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Development of a Downhole Technique for Measuring Enthalpy

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ABSTRACT

A method was developed for measurement of downhole enthalpy of two-phase geothermal wells. It is proposed that measurements of chloride concentration along the wellbore can be utilized to calculate downhole enthalpy, which is inspired by a device that enables relatively accurate measurement of chloride concentration in the geothermal fluid. A model that relates chloride concentration with enthalpy was constructed.

1. INTRODUCTION

Measurement of enthalpy in two-phase geothermal wells is an important monitoring task. The total amount of available energy is determined by the enthalpy and the mass flow rate, so measurement of enthalpy and mass flow rate are routine procedures for geothermal field analysis. Currently surface enthalpy measurement is much easier to conduct, thus more commonly used. However, surface enthalpy cannot reflect real reservoir condition accurately due to heat loss along the wellbore. This is especially true during the drilling and completion stages. The well has been cooled substantially during drilling so the actual downhole enthalpy is unknown. Downhole enthalpy data can help us better understand reservoir performance and predict future performance. So downhole enthalpy determination is of high value both from operational perspective and economic perspective.

Determining downhole enthalpy is not easy, especially for two-phase flow. Boiling of geothermal fluids along the wellbore makes it even more complicated. Measuring downhole pressure or temperature is necessary but insufficient for enthalpy determination, and the key is to determine the flowing steam fraction of the two-phase mixture. Note that flowing enthalpy is different from in-place or static enthalpy. Flowing enthalpy is based on specific flow rate of steam and water while static enthalpy is based on the mass fraction of steam and water in a certain volume. The major difference between the two parameters is caused by the difference in the gas velocity and liquid velocity, typically gas velocity is larger than liquid velocity, which can be reflected by the slip ratio.

$$h_{static} = x_s h_v + (1 - x_s) h_w \tag{1}$$

$$h_{flowing} = x_f h_v + (1 - x_f) h_w \tag{2}$$

$$x_f = \frac{W_v}{W_v + W_w} \tag{3}$$

where h_{static} is static enthalpy, and x_s is static steam fraction. $h_{flowing}$ is flowing enthalpy, and x_f is flowing steam fraction, and W_v and W_w are steam mass flow rate and water mass flow rate respectively. h_v and h_w can be determined by pressure or temperature. We are interested in determining the flowing enthalpy.

Several methods have been developed for calculation or measurement of downhole enthalpy. Atalay et al. (2008) proposed methods to measure steam-phase velocity, gas-phase velocity and void fraction, with fiber optics for example, to calculation flowing enthalpy, as illustrated in Equation (4).

$$h_{flowing} = \frac{u_l (1-\alpha) \rho_l h_l + u_g \alpha \rho_g h_g}{u_l (1-\alpha) \rho_l + u_g \alpha \rho_g} \tag{4}$$

where u_l and u_g are liquid-phase velocity and gas-phase velocity respectively. Similarly, ρ_l and ρ_g are density of liquid phase and density of gas phase respectively. α is void fraction, which represents the space occupied by gas phase. With fiber optics, gas-phase velocity can be measured directly by measuring the time difference for a bubble to pass the two sensors. Void fraction can be measured by a time-averaging procedure. This method is efficient in downhole enthalpy measurement for a bubble flow, but it is ineffective with other flow types, like annular flow. Furthermore, fiber optic sensors can only measure the gas-phase velocity and we have to measure the liquid-phase velocity with other equipment at the same time. Resistivity measurement were also shown to be applicable in terms of measuring void fraction, fluid velocity and enthalpy by Juliusson et al (2006). Relatively accurate estimation of bubble velocity can be obtained from resistivity measurement by utilizing cross-correlation techniques. Khasani et al. (2010) proved that analysis of sound frequency waves can provide information on steam and water flow rate, but the method must be calibrated with many wells using standard flow rate measurement methods in practical application.

Another approach to determine downhole enthalpy is the tracer dilution technique. Conventional tracer dilution techniques require precisely metered injection of liquid and vapor phase tracers, according to Hirtz et al. (1993). Mass flow rate of each phase can be calculated based on the injection rate of each tracer and the concentration of each tracer measured concurrently with tracer injection. Tracers that have been considered for use include inorganic ions (CaF_2, LiCl, etc.) as liquid-phase tracers and volatile organic gases (ethane, alcohol, etc.) as gas-phase tracers. For vapor phase tracers, it is necessary to consider the correction for the tracer gas dissolved in the liquid phase, which is a major drawback of vapor tracer dilution technique.

Chloride is an important component in geothermal fluid and can be utilized as an indicator of various fluid properties. Hess et al. (2015) designed a ruggedized downhole tool to measure real-time concentration of ionic tracers in geothermal reservoirs. Cieslewski et al. (2016) proposed a wireline tool to measure real-time ionic concentration using electrochemical sensor. Corbin et al. (2017) illustrated a downhole tool to measure real-time chloride concentration in the geothermal fluid. Inspired by the downhole tool introduced by Corbin et al., we propose that change of chloride concentration along the wellbore could be utilized to calculate downhole enthalpy. It is known that some solutes in the fluid (e.g. Cl) always stay in the liquid phase and become more concentrated as the geothermal fluid ascends to the surface and boils, because the mass of liquid phase decreases as it boils. So the change of chloride concentration is actually a reflection of change of flowing steam fraction along the wellbore. It is possible to quantify this change and calculate back to the enthalpy of the preboiled fluid. Marini and Cioni (1985) proposed that enthalpy can be calculated from change of chloride concentration based on the assumption that there was no loss of heat along the wellbore and transformation of heat into kinetic energy is negligible, which can render the estimation of enthalpy inaccurate. In our approach, enthalpy is calculated based on chloride mass conservation and total mass conservation without the no-heat-loss assumption. In fact, the approach provides a very useful way of estimating such a heat loss. The method proposed here can provide better estimation of the enthalpy of two-phase flow, thus having more practical significance.

In our method, chloride that is originally in the geothermal fluid can be treated as a tracer to calculate enthalpy, without having to inject artificial chemical tracers. A comparison between the tracer injection method and our approach is summarized in Table 1.

Table 1: Comparison between tracer injection method and original chloride tracer method

	requirement	**advantage**	**disadvantage**
Injecting chemical tracers	Precise metered tracer injection; Precise measurement of downstream tracer concentration;	Freedom in selecting tracer type; Relatively accurate measurement of mass flowrate and enthalpy	Chemical cost of injection; Precipitation of inorganic ion tracers in the pipe; Contamination of reservoir;
Use chloride originally in the geothermal fluid as tracer	Precise measurement of chloride concentration at wellhead and in the downhole;	Save costs; No requirement for injection wells; Complete in shorter time;	Complication in considering multifeed zones.

2. METHOD

2.1 Enthalpy Calculation with Single Feed Zone

As mentioned previously, chloride remains in the liquid phase and become more concentrated as the geothermal fluid boils along the wellbore, and the change of chloride concentration can be utilized to calculate change of flowing steam fraction and enthalpy. Chloride mass balance and total mass balance of liquid and steam have to be considered for this process. We assume that the flow is steady with constant fluid properties. It is also necessary to assume that the chloride concentration in the gas phase is negligible.

In this part, we first consider enthalpy calculation without multiple feed zones, so that mass of chloride and total mass of steam and liquid remain constant.

From chloride mass balance we know that:

$$d(Cl \cdot q_l) = 0 \tag{5}$$

where Cl is chloride concentration on a volumetric base, q_l is volumetric flow rate of the liquid phase. So if we measure the chloride concentration and volumetric liquid flow rate at the surface, which are relatively easy to realize, and the chloride concentration in the downhole, we can use Equation (5) to calculate the volumetric flow rate of liquid phase in the downhole, as illustrated by Equation (6) and (7).

$$\dot{m}_{Cl} = Cl_{wellhead} \cdot q_l = Cl_{wellhead} \cdot \frac{\dot{m}(1-x)}{\rho_l} \tag{6}$$

$$\dot{m}_{Cl} = Cl_{downhole} \cdot q_{ldownhole} \tag{7}$$

where m_{Cl} is mass flow of chloride, which is constant. $Cl_{wellhead}$ and $Cl_{downhole}$ represent chloride concentration at surface and in the downhole respectively. $q_{ldownhole}$ is the volumetric liquid-phase flow rate in the downhole. m is total mass flow rate. x is flowing steam fraction. ρ_l is the density of liquid phase.

Then we consider total mass balance of gas phase and liquid phase.

$$d(\rho_l \cdot \frac{q_l}{1-x}) = 0 \tag{8}$$

where ρ_l is the density of liquid phase, which can be determined from pressure. Now the downhole volumetric flow rate of liquid phase calculated from Equation (5)-(7) can be used in Equation (8) to calculate downhole flowing steam fraction, so that enthalpy can be determined, as illustrated by Equation (9) and (10). Total mass flow at the surface has to be measured to determine the enthalpy of the well discharge.

$$\dot{m} = \frac{q_{ldownhole}\rho_l}{1-x} \tag{9}$$

Total mass flow rate should be constant along the wellbore. The downhole volumetric liquid flow rate that we obtained from chloride mass balance can be used to determine the downhole flowing steam fraction.

$$h_t = (1-x)h_l + xh_v \tag{10}$$

where h_v and h_l can be derived from the measured pressure or temperature.

Table 2 is a summary of input parameter and output parameters.

Table 2: Input parameters and output parameters for enthalpy calculation without multiple feed zones

	Surface	**Downhole**
Input	Pressure; Total mass flowrate *m*; Steam fraction *x*; Chloride concentration $Cl_{wellhead}$;	chloride concentration $Cl_{downhole}$; Pressure;
Output		**Flowing steam fraction *x*;** **Enthalpy h_t;**

Figure 1 shows the process of calculation in detail.

In an example, values for input parameters are set, and output parameters are calculated through the process shown in Figure 1. The results are shown in Table 3.

Table 3: An example for enthalpy calculation without multiple feed zones

	Surface	**Downhole**
Input	Pressure: 38 bar-a; Total mass flowrate: 70kg/s; Steam fraction: 0.5; chloride concentration: 600g/m^3	chloride concentration: 300g/m^3; Pressure: 100 bar-a;
Output		Flowing steam fraction: 0.14; **Enthalpy: 1596kJ/kg;**

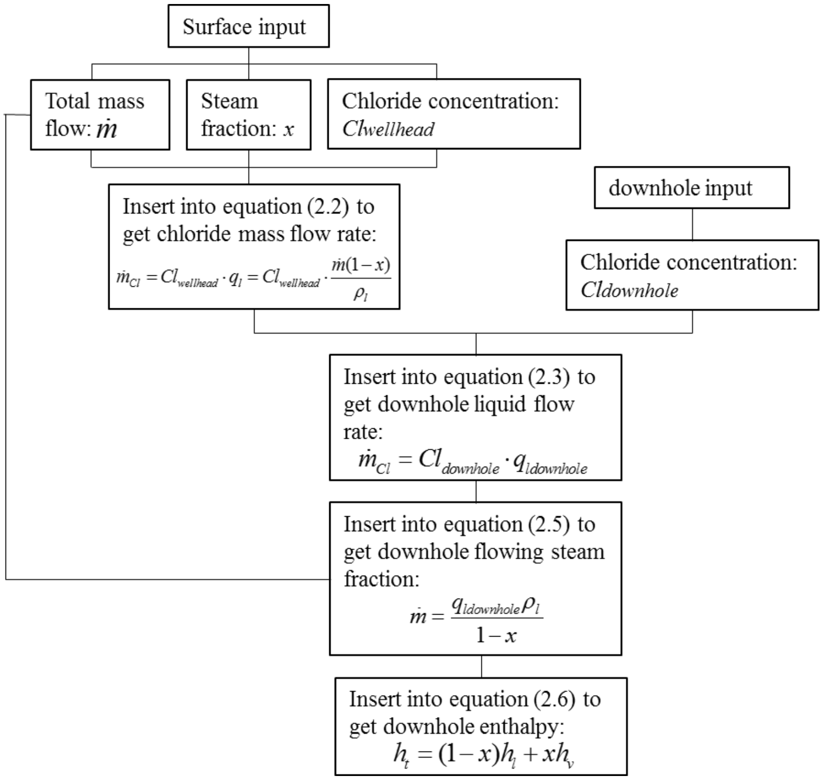

Figure 1: Flow diagram of calculation process

2.2 Enthalpy Calculation with Multiple Feed Zones

If there are more than one feed zone along the wellbore, more assumptions have to be made to adapt to the complication, because both chloride mass balance and total mass balance of geothermal fluids are disturbed. Inflowing geothermal fluid introduces not only steam and water but also chloride. In this section, multiple feed zones are considered in three different cases. In the first case, the feed zone introduces only liquid. In the second case, the feed zone introduces both steam and liquid, but the flow below the feed zone contains only liquid phase. In the third case, the feed zone introduces both steam and liquid, and the flow below the feed zone also contains both steam and liquid. The device used for chloride concentration measurement is small and flexible, so that it is reasonable to assume that the chloride concentration measured at the very entrance of the feed zone could represent the chloride concentration of the inflowing geothermal fluid, as shown in Figure 2. In Figure 2, the small black rectangles represent the device for measurement of chloride concentration. Device 1 measures the chloride concentration above the feed zone, while Device 2 measures the chloride concentration below the feed zone. Device 3 measures the chloride concentration at the feed zone. Zero chloride concentration indicates the passing of gas phase. Similarly, chloride concentration of a finite amount indicates the passing of liquid phase.

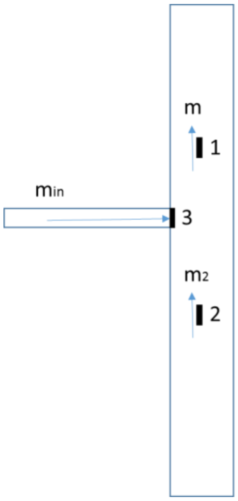

Figure 2: Schematic of chloride concentration measurement with multiple feed zones

If the concentration measured by Device 3 is always larger than zero, Case 1 should be considered. If the concentration measured by Device 3 is sometimes zero but the concentration measured by device 2 is always zero, Case 2 should be considered. If the concentration measured by Devices 2 and 3 both sometimes have zero values, Case 3 should be considered. A schematic of the three cases is shown in Figure 3.

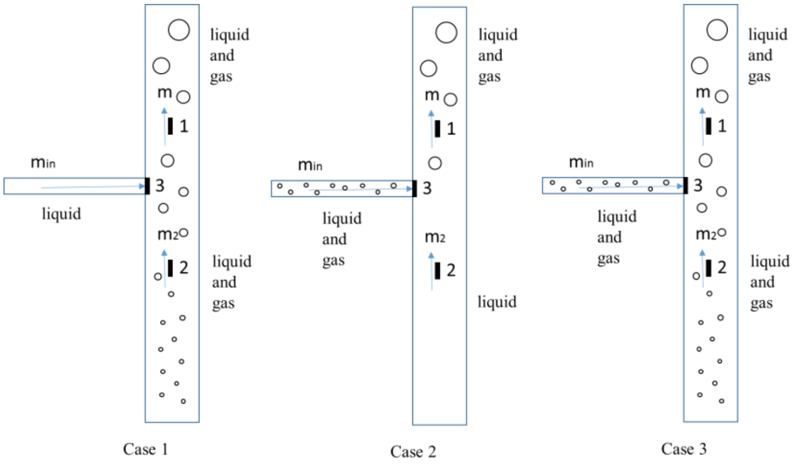

Figure 3: Three different cases of enthalpy calculation with multiple feed zones

2.2.1 Enthalpy Calculation in Case 1

In Case 1, the inflowing geothermal fluids contains only liquid. The chloride mass balance becomes:

$$\begin{aligned} & q_{lin} \cdot Cl_{in} + (q_l - q_{lin}) \cdot Cl_2 = q_l \cdot Cl_1 \\ & q_{l2} = q_l - q_{lin} \end{aligned} \tag{11}$$

where chloride concentration and liquid flow rate at the feed zone are denoted as Cl_{in} and q_{lin} respectively. Cl_1 and q_l are the chloride concentration and liquid flowrate measured after the introduction of geothermal fluid from the feed zone, and Cl_2 and q_{l2} are those measured before the introduction of geothermal fluid from the feed zone. In Equation (10), Cl_{in}, Cl_1 and Cl_2 can be measured, and q_l can be calculated through the process discussed previously in Section 2.1, so the only unknown variable is q_{lin}, which can be calculated from Equation (10), so that q_{l2} can be determined using Equation (11).

Another parameter we need to know is the flowing steam fraction below the feed zone. In Case 1 the boiling process happens in the wellbore, and the introduced geothermal fluid from the feed zone contains little steam. Then we can calculate the flowing steam fraction, and repeat the same process as in previous calculation in Section 2.1. The calculation process is shown in Figure 4.

$$\begin{aligned} & \dot{m}_2 = \dot{m} - q_{lin} \cdot \rho_{lin} \\ & x = \frac{\dot{m}_2 - q_{l2} \cdot \rho_{l2}}{\dot{m}_2} \end{aligned} \tag{12}$$

It is simple to determine the amount of enthalpy introduced by the feed zone in Case 1. Because the inflowing geothermal fluid contains only liquid, measuring the pressure or temperature at the feed zone is sufficient to calculate the enthalpy.

2.2.2 Enthalpy calculation in Case 2

In Case 2, the feed zone introduces both liquid and gas, but the flow below the feed zone contains only liquid, so the enthalpy below the feed zone can be determined by measuring pressure or temperature. The enthalpy above the feed zone can be calculated by following the process discussed in Section 2.1. The enthalpy introduced by the feed zone is simply the difference between the enthalpy above the feed zone and the enthalpy below the feed zone.

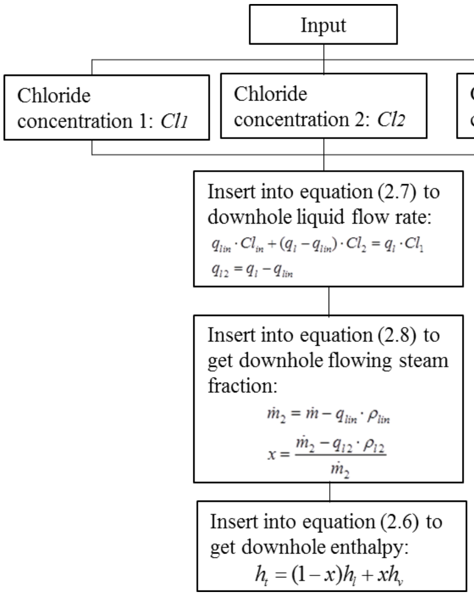

Figure 4: Calculation process in Case 1

2.2.3 Enthalpy calculation in Case 3

Case 3 is the most difficult, because both the feed zone and the flow below the feed zone have liquid and gas. As the chloride remains in the liquid phase, the gas introduced by the feed zone does not affect chloride mass balance, and Equation (11) is still valid, so the same process as in Section 2.2.1 can be followed to determine the liquid flow rate below the feed zone. However, liquid flow rate is not sufficient to determine the enthalpy below the feed zone, because gas flow rate is also needed to calculate the flowing steam fraction. Because the amount of gas introduced by the feed zone is unknown, it is hard to know the gas flow rate below the feed zone. Direct measurement of gas flow rate might be difficult, but measuring the void fraction and gas-phase velocity is more feasible. According to previous study, both void fraction and gas velocity are measurable. A resistivity measurement tool or chloride concentration measurement tool with sufficient resolution can be used to determine gas-phase velocity as well as void fraction by intelligently detecting individual bubble. The procedure to calculate enthalpy based on combination of chloride concentration measurement, void fraction measurement and gas velocity measurement is illustrated in Figure 5.

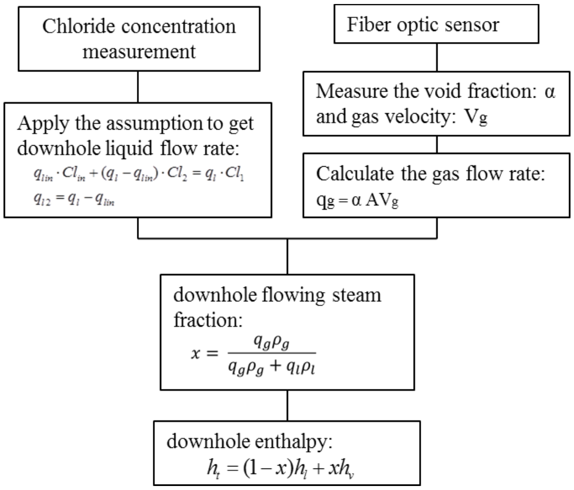

Figure 5: Calculation process in Case 3

In addition, there exist some similarities between the chloride concentration measurement tool and the fiber optic sensor. They can both detect the presence of gas phase. As mentioned before, zero chloride concentration indicates the passing of gas phase. Previous studies demonstrated that fiber optic sensors can measure the gas-phase velocity and void fraction, so it is possible that the chloride concentration measurement tool could do the same job, as long as it could provide sufficient resolution with rapid response time, which may require further development of the tool.

3. CONCLUSTION

1. The downhole enthalpy of the two-phase flow in geothermal wells can be determined by measuring surface chloride concentration and downhole chloride concentration.

2. In the case of single feed zone, the physical model for calculating downhole enthalpy based on chloride concentration involves chloride mass balance and total mass balance of gas and liquid.

3. In the case of multiple feed zones, an assumption has to be made that the chloride concentration in the liquid entering from the feed zone is measurable. Gas flow rate below the feed zone also needs to be determined. Measuring void fraction and gas flow rate could help solve the problem.

4. Future development on the chloride concentration measuring tool to achieve higher frequency of measurement is an important task for wells with multiple feed zones. Such a chloride tool has the potential to measure void fraction and gas velocity at the same time as long as it has sufficient speed of measurement.

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