Permeability correction factor for fractures with permeable walls

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[1] Enhanced Geothermal Systems (EGS) are based on the premise that heat can be extracted from hot dry rocks located at significant depths by circulating fluid through fracture networks in the system. Heated fluid is recovered through production wells and the energy is extracted in a heat exchange chamber. There is much published research on flow through fractures, and many models have been developed to describe an effective permeability of a fracture or a fracture network. In these cases however, the walls of the fracture were modelled as being impermeable. In this paper, we have extended our previous work on fractures with permeable walls, and we introduce a correction factor to the equation that governs fracture permeability. The solution shows that the effective fracture permeability for fractures with permeable walls depends not only on the height of the channel, but also on the wall permeability and the wall Reynolds number of the fluid. We show that our solution reduces to the established solution when the fracture walls become impermeable. We also extend the discussion to cover the effective permeability of a system of fractures with permeable walls. **Citation:** Mohais, R., C. Xu, P. A. Dowd, and M. Hand (2012), Permeability correction factor for fractures with permeable walls, *Geophys. Res. Lett.*, *39*, L03403, doi:10.1029/2011GL050519.

1. Introduction

[2] In hot dry rock (HDR) geothermal energy extraction, a thermal reservoir (or EGS) is created by hydrofracturing high heat-producing granites located a few kilometres below the surface of the Earth. These rocks are usually impermeable to flow in their natural state. Hydrofracturing results in the opening of existing fractures as well as the propagation of new fractures which enable fluid percolation through the rock [*Phillips*, 1991]. Once the reservoir has been established, cold water can be introduced through injection wells, allowed to flow through the fracture network and be extracted at a much higher temperature at recovery wells.

[3] A fracture may be described as a 3-d channel in which obstacles of varying sizes may be irregularly distributed. Although various flow regimes are used to study fluid flow through fractures in an EGS [e.g., *Witherspoon and Long*, 1987], the model most widely used is that of flow between parallel impermeable plates. This model, usually applied to 1-d channels, neglects the non-linear terms in the flow equations, giving rise to the well-known cubic law which describes Poiseuille flow within a wide channel with smooth parallel plates as proportional to the cube of the aperture [*Sausse and Genter*, 2005].

[4] The appropriateness of the cubic law to describe flow within rock fractures has been debated [e.g., *Brown*, 1987, 1995], for although it has been useful in predicting fluid transport in fractures, it does not take into account many important characteristics. For example, flow experiments conducted on natural fractures in granite cores show significant deviations from the cubic law [*Abelin et al.*, 1985]. Experiments done by *Raven and Gale* [1985], in which fractures were subjected to a series of loading and unloading cycles, demonstrated that fracture aperture and flow rate deviated significantly from predicted behaviour. *Raven and Gale* [1985] attributed this behaviour to increasing contact area and flow path tortuosity in fractures with increases in normal stress. This view is supported by experimental and numerical studies previously conducted by *Iwai* [1976], who showed that fracture permeability is a function of contact area. Another possible cause of the differences between real and predicted flow in fractures may be the alteration of the properties of rock when subjected to temperature gradients. When Westerly granite is heated to high temperatures, porosity can increase by up to a factor of 3 [*Darot et al.*, 1992; *Heard and Page*, 1982]; permeability can decrease when an aqueous fluid flows down an applied temperature gradient; there is an increase in inter-crystalline crack density between 200°C and 300°C [*Atkinson et al.*, 1994; *Fredrich and Wong*, 1986]; and pores appear along existing cracks [*Vaughn et al.*, 1986].

[5] We endorse the view that flow through a fracture bounded by granular rock walls can be modelled using flow through a channel, however we posit that the walls of the channel are not smooth and they may contain cracks and fissures of varying sizes arising from the initial hydrofracturing process. Furthermore, when cool water enters the propagated fracture, the walls will contract, leading to the creation of more wall cracks [*Christopher and Armstead*, 1978]. The channel walls may therefore be considered to have low permeability. Flow experiments have shown conclusively that when the walls of a channel are comprised of permeable material, then slip boundary conditions should be incorporated in the flow model [*Beavers et al.*, 1970]. Further, imaging studies have revealed that a transition layer, independent of the flow Reynolds number, exists between a porous layer and an overlying fluid layer [*Goharzadeh et al.*, 2005]. In light of these studies, we have addressed the difference between theoretical and experimental flows by introducing the analytical limitation imposed by using no-slip conditions at the fracture walls [*Mohais et al.*, 2011].

[6] Earlier studies on Poiseuille flow in a fluid overlying a porous medium used a two-layer approach in which the governing equations in the separate Newtonian fluid and

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Darcy porous regions were coupled by appropriate interfacial boundary conditions [*Chang et al.*, 2006]. The focus of these studies differs from the work that we present here; *Chang et al.* [2006] studied the instability of the flow and *Liu et al.* [2006] considered the same configuration with Darcy's law replaced by Brinkman's law. The physical basis for using Brinkman's law in the work by *Liu et al.* [2006] is unclear [*Auriault*, 2009], as *Liu et al.* [2006] acknowledge. This does not diminish the intention of *Liu et al.* [2006]; studies have shown that wall permeability can significantly destabilise flows in channels with permeable walls compared to those with impermeable walls [*Tilton and Cortelezzi*, 2006].

[7] *Berman* [1953] was the first to investigate the effects of wall porosity in a channel, followed by *Terrill and Shrestha* [1965], whose study included walls of different permeability. However, Beavers and Joseph were the first to account for the material properties of permeable walls in fluid flow problems [*Beavers and Joseph*, 1967]. Beavers and Joseph hypothesized that when a viscous fluid in a channel flows parallel to the permeable medium, the effects of viscous shear propagate across the interface and result in a thin layer of streamwise moving fluid lying just below the permeable layer. This fluid layer is pulled along by the free fluid external to the permeable layer. The tangential component the free fluid velocity, u_f, at the boundary of the permeable material is considerably higher than the mean filter velocity (seepage velocity), u_m, within the permeable body. This is the Beavers-Joseph slip flow hypothesis which is valid for common viscous liquids at low Reynolds number [*Neale and Nader*, 1974]. Slip generally results from fluid properties, interactions between the fluid and the wall, the shear rate at the wall and surface roughness (for liquid flows) [*Ligrani et al.*, 2010]. The slip boundary condition [*Beavers et al.*, 1970] (Figure 1) can be defined as

$$\frac{du_f}{dy} = \frac{\alpha}{\sqrt{k}}\left(u_f - u_m\right) \quad (1)$$

[8] This condition is evaluated at a boundary limit point from the exterior of the fluid. Here k is the wall permeability and α is a dimensionless quantity that characterizes the structure of the permeable material within the boundary region; α can be considered as a calibrating factor for different materials. Early experiments by *Beavers and Joseph* [1967] provided qualitative support of the slip boundary conditions; quantitative verification emerged later [*Beavers et al.*, 1970]. Using two main materials, foametal and aloxite, *Beavers et al.* [1970] determined a range of values for α in flow experiments using channels of various widths and porous media of various permeabilities. Foametal has a cellular structure consisting of irregularly shaped interconnected pores; the experimental value of α ranged from 0.78 – 4.0 for average pore sizes of 0.016 – 0.045 inches. Aloxite is made from fused crystalline aluminium oxide grains held together with a ceramic bond; the experimental value of α is as low as 0.1. Although α is independent of the fluid viscosity, *Sahraoui and Kaviany* [1992] showed that it is dependent on the flow direction at the interface, Reynolds number and extent of clear fluid at the interface.

[9] The notion of permeable walls has been applied to a limited extent to fractures. *Berkowitz* [1989] incorporated Brinkman's slip boundary conditions in 1-d modelling of fractures with permeable walls. He showed that the omission of slip leads to underestimation of volumetric flow by as much as 19%. *Crandall et al.* [2010] performed numerical computations of flow within open fractures and confined fractures surrounded by a permeable medium using an interface condition and found an increase in flow volume of about 10%. However, apart from these two cases, there has been very little attention to applying slip boundary conditions to flow within fractures. *Mohais et al.* [2011] present an analytical solution, incorporating the Beavers-Joseph slip boundary conditions, which uses a similarity solution followed by a perturbation expansion to determine flow and heat transfer for coupled fluid flow and heat transfer in a channel with permeable walls. We have shown that the axial velocity within the channel is affected by α, k and the height of the channel, h, and the temperature distribution and temperature gradient is affected by k. Based on this model, we now extend our analysis to study the equivalent permeability of a single fracture and of a system of parallel fractures.

2. Analysis

[10] We highlight the main details of the formulation as given by *Mohais et al.* [2011]. We consider a fractured reservoir located at 3–5 kilometres below the surface. We introduce pressurized water of density, ρ, and viscosity, η, into a single fracture. As the water flows through the fracture, it is heated by the surrounding rock (≈200°C) of which the reservoir is comprised. The heated water is extracted via a recovery well located some distance away from the injection well. We neglect end effects at the entry and exit points and model the fracture as a channel with horizontal parallel walls. We define the distance between the channel walls to be *2h*. Assume that both walls have a low permeability, k. The effect of permeability enters through the slip boundary conditions at $y = \pm h$. We define the non-dimensional distance $y^* = \frac{y}{h}$. We write the stream function in terms of the entrance velocity, u_0, a constant wall velocity, v_w, and a similarity function, f, according to *Terrill and Shrestha* [1965], $\psi(x, y^*) = [hu_0 - v_w x] f(y^*)$. The velocity components become

$$u(x, y^*) = \left(u_0 - \frac{v_w x}{h}\right) f'(y^*); \quad v(y^*) = v_w f(y^*) \quad (2)$$

We define a wall Reynolds number by, $Re_w = \frac{v_w h}{\nu}$, where $\nu = \frac{\eta}{\rho}$. The Navier-Stokes equations reduce to:

$$-\frac{1}{\rho}\frac{\partial P}{\partial x} = \left(u_0 - \frac{v_w x}{h}\right)\left(\frac{-v_w}{h}\left((f')^2 - ff''\right) - \frac{\nu}{h^2} f'''\right) \quad (3)$$

$$\frac{v_w^2}{h} ff' - \frac{\nu v_w}{h^2} f'' = -\frac{1}{\rho h}\frac{\partial P}{\partial y^*} \quad (4)$$

Equation (4) is a function of y^* only and so we have $\frac{\partial^2 P}{\partial y^* \partial x} = 0$. This is a useful result which can be used in equation (3) to give after integration

$$f''' + Re_w\left(-ff'' + (f')^2\right) = C \quad (5)$$

Here C is a constant of integration. This third order non-linear ordinary differential equation together with the boundary conditions will yield an exact solution for the equations of

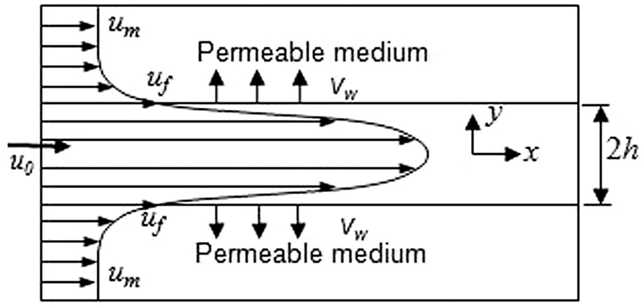

Figure 1. Velocity profile for coupled parallel flows within a channel and bounding porous medium according to the slip flow hypothesis of Beavers and Joseph [after *Beavers and Joseph*, 1967; *Neale and Nadar*, 1974].

motion and the continuity equation. We have expanded the function $f(y^*)$ and the constant of integration using the wall Reynolds number, $f(y^*) = f_0(y^*) + f_1(y^*)Re_w + f_2(y^*) Re_w^2 + \ldots + f_n(y^*)Re_w^n + \ldots$, and, $C = c_0 + c_1 Re_w + c_2 Re_w^2 + \ldots + c_n Re_w^n + \ldots$. Channel symmetry is used to determine the boundary conditions:

$$u(x,1) = -\frac{\sqrt{k}}{\alpha h}\frac{\partial u}{\partial y^*} = -\phi\frac{\partial u}{\partial y^*}; \quad \frac{\partial u}{\partial y^*}\Big|_{y^*=0} = 0;$$
$$v(x,0) = 0; \quad v(x,1) = v_w \tag{6}$$

The slip coefficient is defined as, $\phi = \frac{\sqrt{k}}{\alpha h}$. We obtained after solving up to the first order:

$$f_0 = y^{*3}\left(\frac{-1}{2(1+3\phi)}\right) + y^*\left(\frac{3+6\phi}{2+6\phi}\right) \tag{7}$$

$$f_1 = -\frac{y^{*7}}{840}\left(\frac{3}{(1+3\phi)^2}\right) + y^{*3}\left(\frac{3(7\phi+1)}{280(3\phi+1)^3}\right) + y^*\left(\frac{1}{280(1+3\phi)^2} - \frac{3(7\phi+1)}{280(1+3\phi)^3}\right) \tag{8}$$

$$c_0 = \frac{-3}{1+3\phi}; \quad c_1 = \frac{9}{140(1+3\phi)^3}(7\phi+1) + \left(\frac{3+6\phi}{2+6\phi}\right)^2 \tag{9}$$

Using the analysis of the channel flow problem proposed by *Terrill and Shrestha* [1965], which is similar to ours except for the incorporation of the Beavers-Joseph slip boundary conditions at the walls, the coefficients are identical for $\phi = 0$. This provides validation of our solution for the limiting case of no-slip at the walls. Also, as we have limited our study to walls of low permeability, we have conducted our analysis up to the first order only. Using equations (3) and (5), we can now write,

$$\frac{h^2}{\eta}\frac{\partial P}{\partial x} = \left(u_0 - \frac{v_w x}{h}\right)C \tag{10}$$

Using equations (2) and (10), we get,

$$u = \frac{h^2}{\eta C}\frac{\partial P}{\partial x}f'(y^*) \tag{11}$$

[11] For the case of impermeable walls,

$$f'(y^*)|_{\phi=0,Re_w=0} = -\frac{-3y^{*2}}{2} + \frac{3}{2}; \quad C|_{\phi=0,Re_w=0} = -3 \tag{12}$$

[12] Substituting equation (12) in equation (11) for impermeable walls we get, $u = -\frac{1}{\eta}\frac{\partial P}{\partial x}\left(-\frac{y^2}{2} + \frac{h^2}{2}\right)$. The total volumetric flux though the fracture with impermeable walls, Q_{imp}, for a width w in the y-direction [*Zimmerman and Bodvarsson*, 1996; *Brown et al.*, 1995], follows the well-known result, $Q_{imp} = 2w\int_0^h u dy = -\frac{wh_f^3}{12\eta}\frac{\partial P}{\partial x}$. where $h_f = 2h$. In the present case however, where slip velocity is considered at the permeable walls, the resulting volumetric flux, Q_{perm} is:

$$Q_{perm} = \frac{2wh^3}{C\eta}\frac{\partial P}{\partial x} = \frac{wh_f^3}{4C\eta}\frac{\partial P}{\partial x} \tag{13}$$

[13] From Darcy's law, for 1-d flow through porous media, for a cross-sectional area $A = wh$, volumetric flux is given by $Q = \frac{-kA}{\eta}\frac{\partial P}{\partial x}$ [*Zimmerman and Bodvarsson*, 1996]. For a fracture with impermeable walls, the equivalent permeability of the fracture, k_f, is represented by $k_f = \frac{h_f^2}{12}$. The present analysis for fractures with permeable walls gives rise to an equivalent permeability, k_{fp} of $k_{fp} = \frac{-h_f^2}{4C}$, where C is given by,

$$C = \frac{-3}{1+3\phi} + Re_w\left(\frac{9}{140(1+3\phi)^3}(7\phi+1) + \left(\frac{3+6\phi}{2+6\phi}\right)^2\right) \tag{14}$$

[14] We therefore propose an updated equation for the equivalent permeability of a fracture with parallel walls through the introduction of a correction factor, $\left(\frac{-3}{C}\right)$, as,

$$k_{fracture} = \frac{h_f^2}{12}\left(\frac{-3}{C}\right) \tag{15}$$

[15] Equation (15) can be used to evaluate the effective permeability of parallel-walled fractures with permeable or impermeable walls. For permeable-walled fractures, the equivalent fracture permeability for small Reynolds numbers depends on Re_w and ϕ. Once these parameters are determined, this equation can be used in a similar manner to *Berkowitz* [1989], to determine estimation errors in the evaluation of permeability of a given fracture.

[16] Figure 2 shows the variation of $-\frac{3}{C}$ with ϕ for $\alpha = 0.1$, $Re_w = 0.004$ and $h = 0.00001m$. The plot shows a range of ϕ for wall permeability values between 10^{-15} and $10^{-18}m^2$. The permeability correction factor, $-\frac{3}{C}$, for a fracture with wall permeabilities within this range varies from about 1.01 to 1.19.

[17] *Berkowitz* [1989] considers the root of the ratio of the wall viscosity to the fluid viscosity to be equivalent to the Beavers-Joseph α value. Using an α value of 0.1, an aperture of $10^{-5}m$ and $k = 10^{-15}m^2$, he estimated a difference in effective fracture permeability of 19%. On changing the value of k to $10^{-16}m^2$, the difference was 6%, and for an aperture of $0.0001m$ and $k = 10^{-15}m^2$, the difference was

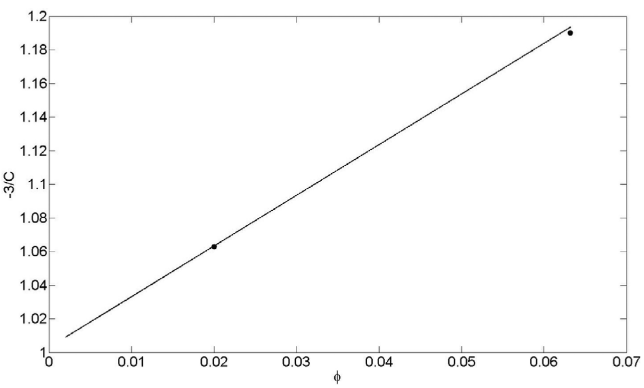

Figure 2. The variation of the correction factor, $-\frac{3}{C}$, with ϕ, for permeability values between $10^{-15}m^2$ and $10^{-18}m^2$, h = 0.00001m, Re_w = 0.004, α = 0.1. We have estimated ϕ values that correspond to *Berkowitz* [1989] solution; the squares show two values of percentage error evaluated by Berkowitz.

2%. We can use our present model to determine the differences in the effective fracture permeability using identical values to *Berkowitz* [1989]. The *Berkowitz* [1989] α value is stricto sensu only an approximation to our Beavers-Joseph α value and our model includes a wall Reynolds number for the first order term of the solution. Using a low wall Reynolds number of 0.004, we found that the effective fracture permeability varies by 19% (see Figure 2), 6% (see Figure 2) and 5% respectively for the Berkowitz cases. The Reynolds number was determined using estimates of velocity and viscosity values of flow through fractures from *Rasouli and Hosseinian* [2011].

[18] *Crandall et al.* [2010] used Fluent to determine a numerical solution for flow in fractures within a permeable matrix. Using an aperture of h = 240 μm and $k = 2 \times 10^{-16}m^2$, they determined a difference in effective permeability of 9.7%, and for $k = 2 \times 10^{-12}m^2$, a value of 14.7%. The critical point to note is that in the *Berkowitz* [1989] and the *Crandall et al.* [2010] studies, as well as ours, the effective permeability of permeable-walled fractures, especially narrow fractures in a moderately permeable matrix, can be underestimated. We can further state that for a system of parallel fractures with permeable walls, separated by a distance l, assuming no interactions between the flow regimes of different fractures, equivalent permeability of the system, k_{fps}, can be written as: $k_{fps} = \frac{-h_f^2}{4lC}$.

3. Discussion

[19] Successful generation of geothermal energy from HDR depends on the initial hydrofracturing process converting an impermeable mass of hot rock to a permeable thermal reservoir. The fractures that result from hydrofracturing are commonly considered to be channels with impermeable walls. The simple cubic law is widely used to describe the flow through these channels. *Brown et al.* [1995] considers the equation to be oversimplified and unable to account for realistic fractures. *Romm* [1966] performed laboratory studies on flow within fractures that were fine ($10 - 100$ μm) and superfine ($0.25 - 4.3$ μm) and found that the cubic law holds for fractures with apertures down to $0.2\mu m$. However, in direct studies of hydraulic fractures, *Warpinski* [1985] observed that they are not the smooth, parallel plates that they are usually modelled to be, rather, that they possess surface roughness and waviness, en echelon fracturing and multiple offsets. For narrow fractures, the surface textures in fractures are seen as large scale waviness, whereas, in wide fractures, the walls of the fracture appear rough. *Raven and Gale* [1985] have shown that the flow rate for rough fractures at high normal stress cannot be adequately represented by a simple parallel plate model.

[20] We have previously presented an analytical solution for the velocity through a 2–d channel with permeable walls where we incorporated slip boundary conditions at the walls of the fracture using the Beavers-Joseph boundary conditions and retained the non-linear terms in the solution of the Navier-Stokes equations [*Mohais et al.*, 2011]. The solution is valid for small Reynolds numbers. The solution showed that the velocity profiles are affected by channel width, wall permeability and α. Based on this solution, we now present the idea of effective permeability of a fracture with permeable walls.

[21] *Berkowitz* [1989] provided an analytical solution for fractures with permeable walls using the Brinkman solution; in his solution, he attributes the root of the ratio of the apparent viscosity in the permeable wall, to that in the free fluid, to be equivalent to the α term in the Beavers-Joseph analysis. *Taylor* [1971] commented that the Beavers-Joseph condition can be deduced as a consequence of the Brinkman equation, although he did not use these labels. The idea was further developed by *Neale and Nader* [1974].

[22] *Nield* [2009] discussed the use of the Brinkman equation versus the Beavers-Joseph condition. He opined that many people believe that the Brinkman equation is precise, rather than semi-empirical, as is the Beavers-Joseph boundary condition. He further points out that in a single domain treatment where the momentum transfer across the interface is not the primary concern, the Darcy equation should be used together with the Beavers-Joseph boundary condition. This view was supported to a degree by *Chandesris and Jamet* [2007], who state that although the Brinkman equation is important in describing the boundary layer of a porous region, it cannot be used to predict the effective viscosity of a permeable layer. They state however, that the Beavers-Joseph condition also has limitations; for instance, the exact location of the interface is necessary to define α and this is an inherent difficulty.

[23] Based on these findings, and as our current analysis is concerned primarily with flow in the channel region, rather than focusing on an apparent viscosity in the permeable wall, or a stress jump at the boundary of the free fluid region, we chose to use the Beavers-Joseph boundary condition to arrive at a solution within the channel. Nevertheless, our method produced results in line with the analytical solution of *Berkowitz* [1989] and the numerical solution of *Crandall et al.* [2010]. We also introduced a correction factor, which has the potential to modify the solutions of permeabilities of fractures with permeable walls, once the parameter α is experimentally determined.

4. Conclusions

[24] We have extended our previous analysis [*Mohais et al.*, 2011] to determine the effective permeability of a

fracture with permeable walls. The present solution shows that the effective fracture permeability can be expressed as a function of the wall Reynolds number, the height of the channel, the wall permeability and the non-dimensional α term. We have introduced a new equation for permeability of fractures through the introduction of a correction factor for fractures with permeable walls. We have also determined an expression for a system of parallel fractures separated by a distance *l*. We observe that the solution reduces to that of the effective permeability of a fracture with impermeable walls (when ϕ and Re vanish).

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References

Abelin, H., I. Neretnieks, S. Tunbrant, and L. Moreno (1985), Final report on the migration in a single fracture: Experimental results and evaluations, *Tech. Rep. 85–03*, Nucl. Fuel Safety Proj., Stockholm.

Atkinson, B. K., D. MacDonald, and P. G. Meredith (1994), Acoustic response and fracture mechanics of granite subjected to thermal and stress cycling experiments, in *Proceedings of the 3rd International Conference on Acoustic Emission and Microseismic activity*, edited by H. R. Hardy and F. W. Leighton, pp. 5–18, Trans. Tech. Publ., Clausthal, Germany.

Auriault, J. L. (2009), On the domain of validity of Brinkman's equation, *Transp. Porous Media*, *79*, 215–223.

Beavers, G. S., and D. D. Joseph (1967), Boundary conditions at a naturally permeable wall, *J. Fluid Mech.*, *30*, 197–207.

Beavers, G. S., E. M. Sparrow, and R. A. Magnuson (1970), Experiments on coupled parallel flows in a channel and bounding porous medium, *ASME J. Basic Eng.*, *92*, 843–848.

Berkowitz, B. (1989), Boundary conditions along permeable fracture walls: Influence on flow and conductivity, *Water Resour. Res.*, *25*, 1919–1922.

Berman, A. S. (1953), Laminar flow in channels with porous walls, *J. Appl. Phys.*, *24*, 1232–1235.

Brown, S. R. (1987), Fluid flow through rock joints: The effect of surface roughness, *J. Geophys. Res.*, *92*, 1337–1347.

Brown, S. R. (1995), Simple mathematical model of a rough fracture, *J. Geophys. Res.*, *100*, 5941–5952.

Brown, S. R., H. W. Stockman, and S. J. Reeves (1995), Applicability of Reynolds equation for modelling fluid flow between rough surfaces, *Geophys. Res. Lett.*, *22*, 2537–2540.

Chandesris, M., and D. Jamet (2007), Boundary conditions at a fluid-porous interface, *Int. J. Heat Mass Transfer*, *50*, 3422–3436.

Chang, M. H., F. Chen, and B. Straughan (2006), Instability of Poiseuille flow in a fluid overlying a porous layer, *J. Fluid Mech.*, *564*, 287–303.

Christopher, H., and H. Armstead (1978), *Geothermal Energy*, E. and F. N. Spon, London.

Crandall, D., G. Ahmadi, and D. H. Smith (2010), Computational modelling of fluid flow through a fracture in permeable rock, *Transp. Porous Media*, *84*, 493–510.

Darot, M., Y. Gueguen, and M.-L. Baratin (1992), Permeability of thermally cracked granite, *Geophys. Res. Lett.*, *19*, 869–872.

Fredrich, J. T., and T.-F. Wong (1986), Micromechanics of thermally induced cracking in three crustal rocks, *J. Geophys. Res.*, *91*, 12,743–12,764.

Goharzadeh, A., A. Khalili, and B. B. Jøhergensen (2005), Transition layer at a fluid porous interface, *Phys. Fluids*, *17*, 057102.

Heard, H. C., and L. Page (1982), Elastic moduli, thermal expansion and inferred permeability of two granites to 350°C and 55 megapascals, *J. Geophys. Res.*, *87*, 9340–9348.

Iwai, K. (1976), Fundamental studies of fluid flow through a single fracture, PhD thesis, 208 pp., Univ. of Calif., Berkeley.

Ligrani, P., D. Blanchard, and B. Gale (2010), Slip due to surface roughness for a Newtonian liquid in a viscous microscale pump, *Phys. Fluids*, *22*, 0520021.

Liu, R., Q. S. Liu, and S. C. Zhao (2006), Instability of Poiseuille flow in a fluid-porous system, *Phys. Fluids*, *20*, 104105.

Mohais, R., C. Xu, and P. A. Dowd (2011), Fluid flow and heat transfer within a single horizontal channel in an Enhanced Geothermal System, *J. Heat Transfer*, *133*, 1126031.

Neale, G., and W. Nader (1974), Practical Significance of Brinkman's extension of Darcy's law, *Can. J. Chem. Eng.*, *52*, 475–478.

Nield, D. A. (2009), The Beavers-Joseph boundary condition and related matters: A historical and critical note, *Transp. Porous Media*, *75*, 537–540.

Phillips, O. M. (1991), *Flow and Reactions in Permeable Rocks*, Cambridge Univ. Press, Cambridge, U. K.

Rasouli, V., and A. Hosseinian (2011), Correlations developed for estimation of hydraulic parameters of rough fractures through the simulation of JRC flow channels, *Rock Mech. Rock Eng.*, *44*, 447–461.

Raven, K. G., and J. E. Gale (1985), Water flow in a natural rock fracture as a function of stress and sample size, *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, *22*(4), 251–261.

Romm, E. S. (1966), *Flow Characteristics of Fractured Rocks* [in Russian], 283 pp., Nedra, Moscow.

Sahraoui, M., and M. Kaviany (1992), Slip and no-slip velocity boundary conditions at interface of porous, plain media, *Int. J. Heat Mass Transfer*, *35*, 927–943.

Sausse, J., and A. Genter (2005),Types of permeable fractures in granite, in *Petrophysical Properties of Crystalline Rocks*, edited by P. K. Harvey, *Geol. Soc. Spec. Publ.*, *240*, 1–14.

Taylor, G. I. (1971), A model for the boundary condition of a porous material, *J. Fluid Mech.*, *49*, 319–326.

Terrill, R. M., and G. M. Shrestha (1965), Laminar flow through parallel and uniformly porous walls of different permeability, *Z. Angew. Math. Phys.*, *16*, 470–482.

Tilton, N., and L. Cortelezzi (2006), The destabilising effects of wall permeability in channel flow: A linear stability analysis, *Phys. Fluids*, *18*, 051702.

Vaughn, P. J., D. E. Moore, C. A. Morrow, and J. D. Byerlee (1986), Roles of cracks in progressive permeability reduction during flow of heated aqueous fluid through granite, *J. Geophys. Res.*, *91*, 7517–7530.

Warpinski, N. R. (1985), Measurement of width and pressure in a propagating hydraulic fracture, *SPE J.*, *25*, 46–54.

Witherspoon, P. A., and J. C. S. Long (1987), Some recent developments in understanding the hydrology of fractured rocks, in *Rock Mechanics: Proceedings of the 28th U.S. Symposium*, edited by I. W. Farmer et al., pp. 1–12, A. A. Balkema, Rotterdam, Netherlands.

Zimmerman, R. W., and G. S. Bodvarsson (1996), Hydraulic conductivity of rock fractures, *Transp. Porous Media*, *23*, 1–30.

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