INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

SIMSG ISSMGE

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3
© The authors and IGS: All rights reserved, 2019
doi: 10.32075/17ECSMGE-2019-1013

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Assessing the impact of fracture properties and wellbore configuration on the energy extraction from hot dry rock

Évaluation de l'impact des propriétés de fracture et de la configuration des puits de forage sur l'extraction d'énergie de la roche sèche et chaude

J. R. Encalada
Norwegian University of Science and Technology, Trondheim, Norway

E. A. Quichimbo
Cardiff University, Cardiff, The United Kingdom

R. F. Vázquez
Dirección de Investigación (DIUC), Universidad de Cuenca, Cuenca, Ecuador

ABSTRACT: Future energy development relies on the use of alternative energy sources such as exploitation of deep geothermal energy from Hot Dry Rock (HDR). HDR reservoirs are considered strategical because of the great amounts of heat stored in deep basement. Here, a numerical model considering a discrete fracture network and data from the Soultz-Sous-Forets HDR reservoir (France) was developed. The model setup consists of injection and extraction wells with two-phase circulation fluid (water). Flow rate, permeability, distance from the injection well, and fracture aperture were considered in the analysis. Results indicate that thermal decline is mostly influenced by the permeability of the fractured medium and wellbore configuration. Marginal increments in permeability caused noticeable decrements in temperature in a short lifespan of about 10 years. A simulation of the current scenario shows that sustainable heat extraction for the purpose of electricity generation is achieved for a lifespan of 30 years. The results of this study emphasize that permeability is a critical parameter to be addressed during field investigation and conceptualization of a HRD reservoir; it also provides a better understanding of the viability of deep geothermal projects.

RÉSUMÉ: Le développement énergétique futur repose sur l'utilisation de sources d'énergie alternatives telles que l'exploitation de l'énergie géothermique profonde à partir de roches chaudes et sèches (HDR). Les réservoirs HDR sont considérés comme stratégiques en raison de la grande quantité de chaleur stockée dans les sous-sols profonds. On a mis au point, un modèle numérique prenant en compte un réseau de fractures discrètes et des données du réservoir HDR de Soultz-Sous-Forets (France). La configuration du modèle comprend des puits d’injection et d’extraction avec un fluide de circulation à deux phases (eau). Le débit, la perméabilité, la distance du puits d'injection et l'ouverture de fracture ont été pris en compte dans l'analyse. Les résultats montrent que le déclin thermique est principalement influencé par la perméabilité du milieu fracturé et par la configuration du puits de forage. Des augmentations marginales de la perméabilité sont à la base des baisses remarcables de la température sur une courte durée de vie d'environ 10 ans. Une simulation du scénario actuel montre que l'extraction de chaleur durable dans le but de produire de l'électricité est effectué sur une durée de vie de 30 ans. Les résultats de cette étude soulignent que la perméabilité est un paramètre critique à prendre en compte lors de la recherche sur le terrain et de la conceptualisation d'un réservoir HRD; il fournit également une meilleure compréhension de la viabilité des projets de géothermie profonde.

Keywords: Energy extraction; hot dry rock; permeability; numerical modelling; sensitivity analysis.

1 INTRODUCTION

Global energy consumption is expected to reach by 2050 a level above which biomass resources will not be enough for meeting the constantly growing demand (Fauzi, 2016). To tackle this unbalance, geothermal energy is among the alternative sources expected to satisfy the referred energy demand and even reducing greenhouse emissions (Blöcher et al., 2015).

Geothermal energy is produced in the earth's inner core, mainly due to the radioactive decay of uranium 235; this geothermal energy is manifested in the continental plates (crust) in the form of heat which normally varies 30 °C km^{-1} from the surface. Even higher gradients can be found along the ring of fire and in hot spots (Böttcher et al., 2015; DiPippo, 2016).

As an alternative to exploitation of deep geothermal energy, the concept of Hot Dry Rock (HDR) reservoirs was developed in los Alamos laboratory, New Mexico (USA). Energy (heat) extraction is achieved by the circulation of fluid through hot rock, usually at 250-350 °C, and 4-5 km deep. Most important, temperatures above 145 °C (420 K) are economically feasible for electricity generation (Ghassemi et al., 2003).

The success of the energy production from HDR depends on the permeability of the medium, being necessary the use of hydro-fracturing in order to create or increase the permeability, which is very low in deep basement (Huenges, 2016). In this regard, HDR reservoir falls in the category of Enhanced Geothermal Systems (EGS) and physical properties of fractures such as permeability becomes more or less a confined (fixed) parameter. Contrarily, parameters such as injection rate are flexible.

Fractures in a rock are characterised by their orientation, distribution, aperture and extension. A high permeability or aperture creates preferential channels, reducing the heat transfer between the rock and fluid, and causing a rapid depletion of the heat resource. Limited extension of fractures may cause a lack of connection and poor hydraulic performance, disabling the removal of heat.

It has been observed that high flow rate (mass rate) limit the amount of heat removed and causes a rapid depletion of heat. Excessive flow can also increase thermal stresses, causing contraction of the rock in the cold zones, with the increase in permeability that leads to preferential channelling as reported by Ghassemi et al., (2005). Contrarily, low rates extend the period of heat drawdown of hot rock, but they are commercially unattractive.

Most often, flow in fractures is studied by means of the Cubic law that considers fractures as parallel plates and flow rate being proportional to the cubic power of the aperture, assuming laminar and well distributed flow (Caulk et al., 2016). However, due to the toughness of the rock, fractures are not parallel plates. Hereafter, variable aperture and effects of erosion and transport must be addressed. Furthermore, channelling due to the imminent rugosity and waviness of fracture planes are imminent (Tsang and Tsang,1987).

For the most common HDR, duplet well, the hydraulic connection is ellipsoidal. Optimal arrangement of wells is a triplet set (Chen and Jiang, 2015). Flow patterns change for different well disposition; narrow spacing cause a limited heat exchange, having low production temperatures. Increasing flow paths as much as possible has shown the best results. The location of injection and extraction points as a function of depth represents a challenge as the stress field increases with depth. An acceptable thermal gradient is required for commercial production; however, drilling and hydraulic fracturing becomes more challenging and expensive.

Hereafter, the present study focuses on a three-dimensional (3D) numerical modelling of a HDR reservoir considering variations of physical parameters such as temperature, permeability, geology and stimulation. Its objective was determining the impact of these parameters on the thermal performance and life span of the reservoir in a view of electricity generation. These sort of assessments, based on sound and appropriate numerical analyses, should be implemented while exploring the technical and economic feasibility of geothermal exploitation projects, such as the current one.

2 MATERIALS AND METHODS

2.1 Geological setup

The deep geothermal project Soultz-sous-Forets (Alsace, France) was initially named a HDR reservoir, but it was changed to EGS in 2001 because of the existence of high levels of saline water in the uppermost layer of the reservoir, seated on sedimentary rock. The sedimentary strata is 1.4 km thick and overlays Palaeozoic micaceous granite, fractured, with hydrothermal alterations, and sealed with calcite and illite that causes very low permeability (Gerard et al., 2006; Genter et al., 2010). Major tectonic dislocations in the granite are striking N160°E which matches the present day stress field (Dezayes et al., 2010).

Currently, the reservoir consists of five wells: two intended for exploration and hydrothermal exploitation up to 3.5 km in depth; three wells, GPK2, GPK3 and GPK4 (see Fig. 1), separated each other 650 m, used for reaching the HDR reservoir at 5 km depth where the temperature is about 200 °C (Baujard and Bruel, 2006; Ledésert et al., 2010).

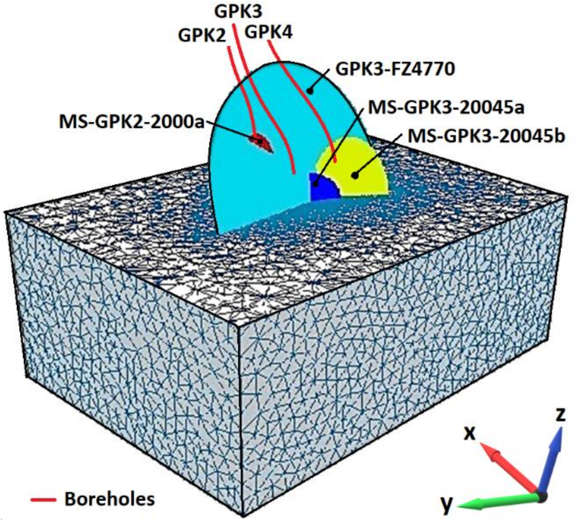

Figure 1 Schematic of the fractured system of Soultz-sous-Forets and of the mesh elements used in the numerical modelling (after Genter et al., 2010).

The hydrothermal reservoir is characterised by major fluid loses as per drilling operations, but the deep HDR reservoir showed less than 20% of losses, which can be rather understood as a fractured reservoir in a low permeable matrix (Hébert et al., 2010; Sausse et al., 2010; Dezayes et al., 2010). A complete discrete fracture network (DFN) for both reservoirs was developed by Sausse et al. (2010) that consists of disc-shaped fracture zones (Fig. 1) inferred from borehole logs, and other geophysical techniques. Average thicknesses for each zone are detailed in Dezayes et al. (2010). A total of 39 zones were recognized between 0.8 and 6.0 km deep.

However, the current study considered the four most relevant zones linked to the wells GPK2, GPK3, and GPK4. The selection of the zones considered their extension, thickness and flow ranking. Thus, MS-GPK3-20045b was selected because of its direct conection with GPK4 (Fig. 1); GPK3-FZ4770 with GPK3 and an infiltration point at GPK2; MS-GPK2-2000a with the bottom hole of GPK2; and MS-GPK3-2003c intersecting GPK3-FZ4770 (Hébert et al., 2010).

2.2 Numerical model and material properties

A mesh generated in GMESH (Geuzaine and Remacle, 2009), consiting of 308,820 tetrahedron elements (Fig. 1), with a total volume of 67.5 km^3, was used for the current modelling. Sink and sources were defined by points, wells by polilines, fractures as surfaces and the rock matrix as a structured mesh. A dense mesh of 5 m was defined near wells and fractures where high hydraulic gradients were expected to occur.

The mesh was imported into the open source software OpenGeoSys (OGS) with capability to model coupled hydraulic and thermal processes (TH). The governing equations for hydraulic and thermal processes implemented in OGS for a fractured medium are respectively:

$$\mathrm{Q_f} = \mathrm{e}S_s^f \frac{\partial \mathrm{p}}{\partial \mathrm{t}} - \overline{\nabla}\left(\frac{\mathrm{k}^f}{\mu}\left(\overline{\nabla}\mathrm{p} + \rho^f \mathrm{g}\right)\right) \qquad (1)$$

$$\mathrm{Q_T} = \mathrm{e}\rho^f c_p^f \frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \mathrm{e}\rho^f c_p^f \mathrm{v} \cdot \overline{\nabla}\mathrm{T} - \nabla(\mathrm{e}\lambda^f \overline{\nabla}\mathrm{T}) \qquad (2)$$

The fluid discharge, Q_f, can be either a sink or source [m^3 s^{-1}]; e is the fracture aperture [m]; S_s^f is the fracture specific storage [Pa^{-1}]; p is the fluid pressure [Pa]; t is time [s]; k^f is the fracture permeability [m^2]; μ is the dynamic viscosity [Pa s]; ρ^f is the density of the fluid [Kg m^{-3}]; and g is the gravity acceleration [m s^{-2}]. Similarly, for heat transport, Q_T is either a source or sink [J s^{-1}]; c_p^f is the specific heat capacity of the fluid [J kg^{-1} K^{-1}]; T is the temperature [K]; v the Darcy's velocity [m s^{-1}]; and λ^f the heat conductivity of the fluid [W m^{-1} K] (Böttcher et al., 2015). For the porous medium, analogous equations are implemented in OGS; nevertheless, they are not discussed herein to keep the extent of this manuscript under reasonable limits.

The physical properties for the fluid (water) were taken from Cengel and Boles (2010). For the rock, specialised literature such as Waltham (2009) and Eppelbaum et al. (2014) was consulted. Thus, for the granite, it was considered a heat conductivity of 2.68 W m^{-1} K^{-1}, and a specific heat capacity of 790 J kg^{-1} K^{-1}. Porosity and permeability of the rock matrix were set up as 4.3% and 4.0×10^{-19} m^2, respectively (Ledésert et al., 2010).

Inputs for fracture aperture were decided upon geological logs. Baujard and Bruel, (2006) reported fracture apertures for GPK2, GPK3 and GPK4 of 0.82 mm, 1.00 mm and 0.86 mm respectively (Table 1). Apertures of 0.1-10 mm are suggested by Dezayes et al. (2010) for the zone between GPK2 and GPK3; while Neuville et al. (2010) reported a mean aperture of 3.60 ± 1.23 mm for fractures in the larger zone FZ4770. In this way, the initial aperture for the largest zone FZ4770 was fixed as 1.7 mm; whilst 0.8 mm for the other zones characterised by low flows.

Table 1 Values of isotropic permeability according to two different criteria.

Zone	**e (mm)**	**Permeability (m^2)**	
		Cubic law	**Calibrated**
MS-GPK2-2000a	0.8	5.30×10^{-8}	7.53×10^{-10}
GPK3-FZ4770	1.7	2.41×10^{-7}	7.53×10^{-10}
MS-GPK3-20045b	0.8	5.30×10^{-8}	9.30×10^{-11}

2.3 Boundary and initial conditions

The extension of the domain was defined by an expansion factor of 2 relative to the largest fracture zone, in order to avoid the influence of boundaries on the TH process. The uppermost and lowest faces were located at -2500 and -7000 m a.s.l., respectively.

As for hydraulic boundary conditions, zero flow was assigned to the outer nodes; while in the sink and sources represented by injection and extraction wells, a Dirichlet condition (as pressure) with linear variation from top to bottom was applied. In the same way, initial conditions for each node in the domain was set as hydrostatic pressure with the gradient 1000 kg m^{-3}.

With regard to the TH boundary conditions, a gradient (Fig. 2) of 0.03 K m^{-1} was assigned to the faces of the domain, with constant top and bottom temperatures. In particular, the temperature at the injection well GPK3 was kept constant at 80 °C (353.15 K). Note that this gradient gives a conservatice value for shallow temperatures, given that above 3000 m of depth hydrothermal activity is present. Furthermore, the initial temperature distribution of the whole domain is the same as defined at the boundaries.

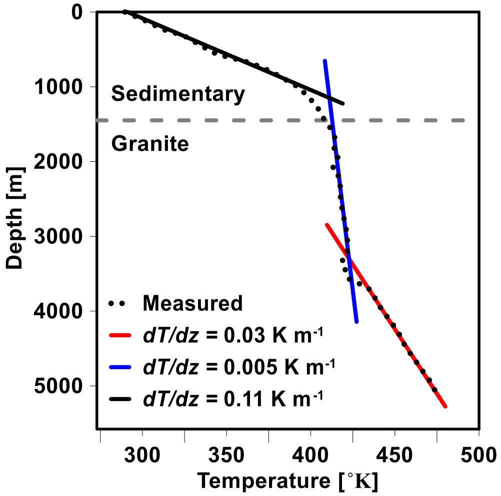

Figure 2 Thermal gradient at the Soutlz reservoir (after Genter et al., 2010).

The model required the hydraulic calibration based on stimulation tests on boreholes (hydrojacking tests for temporary dilatancy of fissures) described in Baujard and Bruel (2006). Injection at GPK3 with 50 l s^{-1} caused the pressure at fractures to escalate to 17 MPa. The response in GPK2 was a flow of 25 lt s^{-1} with a pressure of 7 MPa. The response in GPK4 was neglegeable, because of the poor conection with GPK3. A reproduction of the whole stimulation period was not conducted because the interest of the current modelling lies only on the operational state of the reservoir, with fractures already stimulated; furthermore, a reproduction of hydrojacking required an additional mechanical proces that was not in the capability of the OGS software. In this way, permeability of the fractured medium was approximated by trial an error evaluation of the pressure response to injections.

3 RESULTS AND DISCUSSION

Temperature evolution in fractures was studied with the aid of 3D plots for a 60 year period of fluid circulation and also with curves of temperature vs. time. As shown in Fig. 3, the change in temperature is noticeble in fractures, but there is a very little change in the rock matrix. This is because advection dominates heat transport in fractures.

Two important circulation loops were noticed: (i) a major loop between GPK3 and the bottom of GPK2; and (ii) the shorthest loop between GPK3 and GPK4, which agrees with the findings of Gerard et al. (2006). It is remarkable how the cold front arrives earlier to GPK2 at the bottom hole and infiltration point (Fig. 3b).

For several scenarios of heat extraction, the main flow path occured through the zones GPK3-FZ4775 and MS-GPK2-2000a, which caused a tortuous flow pattern because of the irregular connection among fractures (Fig. 1). This caused the temperature to decrease relatively rapid as colder fluids in the upper regions arrived first at the extraction points (Fig. 3a and Fig. 3b).

The effect of increasing flow rate is shown in Fig. 4a, which depicts a significant decrement in temperature at the production well GPK2, whilst breakthrough occurs no longer than 30 years after the beginning of operation in all of the cases. As flow rate (mass rate) increased, flow paths stretched due to a rapid circulation of fluids; and this caused a sudden drawdown of heat in the short term.

The result of increasing the permeability above the actual estimated value is shown in Fig. 4b for values of 150, 200, and 300% of the actual value. With high permeability the mass rate increased, causing an early heat drawdown and reducing as such the lifespan of the reservoir, noticeably.

Results of increasing the fracture aperture is similar to the increase of permeability (Fig. 4c); this is due to an increase in the hydraulic capacity of the fracture to carry a higher volume of water, hence reducing areas of heat exchange as explained by Tsang and Tsang (1987).

The impact of well location was assed without the zone MS-GPK2-2000a. That is, a direct connection was assumed with the zone GPK3-FZ4775. Then, the distances between the injection point GPK3 and the extraction wells were respectively reduced to 25, 50, and 75% of the current setup. This caused a sudden drecrease of the reservoir lifespan as shown in Fig. 4d.

An additional escenario where GPK3 and GPK4 are injected with 15 and 10 l s^{-1} respectively experinced no sudden TH breakthrough after 60 years of production. Results were comparable with a most robust model of Soultz conducted by Held et al. (2014). Unlike for other excenarios, in this case the temperature incremented gradually before drawdown started. This can be explained by high temperate fluid from lower regions arriving first at the bottom of GPK3, which is relatively lower as compared to the other wells.

4 DISCUSSION AND CONCLUSIONS

A distributed numerical model for a HDR reservoir was implemented for the study site using the concept of a discrete fracture network. Herein, the assessments that were carried out in this study would have been almost impossible to achieve through the use of a lumped model.

The results showed the importance of the permeability and wellbore spacing (over the other inspected parameters) on the TH drawdown throughout the operational period. Herein, sudden decrements in fluid temperature were predicted for increments in permeability and the reduction of the space between the injection and extraction wells.

Wellbore spacing can be controlled in a HDR, but permeability becomes a confined parameter. Higher values suggested by the Cubic law (Table 1) did not give reliable results when compared to the respective results from stimulation tests. Overestimation of this parameter leads to an underestimation of the thermal performance.

Additionally, sensitivity to the fracture network connection was suggested by the shape of the respective temperature curves, as a result of direct or indirect connection and the vertical distance between the injection and extraction points.

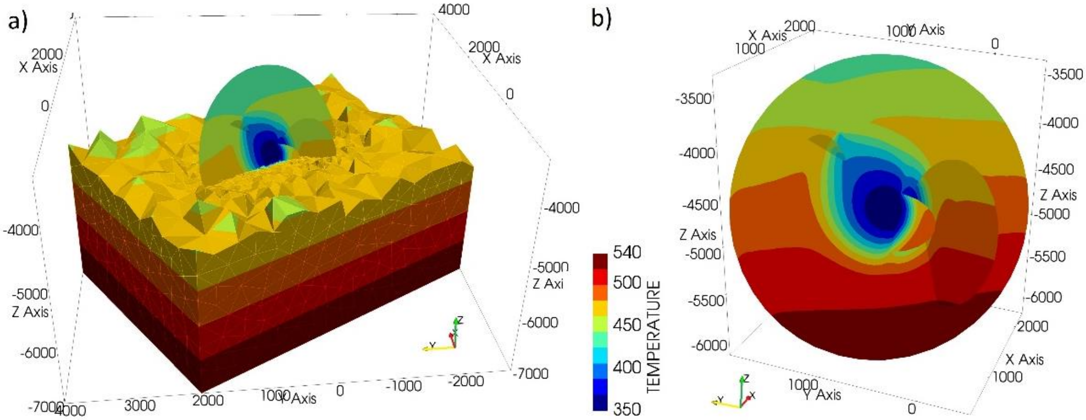

Figure 3 3D temperature field [K] after 60 years of operation with an injection rate of 25 l s^{-1}: (a) complete modelling domain; and (b) main fracture plane.

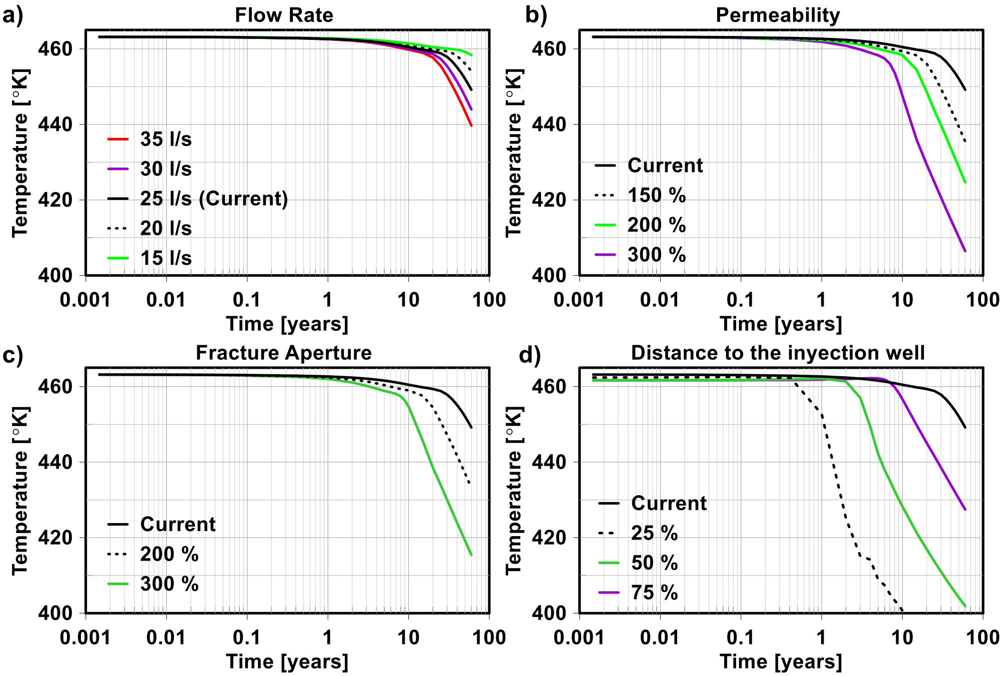

Figure 4 Simulated temporal variation of temperature for a 60 year period of fluid extraction at the bottom of well GPK2, as a function of different physical and operationl scenarios

5 LIST OF REFERENCES

Baujard, C. and Bruel, D. (2006) 'Numerical study of the impact of fluid density on the pressure distribution and stimulated volume in the Soultz HDR reservoir', Geothermics, 35, pp. 607-621.

Blöcher, G., Cacace, M., Reinsch, T., and Watanabe, N. (2015) 'Evaluation of three explotation concepts for a deep geothermal system in the North German Basin', Computer & Geosciences, 82, pp. 120-129.

Böttcher, N., Watanabe, N., and Kolditz, O. (2015) 'OpenGeoSys Higrade Tutorial Computational Energy Systems I', Basics of Geothermal Processes. Leipzig: Springer.

Caulk, R. A., Ghazanfari, E., Perdrial, J. N., and Perdrial, N. (2016) 'Experimental investigation of fracture aperture and permeability change within Enhanced Geothermal Systems', Geothermics, 62, pp. 12-21.

Cengel, Y. A. and Boles, M. A. (2011) Thermodynamics: An engineering approach. 7th edn. New York, NY: The MacGraw-Hill Companies, Inc.

Chen, J. and Jiang, F. (2015) 'Designing multi-well for enhanced geothermal system to better exploit hot dry rock geothermal energy', Renewable Energy, 74, pp. 37-48.

Dezayes, C., Genter, A., and Valley, B. (2010) 'Structure of the low permeable naturally fractured geothermal reservoir at Soultz', Comptes Rendus Geoscience, 342, pp. 517-530.

DiPippo, R. (2016) Geothermal Power Plants. Oxford, UK: Elsevier Inc.

Eppelbaum, L., Kutasov, I., and Pilchin, A. (2014) 'Thermal Properties of Rocks and Density of Fluids' Applied Geothermics. 1st edn. Heidelberg, New York: Springer.

Fauzi, T. A. (2016) 'Geothermal Energy', in Fauzi, T. A. Electric Renewable Energy

Systems. Oxford, UK: Elsevier Inc, pp. 114-139.

Genter, A., Evans, K., Cuenot, N., Fritsch, D., and Sanjuan, B. (2010) ‘Contribution of the explotation of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems’, Computers Rendus Geoscience, 342, pp. 502-516.

Gerard, A., Genter, A., Kohl, T., Lutz, P., Rose, P., and Rummel, F. (2006) ‘The deep EGS (Enhanced Geothermal System) project at Soultz-sous-Forêts (Alsace, France)’ Geothermics, 35, pp. 473-483.

Geuzaine, C. and Remacle, J.-F. (2009) ‘Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities’ International Journal for Numerical Methods in Engineering 79(11), pp. 1309-1331.

Ghassemi, A. Tarasovs, S., and Cheng, A. H. -D. (2003) ‘An integral equation solution for three dimensional heat extraction from planar fracture in hot dry rock’, Intenational journal for numerical and analytical methods in geomechanics, 27, pp. 989-1004.

Ghassemi, A. Tarasovs, S., and Cheng, A. H. -D. (2005) ‘Integral equitation solution of heat extraction-induced thermal stress in enhanced geothermal reservoirs’, Intenational journal for numerical and analytical methods in geomechanics, 29, pp. 829-844.

Hébert, R. L., Ledésert, B., Bartier, D., Dezayes C., Genter, A., and Grall, C. (2010) ‘The Enhanced Geothermal System of Soultz-sous-Forêts: A study of the relationships between fracture zones and calcite content’, Journal of Volcanology and Geothermal Research, 196, pp. 126-133.

Held, S., Genter, A., Kohl, T., Kölbel, T., Sausse, J., and Schoenball, M. (2014) ‘Economic evaluation of geothermal reservoir performance through modeling the complexity of the operating EGS in Soultz-sous-Forêts’, Geothermics, 51, pp. 270-280.

Huenges, E. (2016) ‘Enhanced geothermal systems Review and status of research and development’, in Huenges, E. Geothermal Power Generation. 1st edn. Oxford, UK: Elsevier Inc, pp. 743-761.

Ledésert, B., Herbert, R., Genter, A., Bartier, B., Clauer, N., and Grall, C. (2010) ‘Fractures, hydrothermal alterations and permeability in the Soultz Enhanced Geothermal System’, Comptes Rendus Geoscience, 342, pp. 607-615.

Neuville, A., Toussaint, R., and Schmittbuhl, J. (2010)’ Fracture roughness and thermal exchange: A case study at Soultz-sous-Forets’, Comptes Rendus Geoscience, 342, pp. 616-625.

Sausse, J., Dezayes, C., Dorbath, L., Genter, A., and Place, J. (2010) ‘3D model of fracture zones at Soultz-sous-Foreˆts based on geological data, image logs, induced microseismicity and vertical seismic profiles’, Comptes Rendus Geoscience, 342, pp. 531-545.

Tsang, Y. W. and Tsang, C. F. (1987) ‘Channel Model of Flow Through Fractured Media’, Water Resources Research, 23(3), pp. 467-479.

Waltham, T. (2009) Foundations of Engineering Geology. 3rd edn. London and New York: Spon Press an imprint of Taylor and Francis e-library.