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SUSTAINABILITY OF GEOTHERMAL DOUBLETS

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ABSTRACT

The heat content of a hydrothermal aquifer can be utilized by producing the aquifer's hot fluid whereas the waste cooled water is reinjected into the aquifer and such a scheme is called the doublet operation. The produced hot fluid is continuously replaced by cooled injected water. After the thermal breakthrough time the temperature of the produced fluid decreases. However if after a time the field is shut-in the natural energy flow will slowly replenish the geothermal system and it will again be available for production. Therefore when operated on a periodic basis, with production followed by recovery, doublets are renewable and sustainable.

This paper addresses renewability and sustainability concept by considering a lumped parameter model with new and simple analytical solutions. An analytical approach is presented to analyze the parameters involved to estimate the time that a doublet takes to fully recover to its original state after shut-down at some production time.

A simplified lumped-parameter type of an approach to model the temperature behavior of a single liquid-phase reservoir is discussed here. New analytical equations and correlations are presented to investigate the temperature behavior of doublets. Emphasis is given to understand the characteristics of temperature recovery following some production period. These equations and correlations can be used to design the doublets.

Corresponding calculations with porous reservoir models for a doublet field operation given in the literature demonstrate the validity of the analytical expressions given in this paper.

INTRODUCTION

Sedimentary formations, including aquifers, may not be hot enough to serve as commercial geothermal reservoirs. Unlike conventional geothermal reservoirs which generally occur in fractured formations, sedimentary reservoirs have porosity and permeability, which allows hydraulic flow. In such systems natural hydrothermal convection is absent and generally they are bounded by impermeable overburden and underburden shale layers.

Such systems can be attractive for geothermal production. A well in such a sedimentary formation (hydrothermal aquifer) can penetrate a sufficient thickness of sand layers to achieve enough reservoir flow capacity to allow commercially attractive flow rates. Production of geothermal water from such sedimentary basins has been receiving attention in the last five decades. Geothermal heating and cooling are possible in zones having a normal temperature gradient, and aquifers at reasonable depths have already been exploited in various locations for urban heating purposes and theoretical basis are discussed in relevant literature (Gringarten and Sauty, 1975; Gringarten, 1979; Megel and Rybach, 2000; Bjelm and Alm, 2010; Antics et al., 2005; Toth and Bobok, 2010; Dickinson et al., 2009; Stopa and Wojnarowski, 2006).

The heat content of a hydrothermal aquifer can be utilized by producing the aquifer's hot fluid whereas the waste cooled water is reinjected into the aquifer and such a scheme is called the doublet operation. A cyclic-mode version of the doublet operation is called Aquifer Thermal Energy Storage (ATES) describing the systems generally consisting of two or more wells, where the flow can be reversed to actively store heated and cooled water. Figure 1 shows a schematic view of a doublet. The produced hot fluid is continuously replaced by cooled injected water. After the thermal breakthrough time the temperature of the produced fluid decreases depending on the production rate, the distance between the injection and production wells and the physical and geometric properties of the reservoir. However if after a time the field is shut-in, the natural energy flow will slowly replenish the geothermal system and it will again be available for production. Therefore when operated on a periodic basis, with production followed by recovery, doublets are renewable and sustainable.

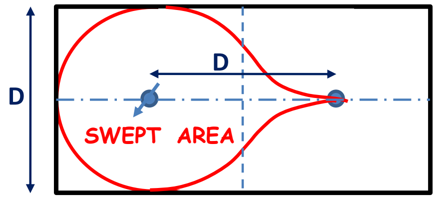

Figure 1: A schematic view of a doublet.

Doublets should be produced and operated at a rate corresponding to the installed capacity of their heating facilities or power plants on a continuous basis. In such operations, doublets are exploited at a rate faster than the energy replaced by the pre-production flow "the renewable capacity". In this sense they are not sustainable continuously. Thus, sustainability becomes a key issue.

Temperature behavior of doublets has been studied with the aid of analytical models which permit the calculation of the evolution of the reservoir as well as of the production wells in an aquifer. The renewability and sustainability concept for the hydrothermal aquifer in which a doublet is located is addressed. A simplified lumped-parameter type of an approach to model the temperature behavior of a single liquid-phase geothermal reservoir is discussed here. New analytical equations and correlations are presented to investigate the temperature behavior of doublets. Analysis of production temperature and volumetric average reservoir temperature data are discussed. Emphasis is given to understand the characteristics of temperature recovery following some production period. The method described here can be used to design the doublets.

The type of analysis used in this paper is limited to intergranular aquifers where the flow is assumed to be Darcian and the porous media is homogeneous.

MATHEMATICAL MODELS

Production Temperature of a Doublet

The doublet concept of heat mining pioneered by Gringarten and Sauty (1975) provided a means for improved designs of well locations, bottomhole spacings and subsequent reservoir/well lifetimes.

Gringarten and Sauty (1975) developed a mathematical model for investigating the non-steady state temperature behavior of production wells during the reinjection of heat-depleted water into aquifers. Their results are presented in terms of dimensionless parameters. The dimensionless production temperature (T_{wD}) versus the dimensionless time (t_D) for various values of λ from 0.3 to infinity is plotted in Fig. 2.

Figure 2 illustrates the temperature evolution in the production well as a function of time for different values of the conductivity of the confining beds, characterized by the dimensionless parameter

$$\lambda = \frac{\rho_w C_w \rho_{av} C_{av} q h}{(k\rho C)_{adj} D^2} \qquad (1)$$

Heat transfer between the aquifer and the cap rock or bed rock is negligible for $\lambda > 10^4$.

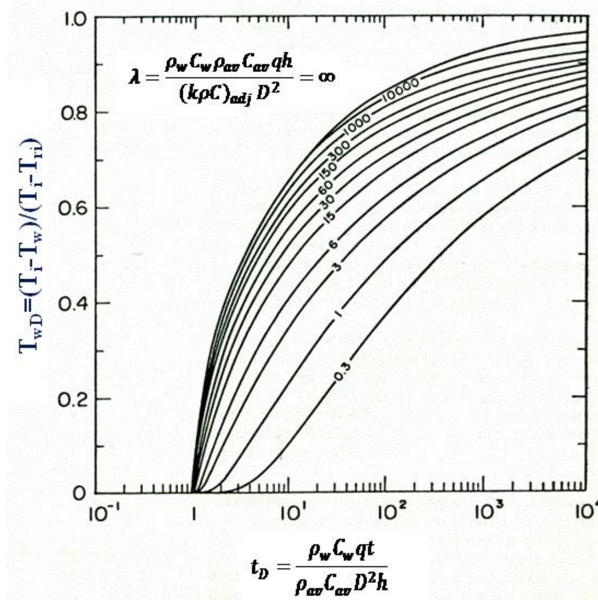

Figure 2: T_{wD} versus t_D at the production well of a doublet in a confined aquifer (Gringarten and Sauty, 1975).

The dimensionless time in Fig. 2 is defined as

$$t_D = \frac{\rho_w C_w q t}{\rho_{av} C_{av} D^2 h} \qquad (2)$$

The case of a single recharging-discharging well pair (called a "doublet") was modeled. The characteristic length D in Fig. 2 is the distance between the two wells. Figure 2 can be used to calculate: (1) the spacing between the two wells in order not to have any change in temperature at the production well during a specified period, and (2) the temperature change at the production well after breakthrough.

Assumptions made in the formulation are following: (1) The aquifer is assumed to be horizontal and of uniform thickness h, (2) The overburden and underburden formations (the cap rock and the bed rock), above and below the aquifer, are impermeable to fluid flow, (3) The total injection rate q is constant and equal to the total production rate, (4) Initially, the water and rock in the aquifer and the overburden and underburden formations are at the same temperature T_i, (5) At time t=0 the temperature of the injected water is set equal to T_{ri}, (6) In the aquifer the effect of the thermal conductivity is neglected in the horizontal direction, and infinite vertical thermal conductivity is assumed in the aquifer, (7) The product of the density and the heat capacity for both the water ($\rho_w C_w$) and the rock ($(\rho C)_{adj}$), and the cap rock vertical thermal conductivity ($(k)_{adj}$), are constant, (8) There is vertical heat conduction type heat transfer in the overburden and underburden formations. In other words, in confining beds heat transfer takes place by means of vertical conduction. Subscript adj refers to the overburden and underburden formations and k is thermal conductivity of those.

According to Gringarten-Sauty (1975) thermal front breakthrough occurs at

t_D=1.04 if λ>10 (3)

$\lambda(t_D$-1)=0.5 if 0<λ<10 (4)

Equations 3 and 4 can be used to estimate the safe distance necessary to avoid the early breakthrough.

Volumetric Average Temperature of a Reservoir Containing a Doublet

Simple lumped-parameter models based on the material and energy balances valid for geothermal systems are discussed by Satman (2010) and given in various studies in the literature (Alkan and Satman, 1990; Sarak et al., 2005; Whiting and Ramey, 1969; Axelsson, 1989).

The doublet system in a hydrothermal aquifer corresponds to the closed tank model given by Satman (2010). It is a closed tank in the sense that there is no natural convective recharge into the reservoir. Production, reinjection and the natural heat flow are considered. The respective schematic diagram of the model is shown in Fig. 3. The reservoir system has a bulk volume V and contains fluid (water) and rock and w represents the flow rate, C_p the specific heat.

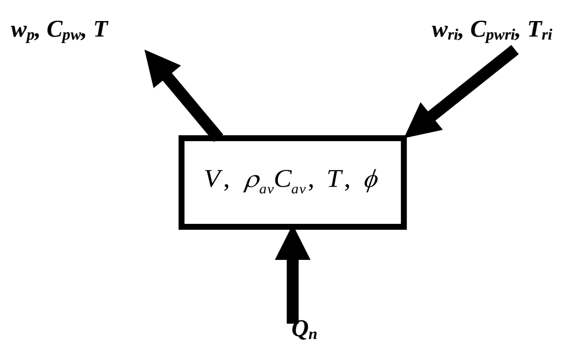

Figure 3: Schematic of production and reinjection case with natural heat flow for a closed system.

Temperature Decline During Production Period: For the case given in Fig. 3 the material and energy balance yields:

$$V\rho_{av}C_{av}\frac{dT}{dt} = -w_p C_{pw} T + w_{ri} C_{pwri} T_{ri} + Q_n \quad (5)$$

where

$$\rho_{av}C_{av} = \phi\rho_w C_{pw} + (1-\phi)\rho_m C_{pm} \quad (6)$$

which is the volumetric heat capacity of the reservoir. Q_n is the natural heat flow to the system. It is defined as heat recharge rate into the reservoir. It represents the conductive heat gained from the underburden and overburden (adjacent) formations. Notice that T corresponds to the volumetric average temperature of the hydrothermal aquifer containing the doublet.

The solution for Eq. 5 is given by:

$$T_i - T = \Delta T = T_i(1-e^{-at}) - \frac{g}{a}(1-e^{-at}) \quad (7)$$

where

$$g = \frac{w_{ri}C_{pwri}T_{ri}}{V\rho_{av}C_{av}} + \frac{Q_n}{V\rho_{av}C_{av}} \quad (8)$$

$$a = \frac{w_p C_{pw}}{V\rho_{av}C_{av}} \quad (9)$$

If a proper value of Q_n is known or estimated, Eq. 7 can be used to determine the average reservoir temperature as a function of production time and relevant fluid and rock properties.

The following approximate expression for Q_n obtained from the Marx and Langenheim (1959) model can also be used:

$$Q_n = q_i\left(1 - \frac{G}{t_{DML}}\right) \quad (10)$$

where

$$G = 2\sqrt{\frac{t_{DML}}{\pi}} - 1 + e^{t_{DML}} erfc\sqrt{t_{DML}} \quad (11)$$

$$t_{DML} = 4\frac{(k\rho C)_{adj}}{(\rho_{av}C_{av})^2}\frac{t}{h^2} \quad (12)$$

$$q_i \cong w_p C_{pw}(T_i - T_{ri}) \quad (13)$$

erfc(x) is the complementary error function, and *erfc(x)=1-erf(x)* where *erf(x)* is the error function. The modified Marx and Langenheim model used here assumes the temperature of the cooled zone to be everywhere the downhole temperature of the injected fluid T_{ri} and the reservoir temperature outside the cooled zone to be at the initial reservoir temperature T_i.

Assuming $w_p=w_{ri}$ and $C_{pw}=C_{pwri}$, then combining Eqs. 7-10 gives

$$T_D = \frac{G}{t_{DML}}\left(1 - e^{-t_{DML}\lambda\frac{D^2 h}{4V}}\right) = \frac{\lambda G}{4t_D}\left(1 - e^{-t_D\frac{D^2 h}{V}}\right) \quad (14)$$

Dimensionless average reservoir temperature, $T_D=(T_i-T)/(T_i-T_{ri})$ is plotted in Fig. 4 versus the dimensionless time with $\lambda D^2h/(4V)$ as a parameter for a confined reservoir containing a doublet. Figure 4 can be used to calculate the average reservoir temperature change for the aquifer during production period.

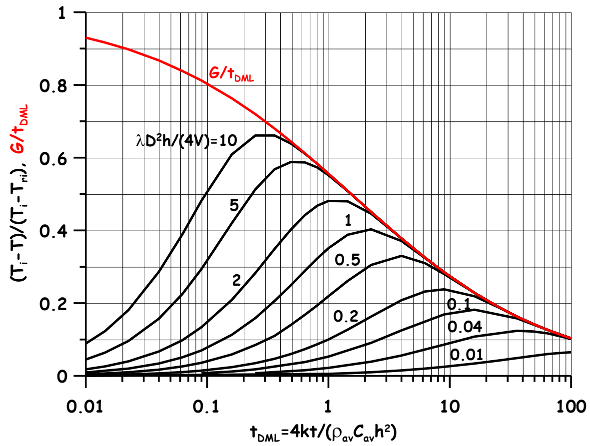

Figure 4: Dimensionless average reservoir temperature versus dimensionless time for a confined reservoir containing a doublet.

As it is observed in Fig. 4 the dimensionless temperature increases and thus the average reservoir temperature decreases initially. However even if the exponential term in the solution (Eq. 14) dies out at sufficiently long production time, the term G/t_{DML} never reaches to a constant value. Therefore a strictly steady state does not exist for the production period and all curves given in Fig. 4 reach to G/t_{DML} for which T_D continues to drop.

The Marx-Langenheim model was originally developed for hot fluid injection into a reservoir. Their model is used for cold water injection into a hydrothermal reservoir as discussed in this paper. We assume the temperature of the cooled zone to be everywhere at the downhole temperature of the injected fluid T_{ri} and the reservoir temperature outside the cooled zone to be at the initial temperature T_i. q_i is the constant rate of heat withdrawal. It is defined as the difference between the total rate at which heat is withdrawn from the reservoir through production of hot water from any number of wells (located anywhere in the reservoir) and the total rate at which heat is injected into the reservoir through any number of wells (also located anywhere).

The areal extent of the equivalent cooled zone (area swept) is calculated from:

$$A_s = \frac{q_i \rho_{av} C_{av} h}{4(T_i - T_{ri})(k\rho C)_{adj}} G = G\frac{t_D}{t_{DML}} D^2 \quad (15)$$

This formulation assumes that the heat gained from the overburden and underburden formations are only by vertical conduction from the adjacent formations.

The model presented here is valid as long as the net rate of heat output (q_i) is constant. The location of the injection and production wells does not affect the results as long as they are not too close to the lateral reservoir boundaries.

One should keep in mind that the ratio of the cooled zone (area swept) to the total reservoir area is inversely proportional with the ratio of the temperature drop in the cooled zone to the temperature drop in the reservoir. This can be seen from the following simple energy balance:

$$VT=V_sT_{ri}+(V-V_s)T_i \quad (16)$$

where V is the volume of the reservoir, T the average temperature of the reservoir, V_s the volume of the cooled zone, T_{ri} the temperature of the cooled zone, and T_i the temperature of the reservoir outside of the cooled zone. Equation 16 yields

$$V_s/V=(T_i-T)/(T_i-T_{ri}) \quad (17)$$

If the reservoir thickness is constant thru the reservoir then

$$\frac{V_S}{V} = \frac{T_i - T}{T_i - T_{ri}} = \frac{A_S}{A} \quad (18)$$

Temperature Recovery During Shut-In Period: The conductive heat flow is the only mechanism to heat the reservoir after shut-in. The energy-material balance for this simple system is given by:

$$Q_n = V\rho_{av}C_{av}\frac{d\Delta T}{d\Delta t} \quad (19)$$

where $Q_n=U(t)A(T_i-T)$ (20)

The model assumes that heat gained occurs from the overburden and underburden formations with a temperature of T_i to the aquifer with T. Here $U(t)$ is the time-dependent overall heat transfer coefficient and is given by the following approximation (Satman et al., 1984):

$$U(t) = \frac{2}{\sqrt{\pi t}}\sqrt{(k\rho C)_{adj}} \qquad (21)$$

Then the temperature during shut-in period is calculated from:

$$\frac{T_i - T}{T_i - T_{si}} = \exp\left(-2\alpha\sqrt{\Delta t}\right) \qquad (22)$$

where T_{si} is the reservoir temperature at the end of production period and Δt is the shut-in time measured after the reservoir shut-in and

$$\alpha = \sqrt{\frac{(k\rho C)_{adj}}{\pi}}\frac{4A}{V\rho_{av}C_{av}} \qquad (23)$$

Dimensionless average reservoir shut-in temperature, $(T_i-T)/(T_i-T_{si})$ is plotted in Fig. 5 versus shut-in time for a confined reservoir containing a doublet for various values of α. Figure 5 can be used to calculate the average reservoir temperature change for the aquifer after shut-in.

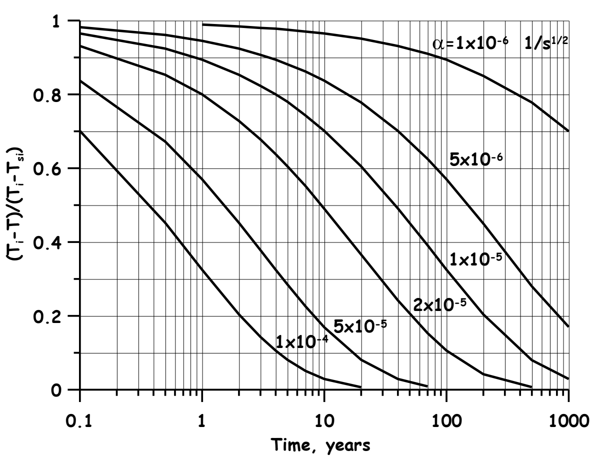

Figure 5: Dimensionless average reservoir shut-in temperature versus shut-in time for a confined reservoir containing a doublet.

Relationship Between Doublet Production Temperature and Reservoir Volumetric Average Temperature

One important finding of this study is the relationship between the doublet production temperature (T_w) and the reservoir volumetric average temperature (T). The doublet production temperature represents the temperature of the water produced in doublet and the dimensionless temperature at the production well can be obtained from Fig. 2. This figure can be used to determine the production well temperature history during the production period whereas Eq. 14 can be used to calculate the volumetric average temperature of the aquifer containing the doublet.

Combining T_{wD} from Fig. 2 and T_D from Eq. 14 yields the relationship between doublet production temperature and reservoir volumetric average temperature

$$\frac{T_i - T_w}{T_i - T} = \frac{T_{wD}}{T_D} = \frac{T_{wD}(Fig.2)}{\frac{\lambda G}{4t_D}\left(1 - e^{-t_D\frac{D^2 h}{V}}\right)} \qquad (24)$$

or

$$\frac{T_{wD}}{T_D} = \frac{T_{wD}(Fig.2)}{\frac{G}{t_{DML}}\left(1 - e^{-t_{DML}\lambda\frac{D^2 h}{4V}}\right)} \qquad (25)$$

The numerical values obtained from Eq. 24 are plotted in Fig. 6. Figure 6 illustrates the relationship between the produced water temperature and the average reservoir temperature for several values of λ from 0.3 to 60 and D^2h/V as a parameter. T_{wD} values in the nominator of Eq. 24 can be read from Fig. 2.

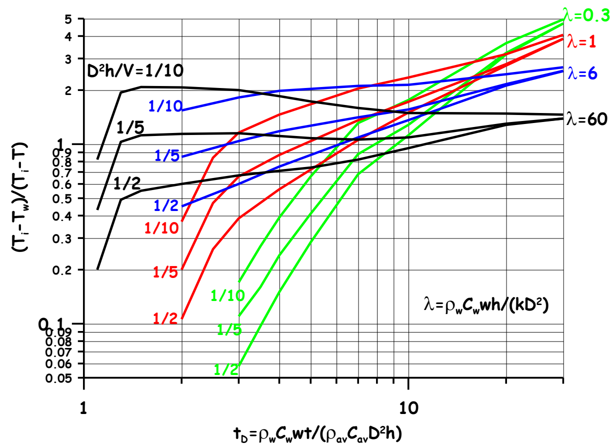

Figure 6: Relationship between the produced water temperature and the average reservoir temperature.

This study found that the following approximate solution can be used to estimate T_{wD}:

$$T_{wD} \cong \frac{\tan^{-1}\left[\frac{1}{2}\left(\frac{A_S}{D^2}\right)^2\right]}{180} = \frac{\tan^{-1}\left[\frac{(G\lambda)^2}{32}\right]}{180} \qquad (26)$$

The dimensionless well temperature values calculated using Eq. 26 closely matches T_{wD} values obtained from Fig. 2. Equation 26 is valid for $\lambda(t_D-1)\geq 0.5$ and gives acceptable results. A_s in Eq. 26 is calculated from Eq. 15. Use of Eq. 26 makes the explicit calculation of T_w possible.

Equation 26 yields the following explicit relationship between the produced water temperature and the average reservoir temperature

$$\frac{T_i - T_w}{T_i - T} = \frac{tan^{-1}\left[\frac{(G\lambda)^2}{32}\right]}{1 - e^{-t_D \frac{D^2 h}{V}}} \frac{t_D}{45\lambda G} \qquad (27)$$

Thus the relationship between the produced water temperature and the average reservoir temperature can be obtained from Fig. 6 or calculated by using Eq. 27.

Relationship Between Extraction Time and Recovery Time

For the production period, the solution of Eq. 5 (Eq. 7) can be written as

$$\Delta T = (T_i - \frac{g}{a})(1 - e^{-at}) \qquad (28)$$

Using

$$e^{-at} \cong 1 - at + \frac{(at)^2}{2} \qquad (29)$$

Eq. 28 yields the following expression for t_{extr}:

$$t_{extr} = \frac{1 - \sqrt{1 - 2\frac{T_i - T_{si}}{T_i - (T_{ri} + \frac{Q_n}{w_p C_{pw}})}}}{a} \qquad (30)$$

where T_{si} is the average reservoir temperature at the time shut-in (t_{extr}) and

$$\frac{Q_n}{w_p C_{pw}} = (T_i - T_{ri})(1 - \frac{G}{t_{DML}}) \qquad (31)$$

For the recovery period, the temperature can be determined using

$$T = T_{si} + x\Delta t \qquad (32)$$

where

$$x = Q_n/(V\rho_{av}C_{av}) \qquad (33)$$

At the time of final recovery, Δt becomes t_{rec} and T becomes T_i, so that

$$t_{rec} = \frac{T_i - T_{si}}{x} \qquad (34)$$

From Eqs. 30 and 34, the following expression is obtained as the ratio of the recovery time to the extraction time

$$\frac{t_{rec}}{t_{extr}} = \frac{T_i - T_{si}}{1 - \sqrt{1 - 2\frac{T_i - T_{si}}{T_i - \left(T_{ri} + \frac{Q_n}{w_p C_{pw}}\right)}}} \frac{w_p C_{pw}}{Q_n} \qquad (35)$$

ANALYSIS OF A FIELD APPLICATION

This field case is discussed by Bjelm and Alm (2010). The Lund Geothermal Heat Pump Project is implemented in an confined unconsolidated sandstone reservoir in Scania the southernmost province in Sweden. After 25 years of heat extraction and reinjection of cold water to the reservoir the expected cooling has been observed recently. About 550 l/s is extracted from four wells and subsequently reinjected into five wells. Yearly about 250 GWh of heat energy is produced to the district heating net. The distance between the production and injection areas is about 2 km. The screened part of the wells is around 100 m long. In the reservoir the temperature is in the range from 21 to 24 ^oC. Injection temperature has been around 3.5 to 5 ^oC.

Figure 7 gives a map showing the location of the geothermal wells; Fig. 8 gives the production temperatures for all wells from the start of operation in 1985; and finally in Fig. 9 the relation between energy production, geothermal water production and mean temperature from start of operation in 1985 till 2009 is shown.

Sk-2 is closest to the injection wells at a distance of 1400 m. As can be seen in Fig. 8 there is a temperature impact in Sk-2 after about 11 years. The temperature drop is around 6 ^oC in 2009.

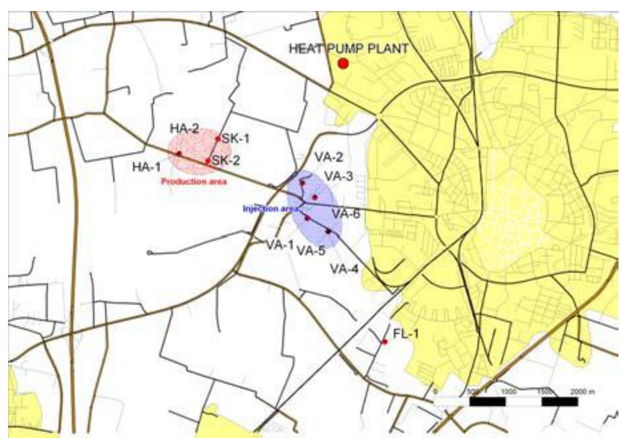

Figure 7: Map showing the location of the geothermal wells west of Lund. (Bjelm and Lund, 2010)

For the analysis, the implemented scheme is simplified and assumed to be a doublet. The data used in the analysis are given in Table 1.

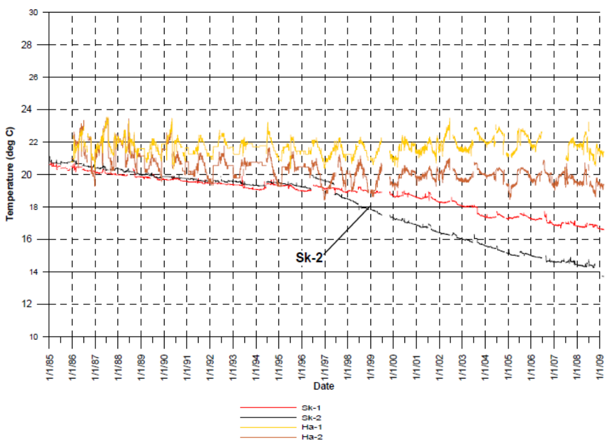

Figure 8: Production temperature for the wells since start of operation. (Bjelm and Lund, 2010)

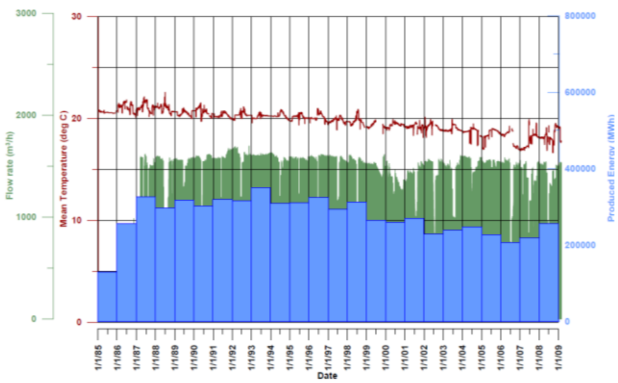

Figure 9: Relation between water production, mean water temperature and total energy production. (Bjelm and Lund, 2010)

Table 1: Data used in the analysis.
q=1500 m^3/h=0.417 m^3/s, w_p=417 kg/s
k=2x10^{-3} kJ/(s.m.^{o}C), $\rho_w C_w$=4100 kJ/(m^3.^{o}C)
$\rho_{av}C_{av}=(\rho C)_{adj}$=2700 kJ/(m^3.^{o}C)
Original reservoir temperature=T_i=21 ^{o}C,
Reinjection temperature=T_{ri}=4.25 ^{o}C

As seen in Fig. 8, the thermal breakthrough in Sk-2 occurred at 11 years of injection time. Thus Eq. 3 is used. Since the distance between the nearest injection well and Sk-2 is about 1400 m, the reservoir thickness is calculated to be 112 m. This value is very close to the screened thickness of the wells (- 100 m as given by Bjelm and Alm (2010)).

The observed production temperature drop in 24 years is about 6 ^{o}C as seen in Fig. 8. Now we can use Eq. 26 to estimate this drop. Using the calculated values of t_D and λ as 2.18 and 48.8, respectively, T_{wD} is determined to be 0.32 which corresponds to T_w=15.6 ^{o}C and a temperature drop of 5.4 ^{o}C. This value matches with the actual temperature drop of 6 ^{o}C reasonably well.

Next step in the analysis is to employ the solutions for the average reservoir temperature. Figure 9 gives the mean temperature for all the four production wells from the start of operation in 1985 till 2009. Looking at the mean temperature development for all production wells, the temperature drop is about 3 ^{o}C. The mean temperature is the average temperature of the production wells distributed in the reservoir. Therefore this mean temperature can be assumed to be the volumetric average temperature of the reservoir for practical considerations. This assumption is based on the analysis of Eq. 27 and Fig. 6 which yields $T \approx (T_w)_m$ for the mean temperature value for all production wells ($(T_w)_m$) and the conditions existed.

Equation 13 is used to determine the net heat withdrawal (q_i) as 2.6x10^7 J/s. Equation 12 gives t_{DML}=0.179 and Eq. 16 yields A_s=2.9x106 m^2. Since h=112 m then V_s is calculated to be 3.28x10^8 m^3. Finally the reservoir volume is determined from Eq. 17 to be 1.8x10^9 m^3. Now it is possible to determine the average reservoir temperature history using Eq. 14. Figure 10 shows the results whereas Figs. 11 and 12 present the comparison of the measured ones with the calculated results.

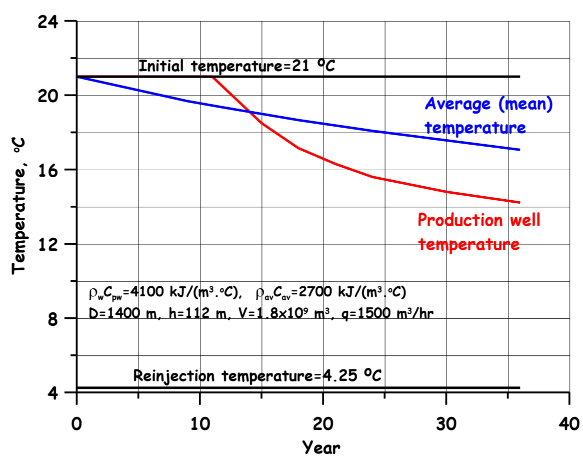

Figure 10: Simulated average (mean) temperature and production well temperature history.

Results presented in Figs. 11 and 12 give almost perfect matches and prove the validity of the expressions presented in this paper.

One further study to simulate the recovery behavior was conducted for this particular field. In this part of the study, the reservoir is assumed to be exploited for various time cycles of production and shut-in periods. First case is the scenario in which the field is produced for a period of 36 years and then shut in.
The temperature behavior during shut-in period is calculated using Eq. 22. It is assumed that heat recovery occurs only from bottom, from the

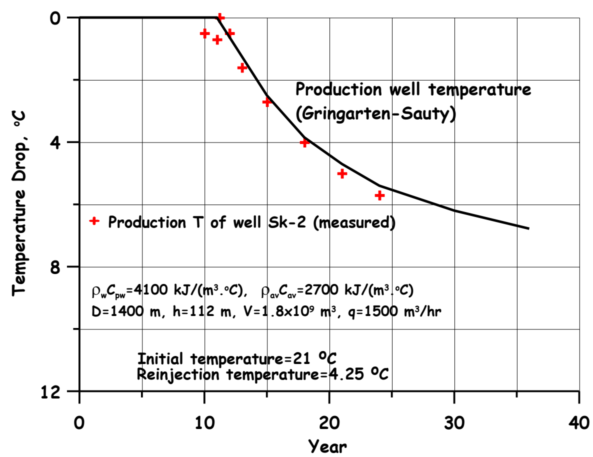

Figure 11: Comparison of measured production well temperature versus calculated one.

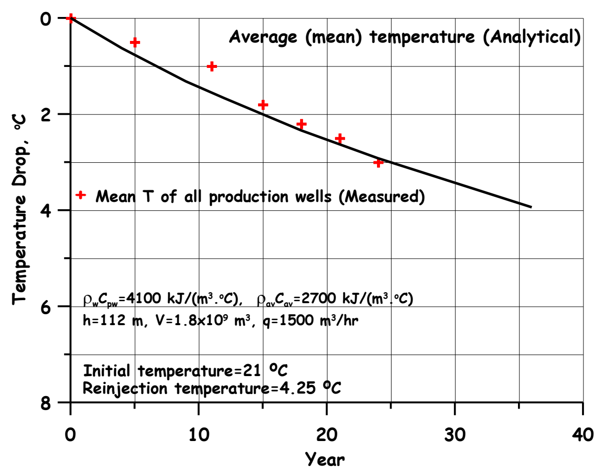

Figure 12: Comparison of measured mean temperature versus calculated one.

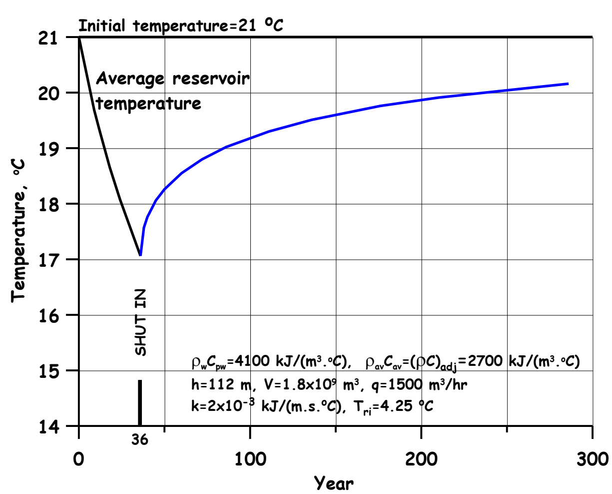

Figure 13: Average reservoir temperature for 36 year production and then shut-in scenario.

underburden formation to the reservoir, through conductive heat transfer. The results are shown in Fig. 13. Eighty percent heat recovery is observed after 250 year shut-in period.

The average reservoir temperature behavior is also studied for production and recovery phases of different durations (18, 36, and 72 years). Results are illustrated in Fig. 14. A comparison of the average reservoir temperature of production-recovery cycles of 18, 36, and 72 years shows that the temperature remains on a higher level for the shorter cycle periods, indicating that short production-recovery cycles produce more energy. The same conclusion was also reached by Megel and Rybach (2000). This is an important conclusion for geothermal projects with doublet and multi-doublet patterns.

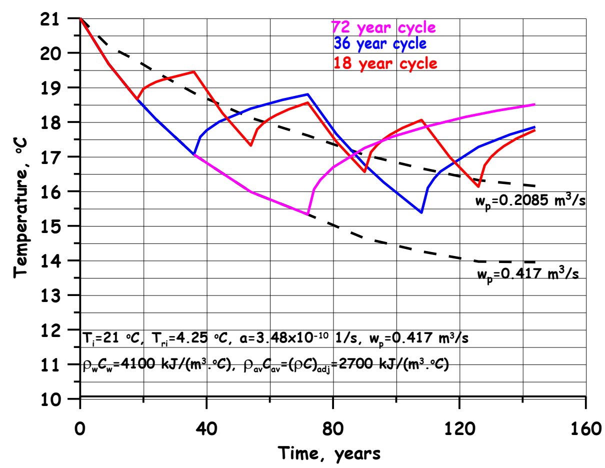

Figure 14: Average reservoir temperature for production-recovery cycles of different duration in a doublet operation.

CONCLUSIONS

The primary objectives of this paper were to outline the fundamental theory of a doublet system in a confined hydrothermal aquifer and validate the applications of new analytical solutions to the temperature behavior of a doublet in a hydrothermal aquifer. The reservoir considered is a porous aquifer in which a doublet is located. It has porosity and permeability for geothermal exploitation, however the natural hydrothermal convection (or natural water recharge into the reservoir) is absent.

An analytical approach is presented to analyze the production temperature and the volumetric average reservoir temperature. Emphasis is given to understand the characteristics of temperature recovery following some production period. New analytical solutions to be used for designing the doublets in such reservoirs are presented.

Using the approach given in this paper, it is possible to estimate the reservoir volume from the analysis of the volumetric average reservoir temperature. Results of the modeling study on the effects of time cycles of production and shut-in periods indicate that short cycles produce more energy and improve the sustainability conditions of doublet projects.

Reliability of the analytical approach was tested against the results of a doublet field operation in the literature and the validity of the approach is demonstrated.

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