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Wet-Steam Well Discharges. I. Sampling and Calculation of Total Discharge Compositions

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ABSTRACT

Samples of water and steam from wet-steam well discharges are often collected under the same conditions, i.e. at the same pressure. It is, however, common to collect steam samples at elevated pressure and water samples from the weirbox. In the latter case some of the steam in the discharge is not collected or analysed. This steam is secondary and can therefore be expected to contain little gas. Indeed the approximation invariably made for calculation of total well discharge composition or aquifer fluid composition, when water and steam samples are collected at different pressures, is to take the gas content of the steam fraction not sampled to be zero. This approximation is unnecessary when water and steam samples are collected at the same pressure. In this contribution, a detailed procedure is given for calculation of the total discharge composition of wet-steam wells for different sampling scenarios. Another contribution (Arnórsson and Stefánsson, 2005) describes methodology for calculating aquifer fluid compositions from data on water and steam samples collected at the wellhead.

1. INTRODUCTION

In the year 2000, the total installed capacity of geothermal power plants worldwide was 7974 MW (Huttrer, 2001), From this, it is deduced that there are some 1600-2000 productive geothermal steam wells in the world (average yield equivalent to 4-5 MW electric). Subtracting steam wells drilled into vapor-dominated systems, one can expect that the total number of wet-steam wells producing from liquid-dominated geothermal reservoirs is on the order of 1200-1500. The steam discharged from such wells forms essentially by depressurization boiling of the aquifer water although a fraction of the steam discharged may be present in the aquifer under initial conditions. Further, steam may be generated by transfer of heat from the aquifer rock to the aquifer fluid in the depressurization zone around discharging wells (see e.g. Arnórsson et al., 1990).

Samples of water and steam are extensively collected from wet-steam well discharges worldwide with the purpose of

(1) establishing the chemical characteristics of the discharged fluid

(2) assessing specific reservoir characteristics

(3) monitoring the response of exploited reservoirs to the production load.

Often published analyses on water and steam samples collected from wet-steam wells are not accompanied by physical data on the wells, such as discharge enthalpy and the temperature and depth level of permeable horizons. Data on sampling pressure may also be lacking and data on gas concentrations in steam are not provided, only the relative amount of the gases analyzed for. Data on gas concentrations in steam are necessary for evaluation of total discharge and aquifer fluid compositions. The physical data are important for maximizing information from the chemical data, e.g. for assessment of total discharge and aquifer fluid compositions, the depth level of producing aquifers, scaling potential and changes in reservoir conditions, such as those caused by colder water recharge or recharge of injected waste fluid.

Although samples of water and steam are frequently collected at the same pressure, it is common to collect samples of water discharged from wet-steam wells at atmospheric pressure, i.e. from the weirbox, but steam samples under pressure, either from wellhead separators or from pipes conveying the two-phase fluid from the wellhead using a webre separator. When sampling is carried out in this way, part of the well discharge is not collected, namely the steam which forms by depressurization boiling from the pressure at which the steam sample is collected to atmospheric pressure.

In the present contribution, existing techniques for sampling water and steam from wet-steam well discharges are briefly summarized. Details are given for calculation of total well discharge composition for various sampling conditions. Some chemical analytical aspects are also discussed. Another contribution (Arnórsson and Stefánsson, 2005) addresses models for reconstructing aquifer fluid compositions from analyses of wellhead samples.

2. SAMPLE COLLECTION

Various methods have been applied to collect samples of water and steam from wet-steam well discharges. They have been described by Ellis and Mahon (1977) and Arnórsson et al. (2000). One method involves the use of a webre separator, which is connected to a two-phase pipeline by the wellhead. It allows separate collection of water and steam samples at the same pressure. Another method involves sampling of the separated phases from a wellhead steam separator or from a steam separator at a separator station, also allowing water and steam samples to be collected at the same pressure. However, the most common method of sampling involves collection of steam samples under pressure from webre- or wellhead separators and water samples at atmospheric pressure from weirboxes. By this last method, not all the well discharge is sampled. Steam escapes from the atmospheric silencer and this steam is not sampled. This method does not provide the best data for assessment of total discharge and aquifer fluid compositions. Since, however, large amounts of chemical data of this kind are available, we suggest methods, which we consider reasonable for calculation of total discharge compositions from analyses of water and steam samples collected under different conditions.

When collecting water and steam samples from wet-steam well discharges using a webre separator, good phase separation is essential. Adjustment of the separator for efficient phase separation should not be a problem, except for wells with either a small or a very large steam fraction. Slug flow can be expected when the steam fraction is small. This is typical for wells of low discharge enthalpy (less than about 900 kJ kg^{-1}). Slug flow, which involves pulsating discharge of water and steam and accompanying fluctuations of pressure in the separator, may cause it to be impossible to achieve satisfactory phase separation. When the steam fraction is high, i.e. the discharge enthalpy is approaching that of dry steam (above about 2500 kJ kg^{-1}), the water flow rate into the webre separator may not be sufficient for collecting a steam-free water sample. When this is the case, the only alternative may be collection of a water sample at atmospheric pressure (from the weirbox) or from a wellhead steam separator, if it has been installed.

The concentrations of some components in fluids sampled from wet-steam wells may differ from those in the aquifer, either due to their precipitation, which occurs as a consequence of cooling and degassing of the water by depressurization boiling, or due to dissolution of minerals from the aquifer rock, casing, or material in the sampling equipment. Dissolution from casing or material in the sampling equipment may be significant for the common trace elements in steel (Mn, Ni, Cr, V). Many trace elements, which form insoluble sulphides, including Fe, Cu, Zn, Pb and Ag, as well as Au, may be largely lost from solution between aquifer and wellhead (Brown, 1986; Seward, 1989; Brown and Webster, 1998; Stefánsson and Seward, 2003). Others may be partly lost, such as As (Ballantyne and Moore, 1988). Many of these elements are environmentally important. It is important to understand their precipitation/dissolution reactions for assessment of the environmental impact of geothermal energy utilization.

Due to difficulties in obtaining representative samples from the wellhead of wet-steam wells, at least for some components, and due to difficulties in assessing aquifer chemistry from these samples, collection of downhole samples, both in discharging and shut-in wells, has been considered as a solution to the problem. Downhole samples collected from shut-in wells may not give much useful information, if there is flow between permeable horizons or if the well intersects a two-phase aquifer. The steam from this aquifer entering the well will rise by buoyancy. If the water in the well above this aquifer is sub-boiling, the rising steam will heat it and condense in the process until the whole water column in the well above the two-phase aquifer has been heated to the boiling point (Fig. 1). Downhole samples taken from such a water column will consist of variable mixtures of the initial water in the well and condensate.

3. ANALYSIS

At vapour pressures to be expected at the wellhead, some components occur in appreciable concentrations only in one phase, either water or steam. Other components occur in significant concentrations in both phases. These components must be determined in both phases for assessment of their concentrations in the total well discharge. Components of this kind include carbonate carbon, sulphide sulphur, ammonia, mercury and sometimes boron. These components form gaseous species, at least partly, but they also react with H_2O molecules in the liquid phase as well as with various dissolved components in this phase to form an array of other species. A good example is given by carbonate carbon which forms CO_2 in the steam phase, dissolved CO_2 in the water (often expressed as H_2CO_3) together with HCO_3^-, CO_3^{-2}, $CaHCO_3^+$ and $CaCO_3^0$ to mention a few carbonate carbon-bearing aqueous species.

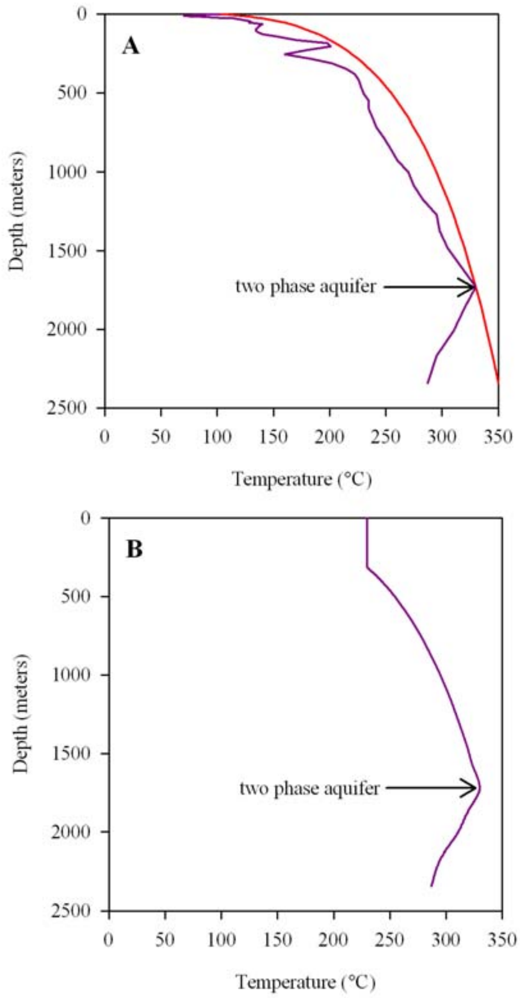

Fig. 1. Hypothetical temperature in a closed wet-steam well with a two phase aquifer. A: Blue line indicates formation temperature and red curve the boiling point curve with depth. B: Temperature distribution in well after steam from two phase aquifer has raised the temperature in the well above the aquifer to the boiling point and developed a steam cap.

3.1 Alkalinity and carbonate carbon

Frequently, alkalinity is determined in water samples and taken to represent bicarbonate. This is generally not acceptable for geothermal waters although it may be a good approximation for surface waters and many non-thermal ground waters. Various bases other than bicarbonate are present in geothermal waters in appreciable concentrations, and will react with the acid added for the alkalinity determination. They include silica, hydrogen sulphide and boron. In some geothermal waters, dissolved iron, aluminium and other hydrolyzed cations may contribute significantly to alkalinity as may organic acids. In their study of oilfield brines, Palandri and Reed (2000) observed that organic acids contributed as much as 90% of the measured alkalinity. Analysis of carbonate carbon must take into account the interfering effects of all bases present in solution that contribute to the alkalinity of the sample. Verma (2004) presents a revised method for determination of bicarbonate and carbonate concentrations in geothermal waters. This can also be achieved by back-titration (see e.g. Arnórsson et al., 2000). Further, ion chromatographs are now available, which allow measurement of carbonate carbon in aqueous solutions. When using back titration, specific correction must be done for aqueous hydrogen sulphide.

3.2 pH

Accurate measurement of pH in water samples from wet-steam wells is very important for reliable prediction of scaling potential of minerals with pH dependent solubility and for assessing the state of saturation in the aquifer water with respect to such minerals.

Unlike most other analytical methods, which measure component or species concentrations, the measurement of pH determines the activity of H^+. The activity of H^+ in geothermal waters is influenced by various weak acids and bases. Dissociation constants for these acids and bases vary with temperature. As a consequence, the pH of the geothermal water will change with temperature. Careful control of temperature is therefore necessary for accurate pH measurement making it also necessary to report the temperature at which the pH is measured. Reliable calculation of pH at temperatures, other than those at which it is measured, requires accurate measurement of the concentrations of components which form acids and bases. Upon storage of water samples, silica in solution in excess of amorphous silica solubility will polymerize. Formation of polymers involves removal of un-ionized silica molecules from solution but un-ionized aqueous silica is a weak acid. Therefore silica polymerization will cause the pH of the solution to increase, if it was initially sufficiently high (>8.5 when measured at room temperature) for a significant fraction of the silica in solution to be on an ionized form (see e.g. Gunnarsson and Arnórsson, 2005). Additionally, silica dimers and trimers form acids, which are stronger than that of monomeric silica (Iler, 1979). Their formation counteracts the pH increase caused by the decrease in un-ionized monomeric silica concentrations. Data on the acid strength of silica dimers, trimers and larger polymers is limited. Also, their concentrations cannot be determined by routine analytical methods. As a consequence, the only method to obtain a value for pH not affected by silica polymerization is to determine it on site, either immediately after quenching the water sample or at the temperature of the water in the weirbox. Measurement of polymerization-unaffected pH in water from the weirbox is, however, not possible if the aqueous silica has already polymerized to some extent when the water entered the weirbox.

The water flowing through the weirbox may lose or gain CO_2 upon contact with the atmosphere, depending on the CO_2 partial pressure of the water in relation to that of the atmosphere. CO_2 loss will cause an increase in water pH but CO_2 absorption will cause a decrease. Changes of this kind affect the value for pH calculated at temperatures other than those at which is was measured. Exposure to the air may cause both degassing and oxidation of H_2S. The latter process tends to cause a decrease in pH if the oxidation proceeds sufficiently to form thiosulphate and/or sulphate. Because of this, exposure of water to be sampled to the atmosphere can cause changes in pH. For the reasons mentioned above, collection of water samples under pressure is preferable to sampling from the weirbox. Such sampling requires, however, a good skill, particularly from wells with high or very low discharge enthalpy. In the former case, there is always the risk that the water sample becomes contaminated with steam.

The calculated pH of the aquifer water or water, which is less boiled than that sampled, depends on three factors: the measured pH of the water sample, the analysed concentrations of acid and base forming components in this sample, and the analysed concentrations of acid gases (CO_2 and H_2S) in the steam. If any of these factors carry substantial error, so does the calculated pH.

4. CALCULATION OF TOTAL DISCHARGE COMPOSITION

To determine the steam to water ratio in a wet-steam well discharge at a specific pressure, it is necessary to know from measurements the discharge enthalpy. The steam fraction of a well discharge at a separation pressure P^j, is given by

$$X^j = \frac{h^t - h^{l,j}}{L^j} \qquad (1)$$

where X^j denotes the steam fraction in the well discharge at vapour pressure P^j, h^t is the fluid discharge enthalpy and $h^{l,j}$ and L^j the enthalpy of liquid water at vapour pressure P^j and its latent heat of vaporization, respectively.

4.1 Water and steam samples collected at the same pressure

When water and steam samples are collected at vapour pressure P^c, it follows from conservation of mass that the concentration in the total discharge of component i, m_i^t, is given by

$$m_i^t = m_i^{v,c}X^c + m_i^{l,c}(1 - X^c) \qquad (2)$$

where $m_i^{v,c}$ and $m_i^{l,c}$ denote its concentrations in the steam and water phases, respectively. X^c represents the steam fraction in the discharge at vapour pressure P^c. X^c is defined by an equation analogous to (1), i.e.

$$X^c = \frac{h^t - h^{l,c}}{L^c} \qquad (1a)$$

In practice most components are analysed for only in one phase: volatile components in the steam phase and non-volatile components in the water phase. The term volatile component, as used here, refers to a component, which largely occurs as a gaseous species that partitions preferentially into the steam phase. The above-stated analytical practice assumes that the concentrations of the volatile and non-volatile components in the water and steam phases, respectively, are taken to be zero in the other phase, in which case equation (2) reduces to

$$m_i^t = m_i^{v,c}X^c \qquad (2a)$$

and

$$m_i^t = m_i^{l,c}(1 - X^c) \qquad (2b)$$

for volatile and non-volatile components, respectively.

Some components may be present in significant concentrations in both phases, such as sulphide sulphur, carbonate carbon, ammonia, mercury and boron. Such components must be determined in both phases for reliable determination of their concentration in the total discharge with the aid of equation (2).

4.2 Steam samples collected at elevated pressure and water samples from weirbox

If water and steam samples are collected at different pressures, i.e. the water sample from the weirbox at atmospheric pressure and the steam sample from a separator at elevated pressure, equations (2), (2a) and (2b) cannot be used to obtain m_i^t. Inspection of sampling practices presents three alternatives. The steam sample may be collected from a

(1) wellhead steam separator separating the total discharge

(2) webre separator on a two-phase pipeline discharging into an atmospheric silencer

(3) webre separator upstream from a wellhead separator.

In all cases some of the discharged steam is not collected and analysed. In the first case, it is the steam which forms by depressurization boiling of the separated water flowing from the wellhead steam separator to the atmospheric silencer (Fig. 2). In the second case, it is the steam which forms by depressurization boiling in the two-phase pipeline between the pressure at which the steam sample is collected and atmospheric pressure (Fig. 3). In the third case, two steam fractions are not collected: the fraction that forms by depressurization boiling between the webre and the wellhead separators and the steam fraction which forms by depressurization boiling of the water flowing from the steam separator and into the atmospheric silencer (Fig. 4).

If it is assumed that the concentrations of volatile species in steam fractions not sampled are zero, the concentration of component i in the total well discharge is given by

$$m_i^t = m_i^{v,c} X^c + m_i^{l,a}(1 - X^a) \tag{3}$$

where $m_i^{v,c}$ represents the concentration of component i in steam collected at vapour pressure P^c and $m_i^{l,a}$ its concentration in water sampled from the weirbox at atmospheric pressure, P^a. X^c and X^a denote the fractions of steam relative to the total well discharge at the pressures at which the steam and water samples were collected, respectively. Since the concentration of volatile species i in the steam fractions not sampled is taken to be zero, we have

$$m_i^{v,c} X^c = m_i^{v,a} X^a \tag{4}$$

The value of X^a depends on h^t and the three cases listed above for the conditions of steam sampling. Below, it is demonstrated how to obtain X^a for each of the three cases.

Case (1)

The steam fraction discharged from the well according to case (1) X^{a1}, relative to the total well discharge is given by

$$X^{a1} = X^s + X^{s\text{-}a} \tag{5}$$

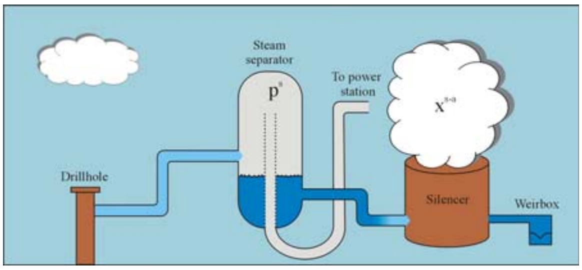

Fig. 2. View of wellhead steam separator, atmospheric silencer and weirbox. When steam is collected from the steam separator and water from the weirbox, the steam ($X^{s\text{-}a}$) discharged from the atmospheric silencer is not sampled. This steam forms by depressurization boiling from the pressure in the steam separator to atmospheric pressure.

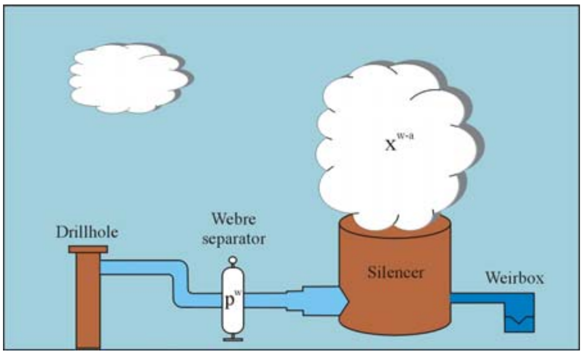

Fig. 3. View of wellhead steam separator, atmospheric silencer and weirbox. When steam is collected from a webre separator on a two phase pipeline upstream from the atmospheric silencer and water from the weirbox, a part of the steam ($X^{w\text{-}a}$) discharged from the atmospheric silencer is not sampled, i.e. the steam which forms by depressurization boiling from the pressure in the webre separator to atmospheric pressure.

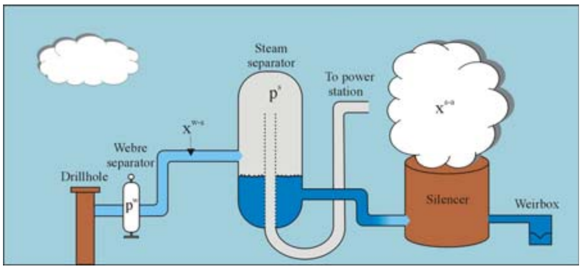

Fig. 4. View of wellhead steam separator, atmospheric silencer and weirbox. When steam is collected from the webre separator upstream from the wellhead steam separator and water from the weirbox, two steam fractions ($X^{w\text{-}s}$ and $X^{s\text{-}a}$) are not sampled: firstly, the steam which forms by depressurization boiling between the pressures in the webre and wellhead steam separators and secondly the steam which forms by boiling of the water separated in the wellhead steam separator.

Here, X^s, which represents the steam fraction in the wellhead steam separator, is defined by equation (1). The steam fraction which forms by depressurization boiling of the separated water flowing from the wellhead steam separator to the atmospheric silencer, X^{s-a}, relative to the total discharge, is given by

$$X^{s-a} = \left(\frac{h^{l,s} - h^{l,a}}{L^{a}}\right)(1 - X^{s}) \tag{6}$$

The first factor in parentheses on the right hand side of equation (6) represents the fraction of the separated water that has been converted into steam, and the second factor the fraction of this water in the total well discharge. $h^{l,s}$ is the enthalpy of liquid water at the vapour pressure in the wellhead steam separator. $h^{l,a}$ and L^{a} denote the enthalpy of steam saturated water and its latent heat of vaporization at atmospheric pressure, respectively, and X^{s} the steam fraction in the wellhead separator: hence $(1- X^{s})$ is the water fraction.

Case (2)

For case (2), the total steam fraction relative to the total well discharge is

$$X^{a2} = X^{w} + X^{w-a} \tag{7}$$

Here X^{a2} denotes the total steam fraction of the well discharge at atmospheric pressure, X^{w} the steam fraction in the webre separator and X^{w-a} the steam fraction that forms by depressurization boiling from vapour pressure P^{w} to atmospheric pressure. The steam fraction not sampled, i.e. X^{w-a}, is given by

$$X^{w-a} = \frac{h^{t} - h^{l,a}}{L^{a}} - \frac{h^{t} - h^{l,w}}{L^{w}} = X^{a} - X^{w} \tag{8}$$

$h^{l,w}$ and L^{w} denote the enthalpies of steam saturated water at the vapour pressure in the webre separator and its latent heat of vaporization, respectively. Both X^{a} and X^{w} are defined by an equation analogous to equation (1).

Case (3)

In case (3), the steam fractions not collected upstream and downstream from the wellhead separator, respectively, are symbolized as X^{w-s} and X^{s-a}, respectively. Hence the steam discharged from the well relative to the total well discharge, X^{a3} is given by

$$X^{a3} = X^{w} + X^{w-s} + X^{s-a} \tag{9}$$

As for case (2), X^{w} is given by an equation analogous to equation (1), X^{w-s} by

$$X^{w-s} = \frac{h^{t} - h^{l,s}}{L^{s}} - \frac{h^{t} - h^{l,w}}{L^{w}} = X^{s} - X^{w} \tag{10}$$

and X^{s-a} by equation (6). For the meaning of the symbols the reader is referred to the nomenclature section.

4.3 Total well discharge composition

For cases (1) to (3), respectively, the concentration of component i in the total well discharge is given by

$$m_i^{t} = m_i^{v,s}X^{s} + m_i^{l,a1}(1-(X^{s} + X^{s-a})) \tag{11}$$

$$m_i^{t} = m_i^{v,w}X^{w} + m_i^{l,a2}(1-(X^{w} + X^{w-a})) \tag{12}$$

and

$$m_i^{t} = m_i^{v,w}X^{w} + m_i^{l,a3}(1-(X^{w} + X^{w-s} + X^{s-a})) \tag{13}$$

Here, m_i^{t} designates the concentration of component i in the total well discharge, and $m_i^{v,s}$ and $m_i^{v,w}$ its concentration in steam samples collected at vapour pressures P^{s} and P^{w}, respectively. X^{s} and X^{w} stand for the steam fraction in the discharge at these pressures and $m_i^{l,a1}$, $m_i^{l,a2}$ and $m_i^{l,a3}$ the concentration of component i in the water sample from the weirbox according to cases 1, 2 and 3, respectively. Also, X^{s-a}, X^{w-a} and X^{w-s} are defined by equations (6), (8) and (10), respectively. The above equations assume zero concentration of i in the steam fractions not sampled.

If it is assumed that component i represents a volatile species present in insignificant concentration in the water sample collected from the weirbox, equations (11) to (13) are reduced to

$$m_i^{t} = m_i^{v,s}X^{s} = m_i^{v,a1}(X^{s} + X^{s-a}) \tag{14}$$

$$m_i^{t} = m_i^{v,w}X^{w} = m_i^{v,a2}(X^{w} + X^{w-a}) \tag{15}$$

and

$$m_i^{t} = m_i^{v,w}X^{w} = m_i^{v,a3}(X^{w} + X^{w-s} + X^{s-a}) \tag{16}$$

Assuming that a non-volatile component i is present in insignificant concentration in steam, equations (11) to (13) are reduced to

$$m_i^{t} = m_i^{l,a1}(1-(X^{s} + X^{s-a})) \tag{17}$$

$$m_i^{t} = m_i^{l,a2}(1-(X^{w} + X^{w-a})) \tag{18}$$

and

$$m_i^{t} = m_i^{l,a3}(1 - (X^{w} + X^{w-s} + X^{s-a})) \tag{19}$$

Equations (17) to (19) give the concentrations of non-volatile components in the total well discharge according to cases (1) to (3). Equations (14) to (16) permit calculation of gas concentrations in the total steam discharged from the well at atmospheric pressure, i.e. at the same conditions as the water sample is collected, according to cases (1) to (3). All these equations are convenient for calculation of total discharge compositions by some computer codes, e.g. WATCH (Arnórsson et al., 1982; Bjarnason, 1994) and CHILLER (Reed, 1982; Reed and Spycher, 1984). In particular, it is important to have values for $m_i^{v,a1}$ to $m_i^{v,a3}$ for calculation of water pH at temperatures other than that at which is was measured in the weirbox water sample. Such pH calculations are a prerequisite for assessment of scaling potential of minerals with pH-dependent solubility and for calculation of the aquifer water pH.

5. TRANSFER OF VOLATILE SPECIES INTO STEAM

Upon boiling of water dissolved gases will be transferred to the steam phase to an extent dictated by the solubility of these gases in the water and by how closely equilibrium gas distribution between the water and steam phases is approached. Gas solubility in aqueous solution is described by a solubility constant, K_{s}, which for gaseous species s is

$$m_s^{l} = K_s \cdot P_s \tag{20}$$

where m_s^l designates the concentration in the aqueous phase in moles (kg H_2O)$^{-1}$ and P_s its partial pressure over the solution. From $P_s = n_s^v \cdot P^t$ and the following definition of the coefficient D_s describing the distribution of gaseous species s between the water and steam phases

$$D_s = \frac{n_s^v}{n_s^l} \qquad (21)$$

it follows that

$$D_s = \frac{55.51}{P^t \cdot K_s} \qquad (22)$$

Here, n_s^v stands for the mole fraction of gaseous species s in the steam phase and P^t is the sum of the vapour pressure and all gas partial pressures ($P^t = P_{H2O} + \sum P_s$). The factor 55.51 is to convert molality into mole fraction ($m_s = 55.51 \cdot n_s$ for dilute solutions).

The gas content of steam discharged from very many wet-steam wells is <1% by volume in which case it is a reasonable approximation to take $P^t \cong P_{H_2O}$. By this approximation n_s^v = moles gaseous species s/moles water. On the basis of this assumption, the relative mass of some common gas species is steam has been calculated which forms by adiabatic boiling of 250°C steam saturated water (Fig. 5). The results in Fig. 5 show that 94-97% of the mass of the less soluble gaseous species, which are relatively abundant in geothermal steam (H_2, CH_4, N_2 and Ar), occupy the steam when it constitutes only 2.7% by weight of the fluid. To form this amount of steam by adiabatic boiling, the fluid has cooled by 10°C from the initial temperature, or to 240°C. The corresponding range at 5% steam is 98-99%. By contrast, only about 90 and 80% of the mass of the more soluble gaseous species, CO_2 and H_2S, occupy the steam phase when it form 5% by mass of the fluid. The results depicted in Fig. 5 demonstrate for relatively water soluble gases that it is necessary to determine their concentration in both water and steam samples for reliable calculation of their concentration in the total well discharge.

6. SUMMARY AND CONCLUSIONS

When samples of water and steam are collected from wet-steam wells at the same pressure, it is simple to calculate the concentrations of the analysed components in the total well discharge. When, on the other hand, samples are collected under different conditions, the calculation procedure becomes somewhat complicated and necessarily involves some approximations. The equations needed to calculate total well discharge compositions from analysis of water and steam samples collected at the wellhead are summarized in Table 1. For components only determined in the water sample, the first term on the right hand side of the four equations listed in Table 1 becomes zero and for gaseous components, only determined in the steam phase, the second term on the right hand side of the equations in question becomes zero.

It is considered that the best data are produced if water and steam samples are collected at the same pressure. For wells with a discharge enthalpy approaching that of dry steam, it may, however, not be possible to collect steam uncontaminated water samples from a webre separator. In this case collection of water samples from the weirbox is the best choice, if a wellhead steam separator has not been installed. Collection of water samples from the weirbox is considered to give the best results for some trace elements, which are present in steel, fittings and other piping equipment. They include Cr, Cu, Mn, Ni, Pb, V and Zn. To assess scaling potential for phases with pH-dependent solubility (calcite, sulphides), it is essential to obtain accurate analysis of pH, carbonate carbon and sulphide

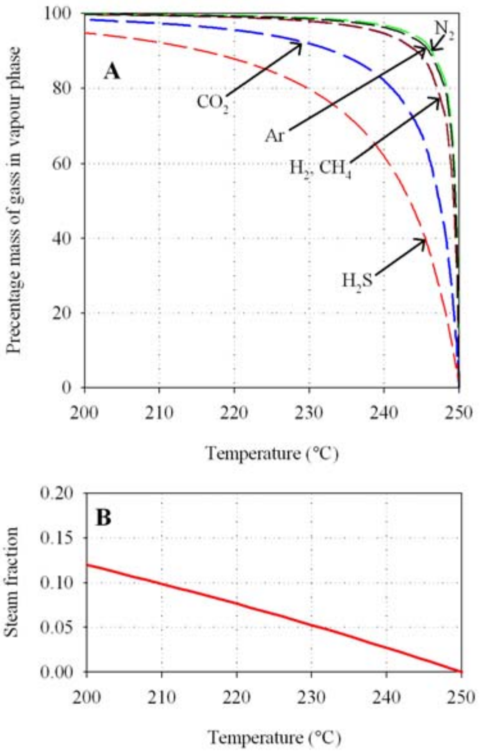

Fig. 5. A: Percentage mass of some common gases in geothermal steam after variable extent of adiabatic boiling of water initially at 250°C. B: Steam fraction formed by adiabatic boiling of water initially at 250°C.

Table 1. Equations for calculation of the composition of total wet-steam well discharges.

Case	Equation
0	$m_i^t = m_i^{v,c}X^c + m_i^{l,c}(1-X^c)$
1	$m_i^t = m_i^{v,s}X^s + m_i^{l,a1}(1-(X^s+X^{s-a}))$
2	$m_i^t = m_i^{v,w}X^w + m_i^{l,a2}(1-(X^w+X^{w-a}))$
3	$m_i^t = m_i^{v,w}X^w + m_i^{l,a3}(1-(X^w+X^{w-s}+X^{s-a}))$

0: Water and steam samples collected at the same vapour pressure, P^c.
1: Water sample collected from weirbox and steam sample from wellhead steam separator at vapour pressure P^s.
2: Water collected from weirbox and steam sample from two phase pipeline with webre separator at vapour pressure P^w.
3: Water sample collected from weirbox and steam sample from two phase pipeline with webre separator uppstream from wellhead steam separator at vapour pressure P^w. Vapour pressure in wellhead steam separator P^s.

sulphur in water samples. The same applies for calculation of the state of saturation of minerals with pH dependent solubility in the initial aquifer water.

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9. NOMENCLATURE

D_s	Distribution coefficient for gaseous species s between water and steam, defined by equation (21).
$h^{l,a}$	Enthalpy of steam saturated water at atmospheric pressure, P^a (kJ kg^{-1}).
$h^{l,c}$	Enthalpy of steam saturated water at vapour sampling pressure, P^c (kJ kg^{-1}).
$h^{l,j}$	Enthalpy of steam saturated water at pressure P^j (kJ kg^{-1}).
$h^{l,s}$	Enthalpy of steam saturated water at vapour pressure in wellhead separator, P^s (kJ kg^{-1}).
$h^{l,w}$	Enthalpy of steam water at the vapour pressure in the webre separator, P^w (kJ kg^{-1}).
h^t	Enthalpy of well discharge (kJ kg^{-1}).
K_s	Solubility constant for gaseous species s, defined by equation (20), (moles kg^{-1} bar^{-1}).
L^a	Latent heat of vaporization at vapour pressure equal to atmospheric pressure, (kJ kg^{-1}).
L^c	Latent heat of vapourization at sampling pressure P^c (kJ kg^{-1}).
L^j	Latent heat of vaporization at pressure P^j (kJ kg^{-1}).
L^s	Latent heat of vaporization at vapour pressure in wellhead steam separator, P^s (kJ kg^{-1}).
L^w	Latent heat of vaporization at vapour pressure in webre separator, P^w (kJ kg^{-1}).
$m_i^{l,a1}$	Concentration of component i in water from weirbox according to case 1 (moles kg^{-1}).
$m_i^{l,a2}$	Concentration of component i in water from weirbox according to case 2 (moles kg^{-1}).
$m_i^{l,a3}$	Concentration of component i in water from weirbox according to case 3 (moles kg^{-1}).
m_s^l	Concentration of gaseous species s in water (moles kg^{-1}).
$m_i^{l,c}$	Concentration of component i in water sample collected at vapour pressure P^c (moles kg^{-1}).
m_i^t	Concentration of component i in total well discharge (moles kg^{-1}).

$m_i^{v,a}$	Calculated concentration of component i in the total steam formed by boiling to atmospheric pressure P^a (moles kg^{-1}).
$m_i^{v,a1}$	Calculated concentration of volatile component i in the total steam discharged at atmospheric pressure, P^a, according to case 1 (moles kg^{-1}).
$m_i^{v,a2}$	Calculated concentration of volatile component i in the total steam discharged at atmospheric pressure, P^a, according to case 2 (moles kg^{-1}).
$m_i^{v,a3}$	Calculated concentration of volatile compound i in the total steam discharged at atmospheric pressure, P^a, according to case 3 (moles kg^{-1}).
$m_i^{v,c}$	Concentration of component i in steam sample collected at vapour pressure P^c (moles kg^{-1})
$m_i^{v,s}$	Concentration of component i in steam at vapour pressure in steam separator P^s (moles kg^{-1})
$m_i^{v,w}$	Concentration of component i in steam at vapour pressure in webre separator P^w (moles kg^{-1}).
n_s^l	Mole fraction of gaseous species s in water (moles gaseous species s/(moles H_2O + moles of all solutes)).
n_s^v	Mole fraction of gaseous species s in steam (moles gaseous species s/(moles H_2O + moles of all gaseous species)).
P_s	Partial pressure of gaseous species s (bar-a).
P^a	Atmospheric pressure (bar-a).
P^c	Vapour pressure at which samples are collected (bar-a).
P^j	Vapour pressure j (bar-a).
P^s	Vapour pressure in wellhead separator (bar-a).
P^t	Total pressure, i.e. vapour pressure plus partial pressures of all gases in steam (see section 5) (bar-a).
X^a	Mass fraction of steam in total well discharge at atmospheric pressure P^a.
X^{a1}	Mass fraction of steam in total well discharge at atmospheric pressure according to case 1.
X^{a2}	Mass fraction of steam in total well discharge at atmospheric pressure according to case 2.
X^{a3}	Mass fraction of steam in total well discharge at atmospheric pressure according to case 3.
X^c	Mass fraction of steam in well discharge at vapour pressure P^c.
X^j	Mass fraction of steam relative to total well discharge at vapour pressure P^j.
X^s	Mass fraction of steam in wellhead separator relative to total well discharge at vapour pressure P^s.
X^{s-a}	Mass fraction, relative to total well discharge, of steam, which forms by depressurization boiling of water between the vapour pressure in the wellhead steam separator and a vapour pressure equal to atmospheric pressure. Defined by equation (6).
X^w	Mass fraction of steam relative to total well discharge in the webre separator at vapour pressure P^w.
X^{w-a}	Mass fraction, relative to total well discharge, of steam, which forms by depressurization boiling of water from the vapour pressure in the webre separator (P^w) to a vapour pressure equal to atmospheric pressure (P^a). Defined by equation (8).
X^{w-s}	Mass fraction, relative to total well discharge, of steam, which forms by depressurization boiling of water from the vapour pressure in the webre separator (P^w) to the vapour pressure in the wellhead separator (P^s). Defined by equation (10).