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Flow Performance of the Habanero EGS Closed Loop

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ABSTRACT

Geodynamics Limited has been developing an Enhanced Geothermal System (EGS) in hot granite beneath the Cooper Basin in central Australia since 2002. Four wells have been drilled at the Habanero site to depths exceeding 4,200 m and all four wells have penetrated a major sub-horizontal fault which forms the reservoir within the granite. The temperature in the reservoir has been measured at 244°C at ~4,220 m below surface.

From April to October, 2013, Habanero 4 and Habanero 1 were operated in closed-loop mode, with Habanero 4 as the producer and Habanero 1 as the injector. Circulation was established and maintained with the aid of a surface pump, re-injecting the produced geothermal brine back into the reservoir. The heat produced was used to power a 1 MW_e pilot binary power station.

During the trial, the performance of the closed-loop steadily improved. Production temperatures increased to 215°C and flow rates reaching 19 kg/s at the end of the trial. During the trial, two step-rate tests of the closed-loop system were conducted. These step-rate tests involved operating the closed-loop at several different pump speeds to assess the system performance and the potential for thermosiphon flow.

In an effort to reduce temperature losses in the wellbore, Nitrogen was injected into the tubing-casing annulus part way through the trial period. At the end of the trial, production logs were run in both wells to provide temperature and pressure profiles for each well. These production logs were used to calibrate analytical models of both wellbores and to assess the effect of the Nitrogen.

The performance of this closed-loop will be discussed and compared to an earlier closed-loop trial conducted at Habanero in 2009. By combining surface data, production logs and wellbore models, pressures, temperatures and fluid densities around the closed-loop will be discussed.

1. INTRODUCTION

Geodynamics' Habanero EGS project is located near the township of Innamincka, about 900 km north of Adelaide, South Australia. Four wells have been drilled at the Habanero site to depths exceeding 4,200 m and all four wells have penetrated a major sub-horizontal fault which forms the reservoir within the granite. The temperature in the granite has been measured at 244°C at ~4,220 m below surface and the temperature gradient within the granite is ~ 32°C/km.

Two closed-loop tests have been conducted at Habanero. Wells Habanero 3 (H03) and Habanero 1 (H01) were tested in 2008-2009, with H03 as the producer and H01 as the injector. This first closed-loop test involved circulating brine for a period of 78 days and reached a maximum flowing temperature of 213°C at a maximum daily average rate of 15.6 kg/s (Wyborn, 2009, and Chen and Wyborn, 2009).

From April to October, 2013, wells Habanero 4 (H04) and H01 were tested in closed-loop mode, with H04 as the producer and H01 as the injector. Circulation was established and maintained in both tests with the aid of a surface brine re-injection pump, re-injecting the produced geothermal brine back into the reservoir. The heat produced during the H04-H01 closed-loop test was extracted through a brine heat exchanger and used to power the 1 MW_e Habanero Pilot Plant (HPP).

2. WELLS AND SURFACE EQUIPMENT

2.1 Wells

Both H01 and H04 are essentially vertical wells which have been completed with a production casing set more than 250 m into the granite and a barefoot section across the fault system within the granite. The bare-foot granite section of H04, the producer, was drilled with an 8½" bit, but borehole break-out has resulted in an oval hole equivalent to an average diameter of ~9½". The bare-foot granite section of H01, the injector, was drilled with a 6" bit but again break-out has resulted in an oval hole equivalent to an average diameter of ~7". A summary of the well sections and their lengths and internal dimensions is provided in **Table 1** below.

2.2 Reservoir Conditions

The fault system at Habanero contains over-pressured brine. Static surface conditions have been recorded at H01 in 2005 after the well had been shut-in for 18 months. The static surface pressure recorded was 33.7 MPa (4,900 psi) with brine in the well.

An arbitrary reservoir datum depth has been established at 4,140 m below sea level, approximately the depth of the Habanero Fault half-way between H04 and H01. Static reservoir conditions at this datum have been estimated from production logs and pressure build-up tests to be 244°C and 73.0 MPa (10,600 psi).

Well	Section	Top (metres below ground level)	Bottom (metres below ground level)	Description (OD, weight)	Internal Diameter (inches)
H04	Tubing	0	3,044	7", 41 lb/ft	5.820
H04	Casing	3,044	4,017	9 7/8", 62.8 lb/ft	8.625
H04	Open Hole	4,017	4,142	Granite	~9.5 average
H01	Tubing	0	3,113	4½", 21.6 lb/ft	3.50
H01	Casing	3,113	4,127	7", 29 lb/ft	6.184
H01	Open Hole	4,127	4,237	Granite	~7.0 average

Table 1: Summary of well completion internal diameters and lengths.

2.2 Surface Equipment

Because of the substantial reservoir overpressure, Habanero wells will flow naturally without any need for pumping. The brine flow from H04 was controlled at the well head by a variable control valve which, during closed-loop flow, was mostly fully open to provide minimal pressure losses. From H04, the brine flowed at well head pressure to the brine heat exchanger at the power plant through approx 800 metres of insulated pipe with a nominal ID of 124 mm. From the heat exchanger, the brine was routed through a brine cooler to bring the temperature down to 80°C before entering the brine reinjection pump.

The brine re-injection pump boosted the pressure of the brine by up to 11 MPa (1,600 psi) to return the brine to the reservoir. For the short distance (~20 m) from the re-injection pump to the H01 well head, un-insulated pipe was used with a nominal ID of 80 mm. **Figure 1** shows the location of the main equipment around the Habanero pilot plant and H01 well head.

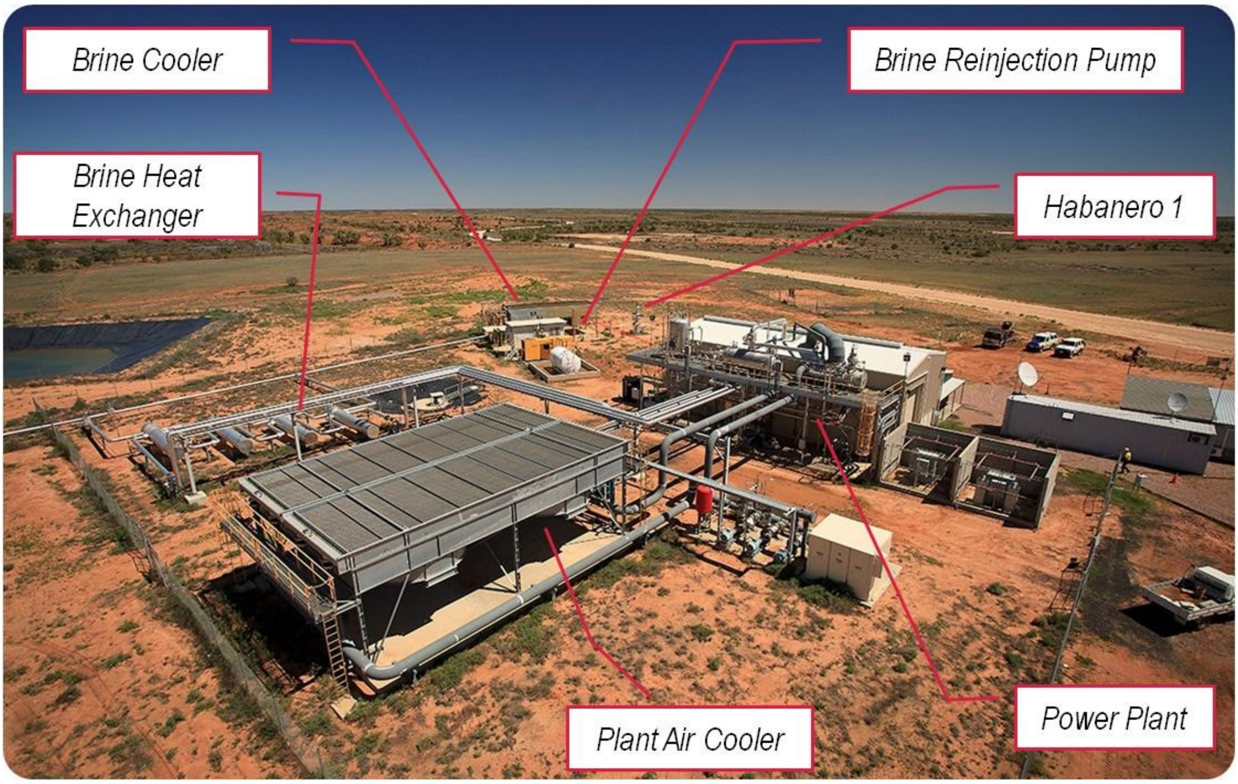


Figure 1: Habanero power plant site, showing location of brine heat exchanger, brine cooler, brine reinjection pump, power plant, plant air cooler and Habanero 1 injection well.

3. CLOSED-LOOP PERFORMANCE

3.1 Flowing Temperature

Because the granite is deeply buried, there is ~4,200 m of borehole to heat in the production well and the same length of borehole to cool in the injection well. The impact of these deep boreholes is a long, slow build-up of flowing temperatures over time, particularly at lower flow rates. **Figure 2** shows the build-up of temperatures in H04 versus cumulative mass flow from the production well. Also shown for comparison is the build-up of temperature at H03 during the H03 closed-loop test in 2008-2009. Flowing temperature at H04 rose steadily over the term of the test, eventually reaching 215°C. Both tests show a continuing trend towards higher temperature even at the end of long periods of stable flow.

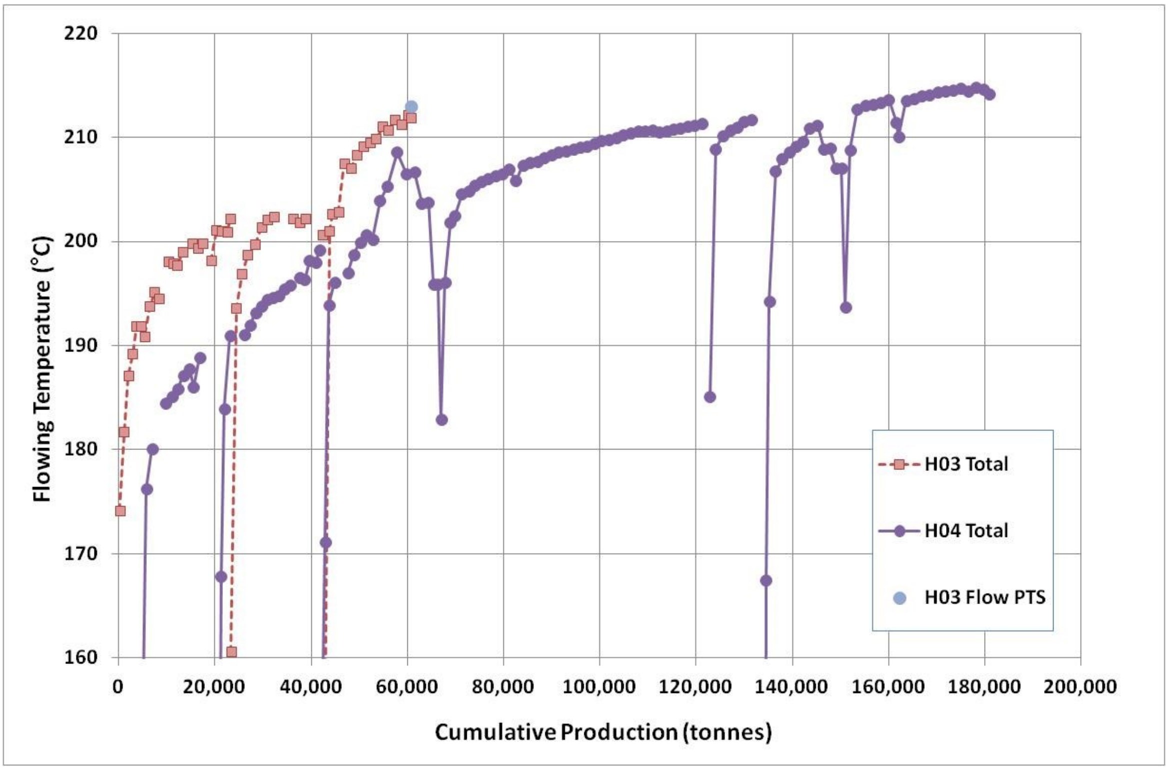


Figure 2: Flowing well head temperature versus cumulative production from H04 and H03, including the flowing PTS temperature reading at the end of the H03 closed loop test.

The lower temperature at H04 early in the closed-loop is interpreted to be a result of the stimulations in October 2012 which placed 36.5 ML of cool water into the Habanero Fault. Some of this temperature drop has been slowly recovered over time. A production log run before stimulation recorded flowing bottom hole temperature of 241°C. A production log run at the end of the H04 closed-loop recorded flowing bottom hole temperature of 236°C, still five degrees less than that recorded before stimulation. The lesson to be taken from this finding is that massive stimulation of future production wells should be avoided unless required to extend the stimulated reservoir area.

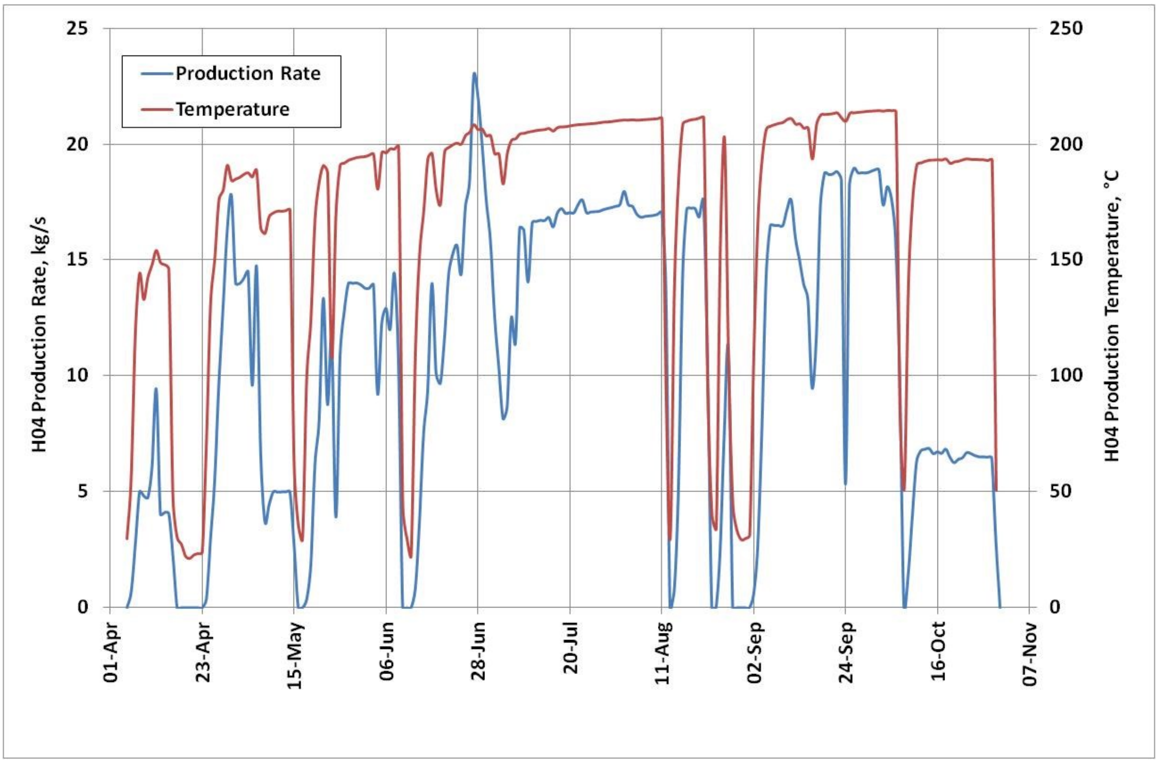


Figure 3: End of Day Flowing Temperature and Average Daily Mass Flow Rate for H04 during the HPP Trial

The slow build-up of wellbore temperature during production also means that wellbore temperatures drop slowly during shut-downs. **Figure 3** displays flowing temperature and rate versus time, showing clearly that temperature returns to trend quickly after shut-downs.

3.2 Step-Rate Testing

Unlike conventional petroleum systems, the performance of two (or more) wells in closed-loop mode is more like the performance of a closed pipe system. Such a system is best characterised by establishing the relationship between flow rate and pressure loss through the system (the wells, the surface pipes and the reservoir), a relationship known in hydraulics as the "system curve". In testing of a deep geothermal closed-loop, there is an additional feature not often observed in classical hydraulics testing: the thermosiphon effect, where flow is driven by the density difference between the hot and the cold well.

Whilst most of the HPP trial was conducted with the pump operating at the maximum allowable speed of approximately 60 Hz, two step-rate tests were conducted to attempt to characterise the system curve and the thermosiphon flow. In these tests, the closed-loop was operated at each rate for 1-2 days to allow sufficient time for operating rates, temperatures and pressures to stabilise. **Figure 4** shows a typical stabilisation of flow parameters during one step of the 2nd step-rate test. The flow rate was changed by altering the flow rate set-point in the control system, and then the whole closed-loop system slowly adjusted to that new rate, taking about 24 hours to reach stability.

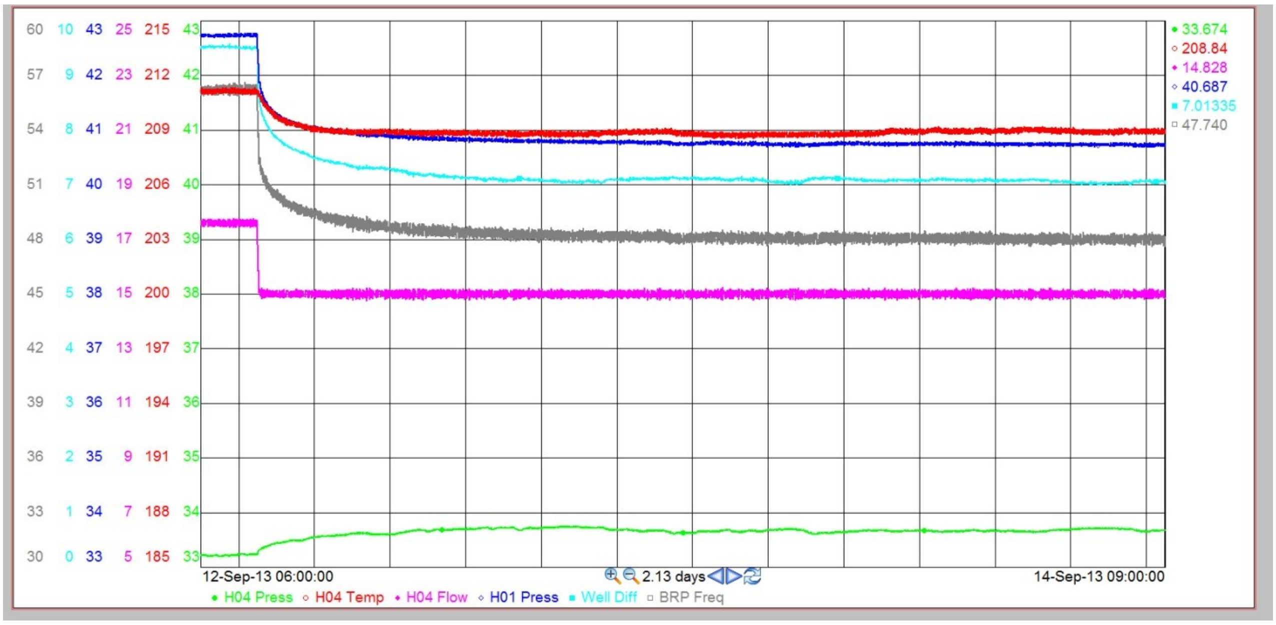


Figure 4: System stabilisation during 2nd Step-Rate Test, showing wellhead pressures (green and dark blue) in MPa, temperature (red) in °C, rate (pink) in kg/s and BRP frequency (gray) in Hz

3.3 First Step-Rate Test

The 1st step-rate test was conducted from 27 June to 5 July, 2013. Only two closed-loop rates (15.9 and 10.4 kg/s) were tested, corresponding to the maximum and minimum operating speeds of the pump.

A thermosiphon test was done by maintaining the pump speed at its minimum operating level and choking back the flow with the control valve at H04 until the pressure differential between H01 and H04 was close to zero, but still positive.

The test results are shown in **Figure 5**. This figure shows closed-loop mass flow rate versus the pressure differential between H01 and H04. This well head pressure differential is effectively the same as the pump head because the pressure losses in the surface pipe work are small. However, by using well head pressure differential instead of pump head, the thermosiphon flow can also be included in the plot.

For the 1st Step-Rate Test, the thermosiphon flow was estimated to be 5.6 kg/s and the system curve was linear. This linearity shows that system pressure loss is proportional to flow rate, which is the condition to be expected with laminar flow as described by Poiseuille's and Darcy's Laws. The test result indicates that there is no discernible influence of turbulence in the system.

3.4 Second Step-Rate Test

The 2nd Step-Rate Test was conducted from 8 to 17 September. Four rates were established with normal operating conditions and again a choked rate was established to assess thermosiphon flow. **Figure 5** shows the results of this second test compared to the first test. The entire system curve had improved, with thermosiphon flow now ~7 kg/s and the maximum flow rate ~2.5 kg/s greater than in the 1st test. Again the system curve is linear, indicating that there are no significant turbulent pressure losses in the system at these rates

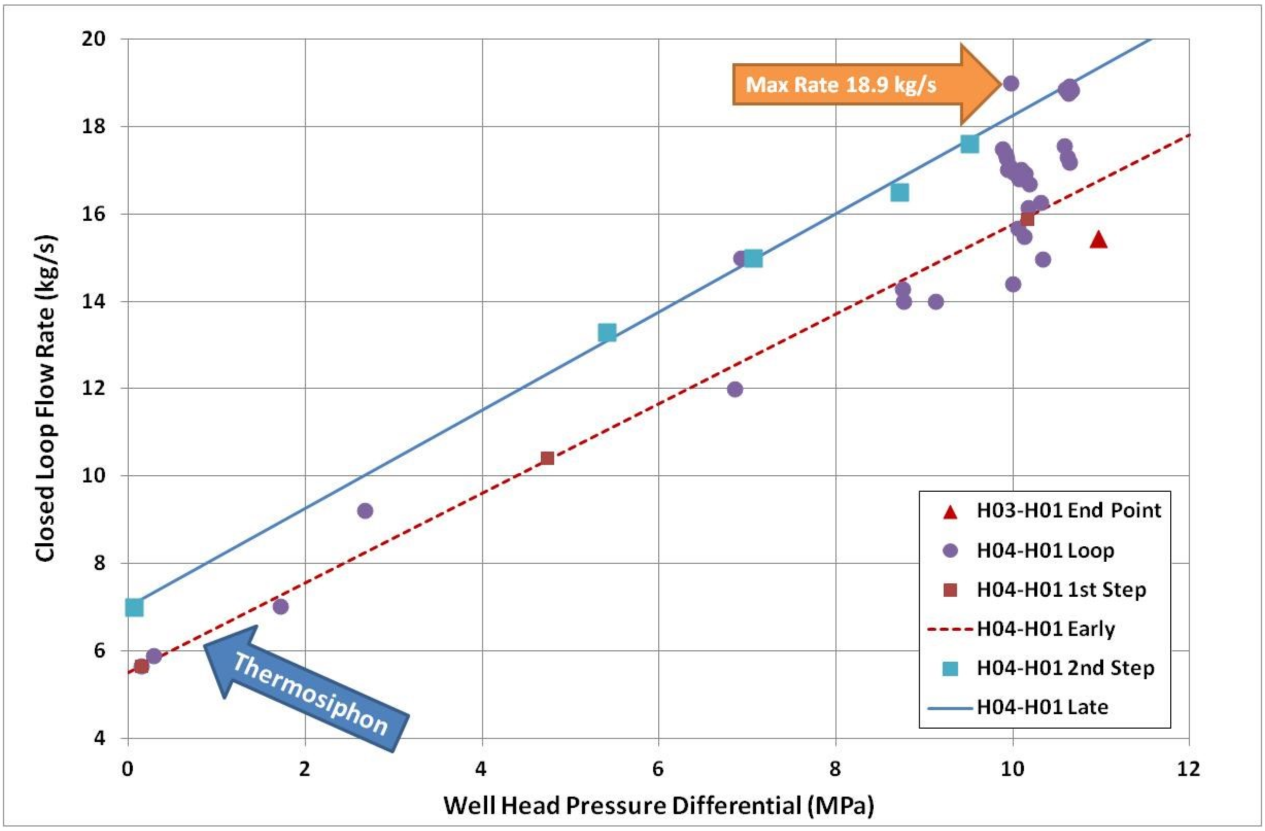


Figure 5: Step-Rate Test results, showing closed-loop flow rate versus well head pressure differential and illustrating thermosiphon effect.

3.5 System Improvement

Figure 5 also shows other closed-loop test results from stable operating periods throughout the HPP trial (purple points). Between the 1st and 2nd step-rate tests, there is a cluster of points trending towards higher rates as the system steadily cleaned up. This trend continued after the 2nd step-rate test, culminating in the highest closed-loop rate achieved to date, 18.9 kg/s. This improvement of the closed-loop is attributed to clean-up of H01 which was damaged by mud losses during drilling. It appears likely that the mud solids are being progressively swept further into the fault system, reducing impedance around the H01 wellbore.

4. PRODUCTION LOGS

4.1 Measured temperature Profiles

Production logs recording pressure and temperature were recorded in both H04 and H01 whilst circulating in closed-loop mode. The logs (**Figure 6**) were recorded as a series of stationary recordings at approximately 100 m intervals, starting at the bottom of the hole and working upwards.

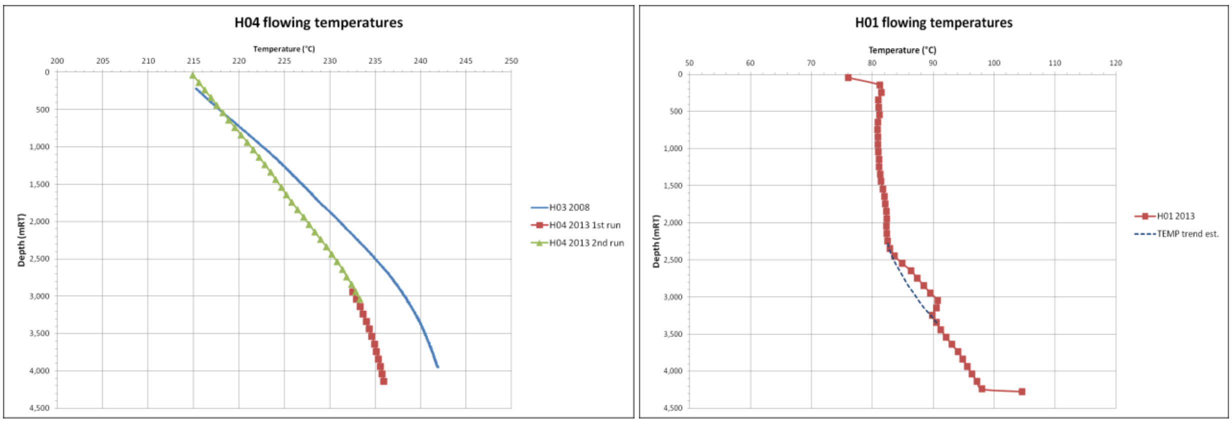


Figure 6: Flowing temperatures recorded in H04 and H01 whilst circulating at 18-19 kg/s

The log of H04 was recorded in two runs because of a tool failure on the first run, but the two runs repeat well and show a smooth temperature profile dropping from 236°C at the fault to 215°C at surface. For comparison, **Figure 6** also shows the temperature profile recorded in H03 during closed-loop flow in 2008-2009. Temperatures in H04 are ~6°C less than in H03 at the fault depth. As mentioned earlier, this cooling is believed to be a consequence of the massive stimulation of H04 conducted in 2012. The reservoir temperature has partly recovered during closed-loop testing, but not fully.

The temperature log of H01 shows the cool re-injected brine near surface remaining at ~81°C down to about 1,000 m before the temperature starts to increase. The profile has a disturbed section around the tubing shoe (3,113 m) because re-injection had to be halted to allow the logging tool to be pulled through the tubing shoe. Over this zone, the wellbore began re-heating during this brief shut-down so recorded temperatures are too high. **Figure 6** shows the estimated temperature trend over this interval for undisturbed conditions.

4.2 Nitrogen Insulation

In an effort to reduce the heat losses from the tubing of Habanero 4, nitrogen gas was injected into the tubing-casing annulus of the well. Approximately 6,200 Sm^3 of nitrogen gas was injected under pressure, displacing the brine in the annulus. At the pressures encountered in the well the nitrogen column extended to between 1,500 and 2,000 metres below surface, depending upon the temperature in the annulus. It was expected that this nitrogen column would have resulted in an inflection in the temperature versus depth trend at the nitrogen-brine interface. However, from the recorded temperature profile in Habanero 4 (**Figure 6, left**) there does not appear to be any significant inflection, indicating that there is no significant insulation effect.

5. WELLBORE MODELLING

Wellbore temperature modeling was done using a commercially available program for modeling fluid temperatures and pressures within wellbores. This program uses the dimensions, specific heat and thermal conductivity of the fluids, tubulars, cement and rocks surrounding the wellbore to model heat flow between the well fluids and the surrounding rocks. Models for H04 and H01 were developed, matching the known casing, cement and hole geometries as closely as possible.

The thermal properties of the surrounding rocks were modeled as five discrete layers, corresponding to five intervals of relatively constant temperature gradient on the static temperature profile (**Figure 7**).

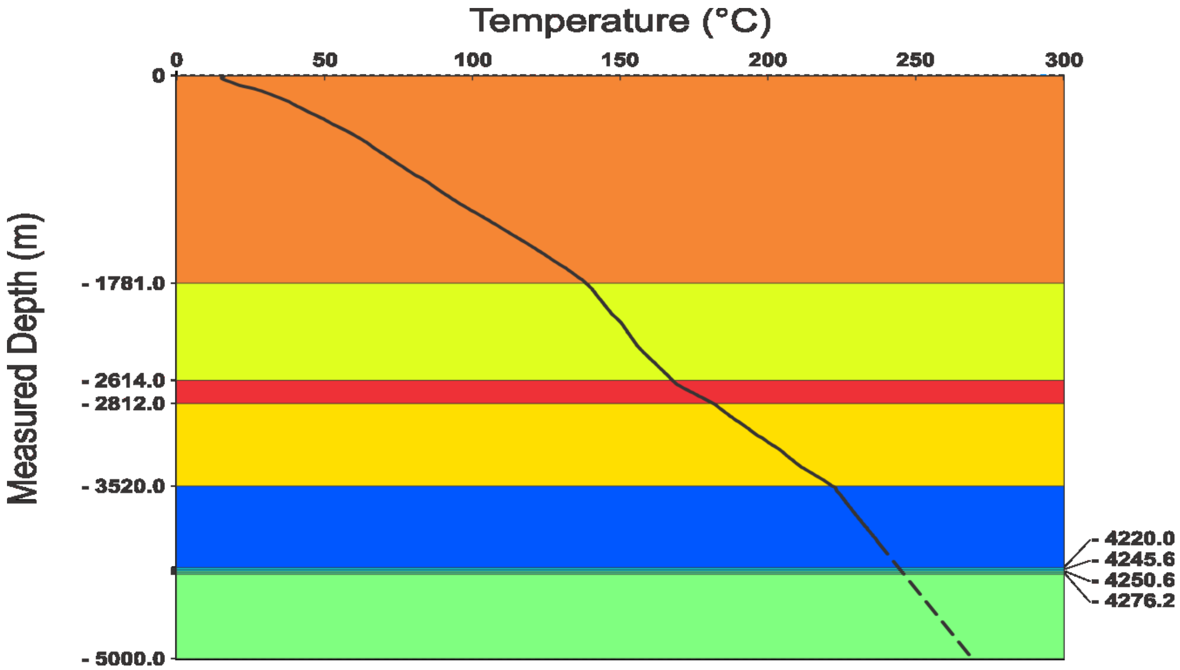


Figure 7: Rock layers used in thermodynamic and wellbore models, showing static temperature profile recorded at Habanero 1 (after Llanos et al, 2014)

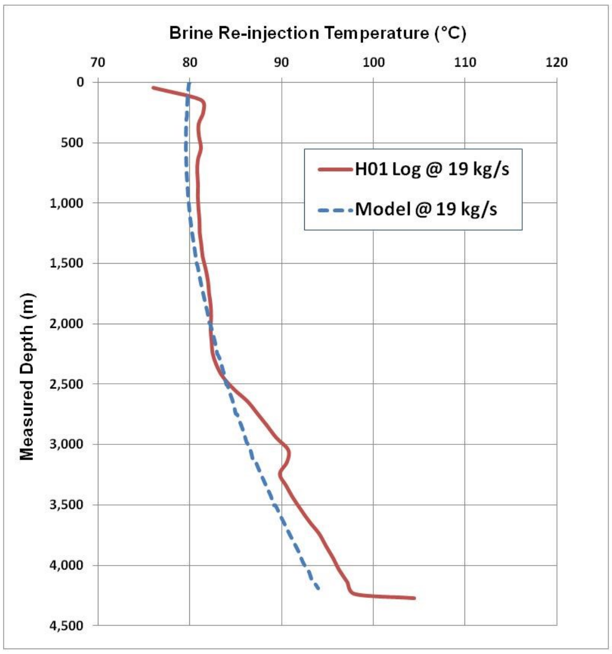
The thermal properties of these five layers were derived from thermodynamic modeling of the natural state temperature profile at Habanero (Llanos et al, 2014) and are given in **Table 2** below.

Layer Name	Porosity (fraction)	Permeability (mD)	Rock Density (kg/m^3)	Specific Heat (J/(kg.K)	Thermal Conductivity (W/(m.K))
TERT1	0.05	0.1	2,500	950	1.95
JURA1	0.03	0	2,500	960	4.99
TRIA1	0.02	0	2,500	960	2.00
PERM1	0.01	0	2,000	960	2.20
GRAN5	0.003	0	2,700	960	4.16

Table 2: Physical Properties of Rock Properties used in Temperature Modeling

The wellbore model for Habanero 1 assumed steady injection of 80°C brine at 19 kg/s for 30 days. The model-derived temperature profile is a reasonable match with the production log data recorded in the well (**Figure 8, left**). At the reservoir depth, the model-derived temperature is only 3°C less than the recorded value (93°C modeled versus 96°C recorded).

The wellbore model for Habanero 4 assumed a bottom hole flowing temperature of 236°C as recorded in the production log. Model-derived temperature profiles were estimated for steady flow for 30 days at 19 kg/s and 6 kg/s, corresponding to the final closed-loop flow rate and long-term open flow rate during the HPP test program. Again, the model-derived temperature profiles (**Figure 8, right**) provide a reasonable match with the recorded production log data and with the measured surface flowing temperatures. At 19 kg/s the model-derived flowing temperature is only 2°C different from the temperature measured at the well head (217°C modeled versus 215°C recorded). At 6 kg/s, the model result is less than 1°C different (192°C modeled versus 193°C recorded).



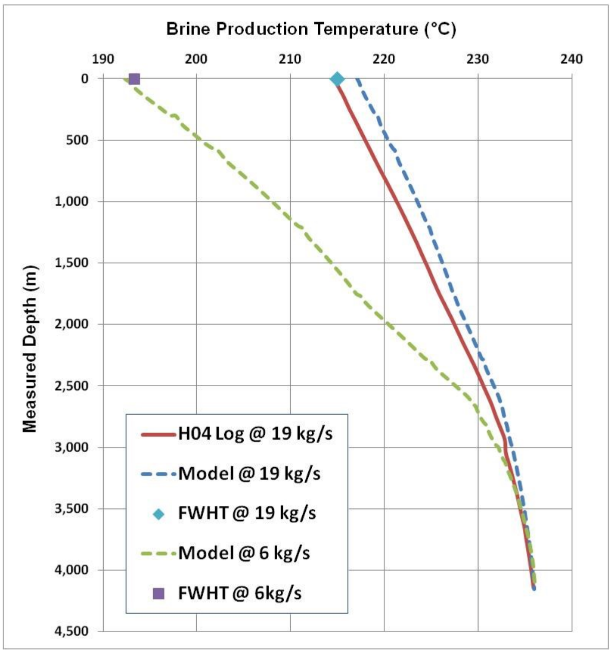


Figure 8: Comparison of model-derived wellbore temperature profiles versus recorded production log data from Habanero 1 (left) and Habanero 4 (right).

6 CLOSED-LOOP FLUID PROPERTIES

Combining the recorded wellbore temperature profiles from Habanero 1 and 4 whilst circulating at 19 kg/s with the static temperature gradient recorded in Habanero 1 (**Figure 9**) illustrates the temperature changes around the closed loop.

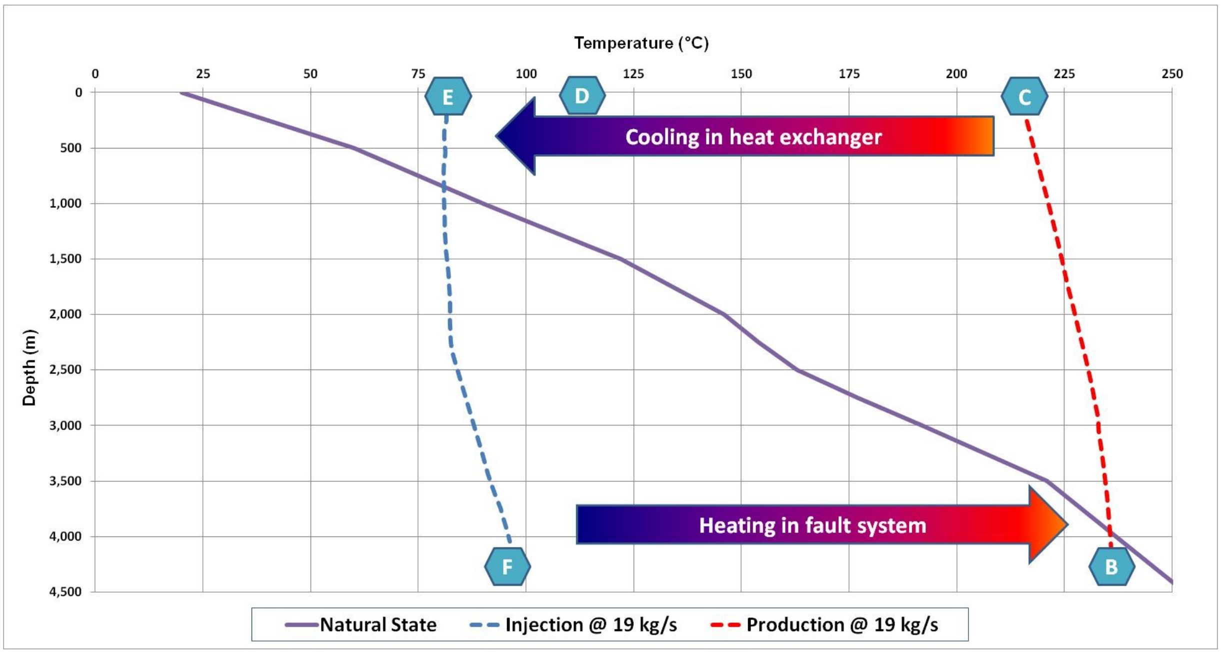


Figure 9: Temperature profiles from Habanero 1 and 4 whilst flowing at 19 kg/s compared to the static temperature profile

These temperature changes, coupled with the pressure changes associated with the pump and the fluid columns in each wellbore, result in significant changes in fluid properties around the closed-loop. Of importance in understanding the overall performance of the closed-loop are enthalpy, fluid density and fluid viscosity. Table 3 (below) lists the pressure and temperature of the brine at six locations around the closed loop, as labeled in Figure 9.

Parameter	*Units*	*Reservoir*	*Bottomhole H04*	*Wellhead H04*	*Inlet to Brine Pump*	*Wellhead H01*	*Bottomhole H01*
Location		A	B	C	D	E	F
Pressure	MPa	73.0	69.4	32.9	32.6	43.0	81.7
Temperature	°C	244	236	215	80	80	95
Enthalpy	kJ/kg	1,076	1,039	932	361	369	461
Density	kg/m^3	874	831	856	983	1,000	1,006
Viscosity	cP	0.13	0.11	0.12	0.36	0.37	0.32

Table 3: Brine properties at various locations around the closed-loop

Of particular note, the viscosity of the brine is three times higher in the cool injection stream compared to the hot production stream. To some extent this is compensated for by the increased brine density in cooler brine, meaning that volumetric flow rates are lower in the injection stream. However, all other things being equal, the net effect of these two differences will result in larger near well pressure losses around the injection wells than around the production wells.

7 CLOSED LOOP PRESSURE LOSSES

One simple way of visualizing the pressure losses around the closed loop is shown in Figure 10. The figure shows the frictional pressure losses around the H04-H01 closed-loop whilst operating at 19 kg/s, rounded to the nearest MPa.

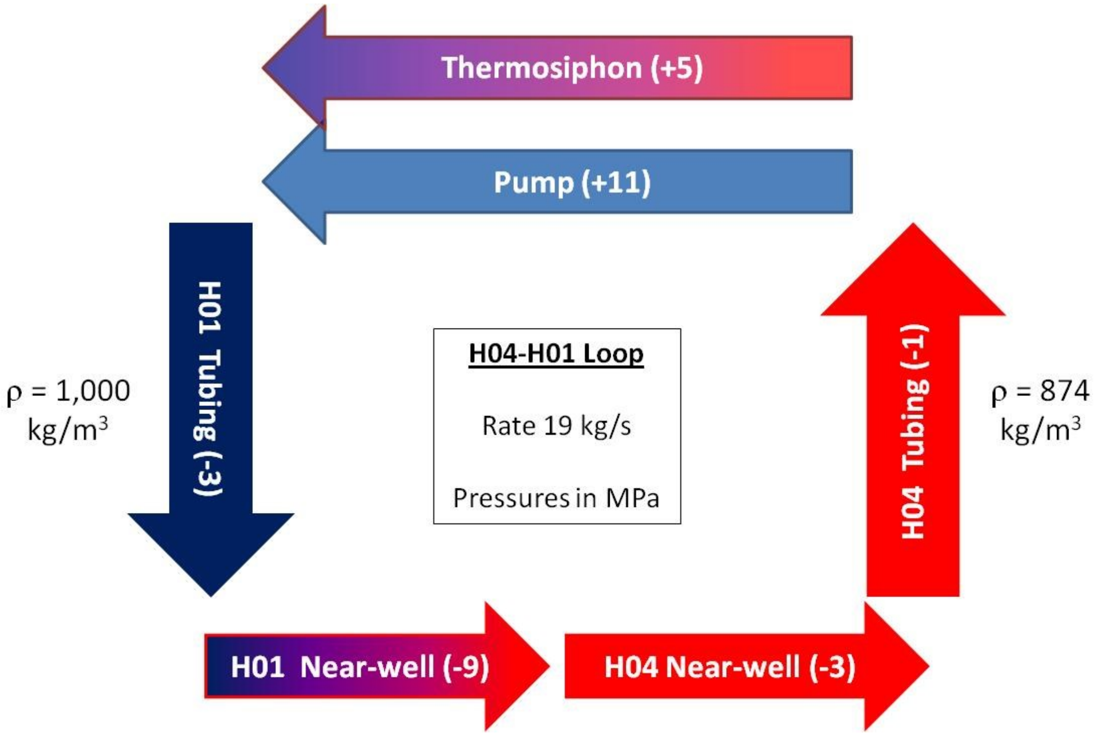


Figure 10: Simplified pressure losses around the H04-H01 closed loop whilst operating at 19 kg/s.

The diagram shows that the cumulative below ground pressure loss is ~16 MPa, made up of losses in the H01 tubing, near-well losses at H01, near-well losses at H04 and losses in the H04 tubing. These pressure losses are balanced, in part, by the pressure increase imparted by the pump and, in part, by the thermosiphon effect driven by fluid density differences between the two wells.

8 CONCLUSIONS

Geodynamics' closed loop trial in 2013 using wells Habanero 4 and Habanero 1 was the most successful trial so far conducted at Habanero EGS reservoir. The closed loop circulation rate of 19 kg/s and the flowing temperature of 215°C were both higher than ever previously achieved and were both continuing to improve even at the end of the trial period. Step rate tests and production logs conducted during the trial have provided an understanding of the system curve for the closed-loop and the pressure and temperature profiles in both injection and production wells.

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