Improvement of Understanding of Vapor-dominated Geothermal Resources

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Abstract

Vapor-dominated geothermal resources were first exploited for commercial power generation, because of the easiness for utilization, i.e. wells in vapor-dominated geothermal fields produce dry steam alone. Understanding of the resource was improved first by accumulation of field experience, examples and data. Then, several different conceptual models were developed based on interpretations of the data. These conceptual models were tested and validated by numerical modeling, and then evolved into the current form. These processes led to the current understanding of the vapor-dominated geothermal resources. Thus, the key factors which contributed for the improvement are the increase of field data and experiences both in quantity and quality, and the advancement of numerical techniques. Among many vapor-dominated geothermal fields, real natural state of a reservoir has only been confirmed at Matsukawa, to date.

Keywords: geothermal, vapor-dominated, reservoir, natural state, modeling

1. Introduction

Among several types of geothermal resources, vapor-dominated geothermal resources were first exploited for commercial purposes, because of the easiness for utilization, i.e. wells in vapor-dominated geothermal fields produce dry steam alone. This paper first reviews past pathways of the improvement of understanding of the vapor-dominated geothermal resources, then discusses key clues for the improvement and finally summarizes remaining questions.

2. Vapor-dominated geothermal systems

There are two definitions on the vapor-dominated geothermal resources from different viewpoints;
1) In some part of a geothermal reservoir, especially below a cap rock, there is a “vapor-dominated zone” in which steam is the pressure controlling phase.
2) Most of wells in a geothermal field produce dry steam without hot-water.

The first one focuses on a natural state of the reservoir and is related to a model of White et al. (1971), which will be described later. This is a definition from a scientific viewpoint. The second one focuses on discharge in an

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exploitation state. This is a definition from a practical viewpoint, and is widely accepted in field development.

In this paper, an entire system is called a “vapor-dominated geothermal system” from an earth-scientific viewpoint. A part of the system from which dry steam can be produced for commercial utilization is called a “vapor-dominated geothermal reservoir”. A geothermal system which includes a vapor-dominated geothermal reservoir that enables commercial energy development is called a “vapor-dominated geothermal resource”.

3. Increase of field data

In early stages of the history of geothermal utilization, increase in field experiences and data first played a very important role in the improvement of understanding of vapor-dominated geothermal resources.

A systematic development of a vapor-dominated geothermal resource was started in Italy since around the 1900s (e.g. Cataldi et al., 1970; Dickson and Fanelli, 2004). By around the 1960s, understanding of the resource had been improved to the following level (e.g. Cataldi et al., 1970);

1) Well drilling revealed that geothermal steam can be produced from subsurface fractured zones.
2) Well drilling also revealed that the distribution of fractured zones are restricted and are not present everywhere. They must be related to faults and/or foldings.
3) Well drilling also revealed the existence of a cap rock above the production formation. It is impermeable and acts as a cover to the reservoir which limits inflow from a shallow ground water zone.

These findings have been brought out by experiences in well drilling. Thus increase in field experiences and filed data improved understanding of the nature of the resource. As a result, success rate of drilling improved stepwise. Also, ideas for selecting drilling targets have been improved.

Fig. 1 is a conceptual model of a geothermal reservoir in Larderello, Italy in the 1960s (Sestini, 1970).

Fig. 2 Conceptual model of vapor-dominated geothermal systems by White et al. (1971).
pressure controlling phase. It is porous heat pipe, in which steam ascends and condensate descends.

2) There is a low permeability barrier at least at the top and sides of the reservoir. This limits inflow into and outflow from the reservoir. Thus it allows the reservoir pressure lower than hydrostatic.

3) Below the vapor-dominated zone, there is boiling brine.

Though most of the factors have been confirmed, the brine has never been confirmed by drilling in any vapor-dominated geothermal fields to date*.

There is another model from a different view point. D’Amore and Truesdell (1979) explained chemical distribution (non-condensable gas concentration) in a shallow part of a vapor-dominated reservoir by introducing effects of conductive heat loss through the cap rock (Fig. 3). They noticed that water-vapor in geothermal steam may condense if there is conductive heat loss through the cap rock, but non-condensable gasses may not condense and remain in the steam. Thus, gas concentration increases towards the margin of the reservoir from its center along its flow.

A summary of the most recent understanding of the vapor-dominated geothermal systems can be found in Grant and Bixley (2011).

5. Quantification

Advancement of technologies of numerical modeling played a very important role in the improvement of understanding of vapor-dominated systems. Ingebritsen and Sorey (1988) tested the conceptual model of White et al. (1971) by numerical modeling of heat and mass flow in porous media (Fig. 4). They succeeded in reproducing the vapor-dominated condition below the cap rock (Fig. 5). They found the characteristics of the vapor-dominated systems as follows;

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* Though many field engineers and scientists noticed it and discussed it in conversations, it has not been described explicitly in any reports to date, to the best of my knowledge.
should be around $5 \times 10^{-17}$ m$^2$. Lower or higher permeability may not form the vapor dominated zone.

4) Maximum pressure at the top of the vapor-dominated zone is controlled by the depth to the top of the vapor-dominated zone. It is not controlled by the maximum enthalpy of saturated steam (Fig. 6).

5) Minimum heat input necessary to maintain the vapor-dominated condition is a function of the depth to the top of the vapor-dominated zone. It is around 1.5 W/m$^2$ when the depth to the top of the vapor-dominated zone is about 300 m (Fig. 7).

Among them, the existence and value of the low permeability barrier are the most essential;

1) If the order of permeability of the barrier is higher than $5 \times 10^{-17}$ m$^2$, the reservoir has much better hydraulic contact with active in and out flow between the reservoir and outside. Thus heat is removed from the reservoir and will lead the system much cooler (Hanano, 1992).

2) If the order of permeability of the barrier is lower than $5 \times 10^{-17}$ m$^2$, the vapor-dominated zone will become much thicker, because fluid leakage from the top of the vapor-dominated zone to the shallow ground water zone through the cap rock is too small. This may not reproduce the natural state of real vapor-dominated reservoirs (Ingebritsen and Sorey, 1988; Hanano, 1992).

Note that above mentioned heat input (1.5 W/m$^2$) is lower than 4 W/m$^2$ which is a typical convective heat flux within liquid-dominated geothermal reservoirs (e.g. Hanano and Kajiwara, 1999). Thus, larger and/or stronger heat source may not be necessary for the formation of a vapor-dominated system compared with that of a liquid-dominated system.

When the heat input is doubled, a much thicker vapor-dominated zone has been created. Thus, a vapor-dominated zone could have easily extended deeper and shrunk with increasing and decreasing conductive heat flux due to repeated intrusion of magmatic heat sources (Hanano, 1992).

Note that thickness of the vapor-dominated condition in the natural state is around 100 m to 200 m (Fig. 5). This is much thinner than that confirmed in Kamojang in the 1970s (Fig. 8). The problem on the natural state of the Kamojang reservoir will be discussed later.

As shown above, quantification of conceptual models by numerical modeling gave various insights for better understanding of the nature of vapor-dominated systems. For the success of such numerical modeling studies, preceding analytical studies also played very important roles (e.g. Schubert and Straus, 1979; 1980; Straus and Schubert, 1981). For example, Fig. 9 is a result of analysis on permeability required for the cap rock (Schubert and Straus, 1980). This result shows that a liquid phase above a vapor phase is stable against any wave length of disturbance when the permeability of the cap rock is below $4 \times 10^{-17}$ m$^2$.

Based on this study, Ingebritsen and Sorey (1988) employed $5 \times 10^{-17}$ m$^2$ as the permeability for the cap rock and surrounding barriers.
The effectiveness of quantification to improve the understanding of a vapor-dominated geothermal reservoir has been clearly demonstrated in Matsukawa. Hanano and Matsuo (1990) numerically analyzed data collected in early stages of the development in Matsukawa and reconstructed the natural state of the reservoir (Fig. 10). Then Hanano (1992) numerically validated its feasibility.

6. Natural state

Shallow well drilling and utilization of steam was started in the 19th century in Larderello (e.g. Cataldi et al., 1970; Dickson and Fanelli, 2004), and in the 1920s in The Geysers (e.g. Barker, 2000). Also, a shallow exploration well in Kamojang has been blowing out steam since 1928 (e.g. Zen and Radja, 1970) (Photo 1). Numerical modeling studies showed that long-term steam production can increase the size of a vapor-dominated zone substantially even though its rate is very small (e.g. Pruess, 1985). Thus, these long-term steam productions have increased the thickness of vapor-dominated zones in these fields. Thus “natural state” of the Kamojang reservoir observed in the 1970s (e.g. Grant, 1979) was not a real “natural state”. That was “current state” in the 1970s instead (Fig. 8).

On the other hand, Matsukawa geothermal reservoir was discovered in 1952. Then, a systematic geothermal exploration was started in 1956, resulting in commencement of commercial power generation in 1966 (e.g. Mori, 1970; Hanano et al., 1993). Thus, real natural state of a vapor-dominated reservoir has only been confirmed in Matsukawa (Hanano and Matsuo, 1990; Hanano, 1992) (Fig. 10). Note that the thickness of the vapor-dominated condition in the natural state is only 200 m, which agrees with the result of Ingebritsen and Sorey (1988) (Fig. 5).

7. Conclusion and suggestions for further research

Understanding of vapor-dominated geothermal systems has been improved first by collection and accumulation of field experience, data and examples. Then conceptual models were developed based on interpretation of the data, and then their feasibility was tested by numerical modeling. A series of these efforts led to the current understanding of vapor-dominated systems. Among many vapor-dominated geothermal fields, real natural state of a reservoir has only been confirmed at Matsukawa, to date.
However, there still remain some questions on the vapor-dominated geothermal systems;
1) Brine has never been confirmed in any vapor-dominated fields. Does it really exist? Is it still necessary or not from both scientific and engineering viewpoints?
2) One more factor, i.e. cap rock and surrounding low permeability barriers, is needed for the formation of the vapor-dominated geothermal systems compared to those of liquid-dominated geothermal systems. Thus probability of occurrence of vapor-dominated geothermal systems is believed to be lower than that of liquid-dominated geothermal systems. However, necessary heat input to sustain vapor-dominated geothermal systems is lower than that of liquid-dominated geothermal systems. Thus, is the probability of occurrence of vapor-dominated geothermal systems really lower than that of liquid-dominated geothermal systems or not? If it is really lower, then how low is it?
3) A porous heat pipe sometimes exhibits instability, e.g. cycling of direction of hydrothermal convection, especially at high Rayleigh Number (e.g. McGuiness et al., 1993). Thus, there is a possibility that this cycling had occurred in existing vapor-dominated geothermal fields. If this is the case, is it possible to confirm this phenomenon in a real geothermal field by mineralogical study and/or other methods?

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* in Japanese with English abstract

短 報

蒸気卓越型地熱資源の理解進展過程

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概 要

蒸気卓越型地熱資源は, 蒸気のみを生産することから利用が容易であり, 最も早くから商業利用が行われてきた。発展の進展によるデータや経験の蓄積とともにその理解は進んで行き, 其の成果として種々の概念モデルが逐次考えられた。その後, 数値解析技術の発達に伴い概念モデルの検証が行われ現在の形に至っている。現在の蒸気卓越型地熱資源に関する理解はこのような過程を経た結果である。従って, 現在の理解に至るまでに重要な役割を果たしたのは, データや経験の質・量両面での充実と数値解析技術の発達であった。多くの蒸気卓越型地域が存在するが, 現在までのところ, 開発前の自然状態が明らかにされたのは岩手県の松川地域である。

キーワード: 地熱, 蒸気卓越型, 貯留層, 自然状態, モデリング