# Monitoring Criteria on Transition of Well Discharge from Two-phase to Dry Steam

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## ABSTRACT

Two-phase geothermal wells sometimes turn to produce dry superheated steam. We have introduced a quantitative monitoring guideline to identify potential two-phase wells which may become superheated. We first estimated enthalpy increase ratio from reservoir to wellhead based on data of some production wells. Then, using the enthalpy increase ratio, we estimated a dryness fraction of two-phase fluid at the wellhead from residual water saturation at the far end of in-flow region. Based on monitoring results of production performance of some wells, we found that this guideline is reasonable and practical. We also found that the transition from two-phase production to superheated steam of a well does not occur gradually but relatively suddenly.

## 1. INTRODUCTION

In high-temperature liquid-dominated geothermal fields, there have been many cases that two-phase wells turned to produce dry superheated steam, after a certain period of steam production. In such geothermal fields, it is worth noting in advance, from a viewpoint of field management, that which well would become dry steam from two-phase fluid production. For this purpose, we have introduced a quantitative monitoring guideline to identify potential two-phase wells which may become dry superheated steam production, based on reservoir engineering consideration. Here we show its fundamental concept, estimation procedure and some examples.

## 2. CONCEPT OF SEMI-DRY WELL AND ITS QUANTITATIVE DEFINITION

Here, we call a geothermal well which has a high possibility to shift from two-phase production to dry superheated steam production a semi-dry well. From a reservoir engineering viewpoint, it is the state immediately before the liquid-phase of the flowing two-phase fluid loses mobility within an in-flow region in the vicinity of a production well.

Then, we assume 0.99 or greater as a value of the steam-phase relative permeability ($krs$) as a quantitative guideline for the semi-dry well. If we employ "Fracture flow" type relative permeability function of Sorey et al. (1980), it is almost equivalent that the water saturation within the in-flow region ($Sw_R$) ranges from 0.5 to 0.3 (Fig.1). Note that $Sw_R$ 0.5 and 0.3 are equivalent to $krs$ 0.99 and 1.0, respectively (c.f. Red arrows in Fig.1). This is the quantitative definition of the semi-dry well.

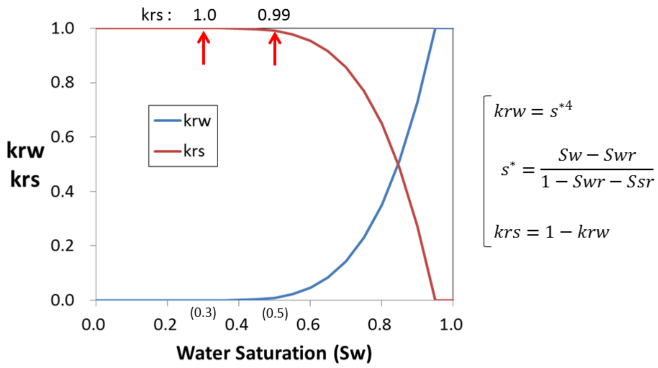


**Figure 1: "Fracture Flow" type relative permeability function of Sorey et al. (1980). $krw$ and $krs$ are liquid-phase and steam-phase relative permeability, respectively. Residual saturations for liquid-phase ($Swr$) and steam-phase ($Ssr$) are 0.3 and 0.05, respectively.**

Of course, these values shall be different if we employ different relative permeability function and/or different residual water saturation value. Unfortunately, the relative permeability function is not very well understood, especially for the in-flow region at very high permeability and very high flowing velocity condition (e.g. Grant and Bixley, 2011; Wang and Horne, 2000). Therefore, further studies are desired in this field.

## 3. WELLHEAD CONDITION OF SEMI-DRY WELL

For a practical field management, we need a quantitative guideline at a wellhead for daily monitoring. For this reason, we converted the above mentioned reservoir condition, i.e. water saturation in the reservoir, to a dryness fraction (i.e. steam quality) at a wellhead.

Specific enthalpy of flowing fluid of a semi-dry well increases during the flow within the in-flow region (Fig.2). This is caused by heat transfer from the reservoir rock to the flowing fluid. Fluid pressure draws down during the flow towards the well face. While the flowing fluid is single-phase compressed water, its temperature remains constant. However, when the fluid pressure falls to its saturation pressure, boiling occurs. After that point, the flashing continues, and then the temperature starts falling along with the pressure draw down. Thus, there occurs heat transfer from the reservoir rock to the flowing boiling two-phase fluid (Fig.2). This is the mechanism of the enthalpy increase due to the flashing steam/water flow in the vicinity of a production well. Thus, we need to take this effect into account when we consider the quantitative monitoring guideline at the wellhead.

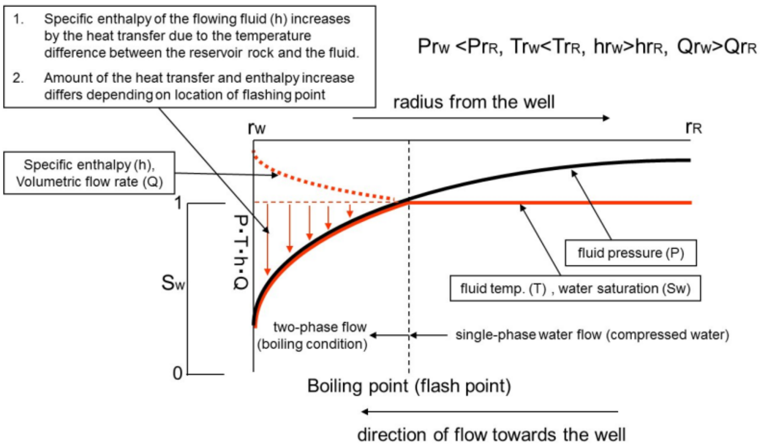


**Figure 2: Schematic mechanism of enthalpy increase due to flashing steam/water flow within the in-flow region. *rw*: radius of well face, *rR*: radius of far end of the in-flow region.**

The enthalpy increase due to the flashing in the vicinity of wells has long been recognized (e.g. Grant et al., 1981; Grant and Bixley, 2011). Quantitative analysis is usually required for scientific studies and field management. However, there still remain difficulties because of the following complexities, though there have been efforts for this purpose.

As described above, relative permeability functions especially for the in-flow region of very high flowing velocity is not very well understood. Also, heat transfer resulting from the flashing steam/water flow in the in-flow region is not very well understood, as described above.

Pressure drawdown of flashing steam/water flow within the in-flow region is not very well understood, also. High-velocity flow in the vicinity of a well has serious non-darcy effects and leads to difficulties in the numerical analysis of a pressure drawdown (e.g. Noh and Firoozabadhi, 2008). There have been efforts for quantitative description of the pressure drawdown for the high-velocity non-darcy flow in the vicinity of a well. However, most of the efforts still appear to be limited in single-phase liquid flow (e.g. Aragon et al., 2008; Zhang and Xing, 2012). It becomes much more complex for the flashing two-phase flow in the vicinity of a well, because volume of the flowing fluid becomes larger along with the flash; this further accelerates the pressure drawdown.

Because of these reasons, numerical modeling techniques for the in-flow performance for the flashing steam/water flow in the vicinity of wells including the enthalpy increase phenomena are still under development due to the complexity of the phenomena (e.g. Gudmundsson et al., 1986). Thus, we employ semi-analytical method to avoid these complexities.

A schematic concept of the estimation procedure of the wellhead condition, i.e. dryness fraction at wellhead, from the reservoir condition is shown in Fig.3. Here, we assume the simplest case; a single-feed production well. During the flow within the in-flow region and the wellbore, the fluid gains heat due to the temperature difference between the formation and the fluid. Thus the specific enthalpy of the fluid increases at the wellhead compared to that at the far end of the in-flow region.

Based on the concept, we derived the following of equations.

$$h_o = x_o \cdot h_o'' + (1 - x_o) \cdot h_o' \quad (1)$$

$$x_R = \frac{(1 - S_{wR}) \cdot v_R'}{S_{wR} \cdot v_R'' + (1 - S_{wR}) \cdot v_R'} \quad (2)$$

$$h_R = x_R \cdot h_R'' + (1 - x_R) \cdot h_R' \tag{3}$$

$$a = \frac{h_o}{h_R} \tag{4}$$

where, $h$, $x$, $S_w$, $v$, $a$ are specific enthalpy (kJ/kg), dryness fraction (steam quality) (-), water saturation (-), specific volume ($m^3$/kg) and ratio of enthalpy increase (-), respectively. Also, $o$, $R$ are subscripts for wellhead and reservoir (far end of the in-flow region), respectively. Then, *'*, *"* are superscripts for hot water (liquid phase) and steam, respectively.

We first estimate $a$ based on data in the reservoir and at the wellheads. Then, using these equations, we obtain $x_o$ which is the quantitative guideline at the wellhead for the monitoring of the semi-dry well. Some examples will be shown in the next section.

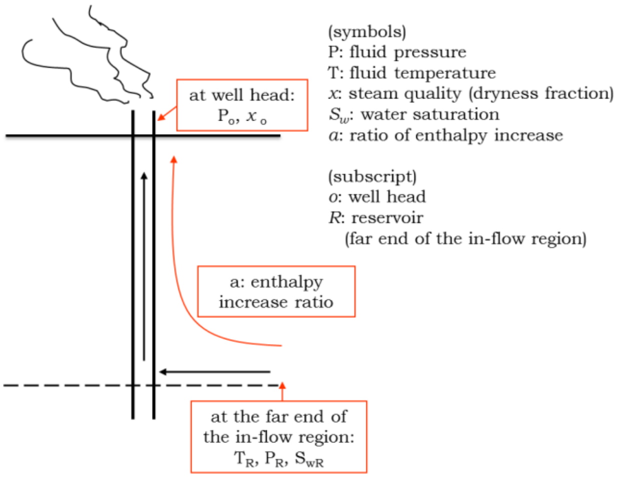


**Figure 3: Schematic concept of estimation procedure of the wellhead condition from the reservoir condition.**

## 4. EXAMPLES AND DISCUSSION

Here we show some examples of transitions of well discharges between semi-dry and dry steam, in the Okuaizu geothermal field in Japan.

### 4.1 Okuaizu Geothermal Field

Okuaizu geothermal field is a high-temperature liquid-dominated geothermal field located in northeastern Japan. Following a reconnaissance survey for mining in 1956, geological, geophysical and geochemical surveys of the geothermal resource were carried out from 1974. Then, Yanaizu-Nishiyama geothermal power station (65MWe) commenced its operation in May 1995 (e.g., Nitta et al., 1988; Saeki, 2004; Ozeki and Adachi, 2010).

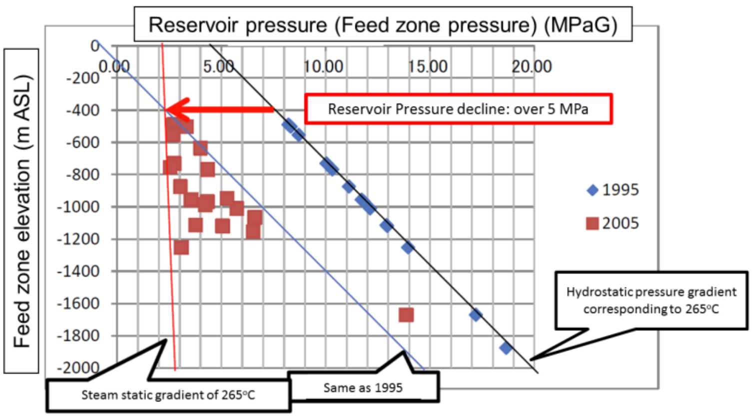


**Figure 4: Reservoir pressure change monitored at feed points of production wells in the Okuaizu Geothermal Field. Black and blue solid lines correspond to density of saturated hot water of 265°C, and red solid line corresponds to that of saturated steam of 265°C.**

Change of reservoir pressure in Okuaizu is shown in Fig.4. Since representative reservoir temperature of the major production zone is around 280 to 300$^o$C, the reservoir pressure profile in its initial state corresponded to density of saturated hot water of 265$^o$C, indicating active super-hydrostatic condition. The reservoir was filled with single-phase liquid within the production depths at that time.

After the start of the power generation, there occurred a large reservoir pressure decline due to the nature of permeability structure of the reservoir. In 2005, it was greater than 5 MPa, possibly 5.3 MPa on average at -400m ASL. Thus, boiling occurred all over the reservoir and two-phase condition evolved in most of the reservoir. Also, vapor-dominated condition evolved in some part of the reservoir, though there still remained liquid-dominated condition in some part.

### 4.2 Enthalpy Increase Caused by Well Production

An overview of the enthalpy increase from the reservoir to the wellheads in Okuaizu is shown in Fig.5. Range of the reservoir temperature in 1995, just before the start of the power generation, was around 240 to 320$^o$C. All of the reservoir fluid in the production zone was single-phase liquid, i.e. compressed water, at that time. As shown in Fig.4, there occurred a large reservoir pressure decline after the start of the power generation, then there occurred boiling in the reservoir. Thus, temperature of the reservoir fluid declined along with the reservoir pressure decline. In 2005, the range of the temperature of the reservoir fluid in the major production zone was thought to be around 220 to 280$^o$C. Then, the specific enthalpy of the reservoir fluid ranged from 0.9 to 1.3 MJ/kg in 2005 (Fig.5).

On the other hand, wellhead pressures of production wells range from 0.7 to 1.0 MPaG. The dryness fraction of the produced fluid ranges from 0.5 to 1.0; some wells are superheated. Thus, the specific enthalpy of the produced fluid ranges from 1.7 to 2.8 MJ/kg (Fig.5). Therefore, the enthalpy increase from the reservoir to the wellhead appears to range from 50 to 100%. However, based on the data of individual wells, that of the semi-dry wells appears to range from 50 to 70%.

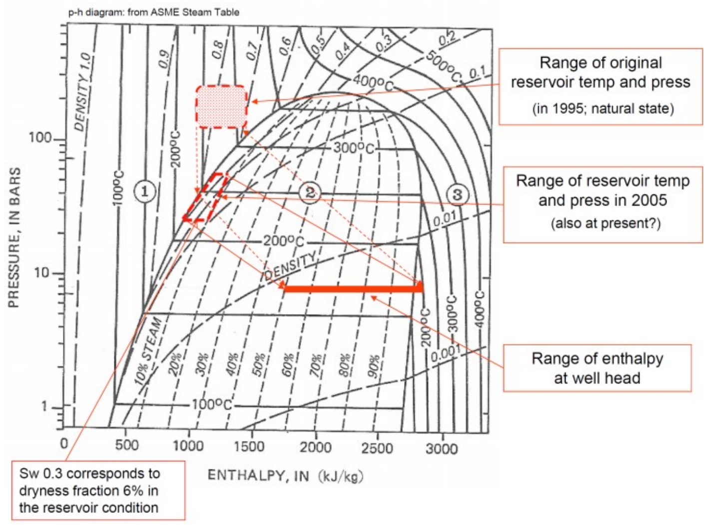


**Figure 5: Enthalpy increase in the Okuaizu geothermal field. Ranges of reservoir temperature and pressure represent those of the main production zone.**

### 4.3 Derivation of the Quantitative Guideline

Based on the above discussion, we estimated the wellhead dryness fraction of the semi-dry well in Okuaizu (Table 1).

**Table 1: Estimated wellhead dryness fraction (steam quality) of the semi-dry well in the Okuaizu geothermal field.**

| $S_{wR}$ | $a$ | $x_o$ |
|---|---|---|
| 0.5 | 1.7 | 0.81 |
| 0.3 | 1.5 | 0.82 |

From this result, 0.8 is thought to be an approximate guideline of the wellhead dryness fraction for the monitoring of the semi-dry well in Okuaizu. Of course, this value shall be different depending on flowing and/or heat transfer condition in the in-flow region and/or relative permeability characteristics in the region.

### 4.4 Behavior of Transition between Semi-Dry and Dry Steam Production

In the above discussion, we employed the assumption that the steam-phase relative permeability ($krs$) is 0.99 or greater in the in-flow region of the semi-dry well. This means that the liquid-phase of the flowing two-phase fluid will soon lose mobility and the flowing fluid will become single-phase steam in the in-flow region, if there occurs any small decrease in the water saturation of the flowing two-phase fluid. This suggests that the dryness fraction (steam quality) at wellhead may jump up from 0.8 to 1.0, if there occurs any small change in the in-flow region. That is, transition of well discharge from two-phase to dry steam may occur relatively suddenly, and thus this transition may not be very smooth and/or gradual.

### 4.5 Cases of Wells 38P and 24P

The production well 38P was drilled in 2006 as a make-up well. Since its wellhead dryness fraction had been around 0.8 from the start of the steam production, we had monitored its behavior as a potential semi-dry well. In 2010, transition to dry steam production was confirmed (Fig.6). The change from two-phase production to dry steam was almost suddenly and stepwise, as expected from the above discussion.

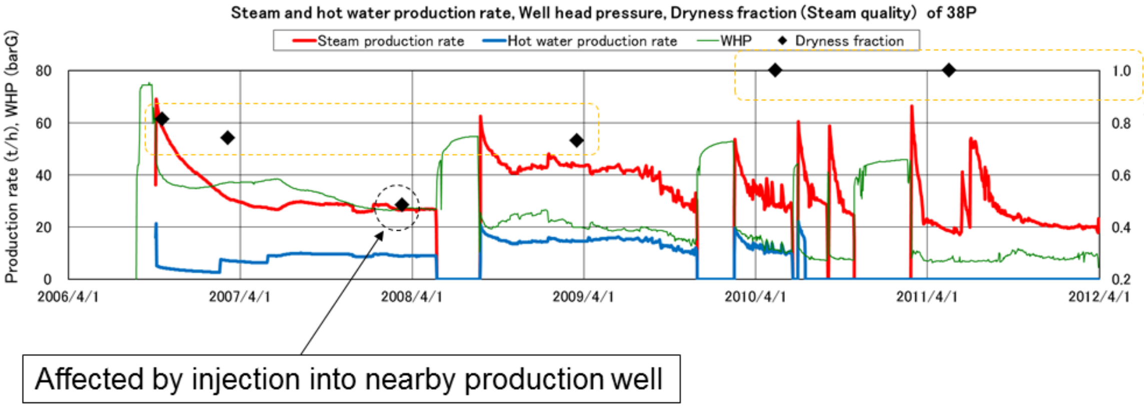


**Figure 6: Production history of well 38P**

Then we show the case of well 24P, along with 38P (Fig.7). Wellhead dryness fraction of 24P had been around 0.9 from the start of the steam production. It once became dry in 1999, but it returned to two-phase production. This return was confirmed in 2010, and was thought to occur suddenly; the wellhead dryness fraction stabilized at approximately 0.9.

Dryness fraction at wellhead of a semi-dry well can be around 0.9, if increase of fluid enthalpy is around 70% and 80%, or water saturation at the far end of the in-flow region ($S_{wR}$) is around 0.15 to 0.3. Thus, wellhead dryness fraction 0.9 can also occur depending on flowing and/or heat transfer condition in the in-flow region, and/or relative permeability characteristics in the region.

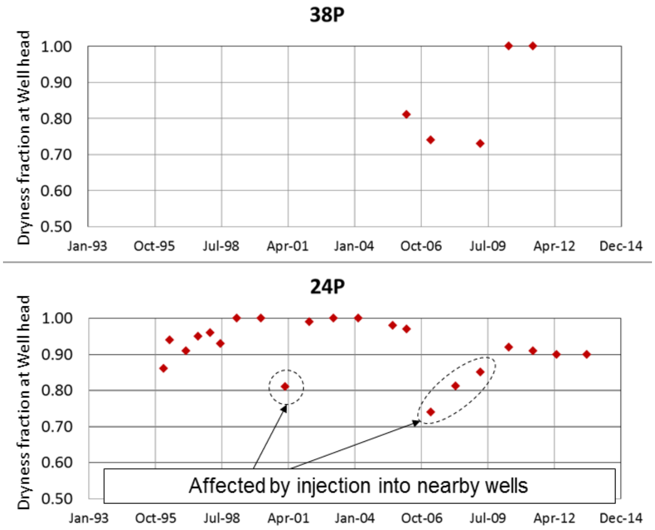


**Figure 7: Histories of wellhead dryness fraction of wells 38P and 24P**

As seen in the examples, wellhead dryness fraction 0.8 to 0.9 is reasonable and practical as a monitoring guideline for semi-dry wells in the Okuaizu geothermal field.

Of course, there are exceptions in this field which do not meet the model proposed in this study. For example, there are several multi-feed wells which have both wet and dry feeds. These wells produce slightly wet steam; Wellhead dryness fractions of these wells are sometimes greater than 0.9. Another exception is a case of casing damage. There occurred a casing break at relatively shallow depth in one production well. This resulted in intrusion of shallow cold water of very small amount. Thus the well turned to produce slightly wet steam from dry superheated steam. Well head dryness fraction of the well became 0.98.

## 5. CONCLUDING REMARKS

1) Wellhead dryness fraction ($x_o$) of potential wells which may become superheated from two-phase production, i.e. semi-dry wells, is estimated from a reservoir engineering viewpoint. It is around 0.8 to 0.9 in the Okuaizu geothermal filed, but it shall be different depending on flowing and/or heat transfer condition, and/or relative permeability characteristics in the in-flow region.

1) Wellhead dryness fraction of semi-dry wells may jump up from around 0.8 to 1.0, if there occurs any small change in the flow within the in-flow region. The change should occur relatively suddenly and stepwise, but not gradually.

2) For numerical analysis of the behavior of semi-dry wells and related phenomena, further studies are desired in the following area:

   - Relative permeability functions especially for the in-flow region of very high flowing velocity
   - Heat transfer and enthalpy increase for flashing steam/water flow in the in-flow region
   - Pressure draw down especially for the high-velocity non-darcy flashing steam/water flow within the in-flow region

## ACKNOLEDGMENTS

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