INTERPRETATION OF WELL LOGGING DATA ON LAHENDONG GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

A presence of hydrothermal convection systems in the Lahendong geothermal reservoir is examined using the Rayleigh number (Ra). Interpretation of well logging data on Lahendong geothermal field suggested that the Lahendong field consists of two reservoirs; shallow one with average thickness of about 450 m and deep one with 1200 m thickness. The Rayleigh numbers for shallow and deep reservoirs calculated using permeability of cores are in the range from 0.0027 to 0.51 which are lower than the classical critical Rayleigh number (≈39.5) and the critical Rayleigh number (Rc) depending on the over-heat ratio ( ). Thus, permeability values of the cores are too low for an onset of natural convection. The Ra calculated using permeability values from well tests imply that convection process occurs in shallow and deep reservoirs in the central area in Lahendong, while it occurs only in the deep reservoir in the southern area.

1. INTRODUCTION

The Lahendong geothermal field, located in the northern part of Sulawesi islands, Indonesia **(Figure-1(a))**, has a typical high-temperature liquid-dominated reservoir. In order to understand hydrothermal system in Lahendong more in detail, we reinterpret well logging data for temperature profiles, permeability, and reservoir thickness. This paper will describe quantitatively the occurrence or the absence of the convective process within Lahendong geothermal field for both shallow and deep reservoirs by applying the Rayleigh number (*Ra*). Both reservoir rock and fluid parameters were determined then by comparing the Rayleigh number (*Ra*) and the classical critical Rayleigh number (*Rc*) and also that calculated from the over-heat ratio ( ) the presence of natural convection was evaluated. We used two kinds of permeability that were determined from core data and well test data.

2. FIELD DATA

2.1. Lithology

The subsurface lithology are summarized as follows (S. Sudarman *et al.*, 1996): Post Pangolombian Formation consists of tuff and breccia, Pre Pangolombian-Kasuratan Formation (Post Tondano Unit) consists of basaltic andesite, Tondano Unit consists of tuff and ignimbrite and Pre Tondano that is dominated by andesitic lava and hyaloclasties.

In the area of the wells, the surface formations have been extensively altered to clay minerals forming a low permeability layer. The Kasuratan Formation that consists of basaltic andesite lava flows and interflow breccias also gives the evidence that this unit has generally low permeability. But the disruption to the smooth temperature profiles in this unit in Wells LHD-1, 2, 5 shows that localized permeability exists within this unit (GENZL, 1994).

GENZL (1994) also reported that the Tondano Unit consists of Tondano Pyroclastics and Minahasa Ignimbrite. Within the Tondano Unit, the upper Tondano Pyroclastics are mainly unconsolidated pumice tuffs, while the ignimbrite is highly welded and unconsolidated airfall pumice tuffs overlay the welded part. It was reported that these rocks have relatively high porosity and permeability from laboratory measurement and this Tondano unit is believed to be the most permeable formation in the Lahendong geothermal field.

The deepest rock formation is Pre Tondano Unit consists of andesitic lava and hyaloclasties except for Well LHD-5 drilled into micro-diorite of 1200 m thick.

2.2. Temperature Profiles

At present, 16 wells have been drilled in Lahendong **(Figure-1(b))**. In general, the temperature distribution of the wells in Lahendong can be grouped into 4 kinds as shown in **Figure-2**. The first group is the temperature profile of wells (Well LHD-1, 2, 5) located in the central and northern areas in **Figure-2 (a)**. The figure indicates that temperature increases linearly down to 400 meter above sea level (m.a.s.l.) suggesting that conductive process dominates the heat transfer within this region. Then, temperature shows slight increase with depth, which implies that convective heat transfer occurs in this depth interval.

The second group is of wells located in the southern block of southern area (Well LHD-4, 11, 12) **(Figure-2(b))** shows that there is a high temperature zone at the elevation of about 400 m.a.s.l. This implies that a cross flow presents at this depth. Linearly increase in temperature at depths 200 m.a.s.l to –200 m.a.s.l suggests that conductive heat transfer is dominated in this zone. This can be interpreted that a low permeable zone presents in this depth interval. The temperature profile below this zone shows constant values down to –1500 m.a.s.l implying that convective process may occur in this region.

The third group is of wells located in the northern block of southern area (Well LHD- 13, 14, 16, **Figure-2 (c)**) shows that the temperature linearly increases with depth and reaches to 300 to 350^0C at the bottom. Temperature gradient decreases near the well bottom indicate a presence of minor upflow. Most of the wells in the last group (Well LHD-3, 6, 7, **Figure-2(d)**) are located at or near the margin of the field and have low temperatures.

2.3. Lost Circulation and Injection Test

The lost circulations either partial or total during drilling in Lahendong were encountered in different situations/characteristics from one well to the other (PERTAMINA, 1999). The drilling history for Well LHD-1 shows that at the elevation of about 67 m.a.s.l the lost circulation was encountered at a rate of 600 liter/min (lpm) and at -329 m.a.s.l of about 200 lpm. The lost circulations found in Well LHD-4 were at two depth intervals; the upper part was about 1310 lpm at 635 and 563 m.a.s.l and the deeper one was ranging between 25 lpm to 1924 lpm at the elevation of between –765 m.a.s.l and –1450 m.a.s.l. The other situation was found in Well LHD-12 where the relatively a small amount of partial lost circulation was encountered. Therefore, hydraulic fracturing was carried out for increasing the permeability. No lost circulation was detected in Well LHD-13. The hydraulic fracturing was also exercised at this well resulted in a slight increase in permeability. A quite similar situation to the Well LHD-13 was found in Well LHD-14. Because a magnitude of lost circulation was small at the elevation between –550 m.a.s.l and –864 m.a.s.l ranging from 10 to 20 m^3, the hydraulic fracturing was also conducted.

In order to identify potential feed points (fluid entries) in the wells and to estimate permeability, injectivity tests were conducted. During the test, temperature logging were carried out for delineating depths of water loss zones. The pressure transient data were analyzed for permeability.

The result of injection test conducted on Well LHD-4 is shown in **Figure-3(a)**. Two kinds of injection rate were used; 890 lpm and 780 lpm. It can be seen that temperature gradient changes near –400 m.a.s.l, indicating some water loss occurs and from the elevation –1000m.a.s.l and below the water loss is poor. And finally at the elevation of about –1500 m.a.s.l sharp increase in temperature indicates that cold water did not flow deeper in the well below this level. The other injection test was carried out at Well LHD-5 presented in **Figure-3(b)**. Temperature profile showed that apparent increase in temperature at the elevation of about -600 m.a.s.l indicates that the permeable zone may present at this depth. The nearly constant temperature down to about –1000 m.a.s.l and abrupt increase below this elevation at Well LHD-13 suggests that permeable zones does not present above –1000 m.a.s.l.

3. CALCULATION OF RAYLEIGH NUMBER

The occurrence of natural convection can be examined using the Rayleigh number (*Ra*) that is calculated by:

$$Ra = \frac{\alpha_f g \rho_f^2 c_{pf} kh(T_1 - T_0)}{\mu \lambda_m} \qquad (1)$$

where, $_f$ is the volume coefficient of thermal expansion of water (K^{-1}), g is the gravitational acceleration (m/s^2) , $_f$ is the fluid density (kg/m^3), c_{pf} is the specific heat of fluid (J/kgK), k is permeability of porous medium (m^2), h is the thickness of the system (m), T_1 and T_0 are the temperature of the bottom boundary and top boundary (^0C), is the fluid dynamic viscosity ($Pa.s$), and λ_m is the thermal conductivity of the medium (W/mK).

Natural convection initiates when *Ra* exceeds the critical Rayleigh number (*Rc*) (usually 4 ^{2}($\approx$39.5)). Geothermal systems are normally over-heated i.e. the bottom boundary temperature is much higher than that of the top boundary. Thus, natural convection starts at much lower *Rc* because of the enhancement in buoyancy force and reduction in flow resistance. This effect can be measured by the over-heat ratio (a ratio of temperature difference between the top and bottom boundaries and the temperature of bottom boundary) (Hanano, 1998).

4. RESULTS AND DISCUSSION

The occurrence or the absence of natural convection can be examined by comparing the Rayleigh number (*Ra*) and the critical value *Rc*. In this study the critical Rayleigh numbers (*Rc*) are estimated from the figure on *Rc* vs of Kassoy and Zebib (1975). As an example of data used to determine the Rayleigh number and its critical value including the other parameters for Well LHD-4 is presented in **Table-1**, while the calculated results shown in **Table-2**.

The permeability plays an important role in calculating *Ra*. The permeabilities were determined from core data and well test data. The permeability values from core analysis data represent permeability of rock matrix, while those determined from well test data represent the permeability of fracture system. Another problem arising in the pressure transient analysis is that wells were cased except deep zone where liner was set. Therefore, the obtained permeability only represents that of the deep reservoir.

The calculated Rayleigh number (*Ra*) for the shallow reservoir ranges from 0.0027 to 0.065 using permeability from core analysis and from 3.99 to 36.68 from the well test data. For the deep reservoir, it falls between 0.44 and 0.51 from the core analysis and 14 to 140 from the well test data. Critical Rayleigh numbers (*Rc*) determined graphically for given over-heat ratios are from 12 to 24 for the shallow reservoir and from 16 to 24 for the deep reservoir. The calculated Rayleigh numbers based on the core data are lower than both the classical critical Rayleigh number ($\approx$39.5) and that obtained from the over-heat ratio for both shallow and deep reservoirs. Therefore a natural convection may not present within the reservoirs if consisted only of rock matrix.

Next, the Rayleigh numbers were calculated using the well test data. For Well LHD-4 a value of calculated *Ra* (=5.23) and the estimated *Rc* (=15) suggested that there is no convection process in shallow reservoir while it may occur in the deep reservoir because *Ra*=140 is greater than *Rc*=16. The lost circulation data and the injection test results also indicate the presence of high permeable zone that is required for convection process.

For Well LHD-5 there is a possibility for convective process to occur both in shallow and deep reservoirs because the *Ra* equals to 36.7 and 134 that are greater than *Rc* that equals to 24 and 19.

Well LHD-13 showed that the convection may not start either in shallow or deep reservoir even though the results of well test data were used. This result does not satisfy the interpretation from the temperature profile where the minor up flow may occur in the reservoir. However, it should be noted in using the

Rayleigh number that the critical Rayleigh number (*Rc*) only applies on the onset of natural convection when the bottom of the system is heated uniformly. If the subjected heat source is not uniform, convection may occur when the Rayleigh number is smaller than the critical Rayleigh number, when there present a temperature difference in the medium.

5. CONCLUSIONS

Interpretation of well logging data as well as calculation of Rayleigh number (*Ra*) at Lahendong lead to following conclusions; The Lahendong geothermal field consists of two reservoirs; shallow and deep reservoirs with the average thickness of about 450 m and 1200 m respectively. The permeability values of the cores are too low for an onset of natural convection. The Rayleigh number calculated using permeabilities from well test data suggest that convection process may occur in most parts of the reservoir in Lahendong except in the northern block of southern area.

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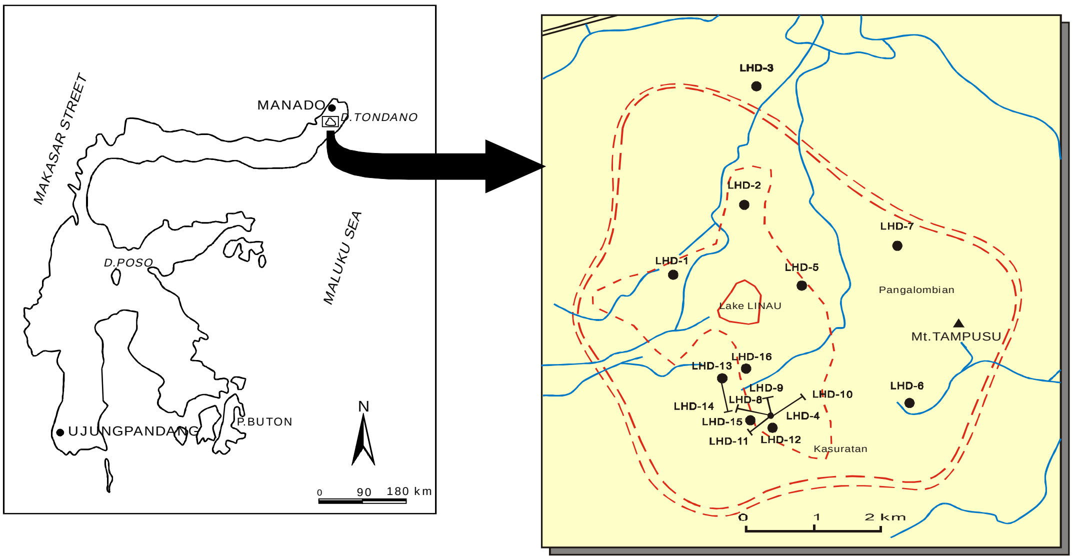

(a) (b)

Figure-1
Location Map of Lahendong Geothermal Field.

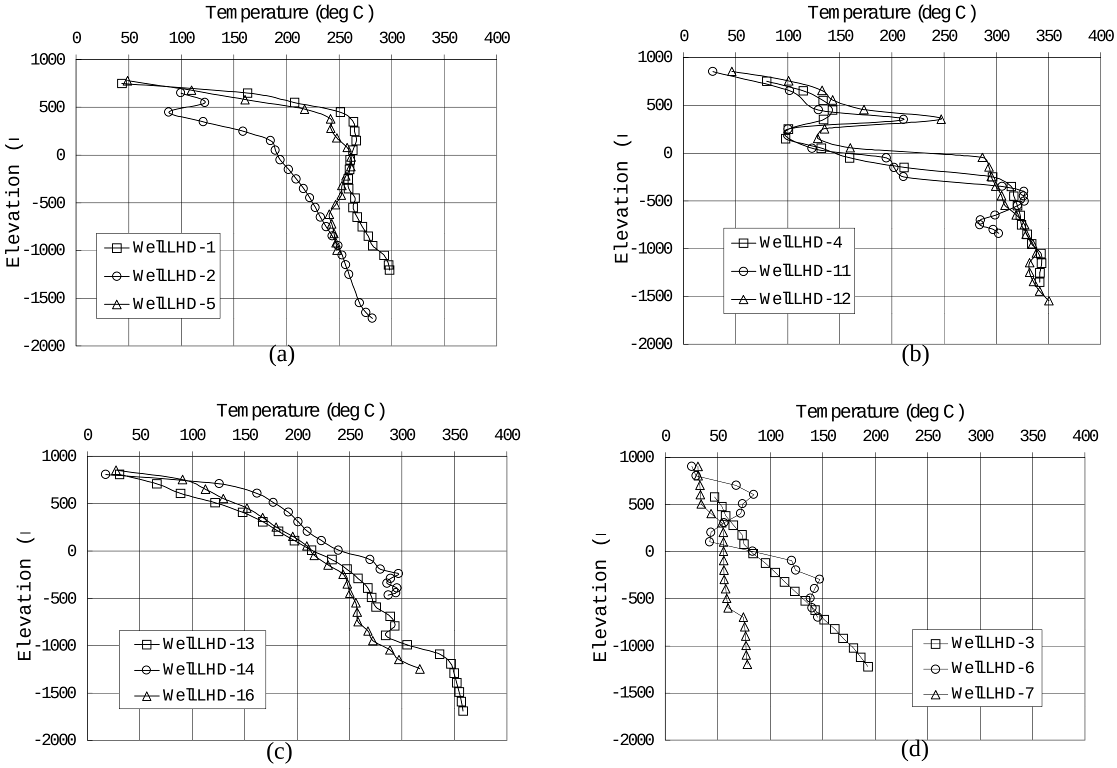

Figure-2
Classification of Temperature Profiles in Lahendong.

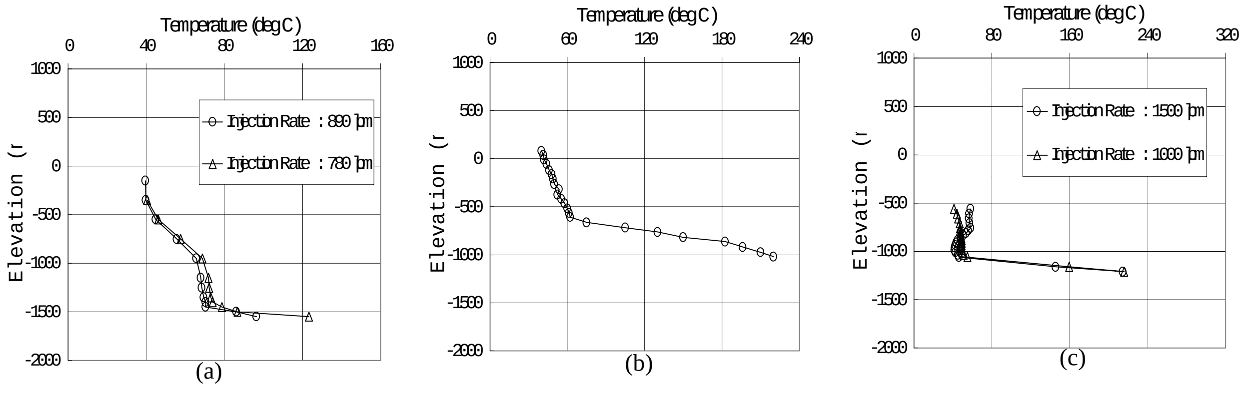

Figure-3
Injection Tests in Lahendong (a) Well LHD-4, (b) Well LHD-5, (c) Well LHD-13

Table-1
Parameters used for calculating Rayleigh number (*Ra*) for Well LHD-4
*) T_0 and T_1 for shallow reservoir are those at 650 m.a.s.l and 200 m.a.s.l in Figure 2 (b), and those for deep reservoir at –250 m.a.s.l and –1350 m.a.s.l.

Parameters			**Shallow Reservoir**	**Deep Reservoir**
$k(m^2)$	Core Data		$2.72\text{x}10^{-18}$	$1.53\text{x}10^{-17}$
	Well Test	$kh(m^3)$	-	$4\text{x}10^{-12}$
		$h(m)$	-	750
		$k(m^2)$	$5.3\text{x}10^{-15}$(assumed)	$5.3\text{x}10^{-15}$
$h(m)$			450	1100
$g(m/s^2)$			9.8	9.8
$T_o(^oC)$ *)			80	210
$T_1(^oC)$ *)			135	340
ƒ ¢$_f$$(K^{-1})$			$0.83\text{x}10^{-3}$	$1.8\text{x}10^{-3}$
ƒ Ï$_f$$(kg/m^3)$			954	775
$C_{pf}(J/kgK)$			$4.216\text{x}10^3$	$4.984\text{x}10^3$
ƒ Ê$_f$(Pa.s)			$261.7\text{x}10^{-6}$	$95.4\text{x}10^{-6}$
$\lambda_m(W/mK)$			2.99	3
Ra (-)	Core Data		0.0027	0.442
	Well Test		5.23	140

Table-2
Calculated Rayleigh number (*Ra*) and critical Rayleigh number (*Rc*).

.		***Ra* (-)**			***Rc* (-)**		
	Wells	LHD-4	LHD-5	LHD-13	LHD-4	LHD-5	LHD-13
Permeability from Core Data	Shallow Reservoir	0.0027	0.065	-	15	24	12
	Deep Reservoir	0.44	0.51	-	16	19	24
Permeability from Well Test	Shallow Reservoir	5.23	36.7	3.99	15	24	12
	Deep Reservoir	140	134	14	16	19	24