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Radial jet drilling for Dutch geothermal applications

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ABSTRACT

Radial jet drilling is a well stimulation technique that has drawn the attention of operators of geothermal doublets suffering from injectivity problems and therefore poor doublet performance. With radial jet drilling, several open hole laterals are created using hydraulic jetting from the main well bore, which enhance the connectivity of the well to the rock and thereby the well productivity or injectivity.

Simulations on representative Dutch geothermal doublets show a potential performance increase by a factor of up to 3 when 8 laterals of 100 meter are successfully jetted and geological conditions are favourable. For fewer or shorter laterals, or in less favourable conditions, the performance increase is considerably less. It should be noted that there appears to be a mismatch between modelled performance enhancement and observed enhancement as documented in publications. Major uncertainties in the production estimates are the long-term (>1 year) stability of the jetted laterals, the actual achieved trajectory of the lateral (which is not observed) and the effect of sub-surface heterogeneity.

1. INTRODUCTION

In the Netherlands, there are currently about a dozen operational geothermal systems (doublets). They target aquifers of about 2 to 3 km deep in sedimentary rock. The temperature of the produced water is 60-90°C and, after usage of the thermal energy, the water is injected back into the formation at a temperature of 25-35°C. When a flow rate through the system of about 150 m^3/hour is maintained, the installation produces in the order of 10 MW of power. The efficiency (or coefficient of performance) of installations is highly dependent on the geological setting (for example, permeability of the rock), the properties of the water and performance of the wells.

A number of geothermal operators have experienced disappointing injectivity in the injection well of their doublets, which can be caused by various problems (see, for example, Degens et al., 2012). To solve some of the injectivity issues, well stimulation (e.g. acidizing or hydraulic fracturing) can be used, which is aimed at improving the injectivity (or productivity). The suitability of any stimulation approach will depend on the specific situation of a geothermal system.

In this paper, a relatively new technique in which open-hole, small-radius laterals are created using hydraulic jetting (called 'radial jet drilling') was evaluated as a potential stimulation technique for the Dutch geothermal sector. First an overview on radial jet drilling is presented. Next the potential production increase for typical Dutch geothermal systems is presented. The analysis of the potential production increase is largely based on a report by Peters et al. (2015).

2. RADIAL JET DRILLING

With radial jet drilling, several open hole laterals are jetted from the main well bore, which enhance the connectivity of the well to the rock and thereby the well productivity or injectivity. In contrast to conventional drilling techniques, the laterals are created using hydraulic jetting. Attractive features of radial jet drilling are the low volumes of water required and the high level of control compared to for example hydraulic fracturing, resulting in lower costs and less risk (e.g. Cinelli and Kamel, 2013). In the oil and gas industry this technology has been used in over 2000 wells. No documented field application in a geothermal well has been found, although the potential benefit of micro-holes has been recognized (Finsterle et al., 2013). A possible reason is that many geothermal systems are developed in hard rock rather than the sedimentary rocks in which radial jet drilling is developed. For hard rock, combinations of drilling and jetting have been investigated (e.g. Kolle et al., 2009).

The goal of radial jet drilling was originally focused on reducing pressure drop near the well (Dickinson et al., 1993; Buset et al., 2001) for example in case of well bore damage creating a skin. However, with the increasing length, the radials move in the direction of conventional multi-laterals and are able to connect the reservoir better to a single well.

As with any stimulation technique, the suitability of radial jet drilling depends on the specific situation of the geothermal system. The formation rock for example needs to have a minimum porosity of about 3-4% to be jettable. The most important criteria for the well are the minimum diameter (about 0.1 m (4 inch)) and maximum along hole depth (about 5 km). Application issues for geothermal wells are the (large) deviations of the wells and the use of open hole completions and/or sand screens/liners rather than casing. Until recently jetting in deviated well bores was not possible (Seywald and Marschall, 2009; Ragab, 2013), but recently this is offered by some companies (Peters et al., 2015).

Two aspects of jet drilling are very important for its performance: the rock breaking capability and the forward thrust. The rock breaking capability of a water jet depends on several processes: surface erosion, hydraulic fracturing, poro-elastic tensile failure and (possibly) cavitation (Buset et al., 2001). Surface erosion is the main effect in conventional drilling. Since the forward speed of jetting is faster than that of conventional drilling, the other effects add to the rock breaking capability. The rock breaking ability of a jet and its dependence on jetting parameters was recently studied by Bi et al. (2014), Lu et al. (2015) and Liu et al. (2015).

The second aspect is the forward thrust needed to advance in the formation, which is provided by the jetting force of the back-facing jets and the underpressure force generated by the forward jet (pull-effect, Buset et al., 2001). Due to the complex processes around the nozzle head, these are difficult to quantify (Wang et al., 2016). The total forward thrust at least depends on the total flow rate, the division of flow between the backward and forward nozzles, the width of the hole and the stand-off distance (distance between the nozzle and the formation) (Buset et al., 2001; Guo et al., 2009; Li et al., 2015). A disadvantage of the backward jets is that a part of the jetting power is lost to these backward jets (Balch et al., 2016).

Compared to the large number of wells that is reported to have been stimulated with radial jetting (see for example http://www.radialdrilling.com/), documented cases are relatively rare. The following cases are described in literature:

- Golfo San Jorge Basin and Neuquen Basin in Argentina (Bruni et al., 2007)
- Mamore block, Bolivia (deep application) (Cirigliano and Blacutt, 2007)
- Usink reservoir (Ursegov et al., 2008)
- Three wells (Bad Hall) (Seywald and Marschall, 2009)
- Urtabulak field, Uzbekistan (Elliott, 2011)
- Belayim field, Egypt (Ragab, 2013; Ragab and Kamel, 2013)
- Tarim field, China (Teng et al., 2014)
- Donelson West field, Kansas, US (Cinelli and Kamel, 2013; Kamel, 2014)
- Liaohe Oilfield, China (Li et al., 2000; Chi et al., 2015)
- Anonymous well in China (Wang et al,. 2016)

The reported productivity improvement from implementation of radials in the field are highly variable. For many wells a good initial increase in production is reported. Several wells showed no or hardly any response to the radial stimulation (no explanation offered). In many wells the initial increase in production declined rapidly and disappeared within a year. This can be caused by pressure decline in the reservoir due to production, but also because the radials may not be stable. An interesting application is in the Usink Permian-Carboniferous reservoir (Ursegov et al., 2008). Radial application alone did not increase productivity in this fractured reservoir with heavy oil, probably due to the low mobility of the oil. However, the radials did improve the effectivity of the production achieved with steam. Another interesting application is the one by Wang et al (2016), because it is the most extensively monitored and analysed in terms of the jetting process itself. They showed for example the effect of heterogeneity on the jetting process. Unfortunately they did not mention the change in the productivity of the well in which the 6 laterals were jetted. In the few cases, in which well tests were done before and after radial stimulation, no increase in productivity could be detected. Overall, best performance of the radial stimulation was observed for cases with near-well damage.

3. POTENTIAL PRODUCTION INCREASE

3.1 Methods

Two different methods were used to calculate the increase in productivity resulting from adding radials to a well:

- A semi-analytical method which can only simulate homogeneous cases and vertical wells. This approach is referred to as Analytical Element method (AEM). The AEM method is developed in-house and is documented in Egberts et al. (2013) and Egberts and Peters (2015). The AEM tool currently cannot simulate a deviated well in combination with radials.
- A full numerical reservoir simulation model which is used to validate the results from the AEM tool, estimate the effect of a non-vertical backbone and estimate the impact of radials in heterogeneous cases.

3.2 Homogeneous case

Two formations were identified as most relevant for the existing geothermal doublets in the Netherlands: the Permian Slochteren sandstone and the Cretaceous Delft sandstone. As a first step, a sensitivity analysis was done to determine the most important parameters for the relative performance improvement resulting from radial implementation. These were found to be the thickness of the reservoir and the anisotropy (vertical over horizontal permeability). Although permeability has a strong impact on overall productivity, the impact on the *relative increase* due to radial stimulation is limited. Since the height and anisotropy of the two currently used formations in the Netherlands (Slochteren sandstone and Delft sandstone) are quite similar, a general setup is chosen. For reservoir height a range of 50 to 200 m is used and for anisotropy a range of 0.01 to 1 is used. From these ranges, 500 samples were taken and the increase in productivity was calculated. Further input used for the simulations is presented in Table 1. The increase in productivity (PIF = Productivity Improvement Factor) is defined as productivity of the stimulated well divided by the productivity of the unstimulated well. Please note that in this paper the term productivity is used for both the injector and producer well.

Table 1: Input settings for the homogeneous cases.

Depth	2500 m
Initial pressure	25 MPa (250 bar)
Injection pressure	1.4 MPa (14 bar)
Porosity	0.2
Permeability	$1 \cdot 10^{-14}$ m^2 (100 mD)
Well bore radius	0.076 m (3 inch)
Radial radius	0.025 m (1 inch)
water viscosity	0.54 mPa·s (0.54 cP)

The simulations were done for 6 radial well configurations. The 6 configurations are: 8 radials of 100 m (Figure 1), 8 radials of 50 m and 4 radials of 100 (Figure 2), 50, 25 or 10 m. For all cases the vertical well is perforated over the entire thickness of the reservoir and is assumed to have zero skin. The radials are open hole and are assumed to have a constant diameter of 0.051 m (2 inch) and no skin.

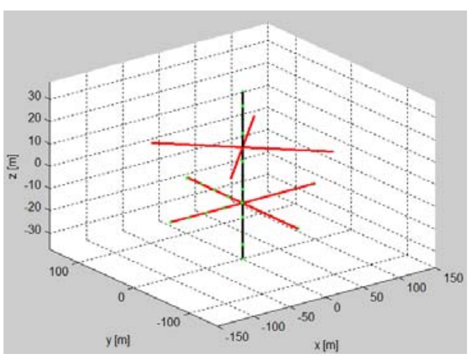

Figure 1: Radial well with 8 radials of 100 m.

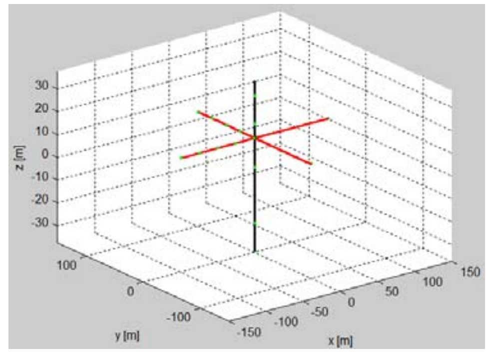

Figure 2: Radial well with 4 radials of 100 m.

In Figure 3, the results for the runs with 8 radials of 100 m is shown. Each circle represents a run with a different choice for net reservoir height and anisotropy. For increasing reservoir height, the effect of the radials decreases (lower PIF). Also for strongly anisotropic reservoirs, the improvement in productivity due to the radials decreases. This is due to the fact that the radials are horizontal and the inflow decreases with lower vertical permeability, whereas the main well bore is vertical and does not decrease in productivity with lower vertical permeability.

Because most geothermal wells in the Netherlands are not vertical, reservoir simulation runs were done to test the effect of a deviated well bore. The settings of the reservoir model are the same as shown in Table 1, with a net reservoir height of 75 m and anisotropy (kv/kh) is 0.1. The results are shown in Table 2. The increase in productivity is slightly higher for the deviated well than for the vertical well.

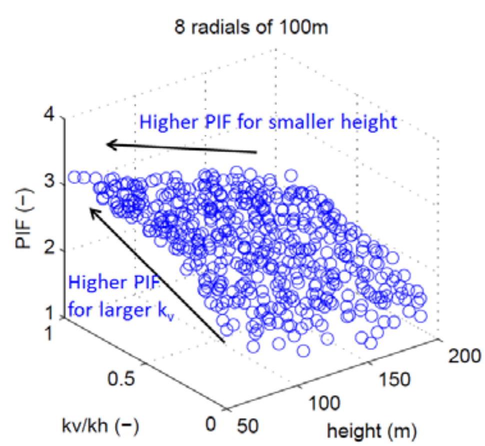

Figure 3: Illustration of the main conclusions showing the increase in PIF (productivity of stimulated well / productivity of the unstimulated well) as a function of anisotropy and reservoir height for stimulation with 8 radials of 100 m long.

Table 2: Increase in productivity (PIF) for radial stimulation in a vertical well and a 35° deviated well.

	Vertical	35°
8 radials of 100 m	2.25	2.31
4 radials of 100 m	1.69	1.73
4 radials of 25 m	1.19	1.23

Figure 4 shows the averaged results for all 6 radial well configurations. The productivity increase (PIF) is shown as a function of the total length of the radials that was jetted. Overall, the increase is almost linear. Jetting a total length of 600 m would result in a doubling of the productivity. However, the configuration of the radial well influences the results: 4 laterals of 100 m increase productivity more than 8 laterals of 50 m.

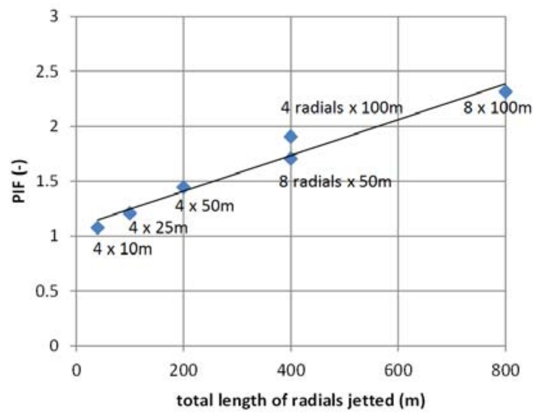

Figure 4: PIF (productivity of stimulated well / productivity of the unstimulated well) as a function of total radial length jetted.

3.3 Heterogeneous case

All simulations so far were done for homogeneous cases. To gain insight into the effect of heterogeneity, two cases with heterogeneous permeability were evaluated:

- A layered reservoir: main heterogeneity in vertical direction
- A 'patchy' reservoir: main heterogeneity in horizontal direction

For these cases the semi-analytical approach is insufficient. Therefore, reservoir simulation was used for these evaluations (see Section 3.1). All the simulations are done for a deviated well.

Layered reservoir

For the layered reservoir, the input is straightforward. It is assumed that the layers are perfectly horizontal. The good reservoir layers have a permeability of 200 mD, the poor-quality layers 5 mD. Porosity is 0.2 and 0.005 respectively. 25% of the reservoir height is poor quality, which is consistent with NTG = 0.75. In fact, this simulation could be interpreted as a case in which NTG is taken into account explicitly. Figure 5 shows the definition of the layers. The length of the radials is sufficient to cross the low-permeability layers. The deviated backbone of the well is clearly beneficent for this case, because it ensures that the radials are not located in a good layer that is trapped between low-permeability layers. An open question is whether the jetting process is able to cross the poor-quality layers.

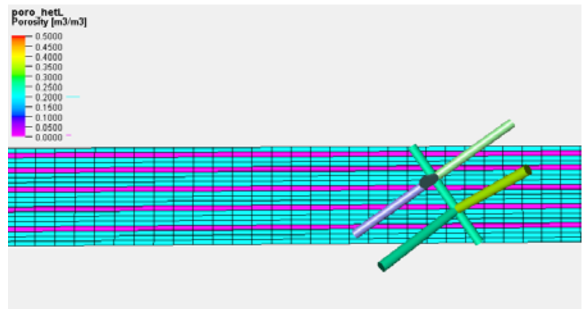

Figure 5: Overview of the layered reservoir showing porosity (blue is high porosity, pink is low porosity) and a radial well with 8 radials of 100 m long with 2 kick-offs (4 radials per kick-off).

Reservoir with horizontal heterogeneity

For reservoirs with horizontal heterogeneity, an infinite number of model setups can be considered. To limit this scope, two main considerations were taken into account:

1. The range in permeability should be large (more than 3 orders of magnitude) to get a clear effect.

2. The scale of the heterogeneities should be in the order of magnitude of the length of the radials. For example, if the size of the low perm areas is small compared to the well/radials, they will average out in the result and little impact is expected.

The pattern and size of the heterogeneity is based on the description in Henares et al. (2014) of the Slochteren formation in the Koekoekspolder area in the Netherlands, with elongated NNE-SSW trending shapes. The porosity was generated using sequential Gaussian simulation with a mean of 0.2, standard deviation of 0.065 and variogram settings of 500 m (major direction), 200 m (minor direction) and 20 m (vertical). The azimuth of the major direction is 30°. The permeability is not generated separately, but based on the porosity via the following relationship that results in a log-normal distribution for permeability in the horizontal direction (permxy):

$$\text{permxy}=10^{(-0.65+10*\text{poro})} \qquad [1]$$

The vertical permeability that was used is 10% of the horizontal permeability. Using these settings, five realisations of the porosity and permeability were generated. An example is shown in Figure 6.

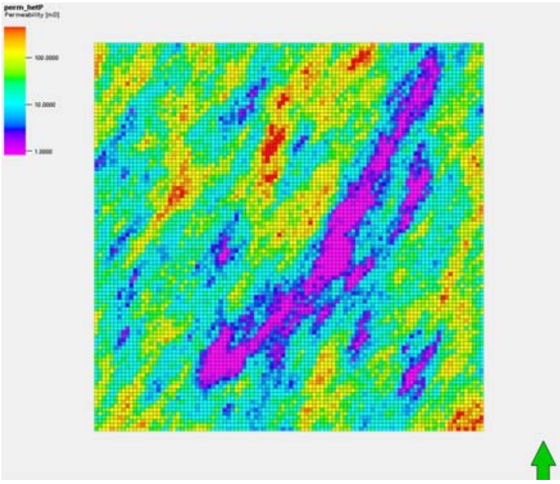

Figure 6: Example of the horizontal permeability for the case with heterogeneity in horizontal direction.

It should be realised that for these simulations it is assumed that the radials can be jetted as planned. It is possible however that in a highly heterogeneous formation, the jetted radials do not follow a straight path. When very tight sections are encountered, the jetting process might be stopped completely. Reversely, when suddenly very friable sections are encountered, jetting may also stop due to a wash-out and the resulting lack of forward thrust.

The results of these simulations are shown in Table 3 and compared to the results for a homogeneous case with the same well configuration. On average, the effect of the heterogeneity as tested here is limited. However for the horizontal heterogeneity the range in the results is large: for four 100m-long radials, PIF ranges from 1.44 to 2.29 for the five realisations tested here.

Table 3: Increase in productivity (PIF) for radial stimulation in heterogeneous reservoirs.

	homogeneous	heterogeneous	
		vertical	horizontal*
8 radials of 100 m	2.31	2.29	2.30
4 radials of 100 m	1.73	1.70	1.80
4 radials of 25 m	1.23	1.20	1.21

* Average of 5 realisations.

3.5 Discussion

The simulation results presented in the previous sections are very positive. It should be realised however that these are theoretical results assuming the radials are jetted perfectly and that the presented productivity increase is compared to a well without skin. From the highly variable results reported in literature, it can be concluded that the results in practice are not consistent. It appears that the actual performance falls short of the theoretical performance. What causes this discrepancy is not clear, but many explanations are possible, such as not achieving the desired length of the radials, unfavourable position of the radials (the radials cannot be steered or observed), skin due to for example clay swelling and instability of the radial. Within the EC funded Horizon 2020 project SURE (Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource) the radial drilling technology will be investigated in more depth for geothermal applications (Reinsch and Bruhn, 2016).

4. CONCLUSIONS

The theoretical productivity improvements as a result of well stimulation by radials in homogeneous reservoirs are very promising for the Dutch settings. Even for shorter radials a considerable increase in productivity can be achieved (for example a 50% increase in productivity for four 50m-radials in a vertical well). Maximum achieved productivity increase is around 230% for 8 radials of 100 m long for a vertical well. Jetting radials from a deviated well, does not harm the effect of the radials. In the cases examined in this report, the productivity increase of the radials even improved for a deviated well, because the vertical coverage is better for a deviated well.

Overall, the realised performance as documented in literature appears to fall short of theoretical performance. The reasons for this are usually not clear from the documentation. Many open questions remain at this point in time as to the jetting process itself and its performance in layered, heterogeneous and fractured formations. However, it should be realised that the same is true for other well stimulation techniques such as hydraulic fracturing or acid stimulation.

REFERENCES

Balch, R.S., Ruan, T., Savage, M., Harvard, J.: Field testing and validation of a mechanical alternative to radial jet drilling to improving recovery in mature oil wells, (2016), SPE-180410-MS.

Bi, G., Li., G., Shen, Zh., Huang, Zh. and Yang, R. : Design and rock breaking characteristic analysis of multi-jet bit on radial horizontal drilling, Proceedings UDC 622.24:622.276, (2014), DOI: 10.5510 /OGP20140300206.

Bruni, M., Biassotti H. and Salomone G.: Radial Drilling in Argentina, (2007), SPE107382.

Buset, P., Riiber, M. and Eek, A.: Jet Drilling Tool: Cost-Effective Lateral Drilling Technology for Enhanced Oil Recovery, (2001), SPE 68504.

Chi, H., Li, G., Huang, Zh., Tian, S. and Song, X.: Maximum drillable length of the radial horizontal micro-hole drilled with multiple high-pressure water jets (2015) *J. of Natural Gas Science and Engineering* 26, (2015), 1042-1049. DOI: 10.1016/j.jngse.2015.07.044

Cinelli, S. D. and Kamel, A. H.: Novel Technique to Drill Horizontal Laterals Revitalizes Aging Field, presented at the SPE/IADC Drilling Conference, Amsterdam, (2013), SPE/IADC 163405.

Cirigliano, R.A. and Talavera Blacutt, J.F.: First experience in the application of radual perforation technology in deep wells, (2007), SPE 107182.

Degens, G., Zijp, M.H.A.A., de Boer, J.P., Obdam, A.N.M. and Jedari Eyvazi, F.: TNO Report into the Causes and Solutions to Poor Well Performance in Dutch Geothermal Projects, (2012), TNO Report 2012 R10719. Available via http://www.nlog.nl/nl/geothermalEnergy/geothermalEnergy.html

Dickinson, W., Dykstra, H., Nordlund, R. and Dickinson, W.: Coiled-Tubing Radials Placed by Water-Jet Drilling: Field Results, Theory, and Practice, (1993), SPE26348

Egberts, P.J.P., Shatyrbayeva I. and Fokker P.A., Well inflow modelling for wells not aligned to a numerical grid, RCSC September 2013, (2013) SPE 165986.

Egberts, P.J.P. and E. Peters.. A Fast Simulation Tool for Evaluation of Novel Well Stimulation techniques for Tight Gas Reservoirs, (2015), SPE174289

Elliott, S., 2011, Coiled-tubing method drills radial laterals to improve oil production from a depleted reservoir. *World Oil*, Oct (2011).

Finsterle, S., Zhang, Y., Pan, L., Dobson, P. & Oglesby, K.: Microhole arrays for improved heat mining from enhanced geothermal systems, Geothermics, (2013).

Guo, R., Li., G., Huang., Z., Tian, S., Zhang, X. and Wu, W.: Theoretical and experimental study of the pulling force of jet bits in radial drilling technology *Pet.Sci.* 6, (2009), 395-399. DOI: 10.1007/s12182-009-0060-6.

Henares, S., Bloemsma, M.R., Donselaar, M.E., Mijnlieff, H.F., Redjosentono, A.E., Veldkamp, J.G. and Weltje, G.J.: The role of detrital anhydrite in diagenesis of aeolian sandstones (Upper Rotliegend, The Netherlands): implications for reservoir-quality prediction. *Sedimentary Geology* 314, (2014), 60-74. Doi: 10.1016/j.sedgeo.2014.10.001.

Kamel, A.H.: RJD revitalizes mature Kansas oil field. *Oil & Gas Journal* 112 (10) (2014).

Kolle, J.: Jet TurboDrill^{TM} for Enhanced Geothermal System Development, Project Report TR-153, (2009). U.S. DOE Grant No. DE-FG02-08ER85156

Li, Y., Wang, C., Shi, L. and Guo, W.: Application and Development of Drilling and Completion of the Ultrashort-radius Radial Well by High Pressure Jet Flow Techniques (2000) SPE 64756.

Li, J., Li, G., Huang, Z., Song, X., Yang, R. and Peng, K.: The self-propelled force model of a multi-orifice nozzle for radial jet drilling. *J. Natural Gas Science and Eng.* 24, (2015), 441-448. DOI: 10.1016/j.jngse.2015.04.009

Liu, X. Liu, S. and Ji, H.: Numerical research on rock breaking performance of water jet based on SPH. *Powder Technology* 286, (2015), 181-192. DOI: 10.1016/j.powtec.2015.07.044

Lu, Y., Huang, F. Liu, X. and Ao, X.: On the failure pattern of sandstone impacted by high-velocity water jet. *Int. J. of Impact Eng.* 76, (2015), 67-74. DOI: 10.1016/j.ijimpeng.2014.09.008.

Peters, E., Veldkamp, J.G., Pluymaekers, M.P.D. and Wilschut, F.: Radial jet drilling for Dutch geothermal applications (2015) TNO 2015 R10799. Available via http://www.nlog.nl/nl/geothermalEnergy/geothermalEnergy.html

Ragab, A. M. S.: Improving well productivity in an Egyptian oil field using radial drilling technique. J. of Petroleum and Gas Eng., 4(5), (2013), 103-117. Doi: 10.5897/JPGE2013.0153.

Ragab, A.M.S. and Kamel, A.M.: Radial drilling technique for improving well productivity in Petrobel-Egypt (2013) SPE164773.

Reinsch, T. and Bruhn, D.: Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource – The SURE Project. *European Geothermal Congress*, Strasbourg, (2016).

Seywald, M. and Marschall, C.: Usage of Radial Drilling by RAG. *OIL GAS European Magazine* 3/2009, (2009), 114-116.

Teng, X., Yang, P., Li, N., Yang, C., Jin, Y., Lu, Y., Zhou, B., Wang, X., Zhang, F., Li, J., Zhang, T. and Zhou, X.: Radial drilling revitalizes aging field in Tarim : a case study (2014) SPE168282.

Ursegov, S., Bazylev, A. and Taraskin, E.: First results of cyclic steam stimulations of vertical wells with radial horizontal bores in heavy oil carbonates (2008) SPE115125.

Wang, B., Li., G., Huang., Z., Li., J., Zheng., D. and Li, H.: Hydraulics calculations and field application of radial jet drilling. *SPE Drilling and completion* 3, (2016), 71-81. SPE179729.

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