PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Applying Decline Cumulative Production Analysis (DCPA) to Geothermal Resources

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Keywords: steady state condition, decline cumulative production, flow rate forecasting, power generation forecasting, Kamojang geothermal field, San Jacinto Tizate geothermal field.

ABSTRACT

A new decline curve analysis has been developed for geothermal resources in Steady state condition; in the present work it has been plotted the natural log of Decline cumulative production $Ln(q/Q)$ against the natural log of cumulative production $Ln(Q)$ and natural log of time $Ln(t)$ respectively. The graphs show linear relationships and combining equations determined by least squares fitting, it yields a new decline curve equation. Semi-log plot of dimensionless production rate (q_d) and time (t) shows a linear correlation, the slope is time decline exponent (τ), this plot can be used as a diagnosis plot.

The present contribution has been applied at a steam geothermal well from Kamojang geothermal field, Indonesia and one geothermal power plant in Nicaragua operating below its installed capacity, it has been possible to get the flow rate and power generation forecasting at the currently condition in both cases. Deviations from the decline curve behavior relates changes in operational conditions, wells behavior, work overs, reservoir response or changes in reinjection strategies. These perturbations help to identify changes effects and to assist at the reservoir engineer to evaluate the field management results.

1. INTRODUCTION

Hydrocarbon resources and geothermal reservoirs use similar drilling technologies, well testing analysis and production data analysis. The greater difference between oil resources and geothermal reservoir is that hydrocarbon is a finite resource in a closed system and a geothermal reservoir is an open system with recharge flow and heat flux. Geothermal reservoirs have three possible water recharge mechanisms than could keep the flowing reservoir pressure and flow rate production: deep reservoir recharge, peripheral recharge and reinjection return. If there is a mechanism present, which maintains reservoir pressure, the production rate would essentially remain almost constant and the decline rate would tend towards zero. Now, geothermal reinjection is an important issue of sustainable management of geothermal resources; an optimum reinjection design should balance the requirements to sustain the reservoir pressure and to prevent the early breakthrough of reinjected cold water, the effects of reinjection on the natural hot recharge and, therefore the energy recovery from the system [1].

2. PRODUCTION DATA ANALYSIS USE IN GEOTHERMAL RESOURCES

In The Geysers geothermal field, Decline curve analysis has been used just from 1969 at the early development of The Geysers geothermal field [2-4], it was considered to utilize the empirical Arp's decline equation, identifying harmonic and exponential decline rate. Ocampo J. et al [5] suggested that it was possible to combine the exponential and harmonic decline models to predict future behavior of Cerro Prieto wells, Mexico. Sasradipoera D. et al [6] analyzed the steam production rate decline of Kamojang geothermal field applying type curve exponential and harmonic decline model by using normalized flow rate, the decline rate shown a large decline rate in some low producing wells within low permeability regions. Reyes J. et al [7] developed a decline curve analysis model based on the theory of fluid flow in porous media determining the linear relationship between the production rate and the reciprocal of cumulative production; it was applied in The Geyser geothermal field, USA. Wahyuningsih S. et al [8] proposed a stochastic approach of Arp´s equation in decline curve analysis and applied in Kamojang geothermal field, Indonesia. Later Sanyal S. K. et al [8] describes a systematic approach to flow rate decline analysis estimating the static pressures as well as correct the fluctuations of the wellhead pressures in the Geysers geothermal field in order to get the true decline in productivity considering pseudo steady state condition too.

3. MATHEMATICAL BACKGROUND

A new decline curve analysis method has been developed for geothermal resources, based on the linear relationship between the Decline cumulative production and cumulative production (Figure 1A) and the linear relationship between Decline cumulative production and production time (Figure 1B). It has been combined equations determined by minimal least squared fitting from both figures to yield the new production rate–time equation and Cumulative production rate.

The present contribution is an attempt to get geothermal production forecast in a Steady State condition.

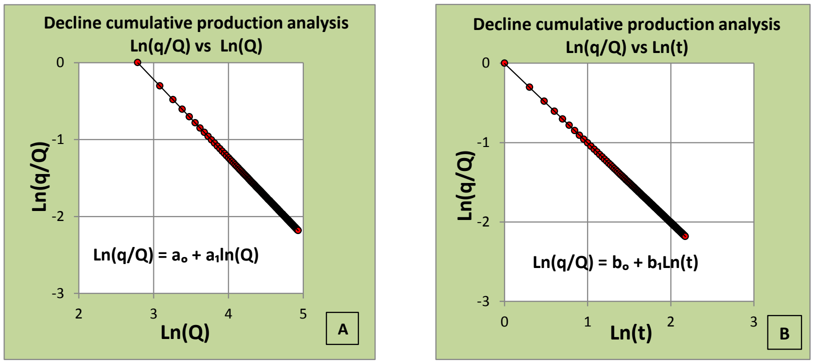


Figure 1: A) Ln (q/Q) against Ln (Q), B) Ln (q/Q) against Ln (t)

The Derivative Cumulative production is equal at the production rate.

$$\frac{dQ}{dt} = q \tag{1}$$

Then the Decline cumulative production is

$$Q_D = \frac{\frac{dQ}{dt}}{Q} = \frac{q}{Q} \tag{2}$$

Plotting the Decline cumulative production against Cumulative production, the linear relationship is expressed by the following equation from figure 1A:

$$Ln\left(\frac{q}{Q}\right) = a_0 + a_1 Ln(Q) \tag{3}$$

Exponentiating both side of equation 3 and solving for q it yields the following expression:

$$q = Exp(a_0)Q^{(a_1+1)} \tag{4}$$

The relationship between Decline cumulative production and time from Figure 1B is expressed by the following equation:

$$Ln\left(\frac{q}{Q}\right) = b_0 + b_1 Ln(t) \tag{5}$$

Exponentiating both side of equation 5 and solving for q it yields the following expression:

$$q = Exp(b_0)Qt^{b_1} \tag{6}$$

Combining equations 4 and 6 and solving for Q, the Cumulative production in terms of time it yields by the following expression:

$$Q = Exp\left(\frac{b_0 - a_0}{a_1}\right)t^{\left(\frac{b_1}{a_1}\right)} \tag{7}$$

Replacing equation 7 into equation 6 it yields q in terms of time.

$$q = Exp\left(\frac{b_0 - a_0}{a_1}\right)t^{\left(\frac{b_1}{a_1}\right)} Exp(b_0)t^{b_1}$$

$$q = Exp\left[\frac{b_0(a_1+1) - a_0}{a_1}\right]t^{\left(\frac{b_1(a_1+1)}{a_1}\right)} \tag{8}$$

Where Initial rate (q_i) is given by the following expression

$$q_i = Exp\left[\frac{b_0(a_1+1) - a_0}{a_1}\right] \tag{9}$$

The time decline exponent (τ) is defined by

$$\tau = \frac{b_1(a_1+1)}{a_1} \tag{10}$$

And replacing equation 9 and 10 into equation 8, the production rate–time equation is given by the following equation:

$$q = q_i t^{\tau} \tag{11}$$

A semi-log plot of dimensionless flow rate (q_d) against time ($\boldsymbol{t}$) shows a linear relationship (Fig. 2) which can be used as a diagnosis plot, the slope is the decline exponent value $\boldsymbol{\tau}$. The dimensionless rate (q_d) used in Fig. 2 is defined by:

$$q_d = \frac{q}{q_i} = t^{\tau} \tag{12}$$

Deviations from the decline curve behavior can be show changes in operational conditions, wells behavior or changes in reinjection strategies. These observations could be used to identify effects and assist at the reservoir engineer to quantify results of the field management. Whenever perturbation is observed in the cumulative data and time, the analysis will be reinitialized at that time and the data plotted to yield the new decline curve, this time will be the new time zero. The difference between the extrapolated old decline and the new decline will be used to determine the response of field management.

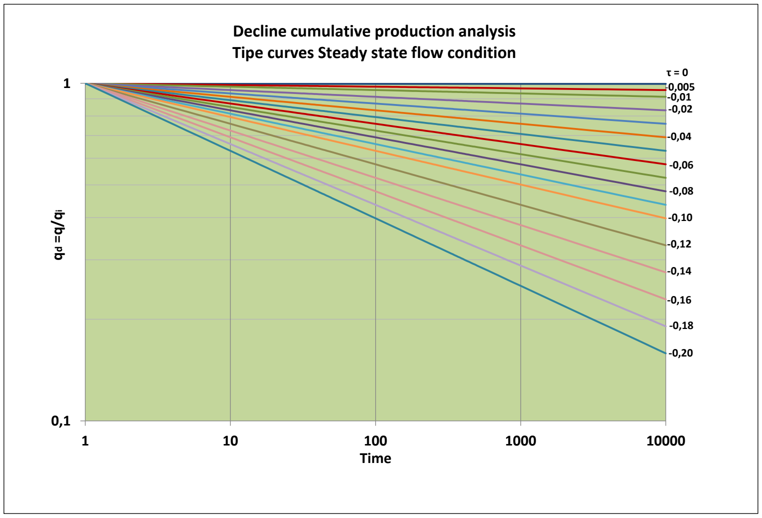


Figure 2. Steady state flow Decline curves.

The relationship between the hyperbolic model and the DCPA parameters is:

$$D = -\tau \quad (13)$$

$$b = \frac{1}{D} \quad (14)$$

If the decline curve determined is matched with the Arp's hyperbolic equation, b value will be greater than one, indicating that some recharge is present.

4. STUDY CASES

The proposal procedure has been applied in two geothermal field situation:

- A steam geothermal well from Kamojang geothermal field, Indonesia and
- Overall performance of San Jacinto Tizate geothermal field, Nicaragua

4.1 Kamojang geothermal field, Indonesia

Kamojang geothermal field is a vapor dominated system located 32 km south of Bandung, capital of West Java province, the field has been operated since 1982. At present Kamojang field is producing about 205 MW/h, with a 235 MW/h installed capacity, the first unit of 30 MW was installed in 1982, an additional (2x55MW) 110 MW started commercial operations in 1987. A 60 MW unit entered commercial operation in January 2008 one additional unit of 35 MW started commercial operation in June 2015, now Unit 1 is off line.

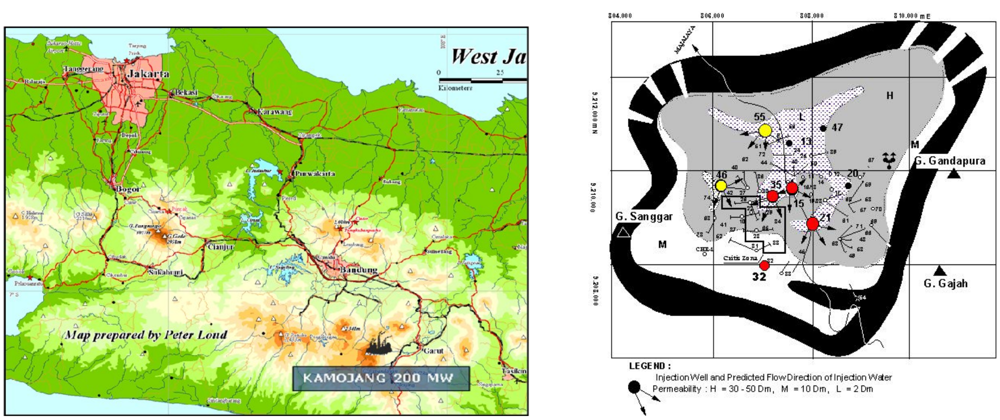


Figure 3. Kamojang geothermal field and reinjection well location

In Kamojang geothermal field, reinjection activity it has been carried out since 1983. Several tracer injection tests have been carried out in order to determine the interconnection between water reinjection and production wells. Tracer of radioisotope tritium as titrated water (HTO) was injected at KMJ-15 in 1983 and 1992 with activity 370 GBq respectively and at KMJ-46 in 2003 with activity 550 GBq. Tritium injected in KMJ-15 was monitored in production wells surrounded the reinjection well. By using TRINV and TRCOOL programs developed by Geoscience Division Orkustofnun - Iceland, simulation data determined breakthrough time of water reinjection and cooling effect to the reservoir. The breakthrough time of water reinjection was about 5 to 7 years and mass recovery of all seven wells production was about 13.5% [10].

4.1.1 Decline cumulative analysis applied to well KMJ-11, Kamojang geothermal field, Indonesia

KMJ-11 Production Data published by Wahyuningsih S. et al [8] it will be used for the application of the proposal analysis. Data from January 96 until October 96 (Table 1) it will be analyzed in order to determine the production rate – time equation, then the production rate estimated with DCPA is compared with the real production and production forecasting using the exponential model and the Stochastic approaches of Arp´s equation in decline curve analysis from the original publication.

Table 1. Production rate KMJ-11 Kamojang geothermal field

Month	Year	ton/hour
January	1996	77,234
February	1996	75,313
March	1996	74,296
April	1996	72,600
May	1996	72,133
Jun	1996	71,135
July	1996	70,351
August	1996	70,262
Sept	1996	69,610
Oct	1996	69,263

It can be seen from the diagnosis plot (Figure 4), the linearity between dimensionless production rate (q_d) and time (*t*), the τ value has a decline trend close to -0.05 in agreement with the τ value of -0.04917 gotten below from equation 10.

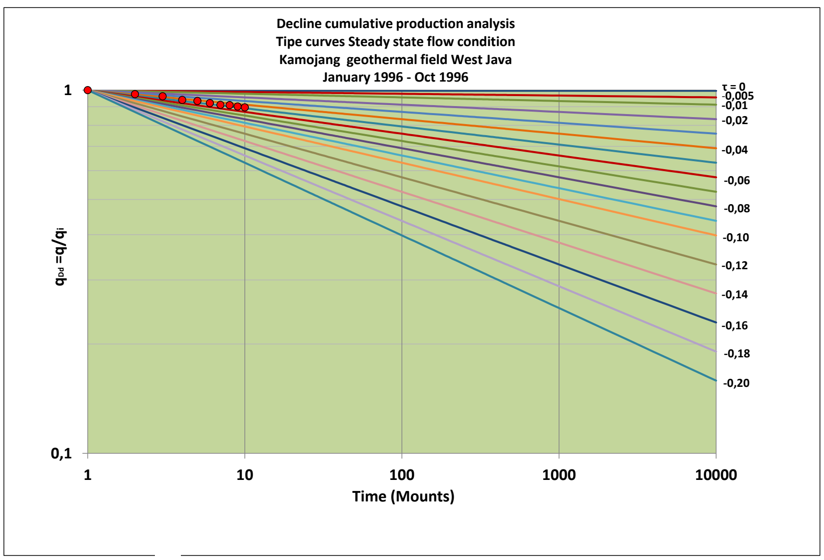
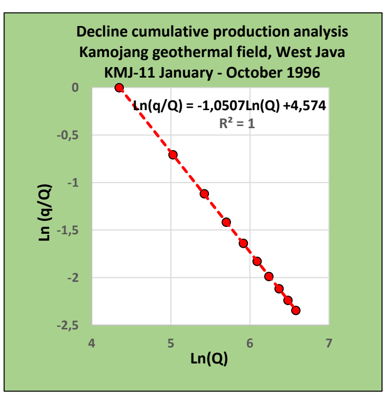


Figure 4. Dimensionless production rate (q_d) versus time (*t*) plot KMJ-11



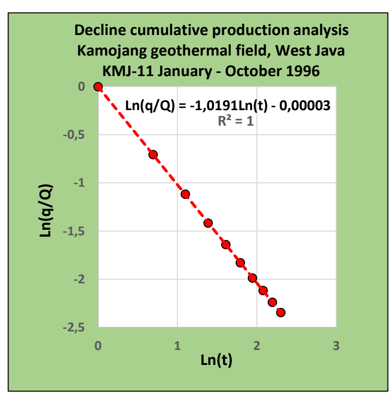


Figure 5. A) Ln (q/Q) versus Ln (Q). B) Ln (q/Q) versus Ln (t) KMJ-11

Decline Cumulative production and Cumulative production relationship is given by:

$$Ln\left(\frac{q}{Q}\right) = 4.574 - 1.0507Ln(Q)$$

And Decline Cumulative production and time relationship is expressed by:

$$Ln\left(\frac{q}{Q}\right) = -0.00003 - 1.0191Ln(t)$$

Substituting values in eq. (9): q_i = 77.7335 ton/hour
Substituting values in eq. (10): τ = - 0.04917519
Then the production rate–time equation is given by Eq. (11):

$$q = 77.7335\left(t^{-0.04917519}\right) \text{ ton/hour}$$

4.1.2 Flow rate forecasting KMJ-11, Kamojang geothermal field, Indonesia

Table 2 shows the KMJ-11 flow rate forecasting, the DCPA estimated has been compared with the original data presented by Wahyuningsih S. et al [8] and the true error has been calculated. The forecast with the method proposed shows the least means error of -0.54%, the stochastic and exponential model give means error of -1.42 and -7.33% respectively, in all the cases the forecasting is underestimated. Figure 6 shows the flow rate forecasting with the three models analyzed and the decline production curve obtained with the DCPA method (red line) plot very close with the production rate data (red circle), the stochastic and exponential forecast are represented by green and brown line respectively diverging from the production data with the time.
The DCPA decline curve can be matched with the Arp´s hyperbolic model using the D value of 0.049175 and b value of 20.3355 obtained from equation 13 and 14 respectively.

Table 2. **Decline cumulative production analysis**
Kamojang geothermal field, West Java, Indonesia
KMJ-11 Production rate forecasting and true error

Date		Real	Production rate estimated (ton/h)			True error		
Month	Year	production	Exp.	Arp´stoch	DCPA	Exp.	Arp´stoch	DCPA
January	1996	77,234			77,734			
February	1996	75,313			75,129			
March	1996	74,296			73,645			
April	1996	72,6			72,611			
May	1996	72,133			71,819			
Jun	1996	71,135			71,177			
July	1996	70,351			70,640			
August	1996	70,262			70,178			
Sept	1996	69,61			69,772			
Oct	1996	69,263			69,412			
Nov	1996	67,781	67,429	68,895	69,087	-0,52	1,64	1,93
Dec	1996		66,625		68,792			
January	1997	68,385	65,830	68,529	68,522	-3,74	0,21	0,20
February	1997	67,902	65,045	68,165	68,273	-4,21	0,39	0,55
March	1997	67,858	64,269	67,803	68,042	-5,29	-0,08	0,27
April	1997	68,705	63,502	67,443	67,826	-7,57	-1,84	-1,28
May	1997	70,434	62,745	67,085	67,624	-10,92	-4,75	-3,99
Jun	1997	69,042	61,996	66,729	67,434	-10,20	-3,35	-2,33
July	1997	67,916	61,257	66,375	67,255	-9,80	-2,27	-0,97
August	1997	67,201	60,526	66,022	67,086	-9,93	-1,75	-0,17
Sept	1997	67,307	59,804	65,672	66,925	-11,15	-2,43	-0,01
				Error		-7,33	-1,42	-0,58

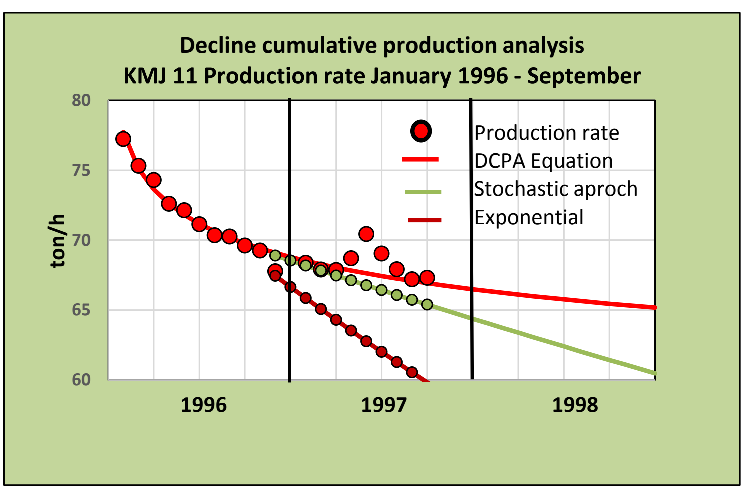


Figure 6. Production rate forecast KMJ-11, Kamojang geothermal field, Indonesia

4.2 San Jacinto Tizate geothermal field, Nicaragua

San Jacinto Tizate is in operation from 1998, during the first development state it was operated with 2-5 MW back pressure units, later in 2011 start to operate a 36 MW condensate unit, in 2013 the third development stage is finalized installing a second 36 MW unit. At date only the two condensation units are in service. Reinjection is further away from the production wells.

Figure 7. San Jacinto Tizate geothermal field location, Nicaragua

San Jacinto geothermal field has experimented a reinjection return [11], the reservoir tracer tests in 2012 and 2015 show that about 18.5% of the injected water into SJ10-1 is produced by SJ4-1, SJ6-2 and SJ9-1. The tracer returns identifies a permeable shallow route for potential recharge; sensitive studies indicated that there is a considerable heating of the injected water before it returns to the production area. A lumped parameter model of chloride concentration increase, noted that SJ4-1 displayed some degree of cooling even before SJ10-1 was used for hot brine injection [12].

The proposal method (DCPA) has been applied to San Jacinto Tizate geothermal field considering the daily Power generation data after the commissioning of the second 36 MW unit on February 2013, (CNDC) [13].

4.2.1 Decline cumulative production Analysis period from February 19 until April 29 2013

It has been assumed which the input pressure at the turbines is almost constant. Diagnosis plot (Figure 8) shows that the τ value decline trend to -0.025, the data represented by orange circle were excluded in the analysis on figures 9A and 9B for the period from February 19 until April 29 2013, the τ value obtained using Equation 10 is -0.0256875 in agreement with the diagnosis plot, at the end of the analysis period is observed which there is a deviation after eighty days and interpreted as a reservoir response, additional diagnosis plot is presented below (Fig 10) restarting the analysis on March 29 2013.

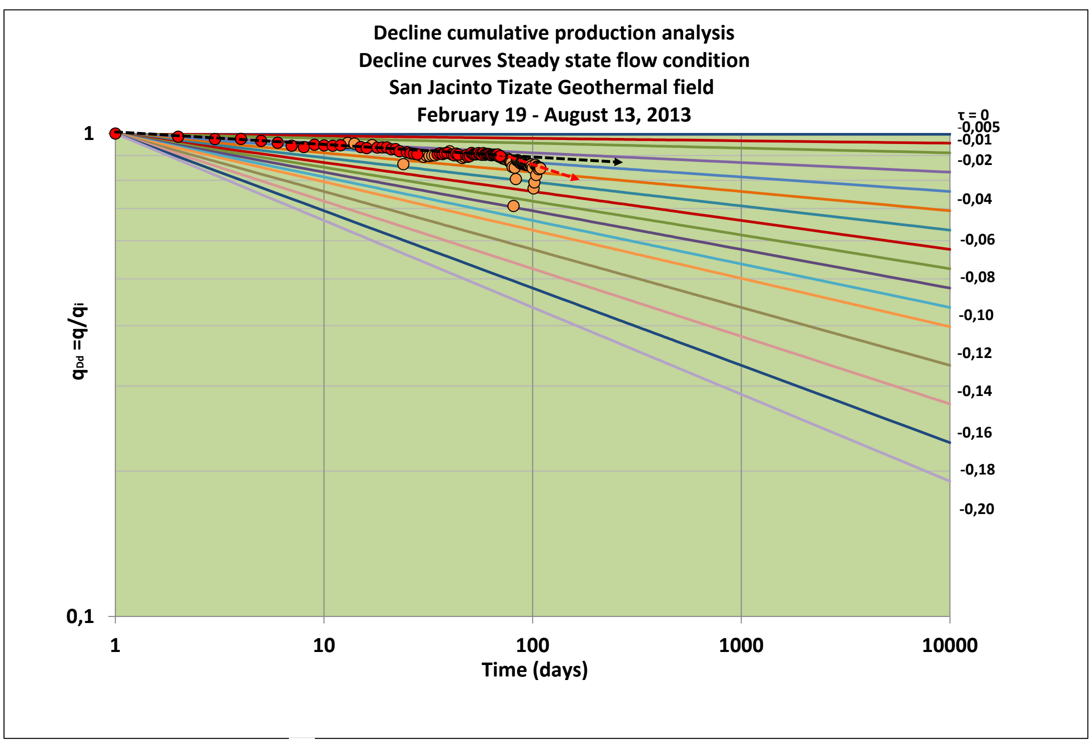


Figure 8. Dimensionless production rate (q_d) versus (t) plot San Jacinto geothermal field February 19 – April 29 2013

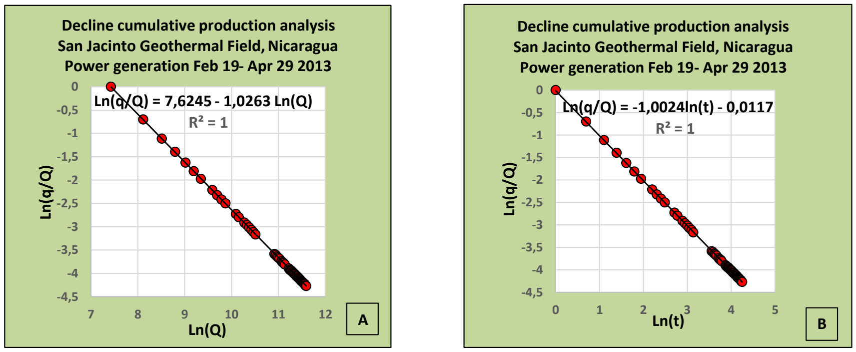


Figure 9. A) *Ln* (*q/Q*) versus *Ln* (*Q*). 9. B) *Ln* (*q/Q*) versus *Ln t*) San Jacinto geothermal field February 19 – April 29 2013

The relationship between Decline cumulative production and the cumulative production (Figure 9A) is given by:

$$Ln\left(\frac{q}{Q}\right) = 7.6245 - 1.0263Ln(Q)$$

The relationship between Decline cumulative production and time (Figure 9B) is given by:

$$Ln\left(\frac{q}{Q}\right) = -0.0117 - 1.0024Ln(t)$$

Substituting values in eq. (9): qi = 1683.81 MW/day = 70.16 MW/h
Substituting values in eq. (10): τ = 0.0256875
Then the production rate–time equation is getting substituting values in Eq. (11):

$$q = [1683.81(t^{-0.0256875})] \quad \text{MW/day}$$

The cumulative production is getting substituting values in Eq. 7:

$$Q = Exp\left(\frac{-0.0117-7.6245}{-1.0263}\right)t^{\left(\frac{-1.0024}{-1.0263}\right)}$$

$$Q = 1703.6265t^{(0.976712)} \text{ MW}$$

The DCPA decline curve can be matched with the Arp´s hyperbolic model using the D value of 0.0256875 and b value of 38.9294 obtained from equation 13 and 14 respectively.

4.2.2 Decline cumulative production Analysis period from April 29 until August 13 2013

Diagnosis plot (Figure 10) shows that the τ value decline trend to -0.02, the data represented by orange circle has been excluded in the analysis, the analytical τ value obtained is -0.02542 in agreement with the diagnosis plot.

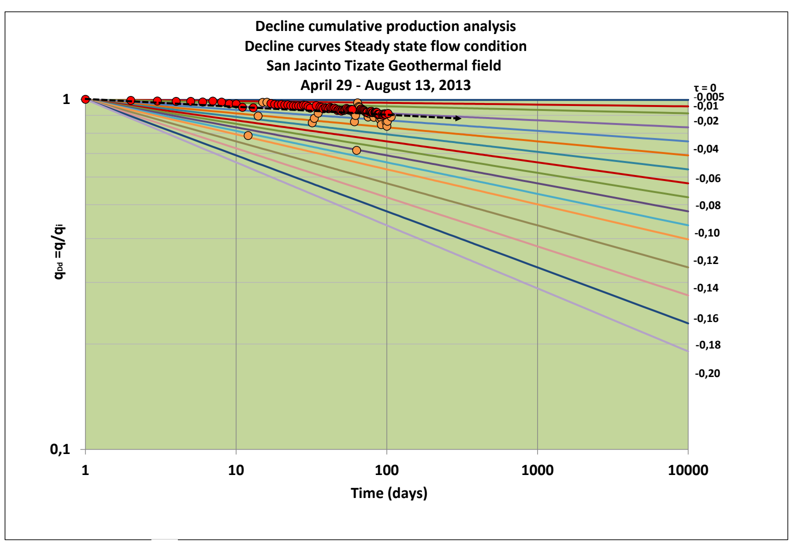


Figure 10. Dimensionless production rate (q_d) versus (t) plot San Jacinto geothermal field April 29 – August 13 2013

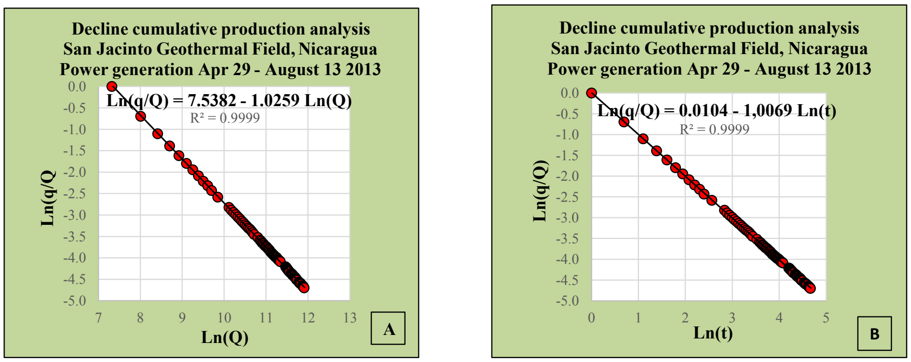


Figure 11. A) *Ln* (*q*/*Q*) versus *Ln* (*Q*). 11. B) *Ln* (*q*/*Q*) versus *Ln* (*t*) San Jacinto geothermal field April 29 – August 13 2013

The relationship between Decline cumulative production and the cumulative production (Figure 9A) is given by:

$$Ln\left(\frac{q}{Q}\right) = 7.5382 - 1.0259Ln$$

The relationship between Decline cumulative production and time (Figure 9B) is given by:

$$Ln\left(\frac{q}{Q}\right) = 0.0104 - 1.0069Ln(t)$$

Substituting values in eq. (9): qi = 1553.3237 MW/day = 64.72 MW/h
Substituting values in eq. (10): τ = 0.0254203
Then the production rate–time equation is getting substituting values in Eq. (11):

$$q = [1553.3237\,(t^{-0.0254203})] \quad \text{MW/day}$$

The cumulative production is getting substituting values in Eq. 7:

$$Q = Exp\left(\frac{0.0104 - 7.5382}{-1.0259}\right)t^{\left(\frac{-1.0069}{-1.0259}\right)}$$

$$Q = Exp(7.337752)\,t^{(0.98148)} = 1537.25t^{(0.98148)} \ \text{MW}$$

The DCPA decline curve can be matched with the Arp´s hyperbolic model using the D value of 0.0254203 and b value of 39.338602 obtained from equation 13 and 14 respectively.

4.2.3 Forecasting curve analysis

Figure 12 shows the Generation curve forecasted (Feb 19 – April 29), with the new proposal analysis (DCPA), it can be seen during that first 80 days is in agree with the production data, later the production data declines as an effect of the reservoir response. Reinitialization of the production data analysis on April 29 2013 gives a new decline curve that is in agreement too with the production data. The flow rate equations for period are:

February 19 – April 29 2013 $q = [1683.81\,(t^{-0.0256875})]/24$ MW/h

April 29 – August 13 2013 $q = [1553.3237\,(t^{-0.0254203})]/24$ MW/h

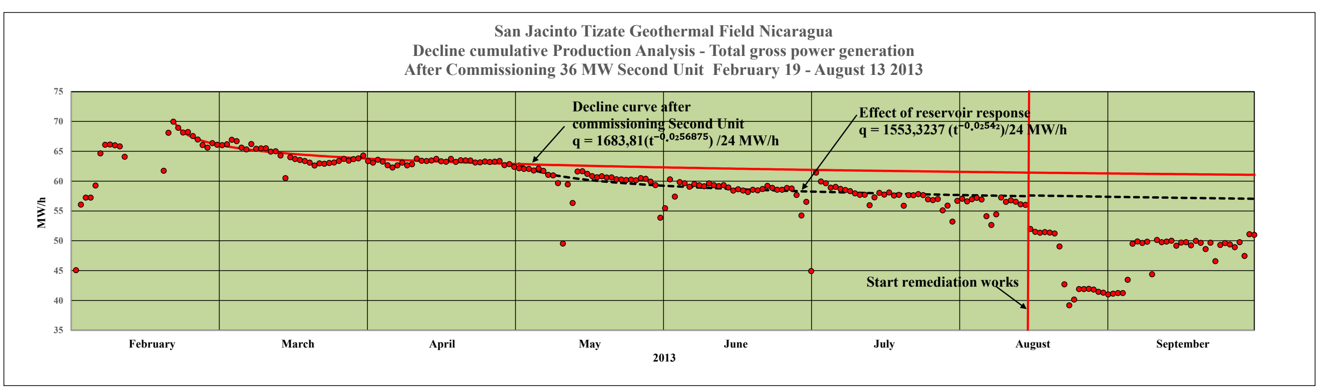


Figure 12. Power generation forecast February - September 2013 period

Figure 13 shows the Cumulative production True Error versus production time comparing the Real Cumulative production with the Calculated Cumulative production determined with the proposal analysis, The plot shows two errors decline trend, for the Feb 19 – April 29 period data the decline trend stars after eighty days and for the April 29 – August 13 period data the decline trend stars after ninety days, in both cases the decline trend star time are very similar at the time reported by Malate et al [12], when the maximum tracer recovery value after the injection tracer in well SJ10-1 is are 84 days in SJ4-1 and SJ9-1 production wells and 95 days in SJ6-2 production well.

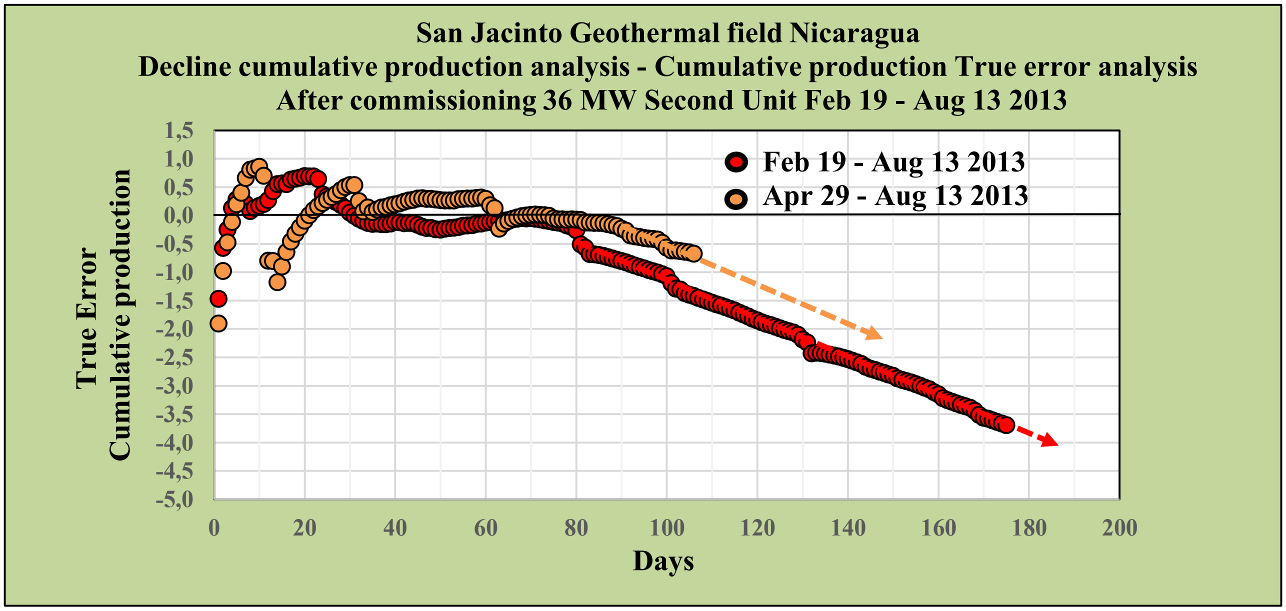


Figure 13. Cumulative production forecast True Error Analysis February - August 2013 period

5. CONCLUSIONS

Diagnosis curve has been determined for production in steady state flow condition using a semi-log plotting dimensionless rate q_d versus time, showing a linear correlation.

A new production rate- time and Cumulative Production equations have been developed for Decline Production Analysis in steady state condition, with the possibility to use as a tool for production forecasting.

The new equation has been applied in a production steam well and a power generation field data, showing which can be used for monitoring particular wells behavior or the overall geothermal system performance.

Deviations from the decline curve behavior can be used to determine changes in operational conditions, wells behavior, reservoir response or changes in reinjection strategies. These observations can be used to identify effects and assist at the reservoir engineer to quantify field management results.

Whenever perturbation is observed the cumulative data will be reinitialized at that time and the data plotted to yield the new decline curve, this time will be the new time zero. The difference between the extrapolated old decline and the new decline should be used to determine the response of field management.

Hyperbolic equation can be matched with the new decline curve, *b* parameter will be greater than one, indicating that there are recharges maintaining reservoir pressure.

Plot of Cumulative production forecast true error versus production time can be used as a tool to identify the start of behavior deviation.

5. ACKNWLEDGMENTS

The author thanks gratefully to Investigación y Desarrollo - Albageneración Nicaragua for the financial support during the research time.

NOMENCLATURE

D : Initial Decline rate
MW/d: Power generation per day
Q : Cumulative production
Q_D : Decline cumulative production
b : Hyperbolic exponent
q : Production rate
t : Production time
a_0 : Independent term of decline cumulative production with cumulative production relationship
a_1 : Slope of decline cumulative production with cumulative production relationship
b_0 : Independent term of decline cumulative production with production time relationship
b_1 : Slope of decline cumulative production with production time relationship
τ : Exponent time
q_d : Dimensionless production rate
q_i : Initial production rate

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