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Numerical experiment on the evolution of vapor-dominated geothermal system

Adrianto*, Ryuichi Itoi

Department of Earth Resources Engineering, Faculty of Engineering, Kyushu Unuversity, Fukuoka 819-0395, Japan

Abstract

The evolution mechanism of vapor-dominated geothermal system has not been well understood. Boundary condition plays an important role in numerical simulation of geothermal reservoirs, especially in natural state simulation. The level of uncertainty at the bottom condition in a geothermal reservoir is very high because it is not provided from the wellbore data. This paper aims to understand an evolution mechanism of the vapor-dominated geothermal system with particular interest on bottom boundary conditions. Numerical experiments with vertical two-dimensional reservoir model of porous type were conducted. Parameters such as bottom heat flux, temperature, and flow rate of deep mass recharge were examined. Additionally, setting up fixed vapor saturation at the bottommost layer was also examined. This study suggests that a proper mass recharge should be set as the bottom boundary condition. The recharge amount, if too large, could reduce the size of two-phase zone in the reservoir. A sufficient heat flux is required and the minimum recharge temperature is 240 °C in order to generate a two-phase zone in the reservoir.

Keywords: geothermal, vapor-dominated, evolution, boundary conditions

1. Introduction

Numerous studies have been conducted to understand the evolution of the formation of the vapor-dominated geothermal system, but it is not fully disclosed. A sufficient heat source at depth and low permeability boundaries to seal the reservoir from the adjacent groundwater are the requirements for vapor-dominated systems [1]. Mineralogical evidence in all vapor-dominated systems was initially liquid-dominated systems [2, 3]. A rapid transition from liquid to vapor-dominated condition was numerically simulated [4]. However, a slow transition is also possible from numerical simulation [5].

Numerical reservoir modeling is an essential management tool which has been used successfully to guide decisions on exploitation and management of geothermal resources in many geothermal fields in the world [6, 7, 8]. In order to develop a geothermal numerical model, the simulation was run until steady-state conditions were reached and the model was calibrated using field data [9]. Boundary condition plays an important role in numerical simulation of geothermal reservoirs. Lateral boundaries should be placed far enough from the main reservoir domain, thus ensuring that the reservoir performance is not significantly affected by the boundaries [10]. Lateral boundaries can either be no-flow boundary (heat or mass), linear temperature profile and hydrostatic pressure profile, or constant temperature and pressure defined as open boundary conditions. The open boundary condition, however, may cause undesired flow; for instance, if the cold water from the groundwater aquifer enters the reservoir. For the

* Manuscript received April 6, 2019; revised January 17, 2020.
Corresponding author. *E-mail address*: adrianto.itb@gmail.com.
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bottom boundary, natural heat convection from the deep upflow is represented by assigning heat and mass input. However, in some cases, constant pressure and vapor saturation are implemented when dealing with vapor-dominated geothermal systems [11]. This might be due to heat pipe stability in vapor-dominated systems [12, 13].

This paper aims to investigate the effects of bottom boundary conditions on the evolution of vapor-dominated system. To investigate each effect of bottom boundary conditions in vapor-dominated reservoir models, we conducted a series of simulation by changing one parameter while the other parameters were kept constant. These parameters include (i) mass rate of deep recharge, (ii) temperature of deep recharge, (iii) bottom heat flux, and (iv) vapor saturation at the bottom layer.

2. Model Design

We built a vertical cross-section two-dimensional model which has dimensions of 5000 m × 50 m with a 2000 m depth. The model domain is divided into 25 grids in x-direction and one grid in y-direction with 25 layers as shown in Fig. 1. The grid size is 200 m × 50 × 80 m for all grid blocks. Seven types of rock material were assigned in the model as summarized in Table 1. The properties of rock type are based on the Darajat geothermal field, Indonesia, because it is a typical vapor-dominated geothermal system [6]. These rock materials represent atmosphere layer, cap rock, reservoir, impermeable boundary, and basement rock.

Table 1. Rock properties for the base case model

Material name	Color	Porosity (-)	Permeability (m^2)	Wet Heat Conductivity (W/m K)
Atmosphere		0.9	1×10^{-12}	2.5
Cap rock		0.05	8×10^{-18}	0.2
Shallow reservoir		0.1	5×10^{-14}	2.5
Deep reservoir		0.1	1×10^{-14}	2.5
Basement rock 1		0.06	1×10^{-15}	2.5
Basement rock 2		0.03	5×10^{-16}	2.5
Outer boundary		0.01	5×10^{-17}	2.5

Boundary conditions and rock type distribution of the base case model are shown in Fig. 1. For all rock types, the rock density of 2650 kg/m^3 and the specific heat of 1000 J/(kg K) are used. The capillary pressure effect is neglected. The porous medium approach is utilized into the whole domain. Relative permeability of Grant's curves is used with residual liquid saturation (S_{lr}) and residual gas saturation (S_{gr}) of 0.3 and 0.05, respectively.

The thickness of reservoir domain is 1200 m which lay down at depth between 320 m to 520 m. It consists of shallow reservoir (320 m to 960 m) and deep reservoir (960 m to 1520 m). The cap rock layer overlies the reservoir with 240 m thick.

The atmospheric condition of 1 bar and 20 °C is specified at the top layer. Conductive heat flux of 0.5 W/m^2 is given at the bottom of the model. High-temperature water of 270 °C at a flow rate of 1 kg/s recharges the reservoir from two locations at the bottom layer. To maintain a hydrostatic condition at the lateral boundary, we assigned an infinitely large volume (volume factor of 1×10^{50}) in some grids at the lateral boundary of the reservoir (grids within the red boxes in Fig. 1).

After setting up the model, it was run for one million years to reach a reasonable steady state. This long simulation time is required to achieve a natural state condition of a geothermal system.

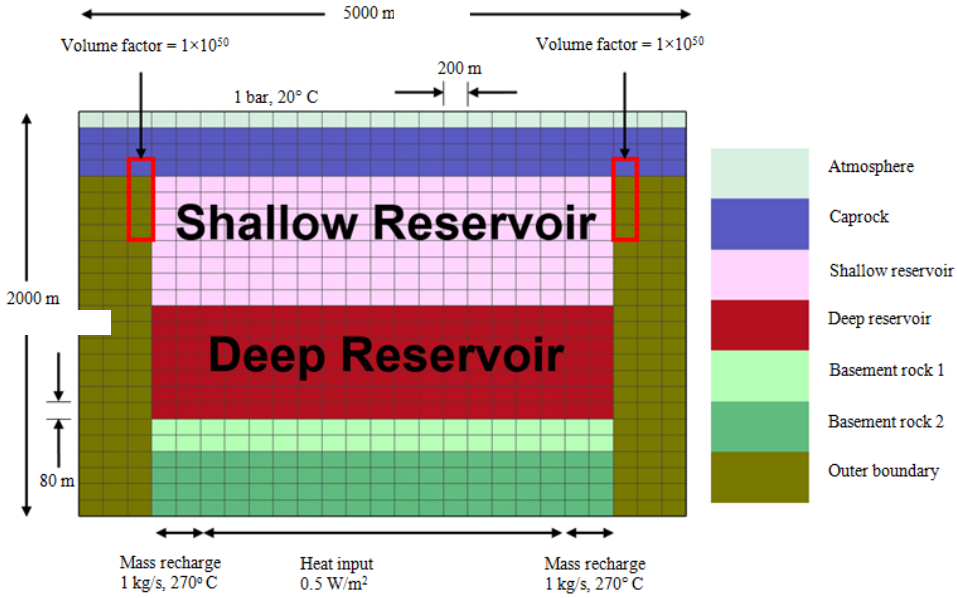

Fig. 1. Two-dimensional model of vapor-dominated system

3. Simulation Results

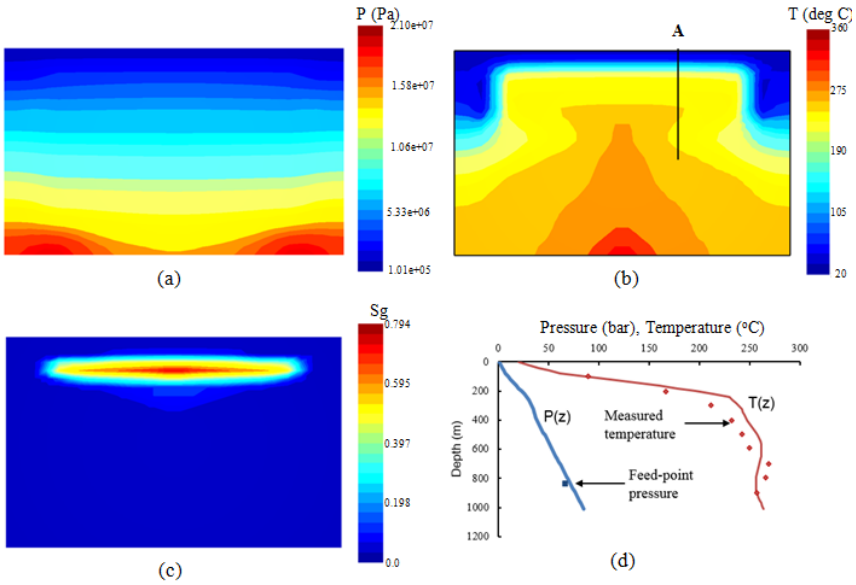

Fig. 2. Simulation results of the base case including: (a) pressure distribution, (b) temperature distribution, (c) vapor saturation distribution, and (d) pressure and temperature profiles along the line A

Fig. 2 captures the simulation results at year 500,000 as the result for the base case for this numerical experiment. It includes distribution of pressure, temperature and S_v as well as pressure and temperature profile at a certain location (line A in Fig. 2(b)).

The highest pressure is found in the grid just above the mass recharge point (Figure 2(a)). This makes the fluid flowing upward from the recharge point to the reservoir domain. The resulting pressure in steady state is about 200 bar at the bottom layer.

The high-temperature zone is formed in the centre of the bottom layer (Figure 2(b)). The temperature at

the margin of the lateral boundary of the upper part of the reservoir seems to be constant because we set an infinitely large volume. If a well is allocated at 500 m from the centre of the model (see A in Figure 2(b)), there is a decrease of temperature at depth between 600 m to 900 m and then an increase again with depth.

Thin vapor-dominated zone is formed at depths from 300 m to 350 m in the shallow zone of reservoir (Figure 2(c)), just below the cap rock. On the other hand, liquid water occupies most of the other zones in the model domain.

In addition, pressure and temperature profiles at the location as indicated by B in Fig. 2(b) are plotted in Fig. 2(d). The temperature decreases at depth 600 m in our simulation. A steep temperature gradient which appears above the reservoir layer indicates that heat transfer is mainly affected by conduction.

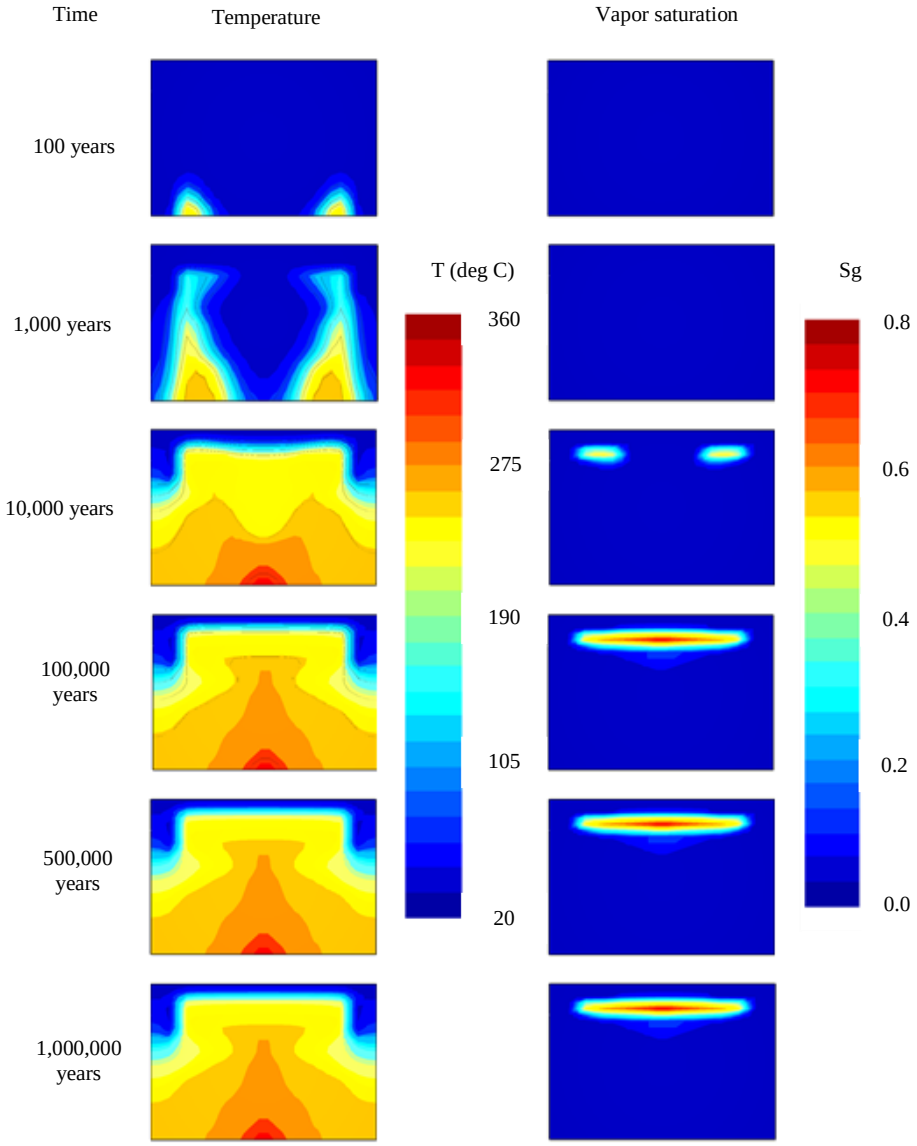

Fig. 3. Distributions of temperature and vapor saturation to reach natural state

Fig. 3 shows the distribution of temperature and vapor saturation (S_v) in the model domain during the simulation. After 100 years, no steam appears elsewhere. The temperature in most parts of the model

domain is 20 °C following the initial condition. The highest temperature is found at the location of deep mass recharge with 257 °C.

The whole domain in the model is still occupied by liquid water after 1,000 years. High-temperature fluid from deep recharge flows upward and mixes with reservoir fluid. At this time, the highest temperature at the uppermost reservoir is 122 °C, while the lowest temperature within the reservoir is 20.5 °C.

The two-phase zone is found after 10,000 years. It appears at two locations in the upper part of the shallow reservoir parallel with the location of deep recharge. The highest S_v is 0.48. Temperature distribution shows that yellow color dominates the reservoir. It means high-temperature fluid of about 220 to 250 °C fills the most part in the reservoir domain.

After 100,000 years, a continuous two-phase zone of thin flat-shaped is formed in the upper part of shallow reservoir. The highest S_v of 0.75 appears at 320 m depth. Pressure and temperature at this location is 35.3 bar and 243 °C, respectively.

No significant changes are observed on the distributions of temperature and S_v when the simulation run reaches 500,000 years. This indicates a steady state may have been achieved. Thus, simulation results after one million years would also be the same as for this time.

4. Parametric Study

4.1. Effects of mass rate of deep recharge

A relatively high-temperature water of 270 °C recharges the reservoir from two locations at the bottom layer. To explore the amount of mass recharge (m_{rc}) on the formation of a vapor-dominated reservoir, the mass rate of recharge is varied from 0.5 kg/s to 10 kg/s. The simulation results after 500,000 years including distributions of temperature and vapor saturation (S_v) for every specified mass recharge are shown in Fig. 4.

At the very small amount of m_{rc} at 0.5 kg/s, the whole domain of the model is saturated with liquid water. The fluid temperature in the reservoir does not reach the saturation temperature, thus no steam is formed. By increasing m_{rc} up to 2 kg/s, a vapor-zone appears at the upper part of the shallow reservoir, just below the cap rock. At the center of the vapor-dominated zone, the highest S_v was 0.75. This implies that boiling occurs and steam occupies pore space in the shallow reservoir.

As m_{rc} increases to 4 kg/s, more steam exhibits in the reservoir. The highest S_v is 0.8. The high temperature zone further extends vertically in the reservoir. This makes boiling occur in the larger part in the reservoir than the case of 2 kg/s; thus, more water is boiled. Consequently, more steam occupies the reservoir.

At the higher m_{rc} of 6 kg/s, the area of the two-phase zone remains relatively the same as the case of 4 kg/s. However, the highest S_v in vapor-dominated zone decreases from 0.8 down to 0.7. This might be because higher m_{rc} results in higher pressure in the reservoir and thus requires more heat to change the fluid phase from water to steam.

For the case of m_{rc} 8 kg/s, the vapor saturation of the two-phase zone is less than the case of 6 kg/s. The plume of high-temperature fluid from the center of the bottommost layer becomes sharp in the shallow reservoir, indicating that water from deep recharge invades the pore space in the reservoir and is distributed horizontally.

By increasing m_{rc} to 10 kg/s, less amount of steam was formed in the reservoir compared to the case of 8 kg/s. This suggests that if we specified m_{rc} more than 6 kg/s, higher m_{rc} would form less amount of steam in the vapor-dominated zone. The recharge water may penetrate two-phase zone; thus, boiling is suppressed. Consequently, less amount of steam is generated by boiling in the deep reservoir.

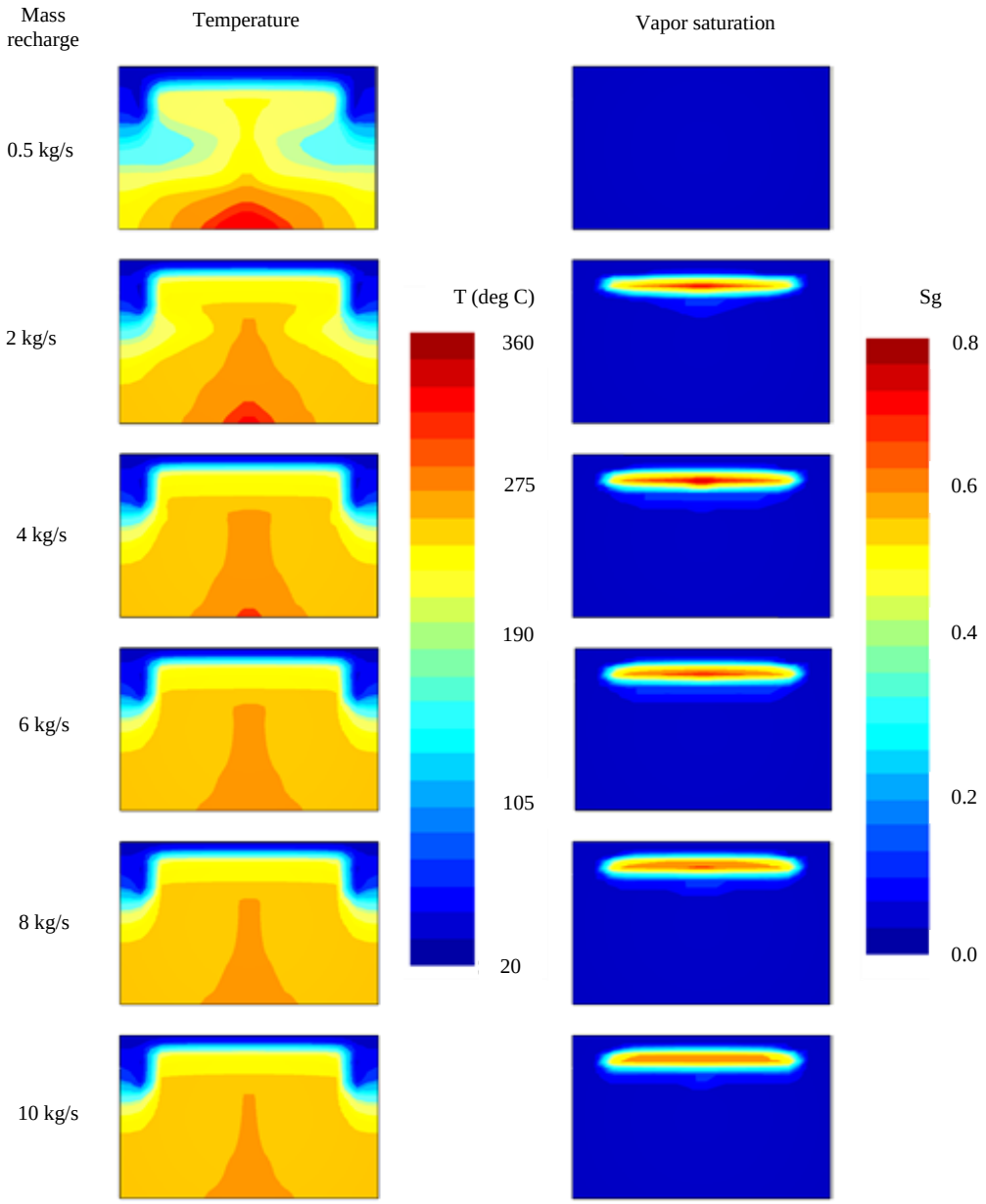

Fig. 4. Effects of mass rate of deep recharge on (a) temperature distribution and (b) vapor distribution

4.2. Effects of temperature of deep recharge

A recharge of high-temperature fluid is one of the main factors affecting the reservoir performance in the vapor-dominated system. If there is no recharge, the reservoir would dry out upon production. This would happen at the late production phase of reservoir. A large amount of heat still remains in the reservoir, while no water remains in the pore space of reservoir rocks. Thus, the heat energy cannot be extracted out of the reservoir in the form of steam.

The recharge water should be hot enough in order to avoid any cooling down of the reservoir. In this study, deep recharge temperature (T_{rc}) was examined in forming vapor-dominated system ranging from

230 °C to 280 °C with an interval of 10 °C.

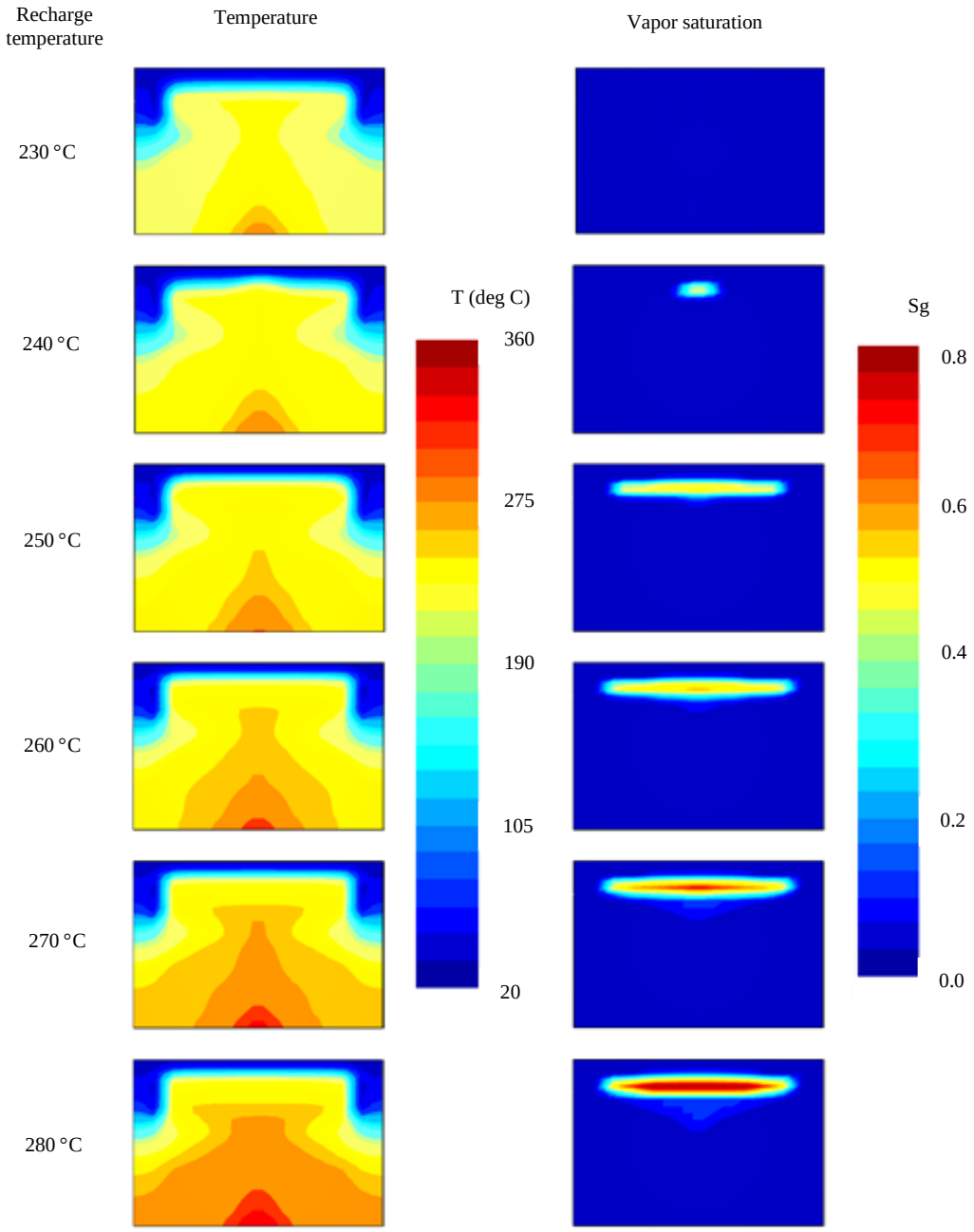

Fig. 5. Effects of temperature of deep recharge on (a) temperature distribution and (b) vapor distribution

Figure 5 shows temperature and vapor saturation profiles for various values of T_{rc}. At T_{rc} of 230 °C, only liquid water fills the whole domain. There is no two-phase zone formed. This means that no boiling occurs in the reservoir as water temperature does not reach the saturation temperature with respect to pressure in-situ.

A two-phase zone is formed in the shallow reservoir by increasing T_{rc} to 240 °C. This indicates that fluid temperature reaches the saturation temperature and steam appears due to boiling. However, the two-phase zone appears only in a small area of the reservoir domain.

For T_{rc} of 250 °C, the two-phase zone expands laterally in the center of shallow reservoir and the vapor saturation decreases toward the lateral boundary. The temperature at the location of the two-phase zone ranges from 240 °C to 256 °C, while its pressure ranges from 33.7 bar to 48.1 bar.

A slightly higher vapor-saturation of the two-phase zone is formed when we increase T_{rc} to 260 °C. This is because boiling occurs in the larger part of the reservoir. For this case, temperature in the two-phase zone (S_v of more than 0.6) is 242.8 °C.

The two-phase zone with S_v of 0.6 appears in the upper reservoir for the case of 270 °C. A temperature range is found between 237 °C and 244 °C in this two-phase zone. As T_{rc} increases, the two-phase zone expands laterally and vertically along with an increase in vapor saturation. The highest S_v in reservoir is observed at the highest T_{rc} of 280 °C. The highest temperature reaches 331 °C at the center of the bottommost reservoir layer.

4.3. Effects of bottom heat flux

Heat flux at the bottom of the model represents the amount of energy provided as conductive heat. Heat source is a requirement to form a geothermal system in hydrothermal environments. In volcanic geothermal systems, heat source is normally considered to be a magma chamber that is located further than 2 km depth from the ground surface.

In order to investigate the effect of heat flux in the formation of vapor-dominated reservoir, a series of simulations with different amount of heat flux (H_{fx}) were carried out. In two-dimensional of Matsukawa, Hanano [14] set the bottom heat flux (H_{fx}) from 0.1 to 1.8 W/m^2. In this study, low to high heat flux is represented by varying H_{fx} from 0.01 W/m^2 to 1.5 W/m^2. The simulation results are illustrated in Figure 6, which consists of temperature and vapor saturation for each heat flux.

The first case is simulation with H_{fx} of 0.01 W/m^2. A very thin vapor-dominated zone with highest S_v of 0.6 appears in the reservoir (orange in vapor saturation profiles in Figure 6). This suggests boiling occurs due to the fluid in the reservoir reaching the saturation temperature; thus, the liquid-water changes to steam-water two-phase. However, the heat flux is insufficient to produce a large vertical-extent of vapor-dominated zone.

A thin but larger vapor-dominated zone in horizontal dimension is formed as we increase the heat flux to 0.25 W/m^2. The highest temperature at the bottommost layer is 298 °C. Due to the temperature difference between reservoir and bottom layer and mass source at the bottom, high-temperature fluid flows upward toward the reservoir.

The size of the vapor-dominated zone increases slightly when we increase H_{fx} to 0.50 W/m^2. This heat flux makes the reservoir temperatures ranging from 248 °C to 279 °C at a depth from 400 m to 1000 m. The highest S_v of 0.74 within the reservoir is found to be at 243 °C and 35.3 bar.

The amount of H_{fx} of 0.75 W/m^2 forms a larger vapor-dominated zone from the previous cases. The highest vapor saturation at two-phase zone is 0.88. At the center of the model, the fluid temperature increases gradually from 20 °C at the surface to 299 °C at 1500 m depth. The highest temperature within the two-phase zone is 278 °C, whereas it is 245 °C at the highest S_v at the vapor-dominated zone.

For the case of 1 W/m^2, the vapor-dominated zone expands vertically and horizontally. The temperature at the location of heat flux also increases due to higher H_{fx}. It becomes 346 °C for this case. A larger expansion of vapor-dominated zone is found as we increase H_{fx} to 1.5 W/ m^2. For the zone with Sv of more than 0.6, the temperature is in the range of 235 to 250 °C. A two-phase zone with S_v of about 0.18 also appears at the bottom layer.

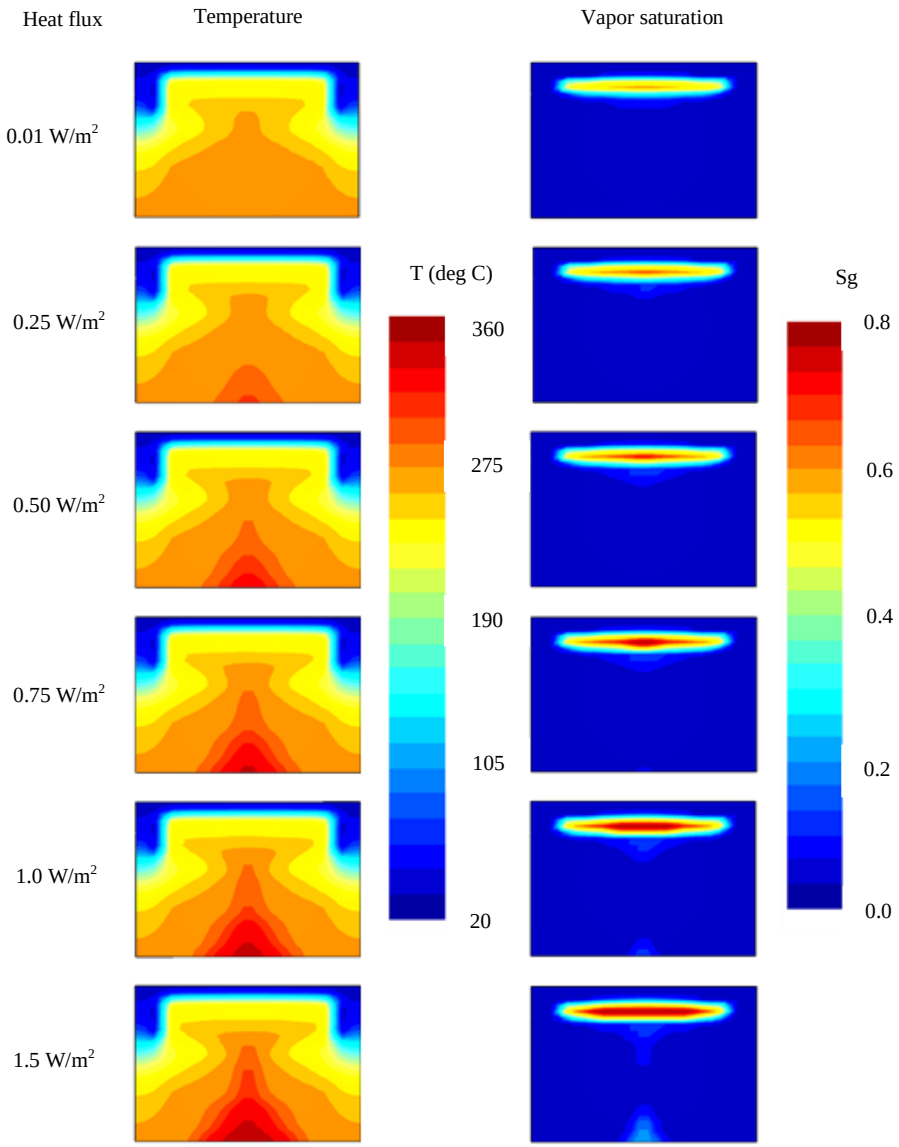

Fig. 6. Effects of bottom heat flux on (a) temperature distribution and (b) vapor distribution

4.4. Effects of bottom vapor saturation

Deep upflow in geothermal system can be represented by heat and mass at the bottommost layer. These bottom boundary conditions can always be applied to the case of liquid-dominated systems but is not adopted in the modeling of vapor-dominated systems. McGuinness [7] suggested assigning constant pressure and vapor saturation at the bottom boundary in order to form a stable vapor-dominated reservoir.

We carried out a series of simulation by varying fixed vapor saturation at the bottommost layer (S_{vb}), i.e., the magnitude of S_{vb} in the range from 0.1 to 0.6 with an interval of 0.1. The simulation results including temperature and S_v are shown in Figure 7.

A significant difference of vapor saturation distribution among all cases is found when we assign a

constant pressure and vapor saturation at the bottommost layer. The area of a two-phase zone is very large even if S_{vb} = 0.1 is given. Fluids with S_v of more than 0.6 (red in vapor saturation profiles) create a continuous two-phase zone in the upper reservoir. The fluid temperature in this zone ranges from 227 °C to 260 °C.

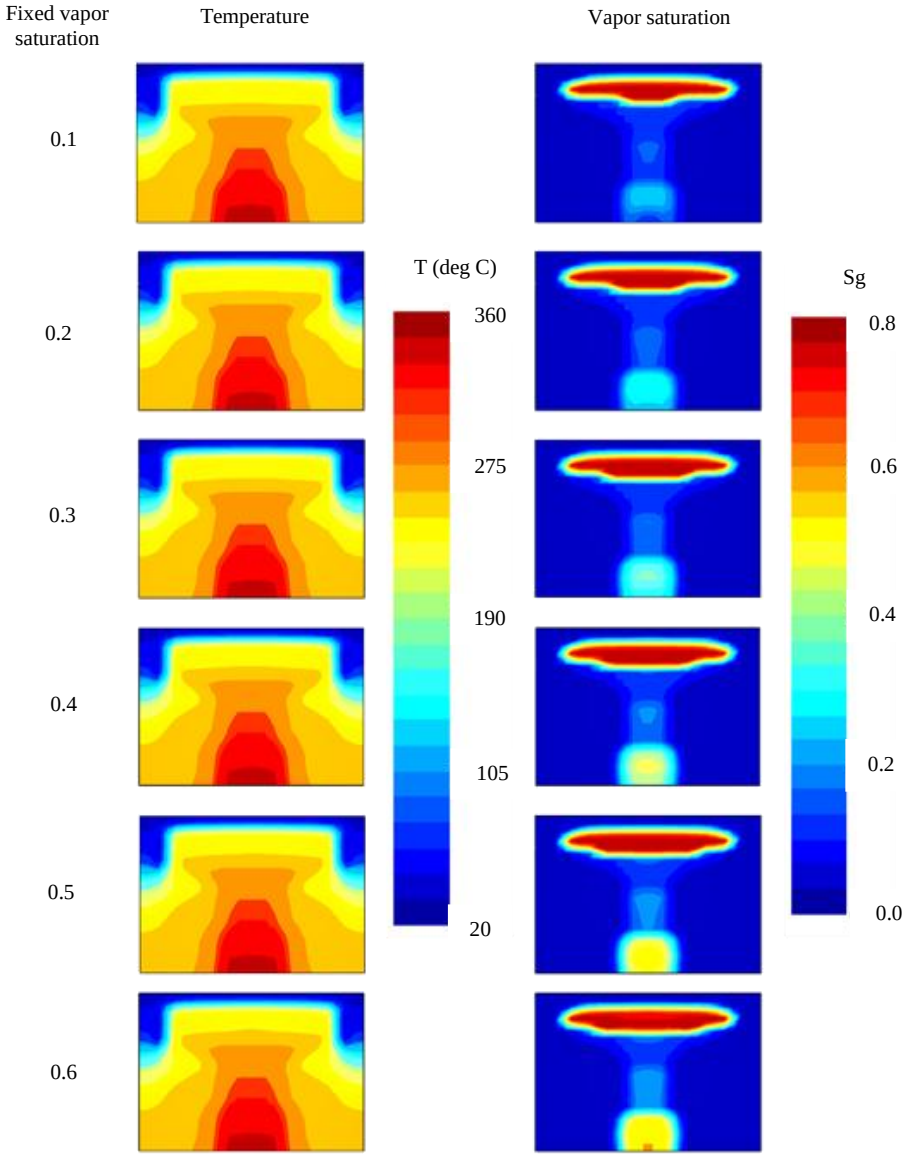

Fig. 7. Effects of fixed vapor saturation on (a) temperature distribution and (b) vapor distribution

We found a slight increase of the two-phase zone in the upper reservoir by increasing S_{vb} to 0.2 at the bottom layer. A two-phase zone also appears in the basement rock layer, but S_v is quite low as 0.3.

For the case of S_{vb} 0.3, the temperature distribution is relatively the same as the previous two cases. No significant changes of the areal extension of the two-phase zone in the reservoir as well as in the basement layer were observed. However, the two-phase zone in the basement layer has a higher S_v compared to the previous two cases. The highest S_v reaches to 0.38.

For S_{vb} of 0.4, the magnitude of vapor saturation and size of the two-phase zone in the reservoir does not show a remarkable change from the previous case. The temperature distribution also does not change. However, the magnitude of S_v changes in the basement layer. Vapor saturation of as high as 0.45 appears in this layer.

Increasing S_{vb} to 0.5 only makes the magnitude of the two-phase zone in the basement layer becomes larger. However, it does not affect the size two-phase zone within the reservoir. In this case, the highest S_v in the basement layer is 0.52.

By increasing S_{vb} to 0.6, the size of the two-phase zone within the reservoir remains the same. The magnitude of S_v in the two-phase zone in the basement layer increases because of the higher vapor saturation we assigned at the bottommost layer.

5. Conclusion

Numerical experiments with vertical two-dimensional reservoir model of porous type were conducted to investigate an evolution of vapor-dominated by considering bottom boundary conditions. The results are summarized as follows:

- Boiling occurs in the reservoir when the fluid temperature reaches the boiling point temperature at depth and forms steam-water two-phase zone.
- A proper mass recharge should be set as the bottom boundary condition. Too large an amount of mass recharge could suppress the fluid in the reservoir. Consequently, the amount of steam in the reservoir decreases.
- The size of the vapor-dominated zone grows with an increase in the recharge water temperature. In our model, the minimum recharge temperature that can generate steam in the reservoir is 240 °C.
- A sufficient heat flux is required for providing heat in order to boil the available fluid in the reservoir. Heat flux of 0.75 W/m^2 can result a thin vapor zone in the reservoir with the highest vapor saturation of 0.8. A higher amount of heat flux yields a larger volume of the vapor-dominated zone.
- A fixed vapor saturation at the bottommost layer results in a large horizontal and vertical extent of the two-phase zone. Additionally, a continuous two-phase zone is also formed from the bottom layer to the reservoir layer.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Adrianto conducted the research and wrote the paper; Ryuichi Itoi contributed to the interpretation of the results. All authors had approved the final version.

References

[1] White DE, Muffler LJP, and Truesdell AH. Vapor-dominated hydrothermal systems compared with hot-water systems. *Economic Geology*. 1971; 66 (1): 75–97.

[2] Allis R. "Insights on the Formation of Vapor-Dominated Geothermal Systems." *World Geothermal Congress*, 2000.

[3] Ramadhan Y, Lukman S, Ahmad T, and Ian B. Geological evaluation of the waringin formation as the host of a vapor-dominated geothermal reservoir at the Wayang Windu geothermal field," *New Zealand Geothermal Workshop*, 2012.

[4] Pruess K. A quantitative model of vapor dominated geothermal reservoirs as heat pipes in fractured porous rock. *Geothermal Resources Council Transactions.* 1985; 9 (2): 10.

[5] Ingebritsen SE., and Sorey ML. Vapor-dominated zones within hydrothermal systems: evolution and natural state. *Journal of Geophysical Research: Solid Earth* 93 (B11): 1988; 13635–55.

[6] Rop E, Hikari F, and Saeid J. An updated numerical model of the greater olkaria geothermal system, Kenya. *Proceedings*

43rd Workshop on Geothermal Reservoir Engineering, Stanford University, 2018.

[7] Nakanishi S, John WPr, Sabodh KG, Chitoshi A, Shigeo T, and Koji K. 2017. "A Numerical Simulation Study of the Wasabizawa- Akinomiya Geothermal Field, Akita Prefecture, Japan." *Geothermal Resources Council Transactions* 41.

[8] Kano Y, Nishi Y, Ishido T, Sugihara M, Yasukawa K, Nomura Y, Kato H, and Ariki K. Numerical modeling of hydrothermal systems at the appi field, Iwate, Japan. *Proceedings 43rd Workshop on Geothermal Reservoir Engineering, Stanford University*, 2018.

[9] Nugraha, Rony P, John O'Sullivan, and Michael J O'Sullivan. "A 3D Geological Model and Natural State Simulation of Jaboi Geothermal Field, Nangro Aceh Darussalam, Indonesia." *Proceedings 40th New Zealand Geothermal Workshop*, 2018.

[10] O'Sullivan, Michael J, Karsten P, and Marcelo JL. State of the Art of Geothermal Reservoir Simulation. *Geothermics*, 2001; 30 (4): 395–429.

[11] Alamsyah O, Boyke B, Viet H, and Jeff WR. Dynamic Modeling of Darajat Field Using Numerical Simulation, *World Geothermal Congress*, 2005.

[12] McGuinness MJ, M. Blakeley, K. Pruess, and M. J. O'sullivan. Geothermal heat pipe stability: solution selection by upstreaming and boundary conditions. *Transport in Porous Media*, 1993; 11 (1): 71–100.

[13] Hanano, Mineyuki. Improvement of Understanding of Vapor-Dominated Geothermal Resources." *Japan Geothermal Resources Society*, 2011; 33 (2): 79–85.

[14] Hanano, Mineyuki. "Simulation Study of the Matsukawa Geothermal Reservoir: Natural State and Its Response to Exploitation." *Journal of Energy Resources Technology* 114 (December), 1992.

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