PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

Conceptual Study of a Well-Fracture-Well Type Fluid Circulation System for EGS

George Danko[1], Davood Bahrami[1], Gyula Varga[2], Matyas Krisztian Baracza[2], and Anita Jobbik[2]

[1]University of Nevada, Reno,1664 N. Virginia Str. MS 173, Reno, NV 89557, USA

[2]Research Institute of Applied Earth Sciences, University of Miskolc, Hungary

danko@unr.edu

Keywords: Single-well EGS design, flow control, flow and thermal models

ABSTRACT

A new arrangement applicable to a single-well EGS is introduced. The new element of the concept is the application of a wing fracture or a series of wing fractures parallel with the centerline of an EGS well. During hydrofracturing, each wing fracture is hydraulically connected to the well over a section from which it is created. A straight well in an ideal arrangement lays in a planar wing fracture intersecting each other along the entire lateral extension of the fracture. A directionally drilled well may follow a planar fracture, intersecting it at multiple points around a section at which the fracture approximates the osculating plane of the well.

In a completed EGS, separation of the incoming and returning fluid flows is accomplished by the liner of the well; and a grouted area within the fracture close to the well. The injected grout as an island forces the return flow toward the edge area of the fracture. The sealing grout also acts as a permanent support to prop the fracture open without the need for opening it by hydraulic pressure. In a single-well, direct flow arrangement, the coolant fluid passes from the injection point along a series of well-fracture-well segments to the production point during operation. In a single-well, counter-current flow arrangement, the coolant fluid is injected through a separated pipe in the well in one direction into the farthest point in the fracture; the fluid is then flows back along the fracture plane in the opposite direction until it returns through the well, creating a geologic heat exchanger over a large fracture surface.

Examples of the new arrangement are presented with single, and multiple wing fractures along a single EGS well. Numerical simulation results are shown from the hydraulic and thermal models of the new EGS layout. Conclusions are drawn regarding the efficiency of the new flow system with a grouted island close to the center of the planar fracture in comparison with a single input, single output, unblocked EGS fracture.

1. INTRODUCTION

Typical arrangements of Engineered Geothermal Systems (EGS) involve at least one injection and one of more production well(s) between which coolant fluid is established through artificially-created fractures for geothermal energy extraction. The expected geometry of the fracture system in an EGS is highly debated. Some consider planar-type fracture shapes as a result of EGS fracturing (Murphy et al, 1981; Smith et al, 1989; DOE, 2006; Ghassemi et al., 2007; Danko and Bahrami, 2013a and 2013b; Danko et al., 2016) while others view the fracture system as a network of discrete, channel-type conduits or a statistically-distributed, equivalent, double-porosity and permeability (fractured and porous) rockmass (Xu and Pruess, (2001); Taron and Elsworth, 2009).

The exact geometry of an as-created fracture EGS fracture system is unknown; yet, indirect evidence supports the expectation of planar fractures. First, hydraulic pressure overcoming the minimum principal stress in a homogeneous, elastic rock formation would create a planar-type fracture opening with an ellipsoid cross section (Sneddon, 1946). This proves the tendency to form a planar-type fracture geometry in an ideally-sited EGS in competent, homogeneous rock formation. Second, numerical model simulation results assuming planar fracture geometry have successfully matched measurement results obtained from EGS experiments. Specifically, flow distribution, pressure resistance related to joint opening of planar fractures, and thermal drawdown have successful matched the monitored measurement results published for Fenton Hill Phase I and Phase II EGS reservoir research studies by the Los Alamos National Laboratory (LANL) between 1978 and 1995 (Murphy et al, 1981; Smith et al, 1989; DOE, 2006) regarding flow rate, coolant injection pressure, and thermal drawdown over significant time periods (Danko and Bahrami, 2013a and b; Danko et al., 2016). Therefore, the working hypothesis of a system of planar fractures has strong foundations for an EGS created in competent, crystalline rock formations.

The first fundamental problem with the planar fractures is the difficulty to establish low-flow-resistance circulation connection to an intersecting well. The worst case for high flow connection resistance is an intersection at a right angle typical to a zip fracture arrangement along a well (Ghassemi, 2016). One flow connection to the fracture can be forced through the collar used for hydrofracturing, enlarged by wear, tear or chemical erosion during fluid injection. The second problem is to construct another well connection with an existing fracture, as the intersection of the well with the fracture plane may not fall in an open flow connection such as happened in many EGS experiments, e.g., at Fenton Hill, New Mexico, USA (Brown et al., 2012); or at an EGS well at the Brady geothermal site (Nevada, U.S.). The third problem is to keep open a planar fracture during operation in great depth at high in situ stress field of the strata. Large injection pressure is necessary to keep the fracture open for low circulation flow resistance. Large pressure drop along the fracture due to hydraulic resistance loss results in losing significant pumping energy for maintaining fluid circulation. The fourth problem is rockmass movement and seismic events during operation caused by the 'soft balance' between hydraulic pressure and fracture aperture determined by the joint stiffness of the fracture. A fifth problem is increased fluid loss from the fracture volume to the surrounding hot rock due to high pressure. The resulting Darcy flow from the fracture washes away thermal energy and wastes coolant fluid continuously to the environment. A transformative solution is needed to create a geological heat exchanger system for an EGS without the five listed problems. The new concept applies a wing fracture or a series of wing fractures parallel with the centerline of an EGS well. During hydrofracturing, each wing fracture is hydraulically connected to the well over a section from which it is created. A straight well in an ideal arrangement lays in a planar wing fracture intersecting each other along the entire lateral extension of the fracture. A directionally drilled well must follow a planar fracture, intersecting it at multiple points around a section at which the fracture approximates the osculating plane of the well.

In a completed EGS, separation of the incoming and exhausting flow connections is accomplished by a grouted area around the center of the fracture and the well. The injected grout as a center island partially separates the intake from the exhaust areas in the fracture volume and forces the passing coolant flow toward the edge area of the fracture. The sealing grout also acts as a permanent support to prop the fracture open without the need for opening it by hydraulic pressure. In a single-well application, the coolant fluid may enter the fracture at the farthest end via a trummy pipe inserted in the well, and returns in the edge area of the fracture along its plane in the opposite direction towards the well, creating a geologic heat exchanger over a large fracture surface with a separated, counter-current flow system.

Examples of the new arrangement are presented with single, and multiple wing fractures along a single EGS well. Numerical simulation results are shown from the hydraulic and thermal models of the new EGS layout. Conclusions are drawn regarding the efficiency of the new flow system with a grouted island close to the well in comparison with a single input, single output, planar EGS fracture.

2. DESCRIPTION OF A NEW EGS DESIGN

The first element is the creation an EGS fracture with a continuous, longitudinal connection between the planar fracture and the well that is used for creating the planar fracture by hydrofracturing. The second element is the coolant fluid flow control method by the application of a permanently grouted, support island, created during fracture completion in the planar fracture. The support island serves two purposes: it permanently props open the fracture and also prevents short circuiting of the coolant fluid flow. The resulting EGS fracture system is characterized by a fixed fracture aperture and low aperture sensitivity to fluid circulation pressure and flow rate. Since the fracture is not opened by the injection pressure of the coolant fluid by pumping during energy production, the EGS system is expected to have low seismic activity during energy production. Large fracture aperture may be opened and stabilized during fracture creation by pressurized injection of hardening grout into controlled areas of the planar fracture to keep open the fracture aperture outside the grouted island without fluid pressure support after setting. The same propping grouting islands created in the planar fracture void space also serves as permeability control during production by blocking the flow along preferential, short-circuit pathways in the fracture plane.

2.1 Examples of the Geometry of the Well-Fracture-Well Type EGS

Well-Fracture-Well (WFW) type EGS arrangements examples are shown in Figures 1 and 2 using a series of single, planar fractures. The building-block element in each example of the new EGS arrangement is a single wing fracture around a well section resembling ‘a popsicle on a stick’ geometry. The EGS can be designed with direct or counter-current coolant flow application, shown in two simplified examples in Figs. 1 and 2, respectively. Many more example may be created as a variation on the same theme, revisited briefly later in the paper.

2.2 Technology Elements of the WFW Type EGS

The first essential technology element for the creation of wing fractures for a WFW flow system is the necessary alignment between the in situ stress filed and the direction of the well sections. Figure 3 illustrates the first planar fraction with the necessary alignment to the well section in such a way that the fracture is in the osculating plane of the trajectory of the well at center point 1. In addition, the normal vector of the first planar fracture, known to be parallel with the direction of the minimum principal stress [Zhang et al, 2011], shown by arrow 2 must be normal to the necessary direction of the well. These criteria can be met by directionally drilling the well according to the stress field that can and must be continuously evaluated during the EGS creation. It is interesting to note that published methods are available to assess the in situ stress field by the evaluation of wing fractures [Kamali and Ghassemi 2016], pointing to the advantage of sequential drilling, fracturing, and evaluating the necessary directional correction as the stress field may slowly change even in a carefully-selected, competent site for the EGS. Such a correction for eliminating angular deviation 3 between the starting direction of the well and the necessary direction at center point 1 of the planar fraction is also shown in Fig. 3.

The creation of the propping and flow-blocking islands is another necessary technological element, illustrated in Fig. 4. Hardening slurry of cemented or geopolymer material is inserted through a trummy pipe under opening back pressure to permanently support the desired fracture aperture. Such a slurry may be injected subsequent to the hydrofracturing phase.

The diameter of the grouted island, $2R_g$, is designed to be large enough for supporting the normal and shear stresses of the strata load upon the entire opened fracture with a diameter of $2R_f$; but small enough not to lose too large of a surface area from the fracture’s surface from geothermal energy extraction. With high- to ultra-high-strength grout properly selected, these criteria should aim to be met with an $R_g < R_f/3$ ratio, giving a lost convective heat surface area for the grout of less than 10%. Note that the geothermal heat reduction is expected to be far less than 10%, associated with the convective surface loss as the three-dimensional heat flow from the strata will not be completely blocked by the grouted plug.

The grouted island positively affects the planar fluid flow field in the ring-shaped open void space. The coolant fluid is forced to the periphery of the ring, where large surface (otherwise inaccessible due to short circuiting along small radii) is now available relative to the small surfaces where the flow is blocked by the grouted island. This positive, flow-field control feature of the grouted island in a planar fracture will be shown to completely overcome the convective surface loss feature resulting in an overall increase of heat recovery relative to an unblocked fracture (with $2R_g=0$) of the same outside dimension $2R_f$. It is beyond the scope of the paper to include the many other technology elements that must be considered in the new EGS arrangement, published as an invention disclosure (WIPO, 2017).

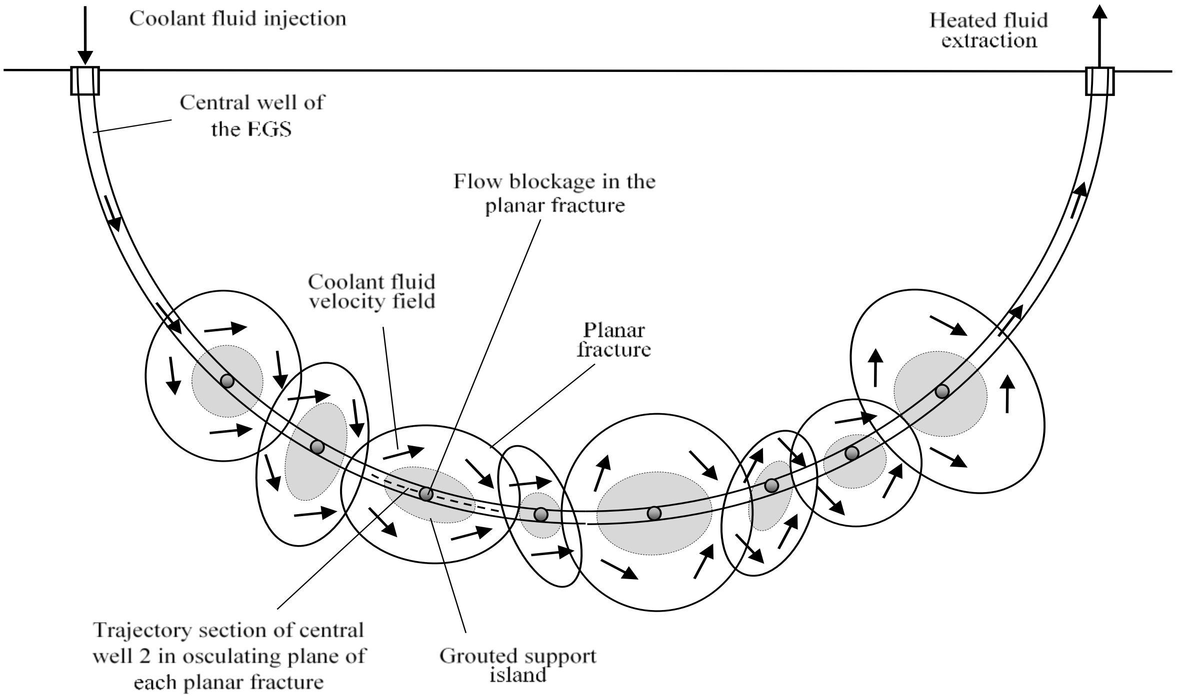

Figure 1: A direct-current, single-well, WFW Type EGS arrangement with a series of planar wing fractures.

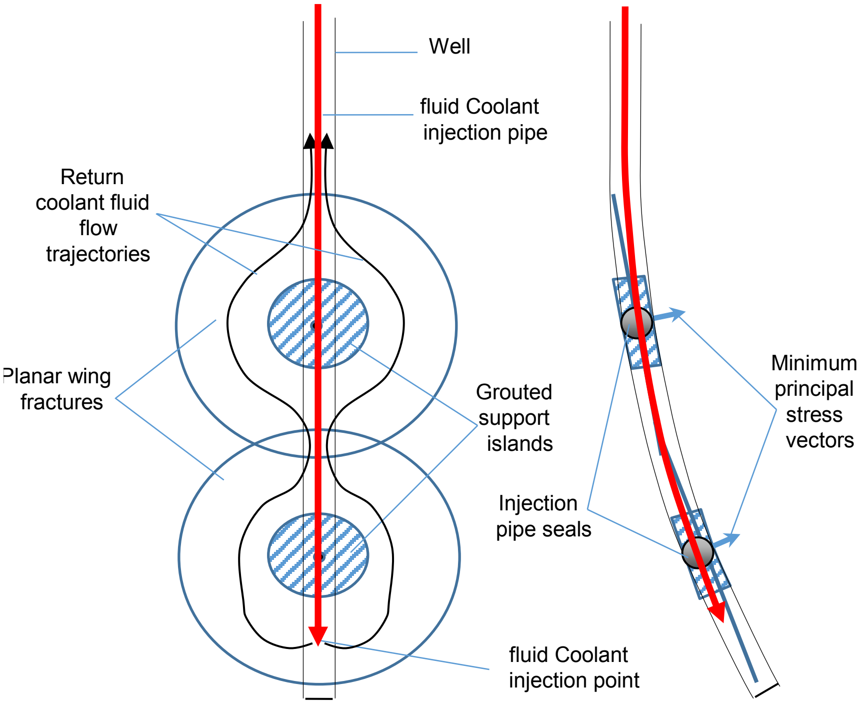

Figure 2: A Counter-current, single-well, WFW Type EGS arrangement with two planar wing fractures.

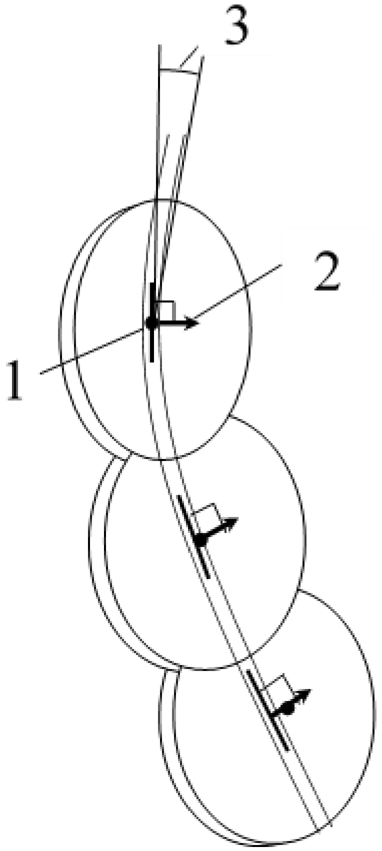

Figure 3: The alignment of wing fractures.

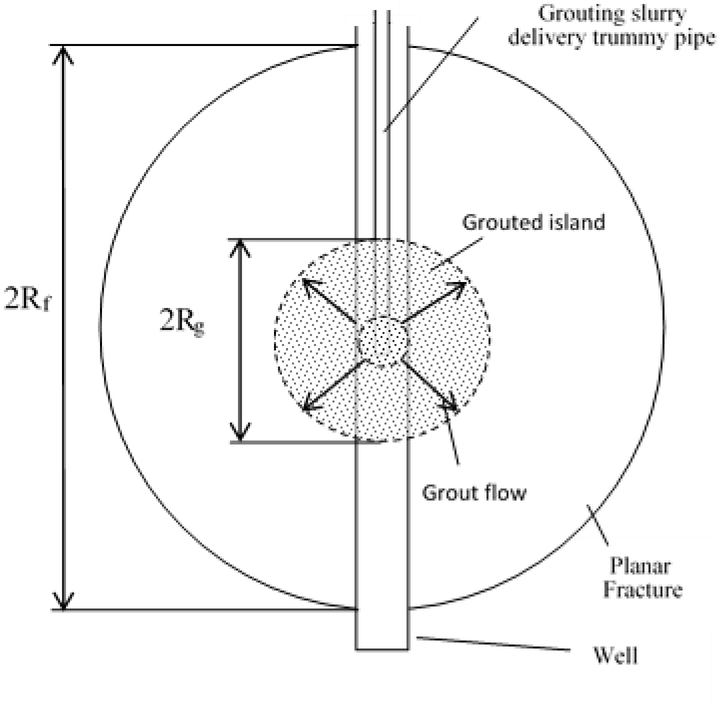

Figure 4: The creation of propping and flow-blocking islands.

3. HYDRAULIC AND THERMAL MODEL SIMULATIONS OF THE NEW EGS SYSTEM

It is necessary to study the new coolant fluid flow system first to check the working expectations and prove the concept's goals in advantageous flow distribution and energy extraction potentials by numerical simulation. The geothermal module of the MULTIFLUX flow and thermal simulation code (Danko, 2008) is used as before for the EGS study (Danko and Bahrami, 2013a, 2013b, Danko et al, 2016, White et al, 2017). The coupled, T-H-M-C network model in MULTIFLUX is reduced for the present study to using only the T-H-M model parts whereas the mechanical model part M is replaced with a fixed-aperture model, assuming a pre-defined, penny-shaped or lens-shaped fracture cross section. The goal of the model simulation is to map the coolant flow field in a WFW system involving a single planar fracture together with the resulting thermal drawdown for a 30-day time period.

3.1 The Input Parameters for the Hydraulic and Thermal Models

The input parameters for the single-fracture model are selected conveniently by importing those used in previous studies for model-matching the Fenton Hill Phase I EGS experiments. The planar fracture diameter is 150 m. The maximum fracture aperture at the center of the fracture is fixed at 0.02 m, a rather large value as compared to the typical aperture of 0.0016 m in the Fenton Hill Phase I experiment. This large aperture is made possible by the one-time fracture opening via a grout-injecting pressure overcoming the minimum principal stress in the rock strata. The thermal conductivity, specific heat and density of the rock are 3.0 W/(m-K), 845 J/(kg-K) and 2700 kg/m^3, respectively, closely following the Fenton Hill data. The water mass flow rate injected into the WFW system is likewise set to 15 kg/s. The virgin rock temperature around the fracture is 180 ^{0}C while the water injection temperature is 60 ^{0}C, constant for simplicity.

3.2 Numerical Simulation Results

Flow and temperature field maps are produced by the T-H numerical model for comparison between an open-fracture and a blocked fracture at the center by the grouted island. For a single, open fracture, one injection and one extraction point each at the opposite end of the horizontal diameter is assumed with no disturbance by the intersecting well for baseline comparison. For a blocked fracture by the grouted support island, the intersecting well section is also considered blocked by the grout plug. The simulation result for the flow and temperature fields at day 30 of energy extraction operation are shown in Fig. 5 through 8.

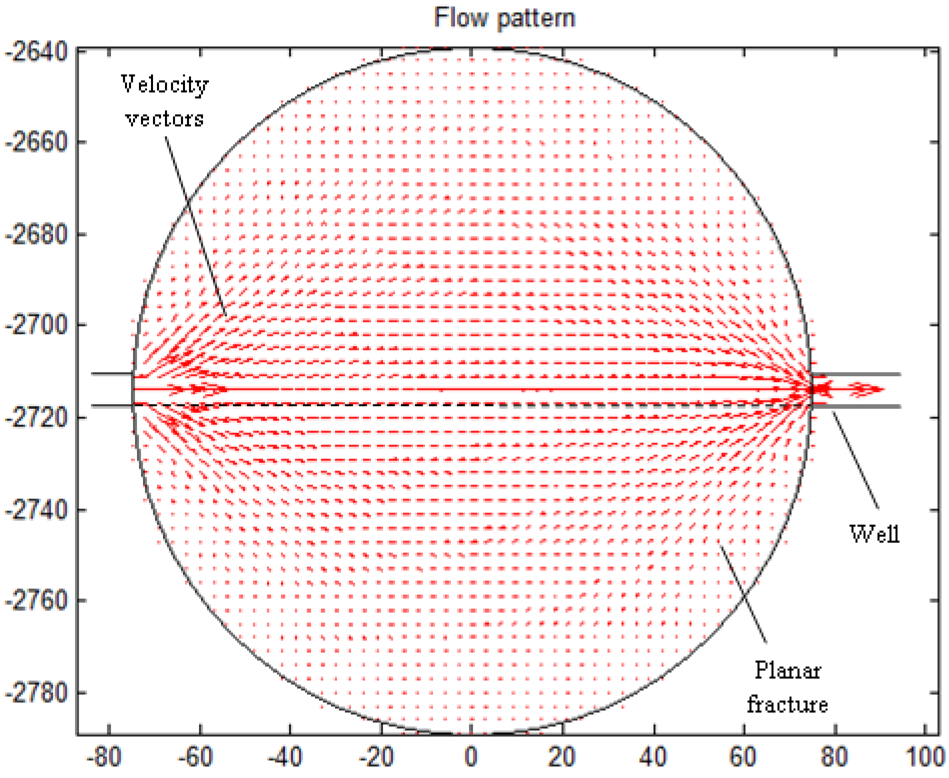

Figure 5: Flow field in an open fracture with no flow blockage

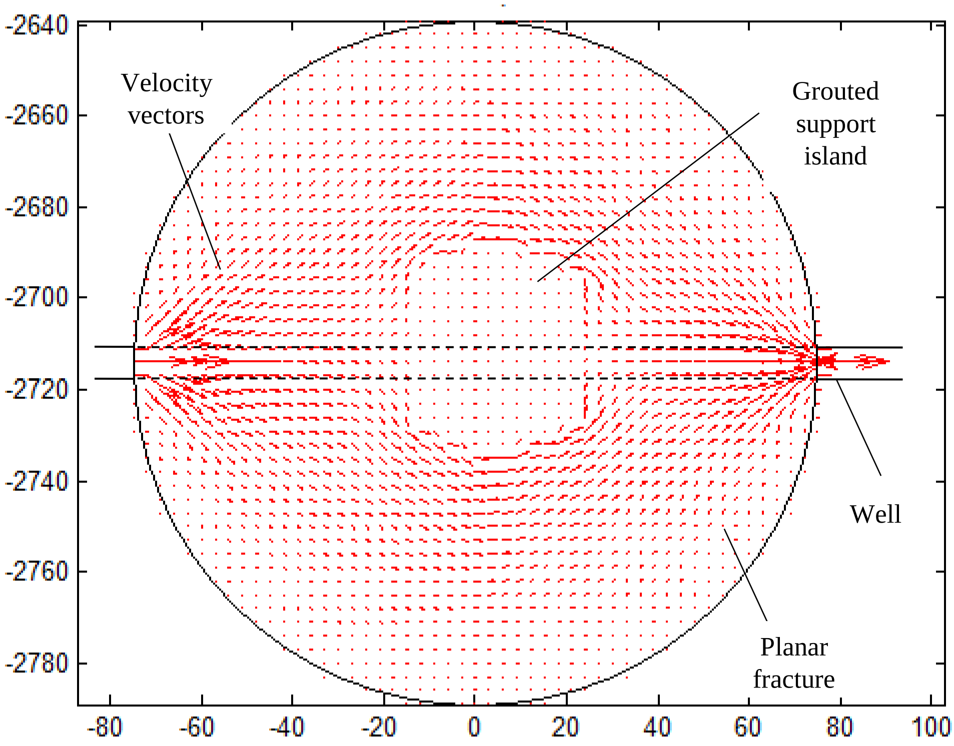

Figure 6: Flow field with a grouted island blocking the flow in the center area of the fracture.

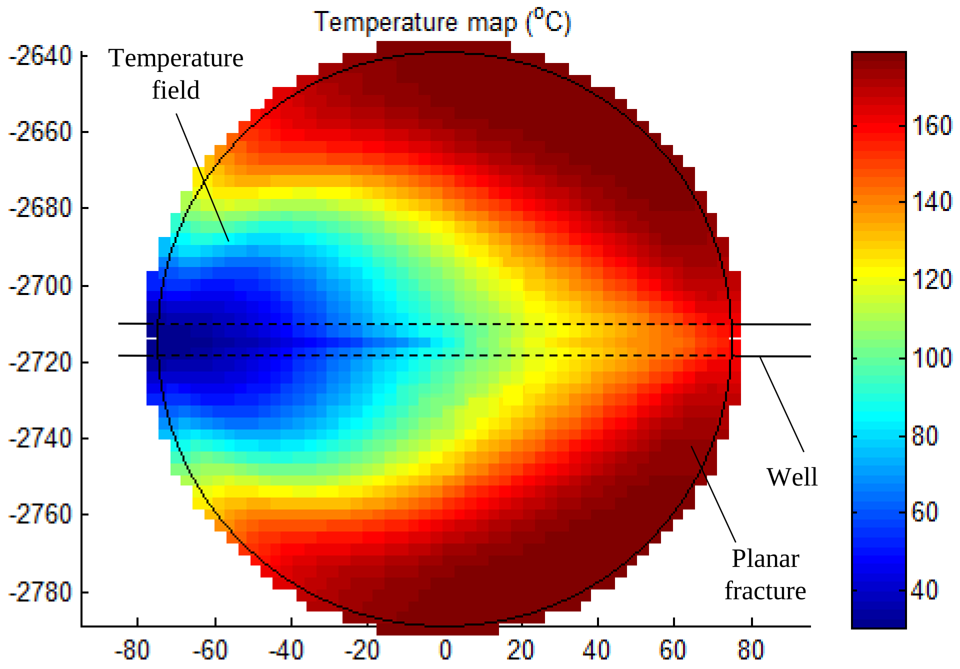

Figure 7: Temperature field in an open fracture with no flow blockage

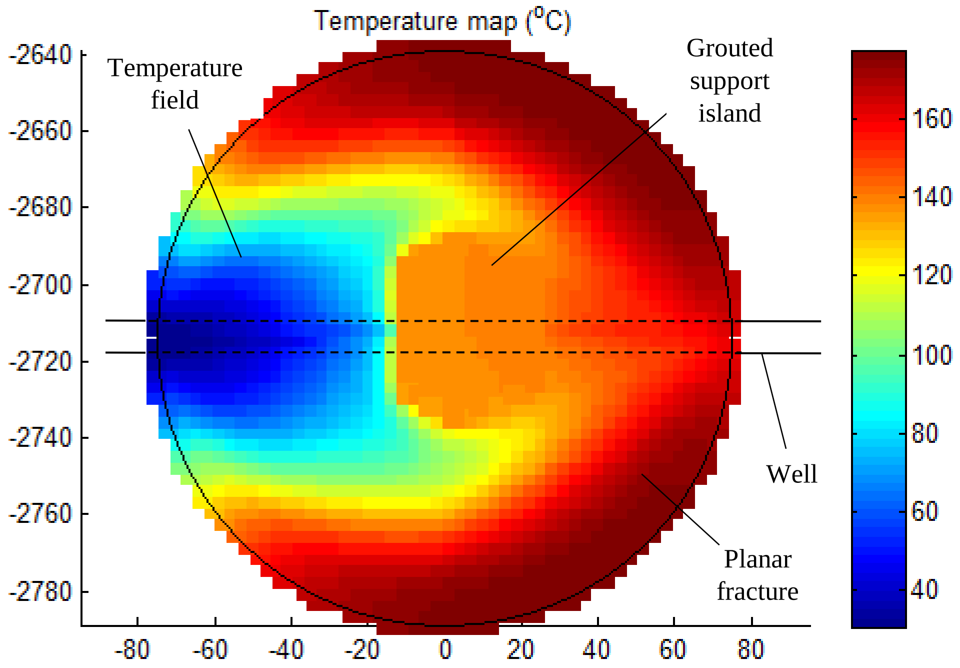

Figure 8: Temperature field with a grouted island blocking the flow in the center area of the fracture.

The expected rate of geothermal energy (that is, thermal power) harvested from the fracture is also simulated as a function of operating time. The power generation is affected by the so called thermal drawdown with time, shown in Fig. 9 for comparison between the open and the blocked fracture due to the grouted support island in the new WFW flow system.

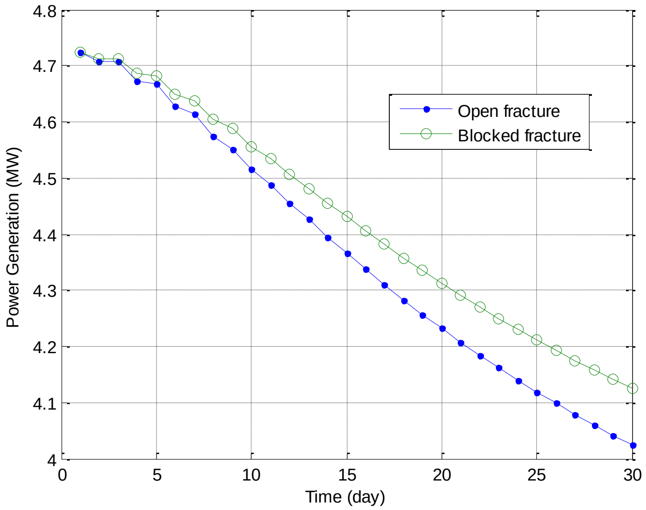

Figure 9: Comparison of the power generation capacities of the open and blocked fractures due to thermal drawdowns.

4. DISCUSSION OF THE RESULTS OF MODEL SIMULATIONS

4.1 Observations from the Velocity and Temperature Maps

The numerical simulation results support the common-sense expectations regarding the shape of vector fields of the fracture flow and also the temperature maps. The coolant flow in the unblocked fracture tends to favor the preferential, shortest distance along the diametrical direction. The velocity vectors are very small around the peripheral surface areas in the unblocked fracture, seen in Fig. 5. It is especially serious of problem in lens-shaped fractures (the case shown in the figures) where the open fracture aperture tapers toward zero at the edges. The consequence of weak coolant fluid distribution along the edges is inefficient heat removal from the large surface area around large radii of the fracture, manifested by high temperatures around the edges in the temperature map in Fig. 7.

On the other hand, the blockage of the coolant flow by the grouted island in the center forces the flow toward the edges as it has been expected, shown in Fig. 6. The effect of the change of the coolant fluid distribution is beneficial for heat extraction. The temperature field map shows lower temperatures due to higher rates of heat removal around the edges than those in the unblocked fracture, shown in Fig.8.

4.2 Observation from the Power Drawdown Trend

It is not surprising that the outcome is a higher geothermal power extraction capacity from the blocked than the open fracture, resulting in lower thermal drawdown, shown in Fig. 9. This is in spite the fact that the overall, direct heat transfer surface area is about 10% lower in the blocked fracture case; and that the three-dimensional heat flow effects have not been kicked in amid the low simulation time period of only 30 days. At longer time, this 10% loss of convective surface for immediate heat exchange is supposed to be fully recovered as the resultant thermal resistance for power extraction coming dominantly from heat conduction resistance from the strata and not from that of the heat transfer on the fracture surface. Therefore, the grouting island is indeed an efficient “fracture permeability control” element in the new EGS arrangement to improve the efficiency of energy recovery.

4.3 Fracture Stability and Low Parasite Energy Loss in the New EGS Arrangement

A large maximum fracture aperture of 0.02 m is assumed which is quite achievable with the injection of hardening grout into the EGS fracture. This is a transformative element of the new EGS solution which aims at using an unusually large fracture aperture and a permanently stabilized geometry for the entire operating life of the system.

Parasite energy loss an EGS system is caused by the necessary pumping energy due to pressure loss mainly within the fracture system. The narrow fracture in a “classic” EGS is kept open by a large pressure difference due to friction resistance in typically very tight fractures in addition to an occasionally applied back pressure. For example, a fracture aperture of typically 0.0016 m was achieved in the Fenton Hill EGS, resulting in a high pressure loss of 90 MPa (90 bar) and significant parasite power loss due to friction. The EGS fracture of approximately of the same lateral size but with increased aperture to 0.02 m with the grouted support island requires only less than 1 bar pressure difference to maintain the coolant fluid flow in the planar fracture.

4.4 Critical Elements of the New EGS with the WFW Flow System

There are many obstacles imaginable in the way of creating first a new system. The mitigation of many foreseeable problems are addressed in an invention disclosure (WIPO, 2017). Critical elements seen are: (1) the simultaneous task of drilling into the direction of an unknown fracture plane to be the osculating plain of the drilling section; (2) the tasks of drilling and tryout fracturing so task 1 can be continuously checked for quality assurance during construction; (3) the task of maintaining a continuous flow connection between the planar fracture(s) and the well for the WFW connections at the required well sections and assessing the quality during construction; (4)

the completion of the planar fractures with the delivery of the grout into the desired area in the center of each planar fracture; and finding the right order of tasks (1) through (4) to accomplish the construction of the new EGS system. Further studies are recommended to address these critical elements and remove all foreseeable obstacles from the routine application of the new EGS solution for wide-scale geothermal energy supply.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A new solution for the arrangement and for the creation of an EGS is presented with a promise of overcoming major uncertainties and risks associated with all the currently considered and published EGS systems utilizing zip fractures.

The main advantage of the new EGS is its arrangement allowing for step-by-step engineering creation under continuous control and quality check for avoiding risks and geohydrologic impasses. The arrangement of the new EGS stands on working hypotheses known to be compatible with current hydrologic and rock mechanics principles.

The geothermal energy extraction efficiency of the new EGS is proven to be better than a conventional EGS of the same size under the same in situ conditions by numerical simulation.

The new EGS having a permanently propped, grouted fracture system is expected to be free of continuous and systematic aperture change in response to operating injection pressure and temperature changes known to be the main characteristics of currently used EGS arrangements.

Consequently, lower pumping energy loss and significantly lower seismic disturbances are expected in the EGS due to the stabilized fracture geometry at generous fracture apertures.

The new EGS system has many strategic advantages with a main disadvantage of being unconventional for the drilling and fracturing sequence

5.2 Recommended Follow-Up Studies

Experiments are planned at the Miskolc University, Hungary, as part of a funded research project, PULSE to study grouting injection into simulated fractures in scaled laboratory arrangements. Furthermore, small-scale, in situ fracturing experiments are planned in the PULSE project to check effective fracture geometry in wing fractures.

ACKNOWLEDGEMENTS

The research was carried out with the support of the GINOP-2.3.2-15-2016- 00010 “Development of enhanced engineering methods with the aim at utilization of subterranean energy resources” project of the Research Institute of Applied Earth Sciences of the University of Miskolc in the framework of the Széchenyi 2020 Plan, funded by the European Union, co-financed by the European Structural and Investment Funds.

REFERENCES

Brown, D.W., Duchane, D.V., Heiken, G., and Hriscu, V.T.: Mining the Earth’s Heat: Hot Dry Rock Geothermal Energy. Springer-Verlag Berlin Heidelberg (2012)

Danko, G., Bahrami, D., and Vazquez, R.: Fracture and Flow System Modeling Method for an EGS Reservoir. *Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24,* (2016), 1-10.

Danko, G. and Bahrami, D.: Dynamic Model of Discrete Fracture Opening Under Fluid Injection. *Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13,* (2013a), 395-404.

Danko, G. and Bahrami, D.: EGS Model Adaptation and Forecasting Studies with MULTIFLUX. *Geothermal Resources Council Transactions, Vol. 37,* (2013b), 141-147.

Ghassemi, A., Tarasovs, S., and Cheng, A.H.-D.: A 3-D Study of the Effects of Thermomechanical Loads on a Fracture Slip in Enhanced Geothermal Reservoirs. *International Journal of Rock Mechanics & Mining Sciences*, v. 44, (2007), 1132-1148.

Ghassemi, A.: Reservoir Stimulation: Multi-Stage Fracturing and Mixed-Mode Fracture Propagation: Some Insights from Numerical Simulations. *2nd GRC Reservoir Stimulation Workshop Sacramento, CA Oct*. (2016).

Murphy, H., Tester, J., Grigsby C., and Potter, R.: Energy Extraction from Fractured Geothermal Reservoirs in Low Permeability Crystalline Rock. *Journal of Geophysical Research,* 86, B8, (1981), 7145-7158.

Danko, G.: Functional or Operator Representation of Numerical Heat and Mass Transport Models. *ASME J. of Heat Transfer,* vol. 128, (2006) 162-175.

Danko, G.: MULTIFLUX V5.0 Software Documentation Qualification Documents, Software Tracking Number: 1002-5.0-00, *Software Management Office, Berkeley National Laboratory*. (2008), 1-1002

Department Of Energy: History of Geothermal Energy Research and Development in the United States, Reservoir Engineering 1978-2006. *Geothermal Technology Program*, (2006), 59-61.

Sneddon, I.N.: The Distribution of Stress in the Neighbourhood of a Crack in an Elastic Solid. Proc R. Soc. Lond. A 1946 187, doi: 10.1098/rspa. 1946.0077 (Downloaded from http://rspa.royalsocietypublishing.org/content/187/1009/229#related-urls on April 24, 2014), 229-260.

Smith, M. C., Hendron, R. H., Murphy, H. D., & Wilson, M. G.: Hot Dry Rock Geothermal Energy Development Program. *Annual Report, Fiscal Year 1987. Los Alamos National Laboratory, New Mexico*, (1989).

Taron J., D. Elsworth, and Min, K.: Numerical Simulation of thermal-hydrologic-mechanical-chemical processes in deformable, fractured porous media. *International Journal of Rock Mechanics & Mining Sciences*, v. 46, (2009) 842-854.

WIPO- : Systems and Methods for Enhancing Energy Extraction from Geothermal Wells. *International Publication* WO/2017/173329 A1 (PCT/US2017/025473) (2017), 1-17.

White, M., Fu, P., McClure, M., Danko, G., Elsworth, D., Sonnenthal, E., Kelkar, S., and Podgorney, R., “A suite of benchmark and challenge problems for enhanced geothermal systems.” Geomech., Geophys., Geo-energ., Geo-resour.,Springer Int., DOI 10.1007/s40948-017-0076-0., pp. 1-39.

Xu, T. and Pruess, K.: Modeling multiphase non-isothermal fluid flow and reactive geochemical transport in variably saturated fractured rocks: 1. Methodology. *American Journal of Science,* (2001) 301, 16-33.

Zhang, X., Jeffrey, R.G., Bunger, A.P. and Thiercelin, M.: Initiation and growth of a hydraulic fracture from a circular wellbore. *International Journal of Rock Mechanics and Mining Sciences* 48.6 (2011), 984-995.