PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 1-3, 2010
SGP-TR-188

MONITORING OF MASS BALANCE MODEL DURING PRODUCTION CAPACITY INCREASE AT KAMOJANG GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

Kamojang Geothermal Field (KGF) located in West Java is the oldest developed geothermal field in Indonesia. It is a typical vapor dominated hydrothermal system. From 1983 to 2005, more than 160 million tons of steam has been exploited from the KGF and more than 30 million tons of condensed water and river water were injected to the reservoir system. Regarding to the electricity demand, installed capacity of KGF increased from 30 MWe to 140 MWe in 1987 and 200 MWe in 2007. The evaluation of steam production in 1999 showed the decline of steam flow rate notably occurred at some production wells in the KGF.

The changes of reservoir condition periodically can be measured by the geophysical method, that is, repeat gravity measurement. Repeat gravity measurements and leveling surveys over the KGF to measure the changes in the gravity and vertical ground movement were conducted since 1984. Gravity monitoring between 1999 and 2005 at 51 benchmarks are interpreted in terms of a change of mass. The amount of mass changed was caused by production and injection activities. Based on Gauss's potential theorem, the 1999-2005 gravity changes in the reservoir area indicate that the system of the KGF has mass decrease of about 3.34 Mt/year. Repeat gravity measurements were conducted in the end of 2008 to monitor the changes of mass balance during production capacity increase. Concerning to the production increase, between 1999 and 2008 the KGF has average mass decrease bigger than between 1999 and 2005. It is very important to balance the mass in the geothermal reservoir to continue the sustainable production.

INTRODUCTION

Research location

Kamojang Geothermal Field (KGF) in the Garut region of west Java, about 40 km from the city of Bandung, is a vapor-dominated system with a reservoir depth of about 600 to 2000 m. KGF is located on the geographical coordinate of $07^o11'02"$ – $07^o06'08"$ S and $107^o44'36"$ - $107^o49'30"$ E. The Kamojang geothermal system resulted from the complex interaction between active volcanoes and tectonic processes and it is influenced by two important faults named the Kendang fault and the Citepus fault (Sudarman et al., 1995) (Figure 1). The area of KGF is about 21 km^2 and it has altitude of about 1400 - 1800 m above sea level (Sumintadireja et al., 2000).

History

In late 1982, production of 30 MWe (Unit 1) was started in KGF, supplied by 6 wells in the central part of the field. Development drilling continued and two 55 MWe units (Units II and III) were added in 1987. More than 30 production wells, including stand-by wells, supply steam to the three units. Since Units II and III started up, the total production from the field has remained relatively constant at about 1,100 tones per hour of steam (Sanyal et al., 2000). Production has been maintained by drilling make-up wells. In the end of 2007, a 60 MWe (unit IV) was added to complete a 200 MWe installed capacity in KGF. The steam is supplied to the power plants through some steam transmission lines. The history of the total production at KGF can be seen at Figure 2.

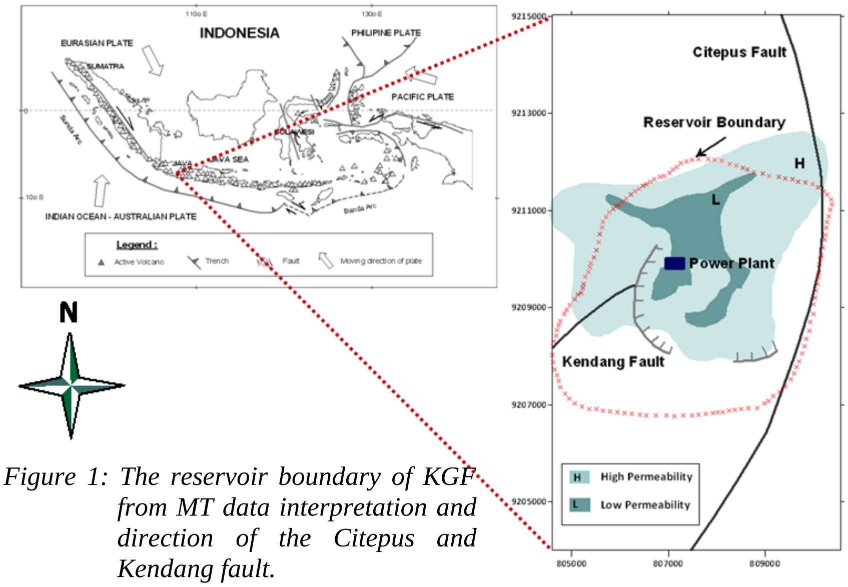

Figure 1: The reservoir boundary of KGF from MT data interpretation and direction of the Citepus and Kendang fault.

Concerning to the evaluation of the steam production in the KGF, the decline of steam flow rate notably occurred at some production wells. Doddy et al. (2000) explained the decline rate of the production wells using the type curve matching in 1999 is about 7.43 %/year. According to increase production capacity in 2007, decline rate of the production wells will be larger than before. This study will monitor the difference of the reservoir mass balance at KGF. The repeat gravity measurements have been conducted to monitor the mass balance change in the geothermal reservoir during exploitation.

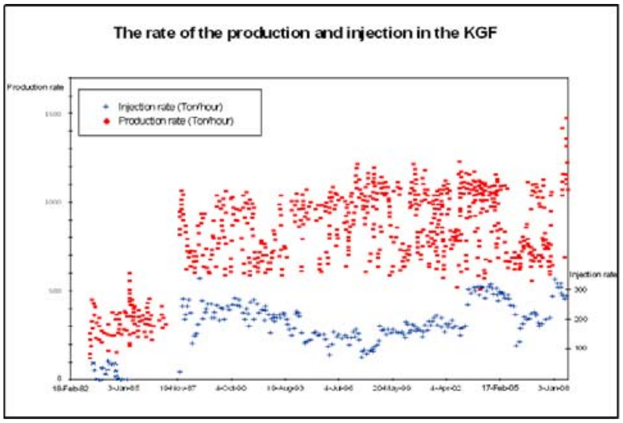

Figure 2: History total production and injection capacity at KGF (Pertamina, 2008)

REPEAT GRAVITY MEASUREMENT (RGM)

Gravity changes for a period of time during exploitation may show places where gravity has increased or decreased. The temporal gravity changes can provide insight into mass variation and indicate the location of places where net mass loss or gain occurred.

The repeat gravity measurement consists of the repeated measurements of the earth gravity field in the same location with different times. The RGM is also called as microgravity measurement, generally used to distinguish data in the range of 1 – 500 micrograls from those in geophysical prospecting (Bouguer anomalies) which usually lie in the range 500-100,000 microgal (0.5-100 milligal) (Hunt, 2000). The differences in the earth gravity value of one benchmark at different times can be caused by many factors. These factors are shown at Table 1.

Pertamina and some other researchers conducted gravity measurements and some leveling surveys over KGF since 1984. The gravity data in 1999, 2005 and 2008 were used to estimate the gravity changes in KGF. The leveling data in 1999 and 2005 were used to calculate the elevation changes correction. We assumed the elevation data in 2008 similar to 2005 is caused by a short difference period of measurement.

The gravity measurements were done with LaCoste and Romberg type G 655 and G 653 gravimeters. Gravimeters were calibrated to the 2 gravity absolute points that have calibration distance about 20 to 30 km. The gravimeter LaCoste and Romberg type G 655 and G 653 have calibration factors of about 0.999636 and 0.999544. These values are eligible for precision gravity measurement.

The round measurement method of the earth gravity field in KGF was conducted with PG 55, the gravity benchmark outside of the Kamojang reservoir boundary, as a reference gravity point. Location of PG 55 can be seen in the Figure 3. The close loop of the gravity measurements was tied to PG 55. Gravity measurements were conducted on the flat benchmarks that were inserted 110 cm to subsurface (size 40 cm lengths x 40 cm wide x 150 cm height). Validation of the observed gravity data limited by the drift correction factor has less than 20 microgal. The gravity measurement in 1999 had more than 51 benchmarks. In 2005 and 2008 some gravity benchmarks were lost or broken and then 51 benchmarks were used to discuss the change in the gravity data between 1999 and 2005. About 30 benchmarks were used to discuss the change in the gravity data between 1999 and 2008.

Table 1: Correction and calculation of the RGM method at KGF

Correction factors	***Difference***	***Correction types***	***At KGF***
Variation with position	- The difference height above sea level (about 300 microgal/m) - The difference latitude position (about 0.8 microgal/m) - The difference longitude position (< 0.01 microgal/m)	Height and tide correction	calculated
Variation with time	The difference position of the sun and moon	Tide correction	calculated
Drift	The difference condition of gravimeter (It can be caused by the movement of the instrument)	Drift correction	calculated
Atmospheric pressure variation	The changes of air pressure (< 5 hPa or about 2 microgal)	Air pressure correction	Negligible (It is too small)
Variation in shallow groundwater level	The difference of the shallow groundwater volume (the rainfall rate changes) (about 5-10 µgal (Goodkind, 1986))	$\Delta g_w = 2\pi G\rho\varphi(1-S)\Delta h$ (Hunt, 2000)	Negligible (The RGM in the similar season)
Variation in soil moisture	The difference in the saturation (The rainfall rate changes)	$\Delta g_a = 2\pi G\rho\varphi\Delta Sd$ (Hunt, 2000)	Negligible (The RGM in the similar season)
Active volcanism	The emplacement of the magma at shallow depths	Volcanism correction	Negligible (No relation to location of the KGF)
Mining operation	The removal of mineral ore, rock, etc from underground mines	Mass change correction	Negligible (No relation to location of the KGF)
Variation of the topographic area	The difference surface topography of the terrain (such as construction of canal, road, etc)	Terrain correction	Negligible (It is too small in the KGF)
Ground subsidence	The difference elevation of the station	Free air correction ($\Delta g_v = (dg/dz)\Delta h$) (Telford, 1976)	calculated

The seasonal changes in the shallow groundwater level can have a significant effect to the microgravity data (e.g. Allis and Hunt, 1986). Therefore the time of the gravity measurements in 1999, 2005 and 2008 were scheduled during the dry season around October. From 30 years measurement, Aldrian et al. (2003) explained the rainfall rate of the region A of Indonesia (including the Java Island) in August to October is in low part of the rainfalls rate in Indonesia.

The changes in the shallow ground water level were calculated in 16 shallow wells of the local people around KGF to prove the above assumption. These wells were located near gravity benchmarks and the depths of water table were measured in 1999 and 2005. The density of water and the rock porosity were assumed to be 1 gr/cc and 15%. Referring to the equation of the changes of shallow ground water level (Table 1), the correction of this factor has been estimated for the observed gravity changes. The gravity correction that is caused by shallow groundwater level changes have average value of about 0.845 µgal. It was very small and this correction factor can be ignored. We assumed the groundwater level condition of 2008 at KGF is similar.

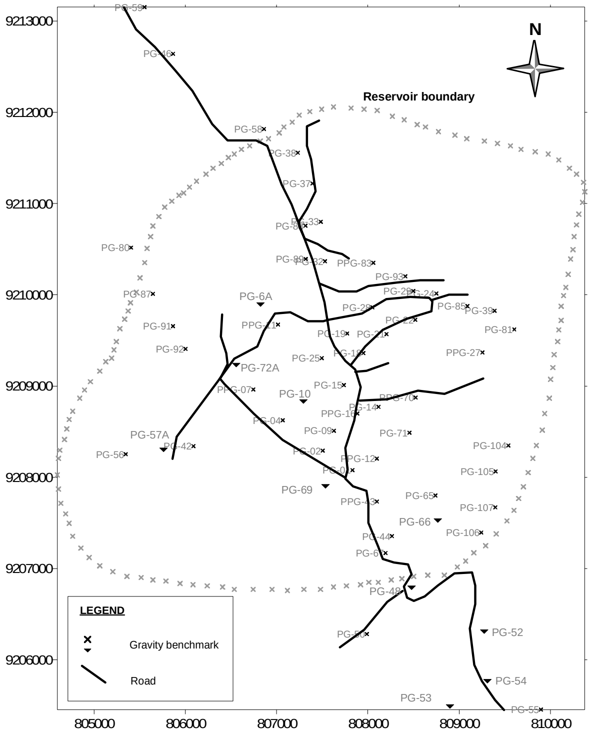

Figure 3: Gravity benchmarks at KGF

MASS BALANCE

A mass balance or material balance is an application of the mass conservation to the analysis of physical systems. The mass balance is used to analyze and to count the mass that enters or leaves the system. The mass balance in the geothermal reservoir is regulated by the amount of production, injection and natural recharge. The mass change (Δm) is a difference of the entering mass and the leaving mass. The mass changes rate ($\frac{\Delta m}{\Delta t}$) is result of the mass flux in ($\dot{m}_i$) and the mass flux out ($\dot{m}_j$).

$$\frac{\Delta m}{\Delta t} = \sum_{in} \dot{m}_i - \sum_{out} \dot{m}_j$$

$$= \dot{I} + \dot{R} - \dot{P}$$

$$= Q_{in}\rho_w + Q_r\rho_w - Q_p\rho_s \quad (1)$$

where m = mass, t = time, $\dot{I}$ = injection rate, $\dot{R}$ = recharge rate, $\dot{P}$ = production rate, Q_{in} = flow rate of the water injection, Q_r = flow rate of the water recharge, Q_p = flow rate of the steam production, ρ_w = water density, ρ_s = steam density. In the geothermal reservoir, the entering mass comes from the injection and natural recharge while the leaving mass comes from the production.

Gauss's theory (Hammer, 1945)[9] explains the mass changes are obtained by gravity changes:

$$m = \frac{1}{2\pi G} \iint g.\,dA$$

$$\Delta m = \frac{1}{2\pi G} \sum (\Delta g.\,\Delta A) \quad (2)$$

where Δm = the mass changes (kg), Δg = the gravity changes (mgal), ΔA = Area concerned (km^2), G = the gravitational constant 6.672x10^{-11} Nm^{2}kg^{-2}. The gravity change Δg for each grid as calculated below:

$$1\Delta g = \frac{dg_{i,j} + dg_{i+1,j}, + dg_{i,j+1} + dg_{i+1,j+1}}{4} \quad (3)$$

where ($dg_{i,j}, dg_{i+1,j}, dg_{i,j+1}, dg_{i+1,j+1}$) are the gravity change at one grid square (ΔA).

DISCUSSION

Gravity changes

The elevation decrease between 1999 and 2005 occurred in 19 benchmarks with the average of 0.75 cm/year or associated with 2.3 µgal/ years. The areas of the elevation decrease are found in the area of high and medium production rate. The corrected gravity data in 2005 was compared to those in 1999 and showed the gravity changes are between -238 µgal and 143 µgal for 6 years. The biggest negative gravity change occured on benchmark PPG-07 that is supported with the negative gravity changes on benchmarks PPG-11, PG-04 and PG-02 (see the location at Figure 3). This high negative value of the gravity change has correlation with the high production rate in this area, that are the KMJ-22, 37, 42, 65, 73 and KMJ-74 (Figure 4). The large negative gravity changes were primarily caused by the net mass loss of geothermal fluids from the geothermal reservoir due to exploitation. The small positive value of the gravity change occurred near the injection wells KMJ-55 and KMJ-21. The gravity changes in gravity are larger in the high permeability zone.

The gravity data in 2008 measurement have an uncertainty average about 12 µgal. The corrected gravity changes data between 1999 and 2008 are among -310 µgal to 260 µgal for 9 years. The distribution of the gravity changes helps to give a picture of the mass movements that have occurred as a result of the production and injection activities between 1999 and 2008 and natural recharge from outside of the reservoir (Figure 4). In this period, the biggest negative gravity change also occured on bechmark PPG-07 that correlated to high production zone. Some strike-slip faults from geology data in the north-east area at KGF are also correlated to the gravity changes distribution between 1999 and 2008. This area has a boundary between positive and negative gravity changes.

Mass balance

The corrected gravity changes map was divided into 3828 grids that are indicated in the reservoir area and the area of each grid is 6097.155 m^2. From the above calculation (above), the mass changes of the 1999-2005 gravity changes show decrease about 20.07 Mt (Million ton) for 6 years period that is about 3.34 Mt/year. During 1999 to 2008, the mass changes calculation by the Gauss theory estimated a decreased mass of about 3.78 Mt/year.

Since 1983 to 2005, more than 160 x 10^6 tons of steam has been exploited from KGF and more than

30 x 10^6 tons of water has been injected to KGF. More than 30 production wells, including stand-by wells, supplied steam to the three units. The total production rate from the field has remained relatively constant at about 1,100 tones per hour of steam (Sanyal et al., 2000). The average of total production rate from the 1999 - 2005 is about 7.98 Mt/ year. It is bigger than the average of the 1999-2005 total injection rates of 1.87 Mt/ year (Pertamina, 2008). Assuming all the injected water entered to the reservoir, the estimation of the total rate of the natural recharge to the Kamojang reservoir system is about 2.77 Mt/year. The recharge rate to KGF of about 45% of the net mass produced has occurred from the natural flow and lateral aquifers.

In 2007, the Kamojang production capacity was improved during the increased install capacity to 200 MWe. More than 40 production wells supplied steam constantly at about 1,400 tones per hour (Sofyan et al., 2009). The average of the 1999 – 2008 total production rates per year increased to about 8.35 Mt/year. In this period, the injection rate decreased to 1.82 Mt/year (Pertamina, 2008). The net mass produced (total mass produced – total mass injected) at KGF during this period is about 6.53 Mt/year. The natural recharge to the Kamojang reservoir system in this period is about 2.75 Mt/year if all injected water entered to the reservoir. This high gap of the total amount between exploited and injected fluid to the reservoir lead to unbalanced mass problem.

The calculation results of the natural recharge rate per year are close to the previous calculation from the 1984-1999 gravity changes data that is 2.71 Mt/year (Kamah et al., 2000). The natural recharge rates between 1999 and 2005 (2.77 Mt/year) and 1999-2008 (2.75 Mt/year) are almost similar. This means the natural recharge rate to the reservoir in KGF is limited. The simple mass balance model of the 1999-2005 and 1999-2008 gravity changes in KGF are shown in Figure 5.

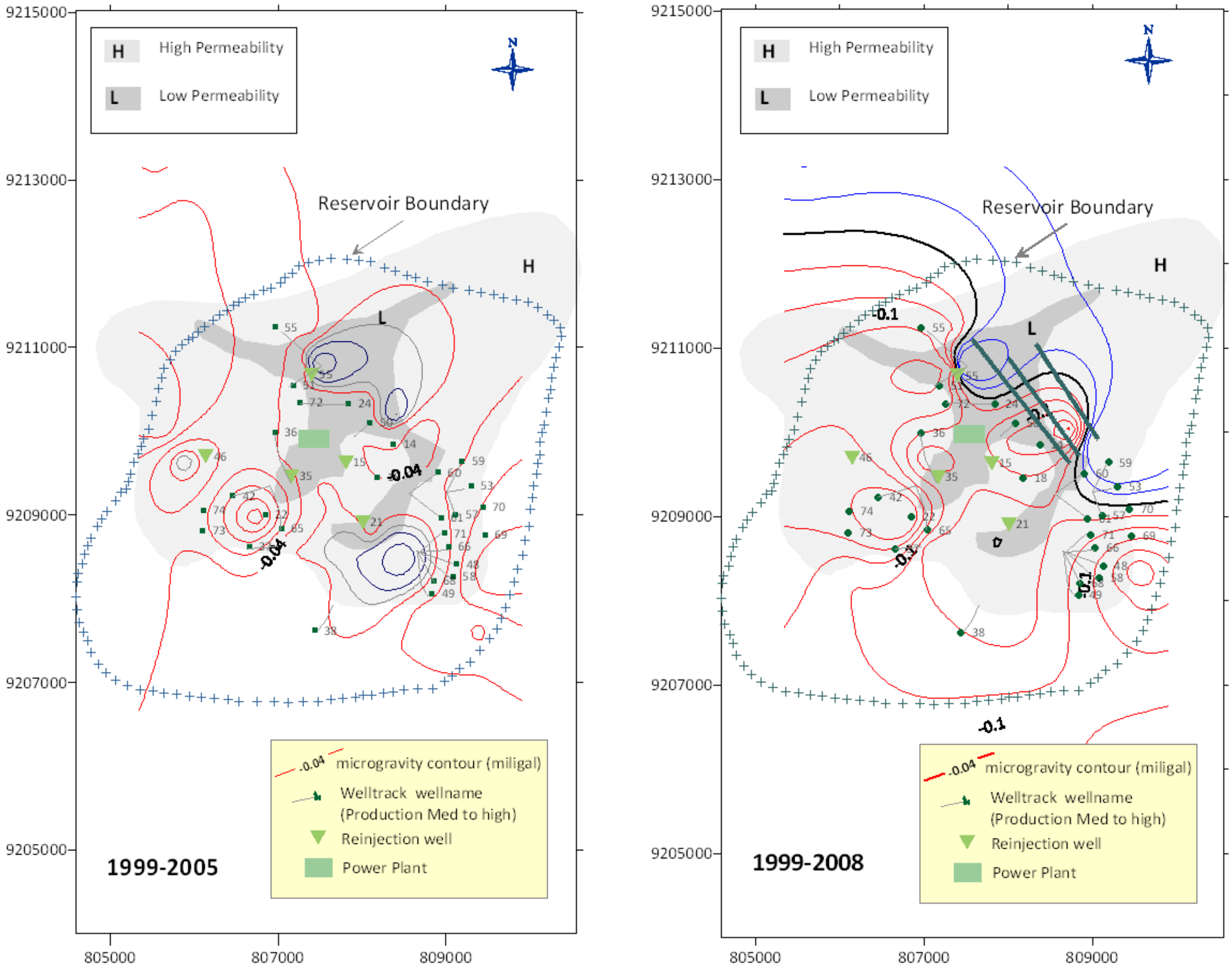

Figure 4: Distribution of gravity changes before increase production (140 MWe, left) and after (200 MWe, right)

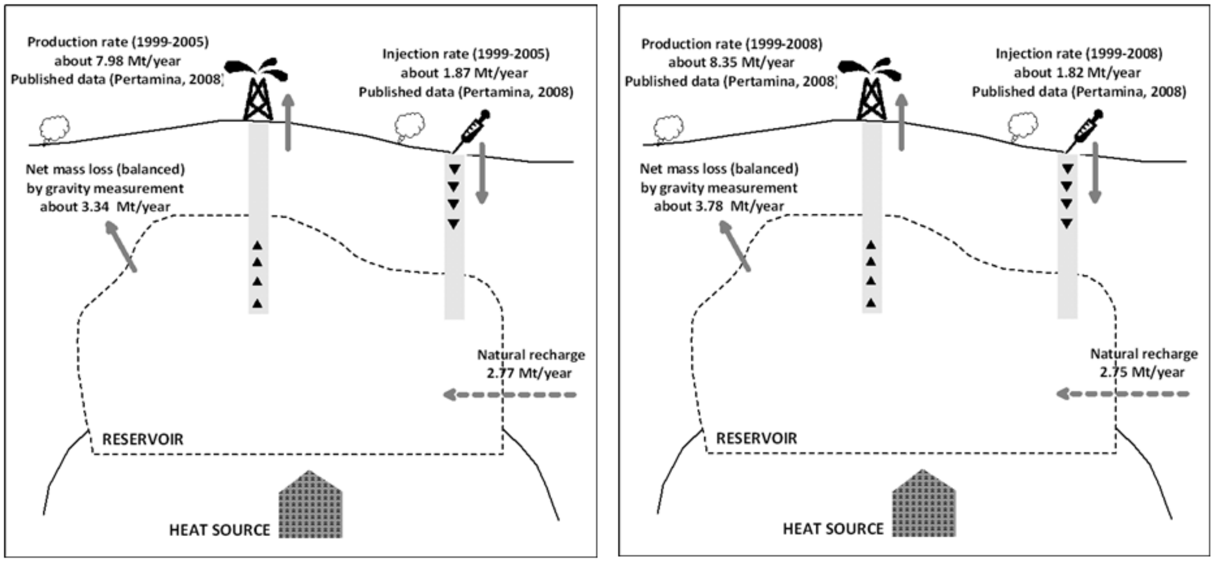

Figure 5: Mass balance of KGF before increase production (140 MWe, left) and after (200 MWe, right)

CONCLUSSION

Repeat gravity measurement in the Kamojang Geothermal Field (KGF) explained some gravity changes through the production and injection activities. From 1999 to 2005, gravity changes occurred in the KGF while produced 140 MWe. After the produced capacity increased to 200 MWe at 2007, repeat gravity measurement was conducted in the end of 2008 that was compared to 1999. Gravity changes during the capacity increased (1999-2008) are bigger than previous one (1999-2005). The estimated mass changes rate from the 1999-2005 gravity changes data is -3.34 Mt/ year while the rate from the 1999-2008 gravity changes data is -3.78 Mt/ year. The mass balance model in KGF reservoir of the 1999-2005 and 1999-2008 gravity changes in KGF are shown in Figure 5.

ACKNOWLEDGEMENT

The author would like to thank to the PERTAMINA, Global Centre of Excellent (G-COE) Kyushu University, Kyushu University and the University of Indonesia.

REFERENCES

Smith, J. S., Bloggs, R. T. and Jones, E. R. (1974), "Magnetic Anomalies in Geothermal Systems," *Journal of Fluid Mechanics*, **254**, 73-79. <Reference Style>

Aldrian, E. and Susanto, D. (2003), “Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature,” *International Journal of Climatology*, **23**, 1435-1452.

Doddy, S., IK.Sujata and Komaruddin, U. (2000), “Evaluation of steam production decline trends in the Kamojang Geothermal Field,” *Proceedings*, World Geothermal Congress 2000, Kyushu, Japan, 2857-2862.

Hammer, S. (1945), “Estimating Ore Masses in Gravity Prospecting”, *Geophysics*, **10**, 50-62.

Hunt, T. M. (2000), “Five lectures on environmental effect of geothermal utilization”, *Geothermal Training Programme,* United Nations University, 104 p.

Kamah, M. Y., and team (2000), “Gravity Survey 99-00 Kamojang Geothermal Field, Jawa barat”, PERTAMINA, 93 p.

Pertamina (2008), “Kamojang, West Java Indonesia, from beginning until now”, *Proceedings*, International Geothermal Sustainability Modeling Workshop, New Zealand, 10 p.

Sanyal, S. K., Robertson-Tait, A., Butler, S. J., Lovekin, J. W., Brown, P. J., Sudarman, S. and Sulaiman, S. (2000), “Assessment of Steam Supply for the Expansion of Generation Capacity from 140 to 200 MW, Kamojang Geothermal Field, West Java, Indonesia”, *Proceedings*, World Geothermal Congress 2000, Kyushu, Japan, 2195-2200.

Sofyan, Y., Daud, Y., Kamah, Y., Nishijima, J., Fujimitsu, Y. and Ehara, S. (2009), “Sustainable production plan in the geothermal energy development – a case study of Kamojang Geothermal Field, Indonesia”, *Proceedings*, The 4th International Symposium on Novel Carbon Resource Sciences, Shanghai, 141-147.

Sudarman, S., Boedihardi, M., Pudyastuti, K., Bardan (1995), “Kamojang Geothermal Field 10 year experience”, *Proceedings*, World Geothermal Congress 1995, Florence, 1773-1777.

Sumintadireja, P., Sudarman, S., Mizunaga, H. and Ushijima, K. (2000), “Misse-a-la-masse and gravity data survey at the Kamojang Geothermal Field”, *Proceedings*, World Geothermal Congress 2000, Kyushu, Japan, 1777-1784.