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NUMERICAL MODELLING OF THE KAMOJANG GEOTHERMAL SYSTEM, INDONESIA

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ABSTRACT

Kamojang geothermal field on the island of Java in Indonesia is in a large volcanic chain, 15 km long and 4.5 km wide. It is a steam-dominated field located at 1500 m a.s.l. The field has been exploited since 1983, currently supplying steam for 140 MWe power production but production will be raised to 200 MWe, scheduled in 2006. To date, 72 wells have been drilled in the field. Reservoir simulation is a numerical method used to simulate the performance of a geothermal reservoir either at natural state conditions (before exploitation) or under a variety of exploitation schemes and future predictions. The TOUGH2 simulator was used for a 2-dimensional numerical modelling of the Kamojang geothermal system to study different boundary conditions from what has been practiced in the past. The model consists of 394 elements in 13 layers. The natural state of the model simulates quite well the reservoir's temperature and pressure down to 1 km depth as observed in well KMJ-11. The model was used to make a 27 year forecast on reservoir response to the 200 MWe production, starting in 2006. The model needs, however, to be recalibrated and compared to more field data to give a more confident estimate of the field's future performance.

1. INTRODUCTION

The Kamojang geothermal field is located in the western part of Java Island, about 35 km south of Bandung, the capital city of the West Java Province, Indonesia. An overview of the field is given in Figure 1. The field has been supplying steam for 30 MWe power production since 1983. Since 1987, production capacity is 140 MWe, and will be raised to 200 MWe, expected to be online in 2006.

Geothermal drilling in the Kamojang area was initiated in 1974-1975 when five exploration wells throughout the area were drilled down to 700 m. Two of these were productive, producing dry steam with temperature of 232°C from shallow feed zones at about 600 m depth (Sudarman et al., 1995). To date, 72 wells have been drilled in the Kamojang geothermal field.

Preliminary studies in Kamojang commenced in 1926-1929 by the Volcanologica1 Survey of the Netherlands East Indies, which drilled five slim holes to depths ranging between 66 and 128 m (Robert, 1988). Only one of these is still active and discharges dry steam. New investigations were

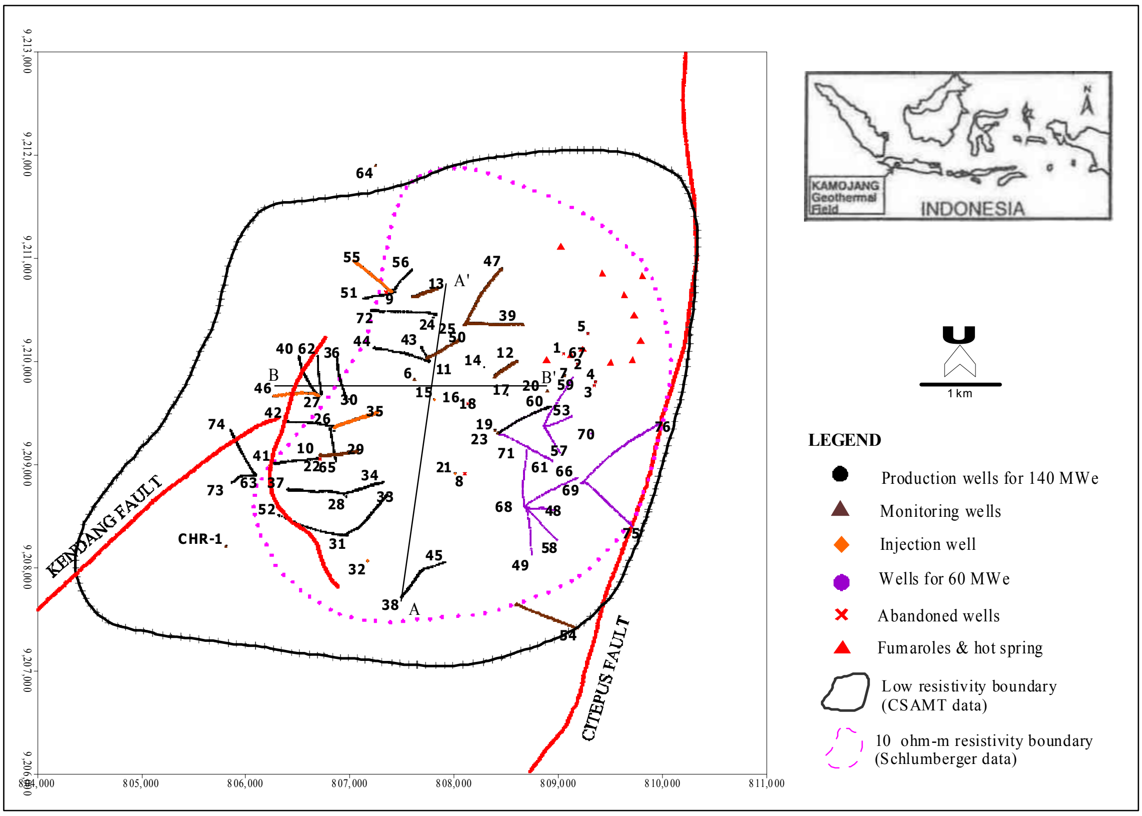

FIGURE 1: An overview of the Kamojang geothermal field, showing location of wells and main geological structures; locations of cross-sections A-A' and B-B' are also shown

performed in 1971 by the cooperative work between the Government of Indonesia and the Government of New Zealand. A geological map was established, chemical analyses were carried out and Schlumberger resistivity mapping done, which delineated the field boundaries.

The field is located in a large volcanic chain at an elevation of about 1500 m a.s.l. The chain is 15 km long and 4.5 km wide, extending from G. Rakutak in the western part to G. Guntur in the eastern part of Java Island. This chain is composed of a succession of volcanic complexes. G. Rakutak is the oldest and inactive while G. Guntur is the youngest, and still active.

Several surface manifestations are found in the Kawah area in the northwestern part of the Kamojang field. They consist of fumaroles, steaming ground, mud pools and hot water pools in an area which approximately covers 500 m × 500 m. The chemical analysis of the hot water manifestations in Kamojang shows low chlorine content. The gas content in the steam is approximately 2% by weight, mostly CO_2 and H_2S.

This report describes a 2-dimensional simulation effort of the Kamojang geothermal field, where the TOUGH2 simulator was applied. Results from natural state modelling were compared with pressure and temperature data from well KMJ-11. The model was used to make a 27 year forecast on reservoir response due to the increase from 140 to 200 MWe production, planned to start in 2006.

2. KAMOJANG GEOTHERMAL FIELD

The Kamojang geothermal field is a steam-dominated system, associated with 400,000 years old Quaternary volcanic products of Pangkalan and Gandapura volcanic centres. It appears to occupy a volcanic depression created by the Pangkalan caldera rim inside the NE-SW graben formed by the Kendang fault in the west and Citepus fault in the east (Sudarman et al., 1995). The Pangkalan caldera rim, the Citepus fault and a W-E trending fault system in the northern part of the field are associated with high steam productivity. Two low-permeability barriers are assumed to exist in the Kamojang field, striking NW-SE and SW-NE. The SW-NE permeability barrier is interpreted as a "shear zone" from normal faulting observed in the area (Robert, 1988).

A reservoir area of 14 km^2 has been estimated from DC-Schlumberger soundings (Hochstein, 1975) and a further field delineation of up to 21 km^2 has been determined from CSAMT studies (Sudarman et al., 1990). Reservoir assessment of the Kamojang geothermal field was prepared by Brian Barnett in 1988 with all well measurements and testing data integrated in order to produce a physical picture of the field. The following account of the Kamojang reservoir is from the work of Brian Barnett (1988).

2.1 Permeability

Values of reservoir transmissivity in the Kamojang geothermal field range from 1 to 120 Darcy metres (Dm) with the productive wells generally displaying values greater than 5 Dm. The reservoir may be considered relatively permeable. Well productivity is not only sensitive to reservoir permeability but depends also on well skin factor, with diminished productivity being suffered by well damage during drilling.

A correlation of well feedzones shows that the production wells at Kamojang have encountered permeability within a relatively thin band of formation. Figure 2 shows a projection of all deep wells at Kamojang onto a N-S trending cross-section. The productive aquifer there is defined with greatest depth in the south rising to the north. Its thickness is variable but appears to range from 100 m to about 500 m. Because of the considerable variation in east-west coordinates of the wells displayed in Figure 2, the exact shape and orientation of the productive zone

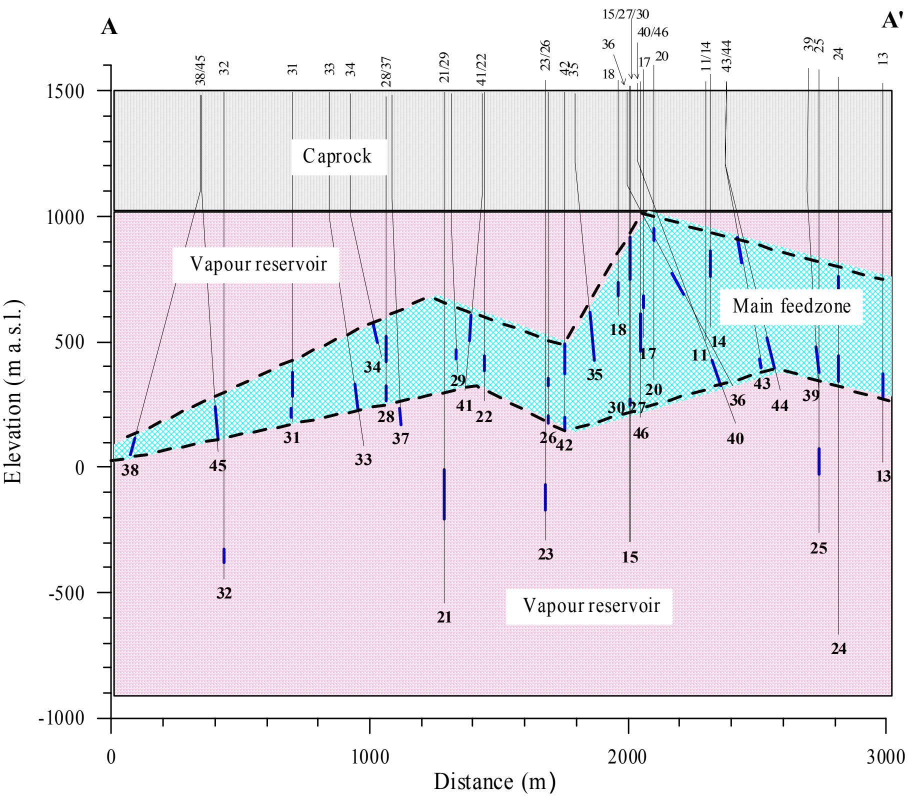

FIGURE 2: Kamojang well feed zone seen on a S-N trending cross-section, showing cap rock, main feedzone and vapour reservoir (adapted from Barnett, 1988); see Figure 1 for location

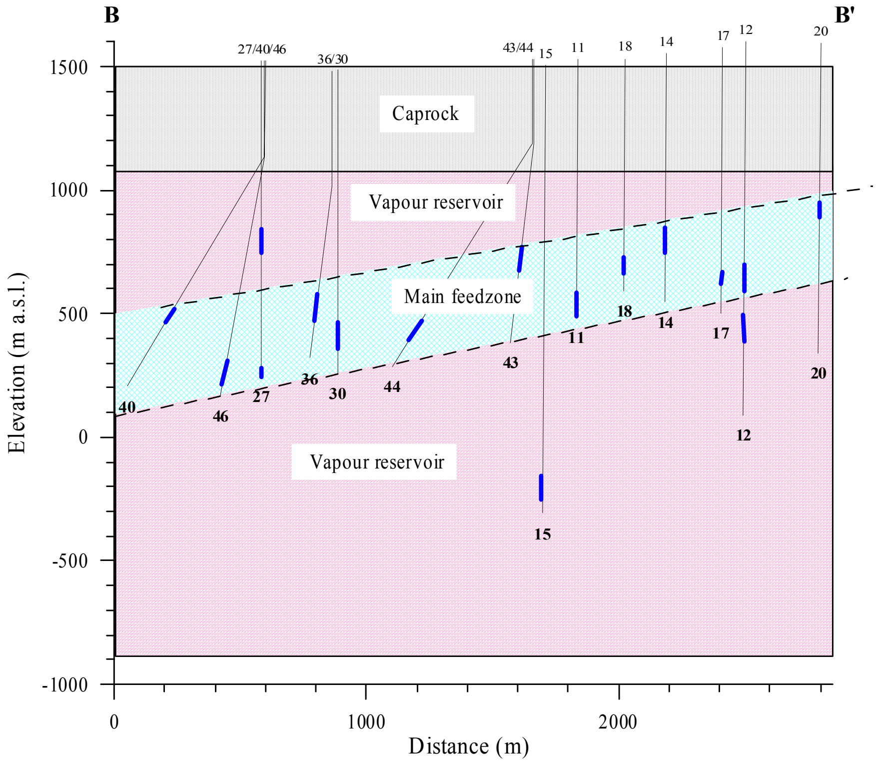

FIGURE 3: Kamojang well feed zone locations on an east-west cross- section, showing cap rock, main feedzone and vapour reservoir (adapted from Barnett, 1988); see Figure 1 for location

is distorted. Figure 3 is an E-W cross-section through wells KMJ-20 and 46. Only those wells located close to the plane of the section are included. In the Figure the productive aquifer is more clearly defined and appears as a reasonably uniform band, about 350 m thick and rising from west to east. The top of the aquifer is located at about 500 m a.s.l. in the west and at about 950 m a.s.l. in the east.

The productive aquifer does not appear to be a uniformly porous permeable layer but contains distinct, highly conductive fractures. It is considered to define the vertical range through which the rock fractures convey hydrothermal fluids and therefore defines the vertical region from which production is possible. Very little production is from zones above or below. At shallower depths it appears that the fractures are sealed (probably by mineralization) to form an impermeable cap rock. At greater depth fractured permeability may be poor because of excessive over-burden pressure, which tends to close fractures.

Figures 2 and 3 show that deep wells drilled through the productive aquifer intersect deeper feed zones located below 100 m a.s.l. Wells KMJ-15, 21, 23, 25 and 32 have all intersected deeper feed zones. This deeper aquifer appears less permeable than the shallow zone as witnessed by the poor productivity and low permeability-thickness values (*kh*) obtained from these wells. Wells KMJ-15, 21, 23 and 32 were designated as reinjection wells, and all reinjection will be into the deep aquifer. The only production well extracting fluids from the same zone is K MJ-25.

2.2 Pressure

The Kamojang field is recognized as a vapour-dominated geothermal reservoir, in which the one distinguishing character is almost constant pressure with depth. In fact, there is a small pressure gradient corresponding to the density of steam (so-called steam static pressure gradient) and an additional gradient associated with the upward movement of steam in the undisturbed reservoir. In practice, the estimated errors in measured vertical pressure gradient are of the same order as the horizontal pressure gradient. It is therefore difficult to estimate accurately the true vertical pressure gradient from measurements in many different wells. However, it is assumed to be slightly over 0.19 bar per 100 m, which is the static gradient for steam at 244°C with a density of 19 kg/m^3. Figure 4 shows the distribution of pressure as measured in the wells.

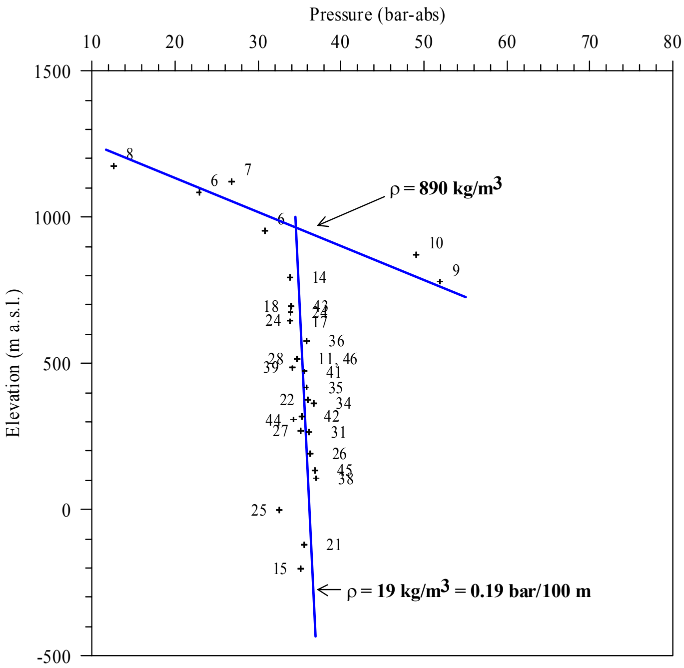

FIGURE 4: Vertical pressure distribution shows fluid density in the cap rock and steam gradient in the reservoir (adapted from Barnett, 1988)

Above the vapour-dominated reservoir the formation contains liquid water. Pressures in this shallow zone lie on a hydrostatic pressure gradient corresponding to hot water with a density of about 890 kg/m^3. The shallow liquid aquifer extends to at least 800 m a.s.l. (about 700 m depth) in the region of well KMJ-9. The high pressures measured in two shallow wells (KMJ-9 and 10) indicate the existence of a low-permeability confining layer or cap rock, at least in these locations, which isolates the vapour reservoir from the overlying liquid water aquifer. Steam discharges in the east of the field in the Kawah region, suggesting that the cap rock is not completely impermeable at all locations and allows discharge to surface.

The pressure distribution in the horizontal plane is shown in Figure 5, at an elevation of 500 m a.s.l. The general west to east and southwest to northeast pressure gradients reflect flow towards the natural surface discharge at Kawah.

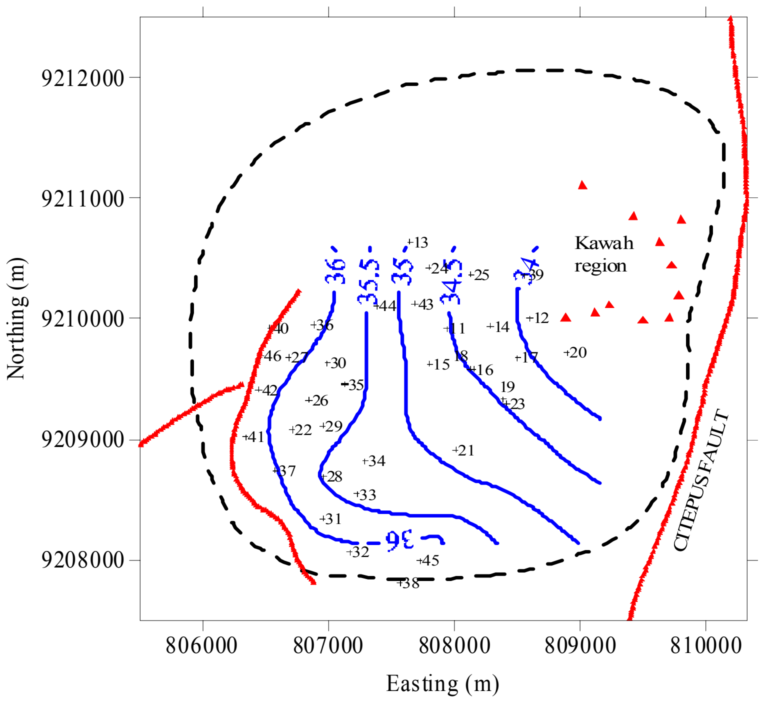

FIGURE 5: Pressure distribution at 500 m a.s.l. (adapted from Barnett, 1988)

2.3 Temperature

In a vapour-dominated reservoir, in which steam and liquid water are present, temperatures and pressures are related or constrained in accordance with the water saturation relationship. The distribution of temperature in the Kamojang reservoir is, therefore, of the same nature as the pressure distribution. Vertical and horizontal temperature distributions are shown in Figures 6 and 7, respectively.

As expected, the isotherms of Figure 7 are of the same form as the isobars of Figure 5 with the vertical distribution of temperature showing a minor increase with depth. Figure 6 shows that temperatures are not boiling throughout the overlying liquid water aquifer. Temperatures in wells KMJ- 8, 9, and 10 are significantly below saturation for the measured pressures.

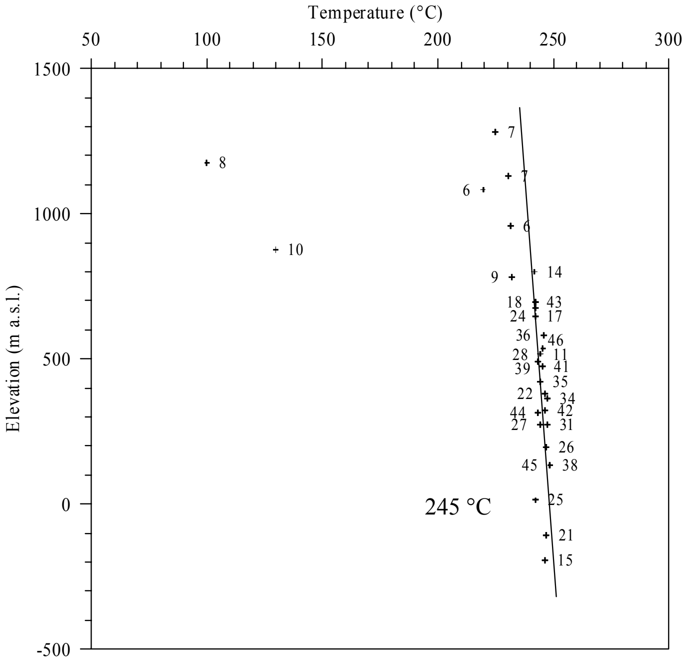

FIGURE 6: Vertical temperature distribution showing average reservoir temperature at 245 °C (adapted from Barnett, 1988)

2.4 Reservoir fluids

The hydrothermal fluid present in the Kamojang reservoir and the vapour-dominated field in general, consists of a mixture of liquid water and steam. The clearest evidence of this phenomenon is the fact that the reservoir pressures response to production propagates relatively slowly. If steam alone was present, the reservoir would deplete very rapidly and interference effects between neighbouring wells would be readily observable. It has been estimated that the reservoir contains about 25% liquid water by volume. Steam is the dominant phase as seen by the steam-static vertical pressure gradient and by the fact that the wells almost entirely discharge steam. These observations may be explained by the fact that steam is the continuous phase with the liquid water being present in isolated pockets and as dispersed droplets. The mobility of steam is much greater than that of water and the presence of vapour tends to inhibit the flow of liquid water to a discharging well.

Although the steam phase is clearly dominant, some liquid water is also present in the discharge. Recent tests have shown that the discharge fluid enthalpy varies with wellhead pressure. Maximum enthalpies around 2800 kJ/kg (i.e. dry steam) are produced at high wellhead pressures while enthalpies as low as 2775 kJ/kg have been measured at low wellhead pressure. Variations in enthalpy correspond to the increased proportion of liquid water in the discharge when pressure gradients are maximised at low wellhead pressures.

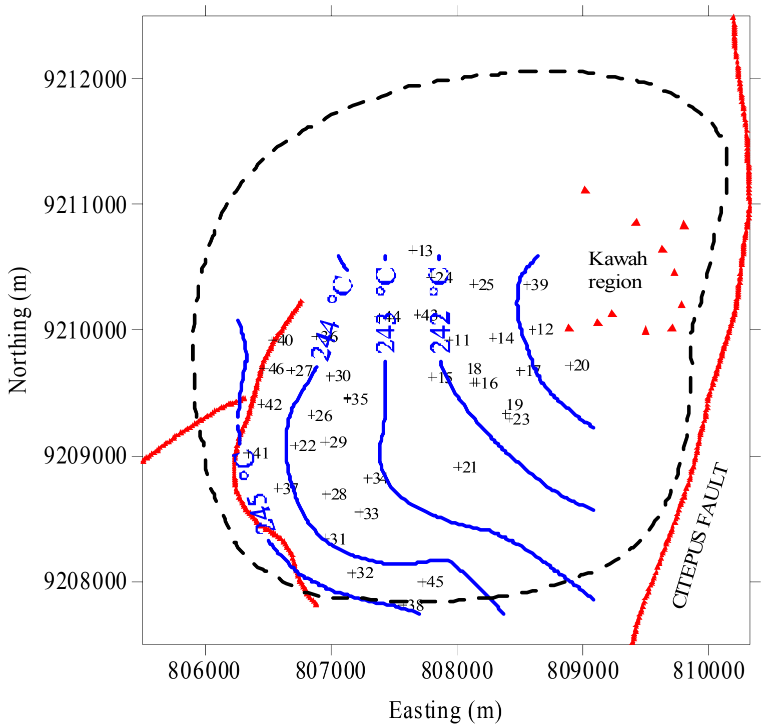

FIGURE 7: Temperature distribution at 500 m a.s.l. (adapted from Barnett, 1988)

2.5 Boundary conditions

To date, drilling has not identified lateral boundaries. In the vertical plane the upper boundary has been identified as a low-permeability cap rock extending to a maximum depth of 800 m a.s.l. in the region of KMJ-9. At other locations it is shallower. For example in well KMJ-6 the base of the cap rock is above 1000 m a.s.l. In the region of Kawah the cap rock has some vertical permeability allowing the emission of steam at the surface.

The permeable aquifer shown in Figures 2 and 3 does not identify the upper and lower limits to the reservoir. This aquifer defines a fractured permeable region through which fluids are transmitted, and from which most of the steam production is derived. However, the vapour-dominated reservoir which under long term exploitation supplies steam to the wells is of much greater vertical extent. The base of the reservoir has yet to be defined. It is anticipated that a deep saline liquid water exists at the lower boundary of the vapour-dominated system.

The side or lateral boundaries are likely to consist of impermeable flow barriers, which isolate the vapour-dominated reservoir from surrounding liquid-saturated formations. Effective isolation of the reservoir from its surroundings is necessary to prevent the flooding or inward flow of liquid water into the vapour-dominated reservoir. The potential for inward flow of liquid water arises from the large pressure imbalance between the hydrostatic pressure gradient in the liquid water outside the reservoir and the steam static pressure gradient, which produces low pressure at depth inside the reservoir.

2.6 Conceptual model

A conceptual model of a reservoir is a model that describes the physical process occurring in the reservoir showing the permeability structure, flow process and heat flow in the reservoir. Usually, this model is used as a preliminary model to construct the computer model. Based on the geological, geophysical and well measurement data, the Kamojang geothermal field is conceptualized as shown in Figure 8. This model assumes that:

- The groundwater layer extends from ground surface to 150 m depth. The condensate layer extends from 150 to 500 m depth. The temperature at the top of the condensate layer is 100°C and at the bottom of the condensate layer is 230°C. Therefore, it is assumed that the average temperature at the condensate layer is 165°C. Generally, the cap rock is 500-600 m thick but seems to be only 200-300 m thick toward the northern and eastern parts.
- The vapour-dominated reservoir extends below 500 m depth. The average temperature of the reservoir is 245°C and average pressure is 34 bar.
- The natural surface discharge of steam at Kawah is 32 kg/s.
- The lateral reservoir boundaries are likely to consist of impermeable flow barriers, which isolate the vapour-dominated reservoir from the surrounding liquid-saturated formations.

3. PREVIOUS NUMERICAL STUDIES

The use of computer models to simulate the performance of the Kamojang geothermal field has been carried out by Sulaiman in 1982, Takhyan in 1985 and GENZL in 1986, 1990 and 1992 (simulation carried out by O'Sullivan). In the last simulation (1992), GENZL used a 3-dimensional model and irregular grid. The bottom reservoir boundary extends approximately 500 m beneath the deepest wells. Within the reservoir, areas of high and medium permeability are included to represent areas of good and poor productivity, respectively.

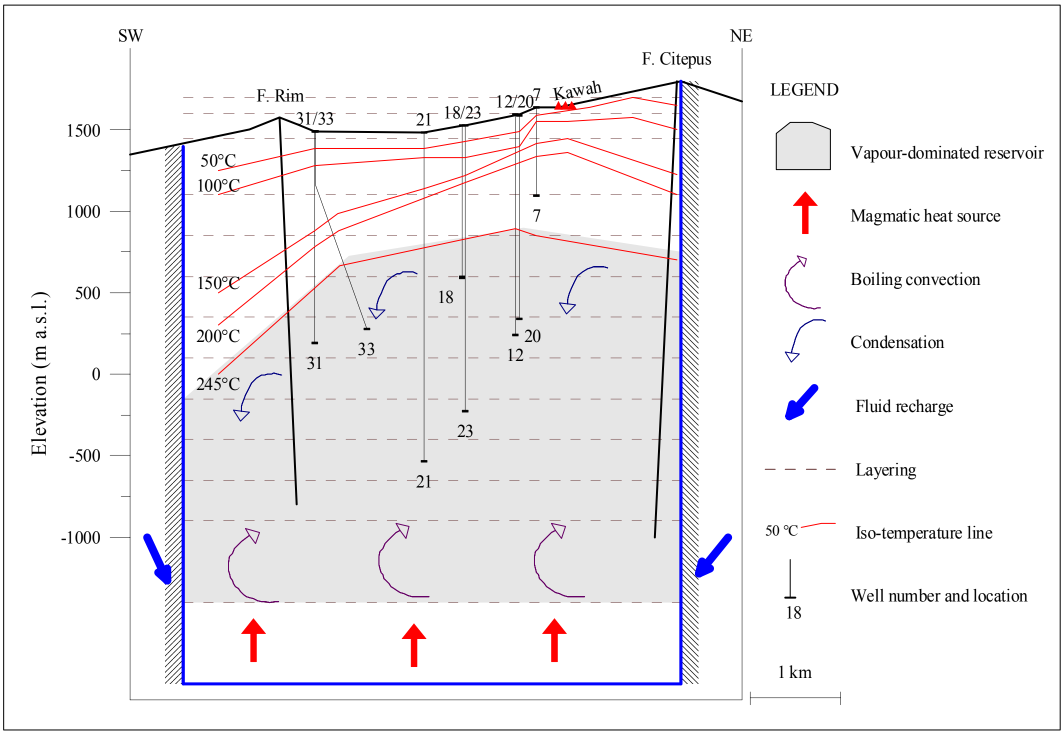

FIGURE 8: A conceptual reservoir model of the Kamojang geothermal field

The high-permeability parts of the reservoir have a thickness of 750 m and extend from 1000 m a.s.l. to 250 m a.s.l. in the central area and from 750 m a.s.l. to sea level in other areas. Underlying the main reservoir, from which present production is drawn, is a 1000 m thick layer of medium permeability (extending to -1000 m a.s.l. or 2500 m depth). An area of low permeability is modelled in the northern area encountered by KMJ-47 and indicated by resistivity data to be a potentially productive reservoir. Low-permeability rocks are modelled below the reservoir. Very low permeability is modelled on the perimeter of the field, and also above the reservoir to confine the reservoir pressure. The porosity of the high- and medium-permeability reservoir is 10%. All other formations have a porosity 1%. Initial reservoir steam saturation is assumed 70% or 30% liquid water.

All lateral boundaries in the abovementioned model are impermeable, and allow no fluid flow through the model sides. In the model, the boundaries were about 2 km from the reservoir and considered sufficiently remote not to affect the model results significantly. The lower boundary is located in the bottom layer at -2000 m depth a.s.l. Beneath the main reservoir this boundary is set with a constant pressure of 60.3 bar and 276°C. Beneath the blocks outside the reservoir, the boundary is set as a no flow boundary. With this setup, the recharge to the reservoir is from below with a constant temperature of 276°C. This results in an increased inflow to the reservoir as the pressure lowers due to production and long time forecasts must tend to be on the optimistic side.

4. NUMERICAL MODELLING

Reservoir simulation is a numerical method used to simulate the performance of the reservoir either at natural state condition or under a variety of exploitation schemes. In this method, the actual reservoir condition is simulated by a computer model as a system having a number of interconnected cells or blocks. The parameters of the reservoir model, such as permeability structure, temperatures, pressures, rock and fluid properties, heat flow and mass flow in each block are initially assigned based on geological, geochemistry, geophysical and well measurement data. The flow of the fluid in the reservoir model is calculated using equations of state, Darcy's law and conservation of energy and mass. The complex equations are solved numerically using computer programs. With this method the pressures, temperatures, enthalpies and fluid saturation in each cell are calculated at defined time steps and compared to the measured data. The main steps required for numerical modelling are an analysis of the conceptual model of the reservoir, choice of simulator, numerical grid design, specifying the material parameters (rock properties) of the grid elements, as well as boundary conditions and source-sink distribution.

For this study the TOUGH2 program was used, which was developed at Lawrence Berkeley Laboratory, coupled with a user interface developed by Kamojang and the Institute of Technology, Bandung.

4.1 TOUGH2

The acronym TOUGH means Transport Of Unsaturated Groundwater and Heat. It is a program for the simulation of multi-dimensional mass and heat flow for multi-component and multi-phase fluids in porous and fractured media. It belongs to the MULCOM family of numerical simulators developed at Lawrence Berkeley National Laboratory (LBNL), USA (Pruess et al., 1999). The first version of the program, TOUGH, was developed in 1983-1985 and made commercially available in 1987. TOUGH2 was released to the public in 1991 and updated in 1994, allowing more complex simulations and faster calculations than TOUGH. TOUGH2 is written in Fortran 77, and was developed under a UNIX-based operating system.

The TOUGH2 program was primarily developed for studies of nuclear waste isolation, but now the spectrum of its applications is much wider. The TOUGH2 release in 1991 included five modules for different fluid properties, or EOS-modules (equations of state):

EOS1: water, water with tracer;
EOS2: water, CO_2;
EOS3: water, air;
EOS4: water, air, with vapour pressure lowering;
EOS5: water, hydrogen.

The new version of TOUGH2 contains updated versions of these modules as well as a number of new fluid property modules. In this work, the EOS1-module is used.

4.1.1 Governing equations

The governing equations of the TOUGH2-simulator are mass- and energy-balance equations since heat and mass transfer are being simulated. The concept behind the modelling approach (porous-fractured medium) involves simulating with a set of elements connected to each other. Mass and heat accumulated in each element, mass and heat flow through boundaries of elements, and possible mass/heat sinks/sources (inflow, wells, hot springs) are defined. Therefore, mass- and energy balance equations for each element having volume *V* are written as (Pruess et al., 1999; Björnsson, 2003):

$$\underbrace{\frac{d}{dt}\iiint_V M^{(\kappa)} dV}_{1} = \underbrace{\oint\!\!\oint_\Gamma F^{(k)} \cdot \vec{n} d\Gamma}_{2} + \underbrace{\iiint_V q^{(\kappa)} dV}_{3} \tag{1}$$

where Term 1 accounts for mass/heat accumulation in element (volume) *V*;
Term 2 gives mass/heat flow through the surfaces of element *V*; and
Term 3 contains sinks/sources of heat and mass;
Index *k* may be equal to 1 for water, 2 for air, 3 for heat, and 4 for tracer, etc.

Mass and heat accumulation in volume V are given by:

$$M^{(\kappa)} = \phi \sum_{\beta=l,g} S_\beta \rho_\beta X_\beta{}^{(\kappa)} \qquad k = 1,2,3... \tag{2}$$

$$M^{(\kappa)} = (1-\phi)\rho_R C_R T + \phi \sum_{\beta=l,g} S_\beta \rho_\beta X_\beta{}^{(\kappa)} \tag{3}$$

where ϕ = Porosity;
S_β = Saturation of phase β;
ρ_β = Density; and
$X_\beta^{(k)}$ = Mass fraction of component k present in phase β.

Mass and heat flow are given by:

$$F^{(\kappa)} = \sum_{\beta=l,g} F_\beta{}^{(\kappa)} \tag{4}$$

$$F^{(\kappa)} = -K\nabla T + \sum_{\substack{\beta=l,g \\ k=1,2}} h_\beta{}^{(\kappa)} F_\beta{}^{(\kappa)} \tag{5}$$

where

$$F_\beta^{(\kappa)} = -k \frac{k_{r\beta}}{\mu_\beta} \rho_\beta X_\beta{}^{(\kappa)} \left(\nabla P_\beta - \rho_\beta g \right) \tag{6}$$

Note that all equations are non-linear, therefore, they can only be solved by numerical methods.

In simulating a geothermal reservoir, it is usually assumed that there is one component fluid only (water). In that case, there are 2 equations of 2 unknowns for each element. Unknowns are pressure and temperature (in single-phase conditions); or pressure and saturation (in 2-phase conditions). Therefore, for a system of N elements, there is a $2N$ equations system of $2N$ unknowns. This equation system is solved by a Newton-Raphson iteration scheme (Pruess et al., 1999; Björnsson, 2003).

4.1.2 Structure of the input file

The TOUGH2 input file is of strict format and contains several blocks. The main blocks are the following (Pruess et al., 1999):

ROCKS: material parameters (i.e. rock properties): density, porosity, permeability, specific heat;
PARAM: initial values of calculated parameters;
ELEME: list of elements;
CONNE: list of connections between elements;
INCON: initial conditions;
GENER: mass and heat sinks/sources.

Some of the blocks of the input file are necessary, while others (INCON, GENER) are optional. Note that calculation may include several stages, the output data of the previous stage being the input for the next one. Therefore, some blocks (INCON, for instance) of the input file may be provided by the output file of a previous stage of calculation. The first stage of calculation is called the "gravity test". It is carried out to check whether the numerical mesh is correct or not, and provides the initial data for the next calculation stage.

5. NATURAL STATE MODEL

To simulate the initial condition of the reservoir (before exploitation), natural state simulation is first carried out. The model is run (processed) to a steady-state condition by carrying out a simulation over a very long time period (100,000 years for example) and the results compared to the natural state before the reservoir is exploited, as defined by formation temperatures and initial pressures. Then, the best natural state model is used to simulate the production behaviour of the field. In this stage, the temperatures and pressures from the model are compared to the actual production data observed in the field.

5.1 Grid structure; boundary and initial conditions

In this study, different boundary conditions are applied to the modelling effort, compared to older work. Instead of having recharge from the bottom, the recharge is from the sides through the vertical barriers at depth. An inflow to the model under the reservoir is kept constant, in agreement with the natural state of the reservoir. The lateral boundaries are pushed further out to eliminate boundary effects in the model and to allow heat conduction from the reservoir to the surroundings, resulting in cooling in the reservoir and lowering the steam saturation near the boundaries. The lateral end blocks have constant pressure and temperature, ensuring that the extra inflow to the reservoir, due to production, comes from the sides with temperatures as found in the vicinity of the reservoir system. This approach is not considered as optimistic as the abovementioned approach, resulting in more conservative forecasts and better field management, which might prevent over investment in surface facilities and equipment.

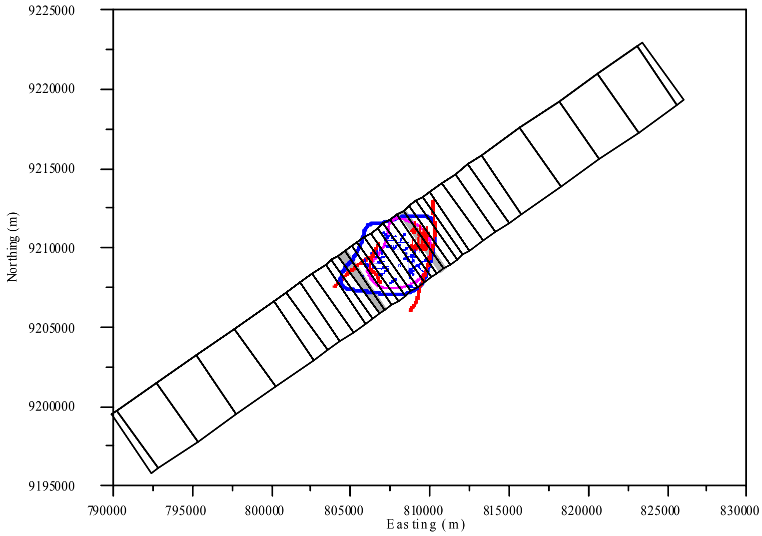

FIGURE 9: The 2-dimensional model grid of the Kamojang geothermal field

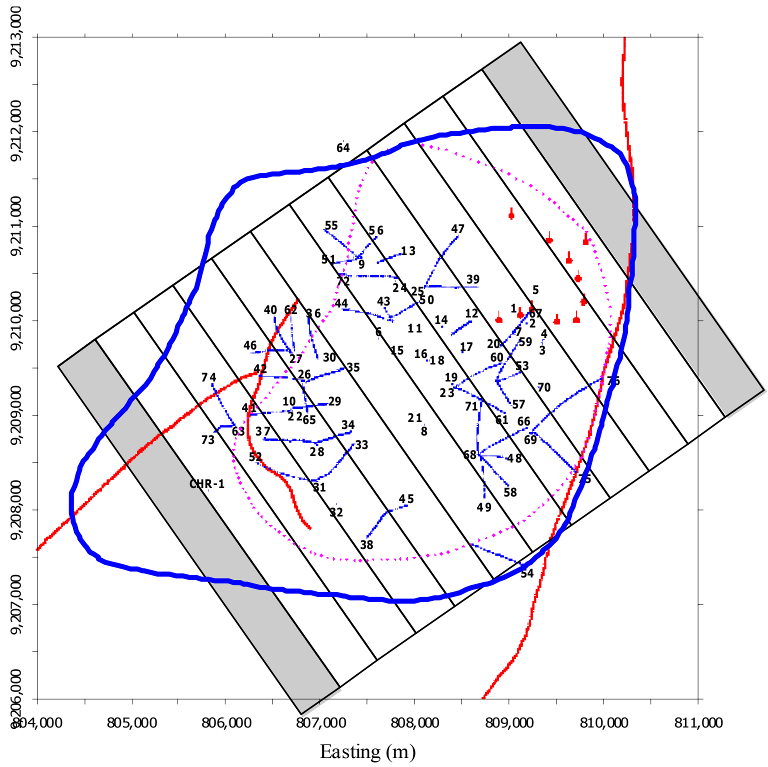

FIGURE 10: The reservoir grid, showing reservoir boundaries, well locations and geothermal manifestation

A 2-D regular mesh was developed for the modelling of the Kamojang field (see Figures 9 and 10). The model consists of 13 layers (1 to 13) with a total number of 394 elements. The shape and orientation of the grid was chosen to match the size and shape of the field. The arrangement of blocks is the same in all layers and shown (for layer 1, in reservoir block) in Figure 10.

The 13 layers extend from an elevation of 1700 m a.s.l. to the base of the model at -1900 m a.s.l., resulting in a total depth of 3600 m. Most of the layers are 250 m thick except the layers representing the atmosphere (100 m), groundwater (150 m), cap rock (350 m) and the base of the model (500 m).

Elements' names are defined automatically by the TOUGH2 interface. The following describes the different layers:

i) Layer-1, from 1700 to 1600 m a.s.l., emulates the atmosphere and is therefore well known and constrained to realistic ambient conditions; namely a pressure of 1 bar-a and a temperature of 15°C.
ii) Layer-2 is the groundwater layer, which extends from ground surface to 150 m depth. The average temperature is 60°C.
iii) Layer-3 is the condensate layer, which extends from 150 to 500 m depth. The temperature at the top of the condensate layer is 100°C. Assumed average temperature is 165°C.
iv) Layer-4 - layer-11 simulate the vapour-dominated reservoir. Each layer is 250 m in thickness. The initial reservoir temperature is 245°C and vapour saturation 0.7. Pressure follows the gradient 0.18 bar/100 m.
v) Layer-12 and layer-13 have a temperature gradient of 80°C/km.

Initial conditions are given by a constant temperature gradient (60-75°C) for each layer, which increases linearly with depth. The initial pressure distribution is hydrostatic, and depends on the temperature. It was calculated by the program PREDYP (Arason et. al., 2003).

5.2 Properties of rocks

Three components of permeability (k_x, k_y, k_z) are provided in the TOUGH2 input file. In this 2-D model only two components (k_x, k_z) are used. Table 1 shows the model permeabilities.

TABLE 1: Estimated permeability of rocks in the numerical model

Layer	**Name of rock type**	**Permeability (mD)**	
		k_x	k_z
1	ATM	1	0
2, 3	CAP1	0.09	0.045
4, 5	RES1	125	100
6, 7, 8	RES2	40	20
9, 10, 11	RES3	8	4
12	BASE2	8	4
13	BASE1	1×10^{-35}	1×10^{-35}
Reservoir boundary		0.00001	0
Surrounding area		0.005	0.005
Outer boundary		5	5

In addition to the permeability, each block has specified rock parameters as listed below:

Rock density = 2500 kg/m^3.
Rock porosity = 0.1 (for reservoir rocks).
= 0.01 (for outer and reservoir boundaries rocks).
Heat conductivity = 2.5 W/m°C (except for bottom layer, 6.5 W/m°C).
Specific heat of rocks = 1000 J/kg°C.

5.3 Sources and sinks

In order to properly simulate the natural state of the Kamojang geothermal system, sources and sinks of heat and mass have to be added to the model, in agreement with the conceptual model of the reservoir. In this model, mass sources are located in layer-12 (-1150 m a.s.l. average depth), the deepest "active layer" in the southwest part.

One sink, representing the surface manifestation in Kawah, is in an element in the northeast part of the field at the top of the reservoir (layer-4), with discharge 32 kg/s. The sink is defined as a well on deliverability with a productivity index 1.5×10^{-10} and a pressure of 32 bar.

In order to increase the heat flow from below to the reservoir, higher heat conductivity (6.5 W/m°C) was defined in the inactive base layer.

5.4 Modelling result

Natural state simulations were done by running the model with all blocks initially containing cool water and with the specified boundary conditions and heat and mass withdrawals driving the model. Simulation continues until the reservoir is stable and there are no appreciable changes with time. In this case, natural state models were run for 530 time steps which correspond to approximately 1×10^{12} years. The steady-state conditions attained are then compared to the pre-exploitation state of the reservoir.

In Figure 11, the vertical pressure and temperature distributions of the natural state model are shown and compared with the observed field pressure and temperature from well KMJ-11. From this Figure it can be seen that the model pressure and temperature closely match the real field pressure and temperature, down to 1 km depth in the reservoir.

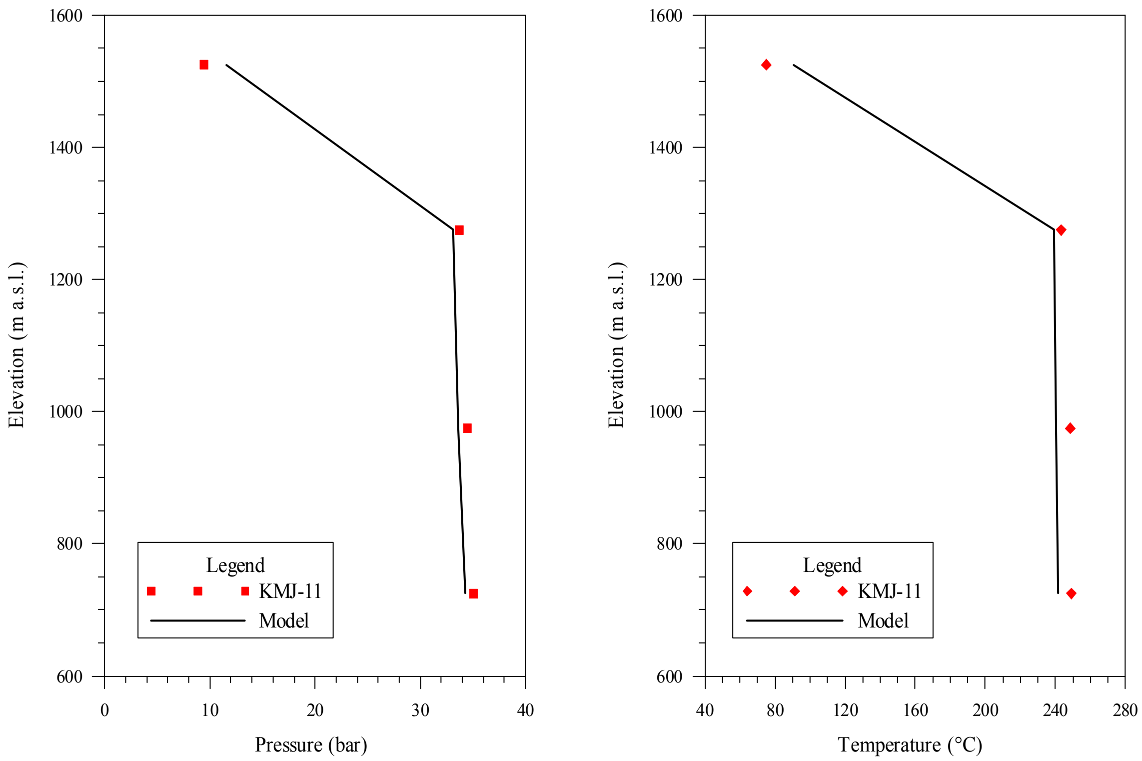

FIGURE 11: Pressure and temperature profile from simulation compared to well KMJ-11

6. PRODUCTION HISTORY MATCHING AND FUTURE PERFORMANCE

Production history matching is a process in reservoir modelling for matching the measured production data such as mass flow, enthalpy and pressures of production wells to the calculated data by tuning the corresponding parameters of the computer model. For this purpose, the production wells were assigned in the computer model based on their permeability depths. The mass produced from each well was assigned based on the current production well data (Table 2) in several blocks and layers.

TABLE 2: Steam production data

Block	Layer	Well number	Production rate (kg/s)	
			140 MWe	200 MWe
5	6	KMJ-52, 74	18.91	18.91
5	7	KMJ-63, 73	24.91	24.91
6	6	KMJ-22, 28, 37, 41, 42, 65	70.16	70.16
6	7	KMJ-31, 38	14.32	14.32
7	5	KMJ-27, 36, 62	52.48	52.48
7	6	KMJ-26, 33, 34	18.04	18.04
7	7	KMJ-40, 45	12.53	12.53
9	5	KMJ-18, 56	29.07	29.07
9	6	KMJ-11, 24, 43, 44, 51, 72, 49*, 58*, 71*	79.54	104.33
9	7	KMJ-48*		12.50
10	5	KMJ-14, 17, 53*, 57*, 59*, 61*	21.76	65.31
10	6	KMJ-69*, 75*, 76*		37.92
11	5	KMJ-67		14.37
		Total	341.71	474.84

* Production wells for 200 MWe

In this study, the 23 years production history of Kamojang, from 1983 to 2006, was simulated by the model. The calculated pressure decline and temperature changes, as predicted by the model in block 9 layer 6, was compared to the measured data from wells KMJ-11, 24 and 51 to demonstrate the accuracy of the model. This comparison is shown in Figures 12 and 13 for pressure decline and temperature change, respectively. Figure 12 shows that the pressure drawdown during the 23 year production history in block 9 layer 6 was 4.5 bar, equal to 0.2 bar/year as the annual average. From the measured data, KMJ-11 has the annual average pressure drawdown 0.29 bar/year, KMJ-24, 0.21 bar/year and KMJ-51, 0.4 bar/year. The average pressure drawdown from the three wells at this block is 0.19 bar/year. This pressure drawdown closely matches the model drawdown, but the initial model pressure might be too high.

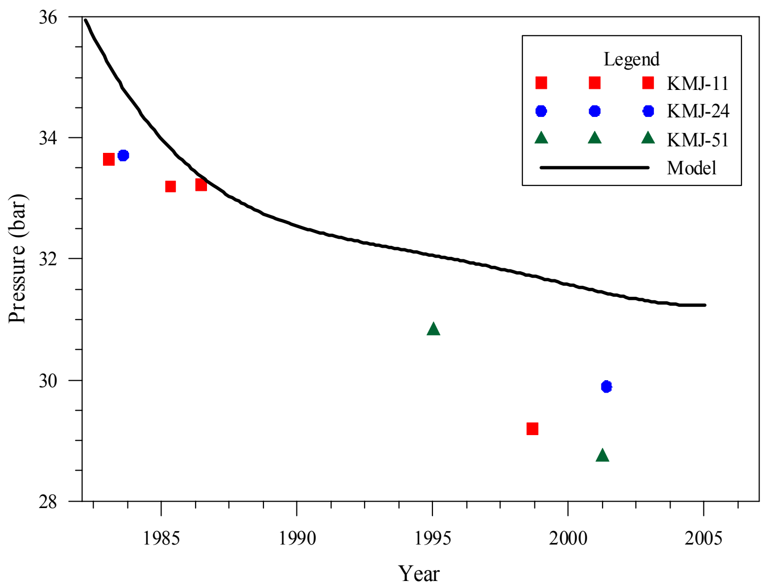

FIGURE 12: Calculated pressure drawdown from 1983 to 2006 compared to pressure decline in three well in Kamojang

Figure 13 shows that the annual average temperature decline during those 23 years is 7.9°C, equivalent to 0.35°C/year. The calculated annual average temperature changes in the three wells on this block is 0.66°C/year. However, the calculated temperature is within the measured range, as seen in the figure.

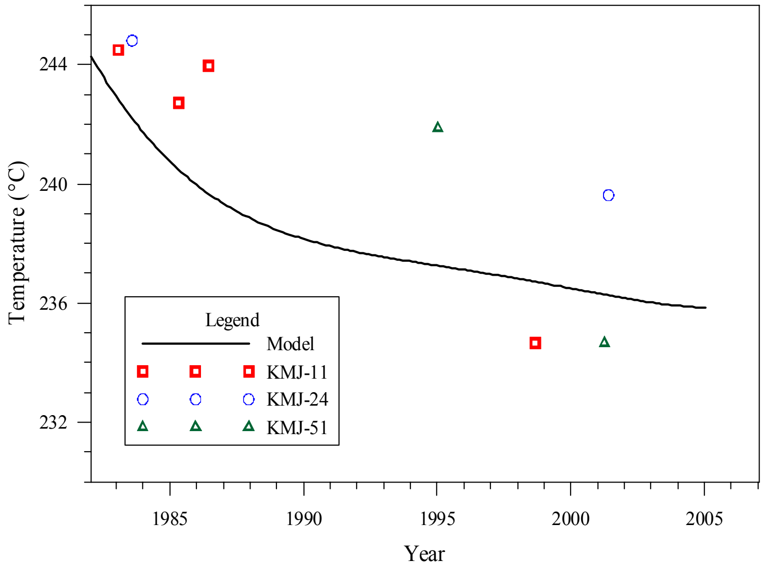

FIGURE 13: Calculated temperature decline compared to observed temperature in three wells in

For future reservoir performance, the model was subjected to fluid extraction at a rate to support 200 MWe power plant from 2006. The locations and rates of production correspond to existing production wells and are shown in Table 2. Water is re-injected into the reservoir from the ten wells shown in Table 3, at a rate of 15 kg/s per well. For a 140 MWe power plant, six wells were used as reinjection wells with a total rate of 90 kg/s. For 200 MWe, ten reinjection wells were used with a total rate of 150 kg/s.

TABLE 3: Reinjection well data

Block	Layer	Well number	Injection rate (kg/s)	
			140 MWe	200 MWe
5	10	KMJ-20*		15
6	6	KMJ-46	15	15
6	7	KMJ-35	15	15
6	7	KMJ-30*		15
6	9	KMJ-55	15	15
6	10	KMJ-13*		15
6	11	KMJ-47*		15
8	8	KMJ-21	15	15
8	9	KMJ-15	15	15
9	6	KMJ-32	15	15
		Total	90	150

* Reinjection wells for 200 MWe

The effect of re-injection on the performance of the reservoir was investigated by repeating the simulation with no water re-injected into the reservoir. Figures 14 and 15 show the pressure drawdown and temperature changes in block 9, layer 6, where most of the mass is taken out.

Figure 14 shows the calculated pressure drawdown with and without reinjection from 1983 until 2033. Figure 15 shows the temperature decline for the same time period. According to Figure 14 the pressure is lower with reinjection than without, which is not in agreement with the general benefits of reinjection experience. Reinjection has been proven to play an important role for sustaining the mass balance in the Kamojang reservoir (Sasradipoera et. al., 2000). The calculated pressure drawdown from 1983 until 2033, after a 50 year production period is about 7.6 bar. The temperature decline for the same period is about 13.5°C, according to the model calculations.

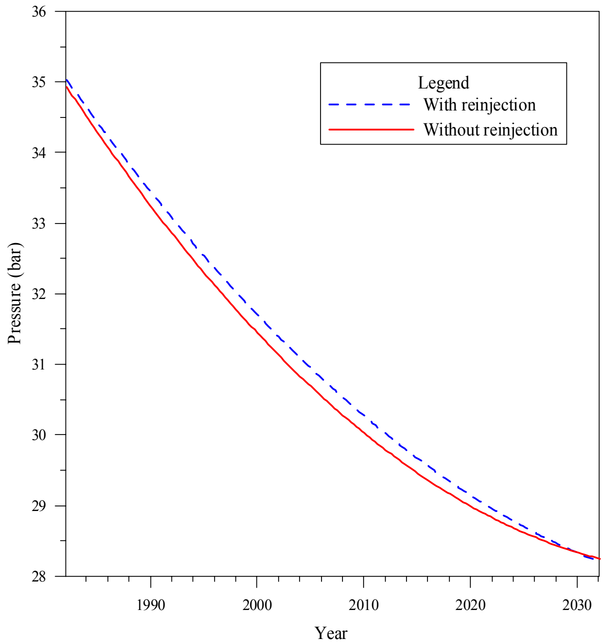

FIGURE 14: Calculated future pressure drawdown with and without reinjection in the Kamojang geothermal field until 2033

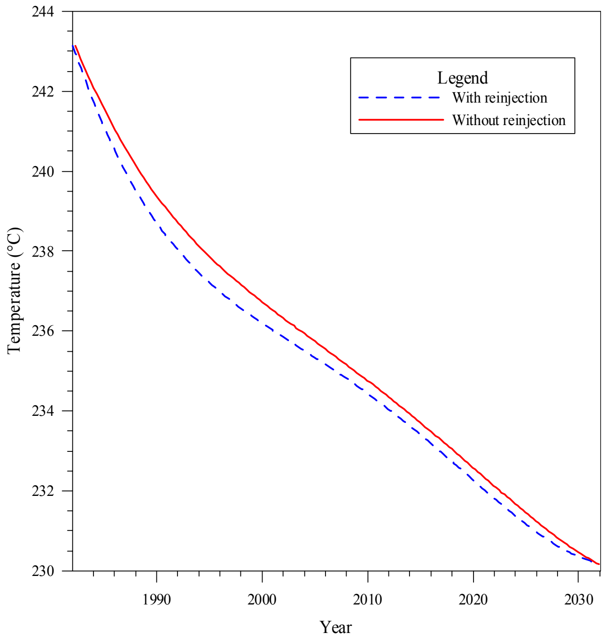

FIGURE 15: Calculated future temperature decline with and without reinjection in the Kamojang geothermal field until 2033

The above results indicate that the model needs to be recalibrated and compared with more field data to give estimations that are more confident of the future performance of the Kamojang geothermal system.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Based on this study, the following concludes the presented analysis on the Kamojang geothermal field:

- A new 2-D numerical model has been developed in TOUGH2 to simulate the natural state of Kamojang geothermal system.
- The model simulates the existence of a 1250 m thick steam zone in the reservoir as indicated by numerous wells in the field
- Pressure and temperature data from well KMJ-11 is simulated quite well.
- Boundary conditions and heat sources play an important role in the natural state simulations.
- The calculated pressure drawdown due to the 23 year production history in the field is comparable to what is observed in wells KMJ-11, 24 and 51.
- The model needs to be recalibrated and compared with more field data to give estimations that are more confident of the future performance of the Kamojang geothermal system

7.2 Recommendations

- The TOUGH2 interface used in this work should be upgraded to not only give the output in the text file but also in a structure file under Windows.

- A 3-D model should be developed with similar boundary conditions as in the 2-D model.

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