Darcy´s Law shown in Eq. (2) relates the mass flow of a one dimensional one phase flow with the fluid condition and the properties of the surrounding media.

$$\dot{m} = -\frac{k}{\nu}A\left(\frac{dp}{dx} + \rho g \sin\alpha\right) \tag{2}$$

The gravity term in Eqs (1) and (2) $\rho g \sin\alpha$ depends on the orientation of the flow channel and the corresponding relations are shown in Fig. 1 for both horizontal and vertical flow directions. The pressure gradients $\Delta p/\Delta x_{hor}$ and $\Delta p/\Delta x_{ver}$ shown in Fig. 1 are constant for each case which is a theoretical simplification since in real flow cases varying pressure gradients would be experienced along the flow line.



$$\dot{m} = -\frac{k}{\nu}A\frac{\Delta p}{\Delta x_{hor}} \qquad \dot{m} = -\frac{k}{\nu}A\left(\frac{\Delta p}{\Delta x_{hor}} + \rho g\right)$$

Figure 1: Representation of a one dimensional one phase flow of a fluid through a porous flow channel in different flow directions

The unit conventionally used for intrinsic permeability is the non SI unit Darcy (or milliDarcy), where 1 Darcy = $9.8692327 \cdot 10^{-13}$ m^2 ≈ 10^{-12} m^2. The Darcy´s Law was first presented by the 19th-century French hydrologist Henry Darcy (Darcy 1856) and works quite well for describing a flow of a one phase fluid through a porous medium. When the fluid is in a multiphase state as can be the case in oil and gas reservoirs and in geothermal reservoirs, the relative permeability approach is used to account for the mobility of each phase. For two phase flow of water and steam through a porous media the concept of the relative permeability is used to define the mass flows of the two phases as shown in Eqs (3) and (4) where the mass flow is defined for water and steam respectively.

$$\dot{m}_w = -\frac{k k_{rw}}{\nu_w}A\left(\frac{dp}{dx} + \rho_w g\ \sin\alpha\right) \tag{3}$$

$$\dot{m}_s = -\frac{k k_{rs}}{\nu_s}A\left(\frac{dp}{dx} + \rho_s g\ \sin\alpha\right) \tag{4}$$

In Eqs (3) and (4) k_{rw} and k_{rs} are the dimensionless relative permeabilites for water and steam respectively and the subscript w denotes the water phase and s the steam phase.

From the Darcy´s Law in Eqs (3) and (4) and the corresponding mass balance the condition of the fluid mixture can be estimated by using the relative permabilities. Eqs (5) and (6) define the total kinematic viscosity of the fluid ν_t and the flowing enthalpy h_f of the two phase mixture, where h_w and h_s are the water and steam saturation enthalpies respectively.

These conditions are calculated from the mass and energy balance for a flow in horizontal direction when $\alpha=0$ and $\sin\alpha=0$.

$$\frac{1}{\nu_t} = \frac{k_{rw}}{\nu_w} + \frac{k_{rs}}{\nu_s} \tag{5}$$

$$h_f = \nu_t\left[h_w\frac{k_{rw}}{\nu_w} + h_s\frac{k_{rs}}{\nu_s}\right] \tag{6}$$

RELATIVE PERMEABILITIES

The concept of relative permeabilities is used to modify the Darcy´s Law for use on a multiphase flow in a porous medium. Together with the mass balance where the sum of the water and the steam flow is the total mass flow $\dot{m}_{tot}$ in Eq. (7)

$$\dot{m}_{tot} = \dot{m}_w + \dot{m}_s = (1-x)\dot{m}_{tot} + x\dot{m}_{tot} \tag{7}$$

the steam fraction, x, is determined from Eq. (8).

$$x = \frac{h_{tot} - h_w}{h_s - h_w} \tag{8}$$

where h_{tot} is the total enthalpy of the flow.

The relative permeabilities and the pressure gradient are unknown in Eqs (3) and (4) and must therefore be determined with measurements. The problem is that there are more unknowns than the number of equations and in order to fix this it is common to relate the relative permeabilities with a common parameter, the fluid saturation S_w. The fluid saturation is defined as the area reduction factor for each phase in the cross section area of the permeable matrix as defined in Fig. 2.

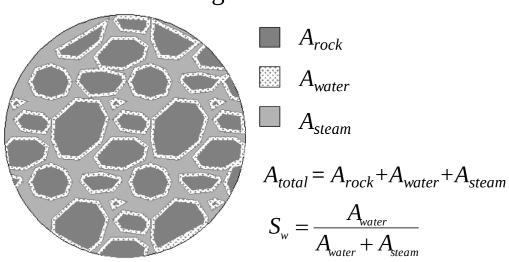


Figure 2: A cross section of a porous flow channel containing water and steam

According to this theory the relative permeabilities must follow the saturation linearly, which leads to the so called X-curves which can be seen in Fig. 3.

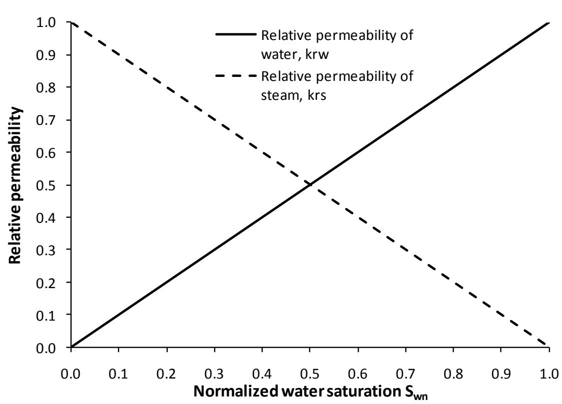


Figure 3: The theoretical X-curve, showing the relative permeabilites of water and steam as functions of the normalized water saturation

The X-curves for the relative permeabilities shown in Fig. 3 are represented as functions of the normalized water saturation, S_{wn}, which is derived from the residual saturation of the two phases shown in Eq. (9).

$$S_{wn} = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{sr}} \tag{9}$$

The values S_{wr} and S_{sr} are the residual saturations of the water and the steam phase respectively. They represent the minimum saturation value that each phase must reach before becoming mobile. These values can vary with the type of rock in the porous matrix, but typical values are S_{wr} = 0.2 - 0.3 for water and S_{sr} = 0.1 for steam (Piquemal 1994, Verma 1986). The residual saturations values have a great influence on the flow conditions shown in Eqs (5) and (6) (Bodvarsson et al. 1980). A representation of residual saturations in a set of relative permeabilities following an arbitrary curve is shown in Fig. 4.

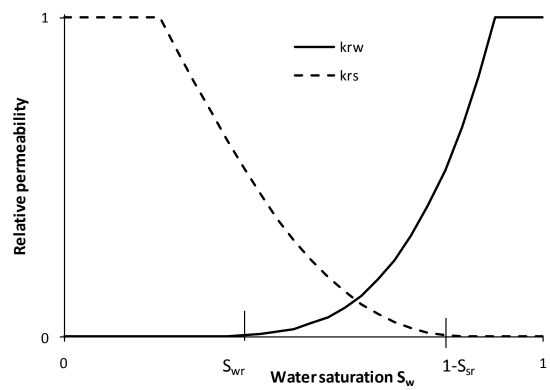


Figure 4: Relative permeability curves showing the "cut offs" of the residual saturations of the two phases

Background for Relative Permeability Studies

The X-curves are the general theoretical relations for the relative permeabilities derived from Darcy´s Law, proposing a linear dependency between the relative permeability curves and the liquid saturation. Several experiments have been performed in the past, where the relative peremabilities of two phase flow through porous medium has been assessed as a function of the liquid saturation. Much of this research was performed within the oil and gas industry (Corey 1954, Brooks and Corey 1966) using other fluids than steam and water for the two phase flow. However, several experiments have been performed where water and steam are the two flowing phases, (Ambusso 1996, Li and Horne 2005, Mahiya 1999, O'Connor et al. 2002, Piquemal 1994, Satik 1998 Verma 1986). A summary of several such experiments can be found in literature (Gudjonsdottir et al. 2010, Horne et al. 2000). Most of the steam water experiments as well as experiments using other fluids show results where the relative permeabilities are nonlinear functions of the water saturation which is in contrary to what is expected from the theory. In such steam-water experiments the relative permeabilities are calculated from the measured flow rates, the phase conditions and the measured pressure gradients. The flow rates can be determined from the measured total flow and the steam quality gained from the enthalpy conservation relations as seen in Eqs (7) and (8). Furthermore, the calculated relative permabilities can be plotted as functions of measured saturation to gain a set of relative permeability curves. The main error factors in those experiments are capillary end effects as well as difficulties in determining the flow rates and the water saturation (Ambusso et al. 1996, Horne et al. 2000).

Another method used to determine the relative permeability curves is to calculate the water saturation from measured capillary pressure (Li and Horne 2005). The capillary pressure measurements may be an easier method for this purpose than measuring the water saturation. A method has also been developed where the relative permeabilities are calculated from resistivity data (Li 2010) making the assessment of the relative permeabilities easier than using the capillary pressure measurements. Experiments have been performed with that method for oil and water (Li 2008).

Previous experiments in this field have resulted in relative permeability curves that can be used for numerical simulations of geothermal reservoirs. Table 1 represents a few of curves that are used in the TOUGH2 simulator (Pruess et al. 1999). The Corey curve was gained with oil water experiments but has been widely used in geothermal applications. Several other relative permeability curves gained from experiments using other fluids than water are also used in geothermal applications. By using two different fluids for the two phases, the effect of phase transformation are excluded and the experiments can be conducted under isothermal conditions, whereas in flow of steam and water the temperature decreases with decreasing saturation pressure. Nevertheless those curves give valuable information for geothermal reservoir applications since there does not seem to be a one definite set of curves that can be used for all conditions in simulations.

Table 1: A number of relative permeability curves gained from previous measurements. (Pruess et al. 1999, Corey 1954, Verma 1986)

Name	k_{rw}	k_{rs}
X-Curve	S_{wn}	$1-S_{wn}$
Corey Curves	S_{wn}^4	$(1-S_{wn})^2(1-S_{wn}^2)$
Functions of Verma	S_{wn}^3	$1.259-1.7615S_{wn}+0.5089S_{wn}^2$

Effect of Flow Direction

As seen in Eqs (3) and (4) and Fig. 1 the direction of the fluid flow plays an important role in determining the relation between the mass flow conditions and the surrounding medium. A comparison for the horizontal and the vertical cases for a two phase flow through a porous medium can be performed for a given pressure interval (pressure decrease) Δp within the flow. By specifying the same pressure decrease for each flow case, horizontal and vertical, a ratio for the relative permeabilities is gained for each phase. It should be mentioned that although the pressure decrease is assumed to be the same for both cases, the pressure gradient is nevertheless different between them. That is because the pressure decline occurs over different length of the flow channel for each flow case. This comparison applies to one dimensional flow.

For a horizontal flow Eqs (3) and (4) become:

$$\frac{1}{k_{rw,hor}} = \frac{1}{k_{rs,hor}} \frac{x}{(1-x)} \frac{\nu_s}{\nu_w} \tag{10}$$

and correspondingly for a vertical flow:

$$\frac{1}{k_{rw,ver}} = \frac{1}{k_{rs,ver}} \frac{x}{(1-x)} \frac{\nu_s}{\nu_w} + \frac{gk(\rho_s-\rho_w)}{(1-x)\frac{\dot{m}_{tot}}{A}\nu_w} \tag{11}$$

Using the relations from Table 1 the relative permeabilities can be defined as functions of the water saturation as shown in Eqs (12) and (13) and inserted into Eqs (10) and (11).

$$k_{rw} = f(S_w) \tag{12}$$

$$k_{rs} = g(S_w) \tag{13}$$

Now the water saturation can be determined numerically from Eqs (10) and (11) and consequently the relative permeabilities can be plotted as functions of the steam quality only.

As seen in Eq. (11) the total mass flow per unit area needs to be estimated before getting any further with the vertical flow case. An estimation of the mass flow needs to be made where a real flow of geothermal fluid in a reservoir is considered. In fact, the vertical flow will behave more like the horizontal flow with increasing mass flow per unit area, as can be seen in Eq. (11).

Mass Flux for a Vertical Flow

To get an estimation of the mass flow per unit area for a vertical flow through a porous geothermal reservoir a definition of a convection cell is used and described in this section. Fig. 5 represents such a convective reservoir.

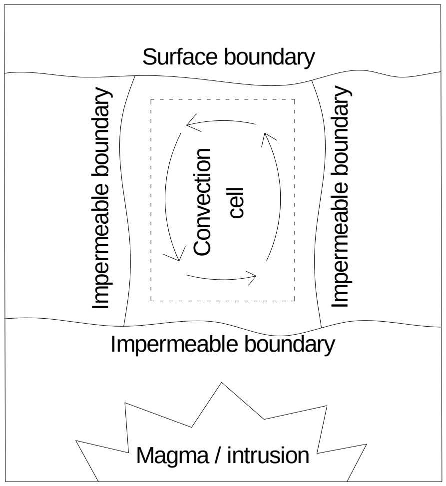


Figure 5: A convective geothermal reservoir where the reservoir fluid flows through the permeable reservoir. The fluid gains heat from the magma below and is cooled at the surface.

White (1967) described this idea of a convective geothermal reservoir and it is considered to be one of the main types of geothermal reservoirs (Axelsson 2008). Heat is conducted from the magma through an impermeable layer up to the impermeable boundary. There, the geothermal fluid flowing through the permeable reservoir is heated at the boundary with the conducted heat. That results in a temperature increase of the fluid and a resulting decrease in the fluids density. Since the fluid becomes lighter it tends to flow upwards due to the density difference. When reaching the surface of the reservoir it cools down again and its density increases causing it to flow downwards. This is an oversimplification of the reservoir but is used here to gain the mass flow per unit area needed for the calculations.

By looking at this convective reservoir and simplifying it to a streamline model, the forces acting on the fluid can be derived from the Darcy´s Law in Eq. (2). The three different forces acting on the fluid flow are due to resistance (F_v), gravity (F_g) and pressure gradient (*dp/dx)* and are shown in Eq. (14).

$$\vec{F}_v + \vec{F}_g + \vec{\nabla} p = \frac{\dot{m}}{A}\frac{\nu}{k} + \rho g + \frac{dp}{dx} = 0 \qquad (14)$$

A simplified convection cell is shown in Fig. 6 where the streamline of the fluid flowing through the reservoir together with the forces acting on the fluid are shown.

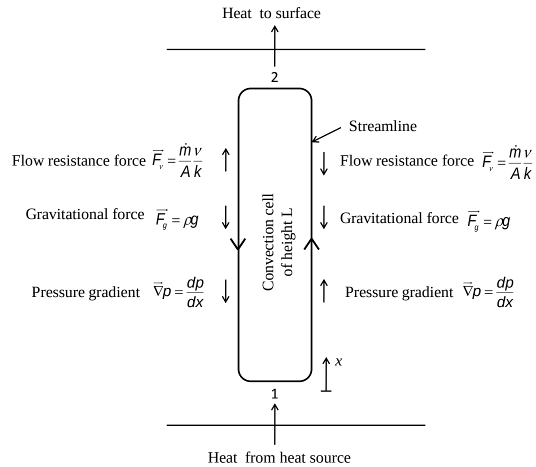


Figure 6: A convection cell and the corresponding forces acting on the fluid flowing in a streamline

By integrating over the whole convection cell with a length (or height) L the pressure gradient term cancels out, and Eq. (14) results in Eq. (15).

$$-\frac{\dot{m}\nu_1}{Ak}L - \frac{\dot{m}\nu_2}{Ak}L - \rho_1 g L + \rho_2 g L = 0 \qquad (15)$$

As a result, the mass flow per unit area becomes:

$$\frac{\dot{m}}{A} = \frac{(\rho_2 - \rho_1)gk}{(\nu_1 + \nu_2)} \qquad (16)$$

Eq. (16) can be used together with Eq. (11) to determine the relative permeabilities for a vertical flow. This analysis of the convective reservoir shown here is a pure estimation only and its purpose is to give a rough idea of the mass flow per unit area occurring in a convective geothermal reservoir. In real reservoirs the parameters are not constant over the whole convection cell and the absolute permeability and the pressure gradient vary within the flow domain. Also, the mass flow per unit area can vary with inflow and outflow section of the flow streamline and with different fluid velocities and flow channel area.

RESULTS FROM CALCULATIONS

As described in the previous section the relative permeabilities can be calculated for different steam qualities using the method described here. The steam qualities were calculated for two adiabatic cases, where the initial conditions are saturated water at absolute pressures 50 and 100 bar_a. The corresponding total enthalpy of the flow is therefore the saturated water enthalpy at that pressure. As the water flows through the surrounding permeable material its pressure decreases and the steam quality increases (the water flashes due to decreasing pressure). The water continues to flash until it reaches the end, where atmospheric condition are present (absolute pressure of 1 bar_a in both cases). Now, the pressure range (49 bar_a for one case and 99 bar_a for the other) is divided into smaller pressure intervals. The water saturation can therefore be deduced by inserting the corresponding relative permeability curve into Eqs (10) and (11). For the vertical case, the mass flows per unit area, as calculated with Eq. (16) are 0.004196 kg/s/m^2 for an initial condition of 50 bar$_a$ and 0.006405 kg/s/m^2 for that of 100 bar$_a$. The results of the calculations of the relative permabilities as functions of the steam quality are shown in Figures 7 to 12.

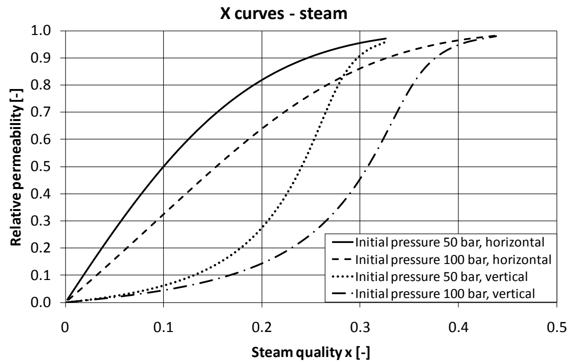


Figure 7: The relative permeabilities for steam as functions of steam quality when the X-curves are used

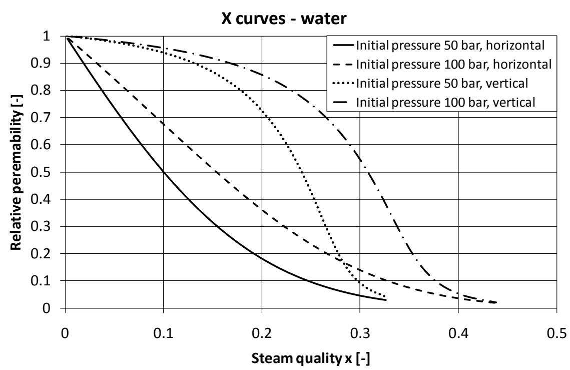


Figure 8: The relative permeabilities for water as functions of steam quality when the X-curves are used

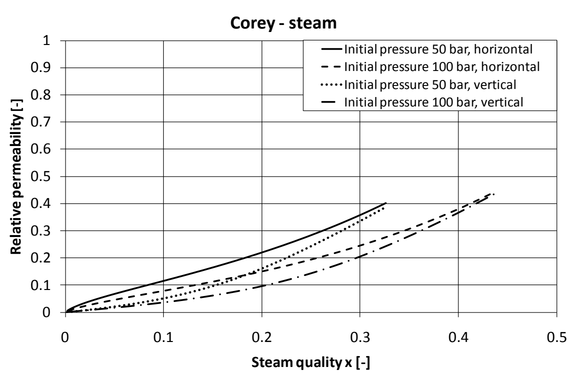


Figure 9: The relative permeabilities for steam as functions of steam quality when the Corey curves are used

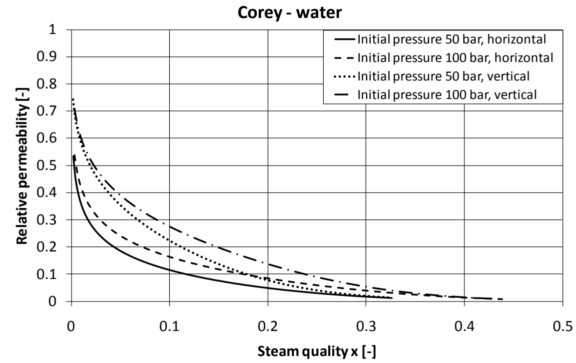


Figure 10: The relative permeabilities for water as functions of steam quality when the Corey curves are used

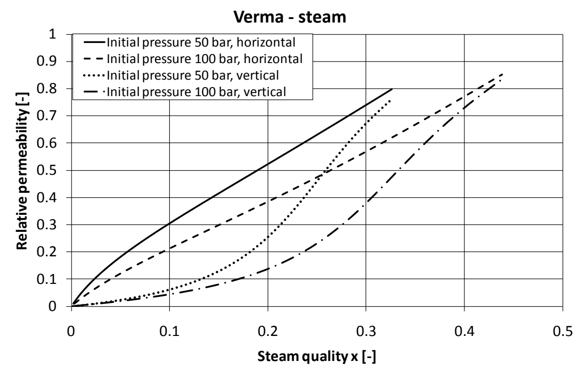


Figure 11: The relative permeabilities for steam as functions of steam quality when the Verma curves are used

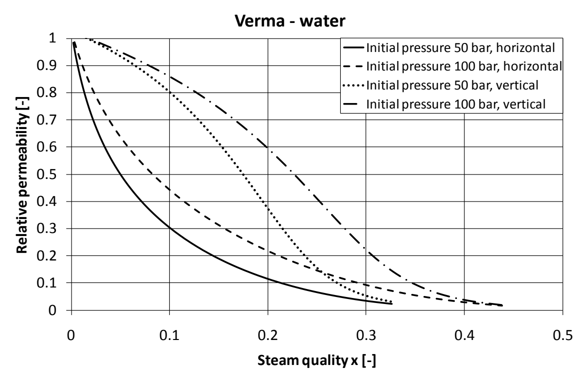


Figure 12: The relative permeabilities for water as functions of steam quality when the Verma curves are used

The graphs shown in Figs 7 to 12 indicate that the relative permeabilities vary with the flow direction and with the initial conditions when calculated for a given steam quality. For a given initial pressure (and corresponding total enthalpy) the pressures and the corresponding conditions are the same for the same values of the steam quality whereas the pressure differs and thereby the conditions change for the same steam quality if the initial pressure is different.

DISCUSSION

The comparison of the relative permeabilities for horizontal and a vertical two phase flow of water and steam shows, that the flow direction plays an important role in the determination of the relative permeabilities. This has been shown for the two flow cases where the conditions like the total enthalpy, steam quality, pressure and the resulting flow conditions (saturation temperature, viscosity and density) are the same for the two flow directions. The relative permeabilities differ in the way that for the water phase it is larger when the two phase fluid is flowing vertically and for the steam phase it is larger when the fluid is flowing horizontally. A higher initial pressure leads to an increase in the water relative permeability and a decrease in the steam relative permeability, for the same steam quality.

Based on these findings, it is questionable if the relative permeabilities can be considered a material constant, only depending on the water saturation as the state of the art relations assume. Thus, further research in this field is necessary where laboratory measurements should be performed to compare the relative permeabilites for different flow directions.

The results presented in this paper indicate the need for further research in the field of two phase flow in geothermal reservoirs, especially in comparing the fluid behavior between horizontal and vertical flow. This work is a theoretical basis for a Ph.D. project now underway at Reykjavik University and The University of Iceland. In 1980, Eliasson et al. conducted experiments where two phase flow of water and steam was injected into a vertical steel pipe (Eliasson et al. 1980). The results from these experiments showed that the fluid could flow upwards although the numerical value of the pressure gradient was less than the hydrostatic force. That is in contrary to the theoretical relations in Eqs (3) and (4). The experimental setup consists of a 4 m long steel pipe with 10" outer diameter has been installed on a wall bracket which allows rotation between horizontal and vertical positions. The mass flow rates of the phases and the pressure gradient of the two phase mixture will be measured as it flows through a porous rock inside the pipe. The objective of this experiment is to compare the horizontal and the vertical flow cases using the measured data. The final goal is then to use the data collected to improve relations describing two phase flow through porous media. Those improved relations can consequently be used to extend and enhance numerical reservoir models. The data collected from the measurements can be used for development of reservoir modeling tools, thus contributing towards a better understanding of the behavior of two phase flow of water and steam in geothermal reservoirs.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The direction relative to the gravitational pull of two phase flow of water and steam through porous medium may have a significant effect on the relative permeabilities.
2. The initial condition (the total enthalpy) of the fluid may also have effect on the relative permeabilities.
3. Relative permeabilities do not depend on material properties only.
4. Further research, especially a laboratory study of vertical flow is needed.
5. Improved empirical relations for the relative permeabilities gained from measurements may be used to enhance and extend geothermal reservoir modeling tools.

ACKNOWLEDGEMENTS

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