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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.

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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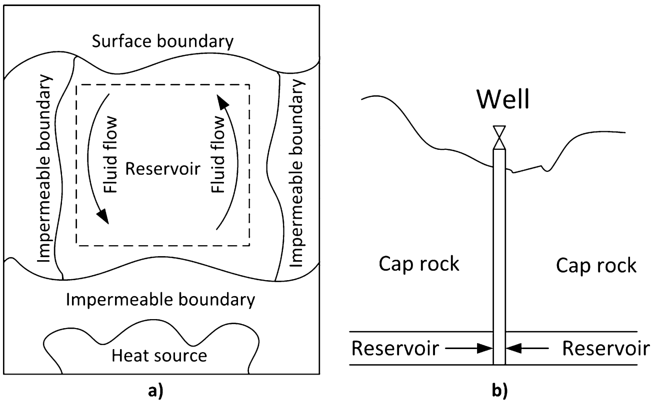

Fig. 1. (a) Convective system representing a convective volcanic geothermal reservoir. (b) A figure showing where a geothermal well is drilled into a reservoir, causing fluid to flow through the fractured reservoir into the well.

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.

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

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:

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

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):

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

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

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).

$$S_w = \frac{V_w}{V_w + V_s} \tag{5}$$

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).

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

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).

$$x = \frac{\dot{m}_s}{\dot{m}_s + \dot{m}_w} \tag{7}$$

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).

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

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

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).

$$k_{rw} = S_{wn}^4 \tag{10}$$

$$k_{rs} = (1 - S_{wn})^2(1 - S_{wn}^2) \quad (11)$$

$$k_{rw} = S_{wn}^3 \quad (12)$$

$$k_{rs} = 1.259 - 1.7615S_{wn} + 0.5089S_{wn}^2 \quad (13)$$

The curves in Eqs. (10)–(13) are shown as functions of the normalized saturation S_{wn} which defines the mobile region of the two phases. It is defined using the local water saturation and the residual saturations for water and steam, S_{rw} and S_{rs}, as shown in Eq. (14).

$$S_{wn} = \frac{S_w - S_{rw}}{1 - S_{rs} - S_{rw}} \quad (14)$$

When the local water saturation, S_w, is not known the relative permeabilities can be determined experimentally by using Eqs. (3) and (4). Then the mass flow needs to be measured directly as well as the fluid thermodynamic state (pressure) as well as the pressure gradient for the two phase flow through the porous sample with the known intrinsic permeability k. The relative permeability can then be determined from Eqs. (15) and (16).

$$k_{rw} = -\frac{\dot{m}_w \nu_w}{kA\vec{n} \cdot (\nabla p - \rho_w \vec{g})} \quad (15)$$

$$k_{rs} = -\frac{\dot{m}_s \nu_s}{kA\vec{n} \cdot (\nabla p - \rho_s \vec{g})} \quad (16)$$

In real applications like when fluid flows to wells in geothermal reservoirs, the water saturation used in Eqs. (8) and (9) and the pressure gradient used in Eqs. (15) and (16) are unknown quantities. For determining the relative permeabilities for such cases, the so called Shinohara method can be applied as described in the following section.

2.2. The Shinohara method

A method introduced by Shinohara (1978) is presented here, which enables the determination of the relative permeabilities of water and steam in a geothermal reservoir using production history and enthalpy measurements for a geothermal well drilled into the reservoir. Using Eqs. (15) and (16) (assuming one dimensional, horizontal flow neglecting gravity effect and rearranging terms) we get the following:

$$k_{rw} = -\frac{\dot{m}_w \nu_w}{kA\nabla p} = \frac{\dot{m}_w \nu_w}{Q^* \nu_s} \quad (17)$$

$$k_{rs} = -\frac{\dot{m}_s \nu_s}{kA\nabla p} = \frac{\dot{m}_s}{Q^*} \quad (18)$$

where:

$$Q^* = -\frac{kA\nabla p}{\nu_s} \quad (19)$$

The total mass flow, $\dot{m}_t$ of the two phase mixture according to Eqs. (3) and (4) is:

$$\begin{aligned} \dot{m}_t &= \dot{m}_w + \dot{m}_s = -kA\nabla p\left(\frac{k_{rw}}{\nu_w} + \frac{k_{rs}}{\nu_s}\right) \\ &= -kA\nabla p\frac{k_{rs}}{\nu_s}\left(\frac{k_{rw}}{\nu_w}\frac{\nu_s}{k_{rs}} + 1\right) = Q^* k_{rs}\left(\frac{\dot{m}_w}{\dot{m}_s} + 1\right) \end{aligned} \quad (20)$$

When applying the Shinohara method on the well data from a geothermal field, the total discharge $\dot{m}_t$ has to be known. Furthermore to determine the mass flow ratio $\dot{m}_w/\dot{m}_s$ at downhole conditions the enthalpy of the fluid h_t has to be known. The steam fraction of the two phase mixture is determined by Eq. (21).

$$x = \frac{h_t - h_w}{h_s - h_w} \quad (21)$$

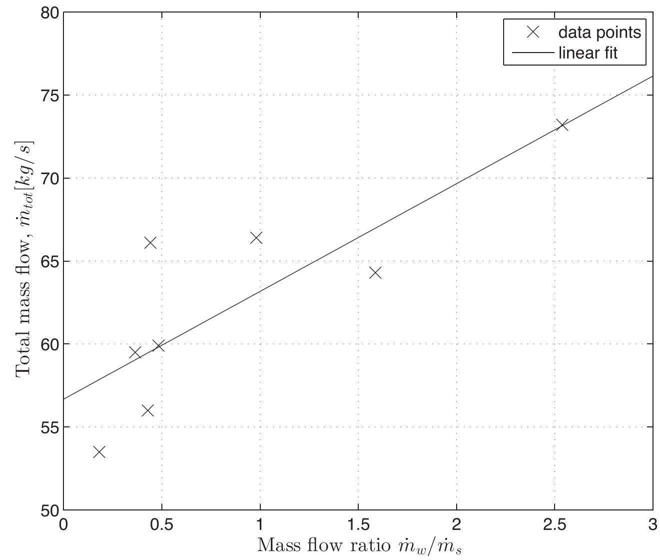

Fig. 2. Representation of how to determine the parameter Q^* for the Shinohara method for an arbitrary well. Q^* is the value where the regression line intercepts the y-axis.

where h_w and h_s are the saturation enthalpies of water and steam respectively. The steam fraction in the two phase reservoir from Eq. (21) can then be used to determine the mass flow of each phase in the reservoir to the well using the total flow rate $\dot{m}_t$ as seen in Eqs. (22) and (23).

$$\dot{m}_w = (1 - x)\dot{m}_t \quad (22)$$

$$\dot{m}_s = x\dot{m}_t \quad (23)$$

Now if $\dot{m}_w = 0$ then $k_{rs} = 1$ and according to Eq. (20) Q^* can be found by plotting $\dot{m}_t$ against $\dot{m}_w/\dot{m}_s$ and noting that Q^* is the intercept to y-axis of the regression line, as demonstrated in Fig. 2. To plot this figure for a production well, a production history of the total mass flow from the well as well as the ratio of the mass flows of the two phases have to be available.

The assumptions made for using the Shinohara method on a geothermal well to determine the relative permeabilities of the two phases in the reservoir, are the following (Shinohara, 1978):

- The pressure gradient is constant for a short time for each well.
- The product of permeability and flowing area, kA is constant for each well.
- Wellhead steam and water discharges are the same as downhole values, thus neglecting flashing of fluid in the wellbores.
- Fluid flows in the reservoir according to Darcy's law.
- Flashing in the reservoir is neglected.

Also, it is assumed that the flow in the two phase reservoir is horizontal, that is without effect from gravity in the momentum balance.

In reality, the two phase fluid will flash in the reservoir and in the well due to decreasing pressure and part of the liquid water will transform into steam. The downhole steam and water discharges are therefore different than at the wellhead. If the downhole properties (that is the temperature and therefore the fluid viscosity and density) are known, a correction to account for flashing in the well can be made. The downhole condition is used to estimate the steam fraction, x, at the bottom of the well at the given enthalpy h_t which is assumed to be constant in the well. Thus a better approximation for the mass flow ratio is gained for the downhole conditions based on the estimated steam fraction. By obtaining Q^* from Eq. (19) and a plot like is shown in Fig. 2 as well as the total flow and the mass

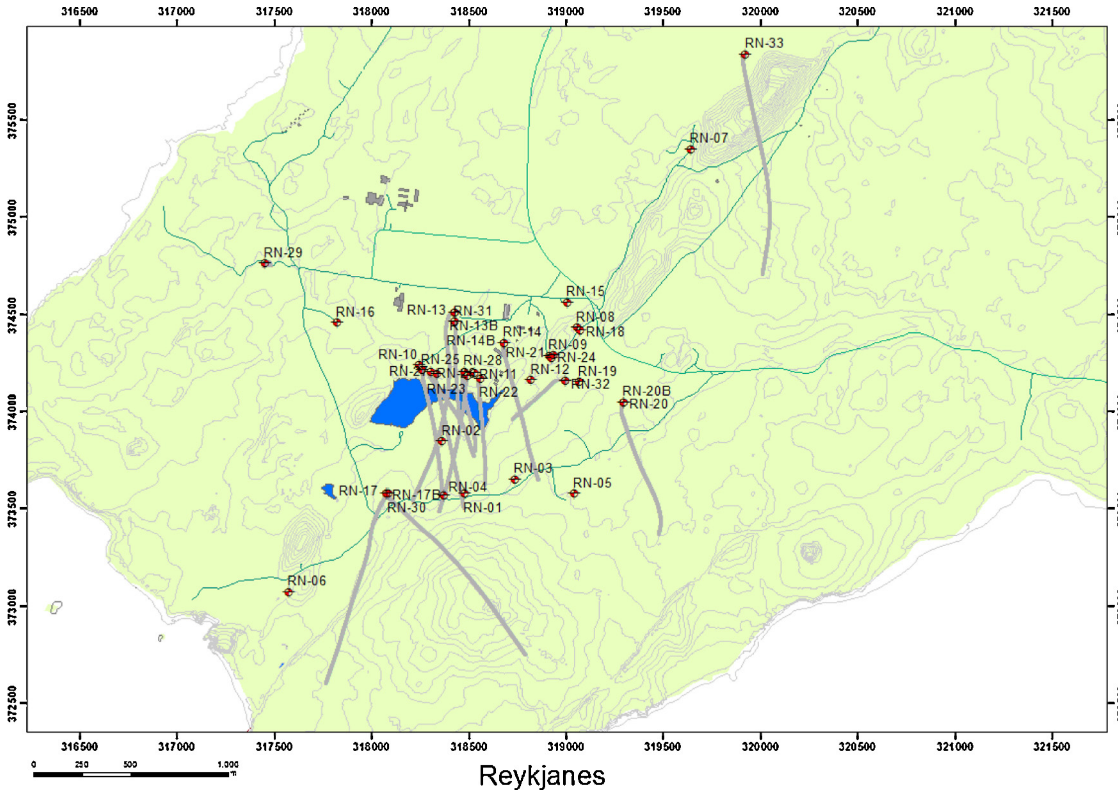

Fig. 3. A map of the Reykjanes geothermal field and the location of geothermal wells. Courtesy of HS Orka and ISOR.

fraction (which can be determined if the total enthalpy of the flow is known), k_{rw} and k_{rs} can be determined according to Eqs. (17) and (18).

For the laboratory data obtained by Chen (2005) the water saturations, S_w and the flowing water saturations $S_{w,f}$ were both known and the correlation in Eq. (24) was gained (Reyes et al., 2004).

$$S_w = 0.1152 \ln(S_{w,f}) + 0.8588 \quad (24)$$

By using Eq. (24) it is possible to estimate the local water saturation in Eq. (6) from the flowing water saturation and to compare the values to known relative permeability curves.

2.3. Field data

The Shinohara method was applied to data from three geothermal fields in Iceland. Data including mass flow, enthalpy, wellhead pressure and downhole temperature was collected for the fields at Reykjanes, Hellisheidi and Nesjavellir, which are described in the following sections. That data was used to calculate the relative permeabilities for the downhole reservoir flow. The enthalpy measurements were made with tracer analysis (Hirtz et al., 2001; Lovelock, 2001). The mass flows and enthalpies were known from the wellhead condition and downhole temperature was determined from temperature profiles from the wells. It is important for this method to use as accurate temperature value as possible since the relative permeabilities depend on the viscosities (see Eqs. (15) and (16)) which are highly temperature dependant (IAPWS, 2007). The results from the relative permeability calculations from field data were compared to measured values from laboratory experiments which are described in Section 2.4.

2.3.1. Reykjanes geothermal area

The Reykjanes geothermal area has been utilized for power production since 2005 and has 2 × 50 MW condensing turbines operating (Ragnarsson, 2010; Bertani, 2012). A map of the area is shown in Fig. 3. The wells that were used for these calculations were wells RN11, RN12, RN14, RN18, RN19, RN21, RN22, RN23, RN24 and RN27. Enthalpy and mass flow measurements used for this study are from years 2010–2012 where several enthalpy measurements were available for each well.

2.3.2. Hellisheidi geothermal area

The Hellisheidi geothermal area has been utilized for power production since 2006 and has 6 × 45 MW condensing turbines plus 1 × 33 MW low pressure condensing turbine operating (Ragnarsson, 2010; Bertani, 2012) as well as capacity of producing 133 MW of thermal energy (ReykjavikEnergy, 2014). A map of the area is shown in Fig. 4. The wells that were used for these calculations were wells HE06, HE07, HE09, HE12, HE15, HE17, HE18, HE19, HE29, HE30, HE47 and HE50. Enthalpy and mass flow measurements used for this study are from years 2008–2013 where several enthalpy measurements were available for each well (Gunnlaugsson, 2013a).

2.3.3. Nesjavellir geothermal area

The Nesjavellir geothermal area has been utilized for power production since 1998 and has 4 × 30 MW condensing turbines operating as well as capacity of producing 300 MW of thermal energy (Ragnarsson, 2010; Bertani, 2012). A map showing the area is shown in Fig. 5. The wells that were used for these calculations were wells NG06, NG10, NJ11, NJ13, NJ16, NJ21, NJ22 and NJ24. Enthalpy and mass flow measurements used for this study are from years 2000–2013 where several enthalpy measurements were available for each well (Gunnlaugsson, 2013b).

2.4. Laboratory measurements

The relative permeabilities from the field data were compared to data collected from laboratory experiments. In those experiments

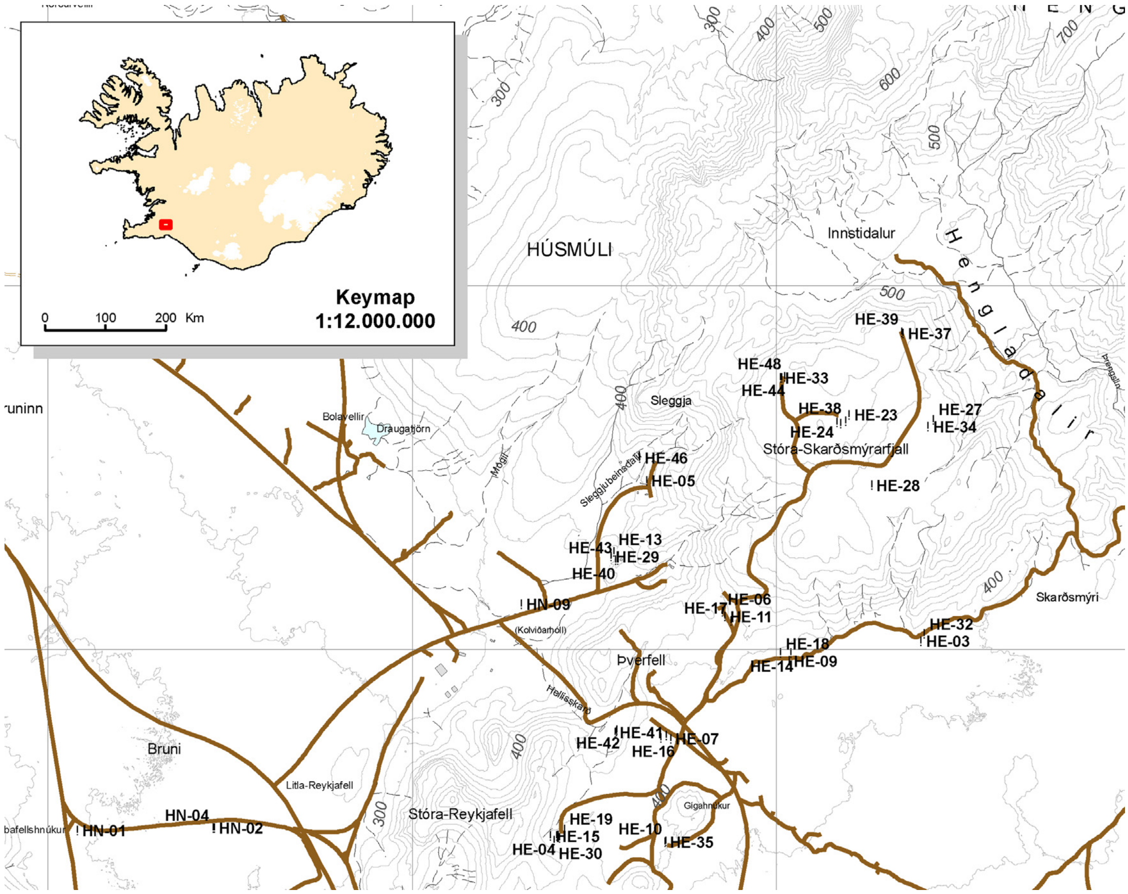

Fig. 4. A map of the Hellisheidi geothermal field and the location of geothermal wells. Courtesy of Reykjavik Energy and ISOR.

the relative permeabilities were determined for a two phase flow of water and steam flowing through porous material.

The device used for the experiment consisted of a steel pipe with 10 inch diameter and 4 m length. Two types of porous filling material were used, each of which had different intrinsic permeability. The fluid used for the experiments was of geothermal origin and was the separated water from Reykjanes Power Plant in Iceland. By using geothermal fluid instead of pure water, conditions of the geothermal reservoirs could be resembled to some extent. The experimental setup is shown in Fig. 6. A detailed description of the experiment is given by Gudjonsdottir et al. (2015).

The separated geothermal water was flashed before entering the inlet to the pipe thus creating a two phase mixture of water and steam. The enthalpy of the fluid was determined using the Lovelock method (Lovelock, 2001). By measuring the pressure at several locations in the flow channel (see Fig. 6) and the total mass flow, and knowing the total enthalpy (hence the steam fraction), the relative permeabilities could be calculated from Eqs. (15) and (16).

In all those calculations thermodynamic data from the IAPWS database was used (IAPWS, 2007) to determine the fluid thermodynamic properties. The geothermal fluid contains dissolved gases and minerals (Arnorsson et al., 2007) which might affect the thermodynamic properties of the fluid. However, in geothermal modelling, the properties of pure water are generally used as properties for the fluid (O'Sullivan et al., 2001).

3. Results

The relative permeability values from laboratory experiments calculated from Eqs. (15) and (16) were compared to the values from the field data calculated using the Shinohara method using Eqs. (17) and (18). The Q^* values as calculated when using the Shinohara method is shown in Table 1 for the Reykjanes wells, in Table 2 for the Hellisheidi wells and in Table 3 for the Nesjavellir wells. An example on how well data fits to a line as described previously with Fig. 2 is shown in Fig. 7. The data for wells that were used for the calculations indicate that two phase flow is occurring in the reservoir before entering the wells. The wells where two phase flow did not occur in the reservoir were not used since the relative permeability approach does not apply to single phase flow in the reservoir. The results for the relative permeabilities from the field data are plotted in Fig. 8 for Reykjanes, Fig. 9 for Hellisheidi, Fig. 10 for Nesjavellir and compared to experimental results in Fig. 11.

The flowing saturation for the fluid flow in the wells was also determined for the downhole condition using Eq. (6). The relative permeabilities are shown in Fig. 12 as functions of the flowing water saturation and as functions of the actual saturation as calculated

Table 1
The Q^* value for the Reykjanes wells.

Well	RN11	RN12	RN14	RN18	RN19	RN21	RN22	RN23	RN24	RN27
Q^*	101.5	46.7	25.2	27.6	20.6	39.0	40.0	45.0	63.1	51.2

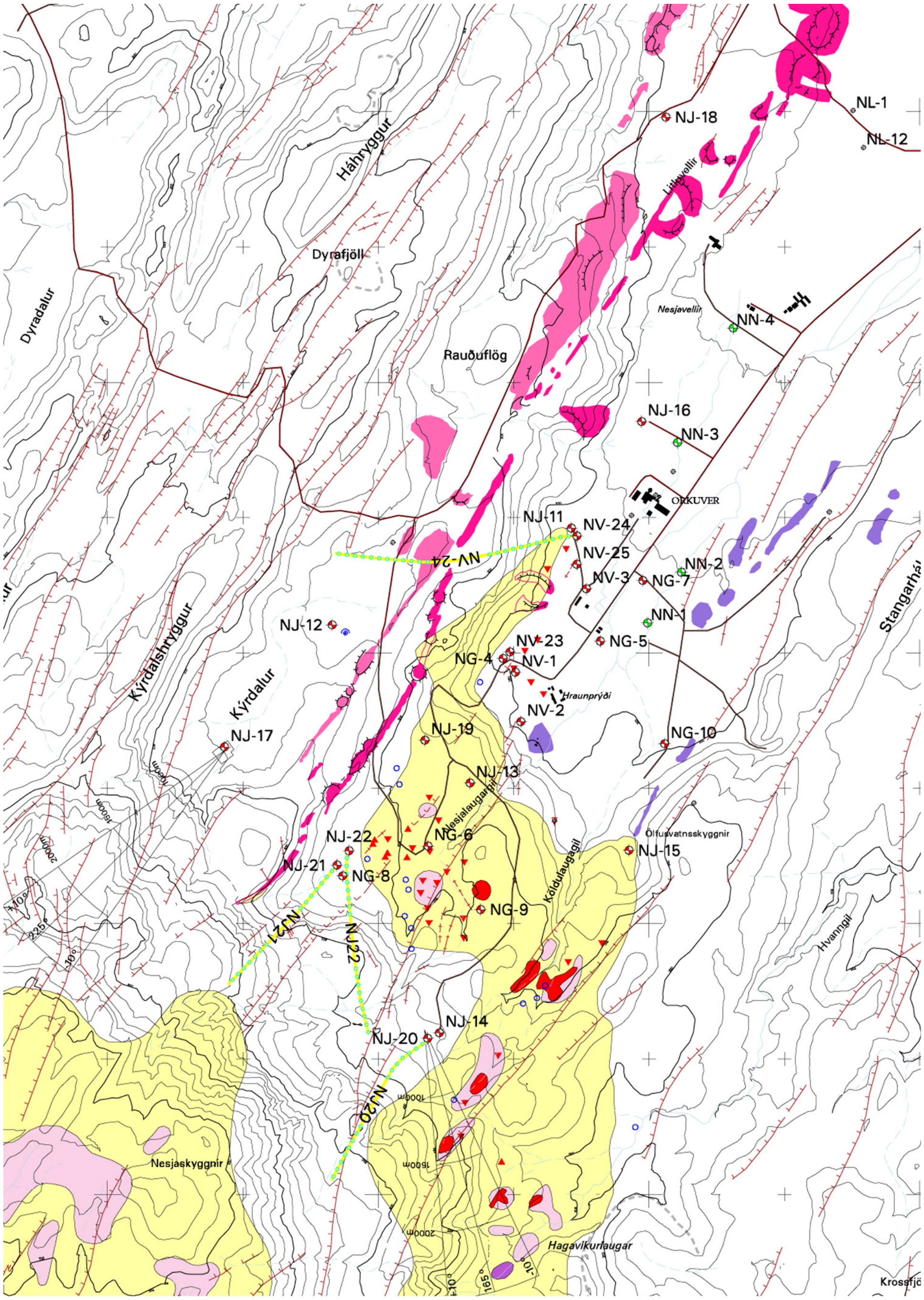

Fig. 5. A map showing the Nesjavellir geothermal field and the location of geothermal wells. Courtesy of Reykjavik Energy and ISOR.

Table 2
The Q^* value for the Hellisheidi wells.

Well	HE06	HE07	HE09	HE12	HE15	HE17	HE18	HE19	HE29	HE30	HE47	HE50
Q^*	25.6	61.3	10.6	32.2	25.1	56.7	32.4	101	20.1	53.3	48.5	40.3

Table 3
The Q^* value for the Nesjavellir wells.

Well	NG06	NG10	NJ11	NJ13	NJ16	NJ21	NJ22	NJ24
Q^*	26.0	17.5	40.5	47.7	23.7	15.0	37.4	50.1

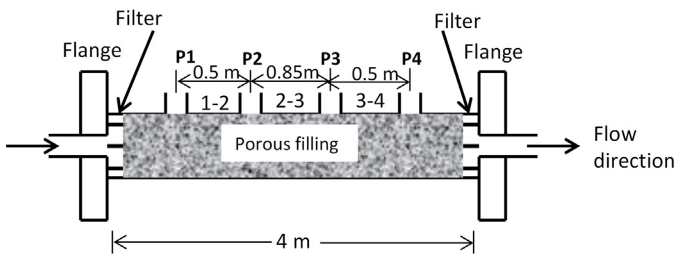

Fig. 6. Location of pressure sensors (labelled P1–P4) on the measurement device.

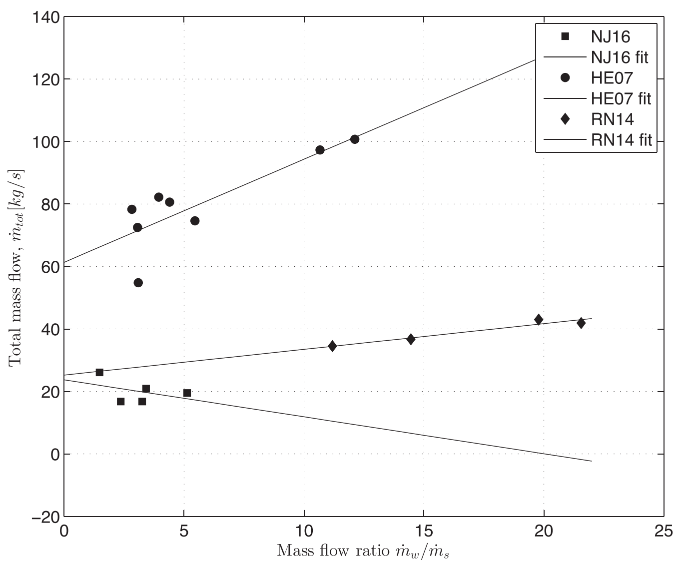

Fig. 7. An example showing how the data points fitted to a linear plot for deciding the Q^* value, which is the intercept of the linear fit to the y-axis.

using Eq. (24) in Fig. 13. In Fig. 13 the residual saturations (which define the mobile region of the phases) of the Verma and the Corey curves which are used for comparison are $S_{wr} = 0.1$ and $S_{sr} = 0.05$. The results from the field data were compared to the results from laboratory experiments as seen in Figs. 12 and 13.

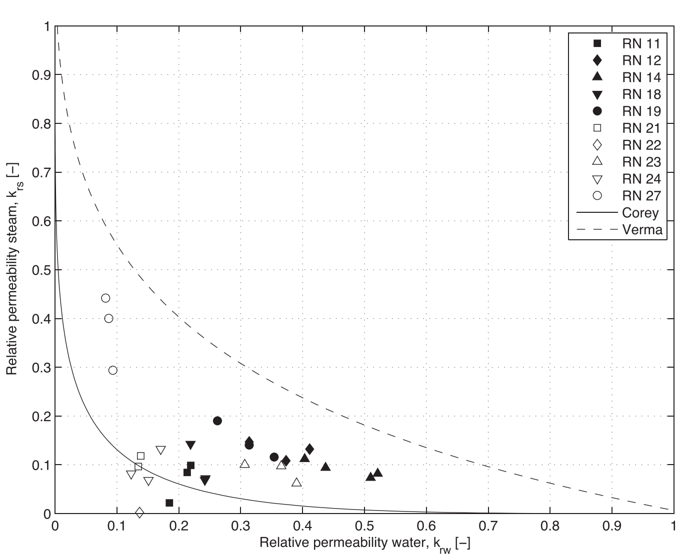

Fig. 8. Relative permeabilities from Reykjanes wells calculated with the Shinohara method as well as the Corey curve (Corey, 1954) and Functions of Verma (Verma, 1986).

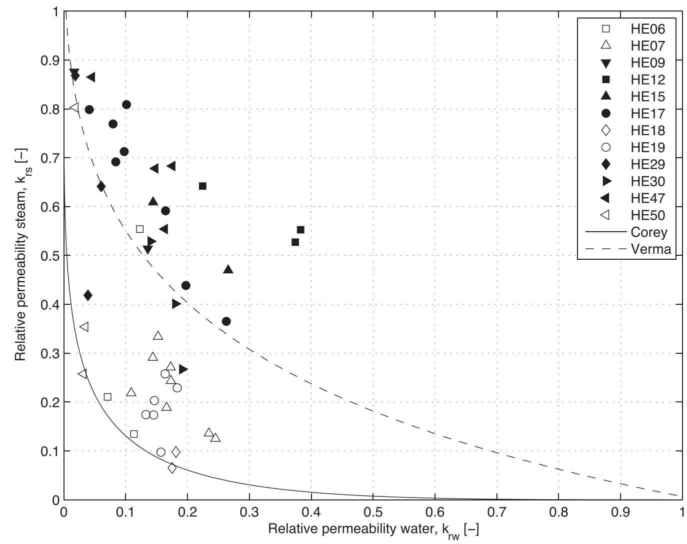

Fig. 9. Relative permeabilities from Hellisheidi wells calculated with the Shinohara method as well as the Corey curve (Corey, 1954) and Functions of Verma (Verma, 1986).

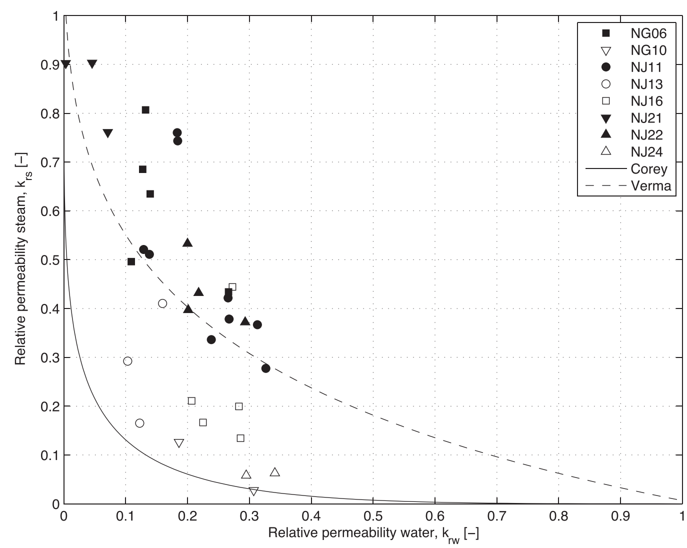

Fig. 10. Relative permeabilities from Nesjavellir wells calculated with the Shinohara method as well as the Corey curve (Corey, 1954) and Functions of Verma (Verma, 1986).

4. Discussion

Although the relative permeability values shown in Fig. 13 are scattered and no clear relative permeability curves can be seen from the data set, it is clear that the relative permeabilities show curvilinear behaviour to the water saturation. This applies both for the laboratory data as well as the field data. According to Fig. 11 the experimental data follows the Corey curve more closely than the field data does. The reason for this difference can be that the relative permeabilities from the experimental data represent two phase flow in porous matrix rather than in fractured material as the relative permeabilities from the field data do.

The intersection of the steam and the water relative permeabilities occurs for much lower flowing saturations than for the actual (local) water saturation, as a result from the underestimation of the flowing saturation compared to the local water saturation. This can be seen by comparing Fig. 12 to Fig. 13.

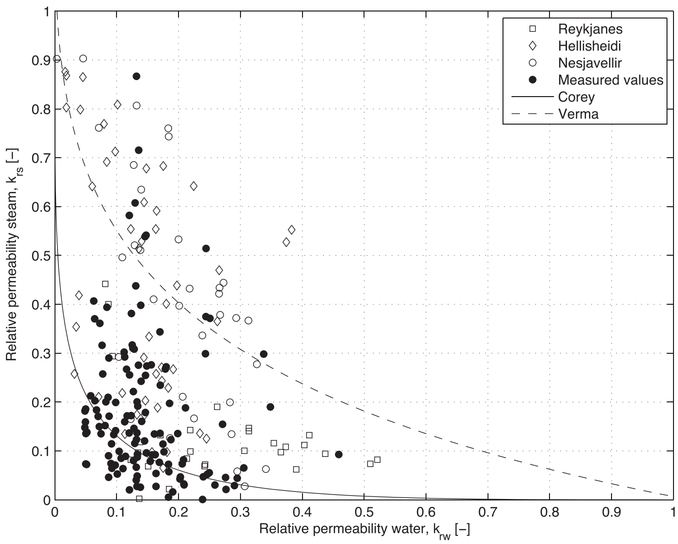

Fig. 11. Comparison of measured values from laboratory measurements and data from geothermal wells as well as the Corey curve (Corey, 1954) and Functions of Verma (Verma, 1986).

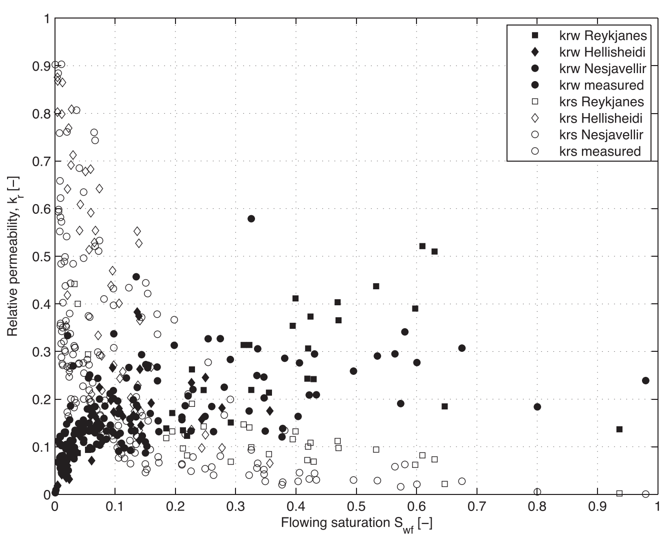

Fig. 12. The relative permeabilities as functions of the flowing saturation.

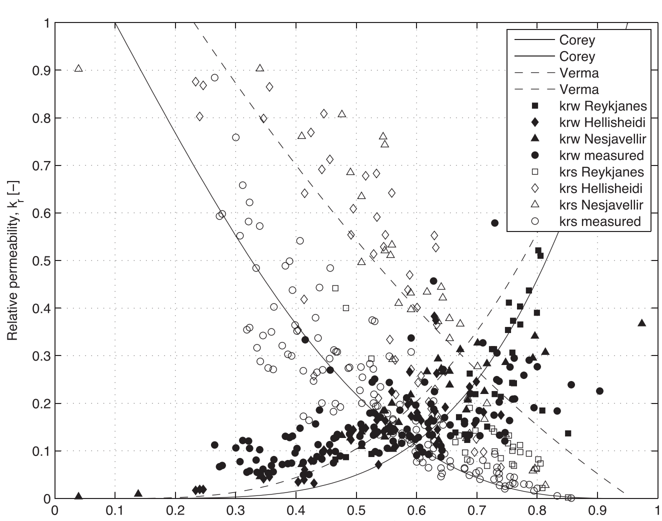

Fig. 13. The relative permeabilities as functions of the actual water saturation together with the Corey curve (Corey, 1954) and Functions of Verma (Verma, 1986).

The relative permeabilities from the Reykjanes wells shown in Fig. 8 show better correlation to known relative permeability curves than the Hellisheidi and Nesjavellir wells. Apparently the wells for Hellisheidi and Nesjavellir in Figs. 9 and 10 divide into two groups, one group following the Verma curve to some extent and the other group follows the Corey curve. The data used for the relative permeability calculations using the Shinohara method are measured values at the wellhead which represent a mixture of the fluid flow from different fractures in the reservoir. The well data therefore represents the well average rather than characteristic behaviour of each feedzone. This can account for the fact that wells in the same field can follow different relative permeability curves since each well can produce fluid from different formation than the neighbouring well in the field does.

5. Conclusions

Darcy's law and the relative permeability theory have been applied both to field data and to data from laboratory measurements. The purpose of this study was to use the Shinohara method to estimate relative permeabilities of reservoir fluid without information about the water saturation needed.

The following conclusions can be drawn from this study:

- The Shinohara method could be applied to data from the three geothermal fields which were subject to this paper, since all the relevant data was available.
- The relative permeabilities for water of both the laboratory and the field data show less interaction (show higher values) than the Corey curves do at low water saturation, but more interaction (show lower values) for higher water saturations.
- For the Hellisheidi and the Nesjavellir wells, the wells do follow different curves, indicating that flow to wells within the same geothermal reservoir can follow different relative permeability curves.
- When modelling geothermal reservoirs, a careful selection of the relative permeability curves has to be made, since according to the relative permeabilities calculated for the wells in Hellisheidi and Nesjavellir, the fluid flow within the same system can follow different relative permeability curves.
- The data used for the relative permeability calculations using the Shinohara method represent well average and therefore fluid flow from different formations. That can explain why wells in the same field can follow different relative permeability curves.

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