Heat Transfer in High Enthalpy Geothermal Wells – A case-study.

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ABSTRACT

It is a common practice to assume an adiabatic process throughout the entire wellbore because of the frequent lack of data required in a formal wellbore simulation. The objective of this paper is to show and quantify the possible inaccuracies get by this practice. A case-study of a low gas and TDS content well at Los Azufres, Mexico, geothermal field, is presented. The problem is analyzed by a non-commercial package of geothermal tools that includes a wellbore simulator.

1. INTRODUCTION

It is hard to develop a reliable geothermal wellbore simulator, due to diverse reasons. The modeling of all types of flow regimes occurring inside a geothermal well, is a complex task, particularly the part concerning to two-phase flows (e. g.: Wallis, 1969 and Chisholm, 1983; Kleinstrever, 2003). Besides, the solution to the pipe-flow problem depends, partially on the solution to the three fundamental equations of fluid dynamics, but also on the equation of state used for these multi-component fluids. Furthermore, the total information required for a formal wellbore simulation usually comes from different technical sources, whose gathering can take long times, and even it can be not completely available. In addition, the errors involved in all the measured parameters (mainly field data) can drastically bias the results.

On the other hand, the use of a wellbore simulator can be an excellent tool to solve varied flow problems, such as: reproduction of downhole pressure-temperature profiles (P-T log); detection and location of feed zones; decide repairing wells in which part of the production casing must be change in diameter due to collapses; detection of fails (leaks) in the production casing; construction of wellhead (production) output curves; and wellbore completion design of new wells. Also, it is possible to be coupled with a reservoir simulator (e.-g.: Gudmundsdottir, 2012) in order to get a global representation of the whole system.

In this work, we utilize a multi-purpose geothermal wellbore simulator which is part of GeothPack, a non commercial package of geothermal tools. This wellbore simulator incorporates a version of a one-dimensional-homogeneous flow model (Wallis, 1969). At present, it utilizes an equation of state (EoS) for the binary system $H_2O - CO_2$ (Sánchez-Upton, 2021), and a three components version ($H_2O - CO_2 - NaCl$) is being updated. This EoS is reduced to that of pure water (Schmidt, 1979) for null CO_2 and $NaCl$ contents, as expected.

The simulator takes the radial-heat-transfer process into account in two parts. Firstly it assumes a steady-state part in the well (production casing and up two three different diameter casings), and an unsteady-state part in the rock formation (Carslaw and Jaeger, 1946; Matthews and Russell,1965-1966). It uses the rock formation stabilized temperature distribution estimated from unsteady-temperature logs carried out during the drilling of the well (Garcia-Estrada and Lopez-Hernandez, 2001). Heat transfer process is considered just in the upper part of the production casing. This means that it is not quantified through the liner length, assuming that most portion of the liner is inside the reservoir, so that, the heat losses must be small or even nil.

The solution of the current system of fundamental equations (mass-momentum-energy-EoS) converges by using an efficient scheme of successive approaches. It can be run in any direction (upside-down, and vice versa). This simulator can be used in problems related to single (liquid/vapor) or two-phase (liquid-vapor mixture) flows.

Then the paper remarks the importance of well characterization and reminds most parameters required in simulation job and how they can be obtained. It is also presented a case study of a well characterized for its low gas and total dissolved solids (TDS) contents, in order to show most of the different tasks carried out in a simulation that takes into account the effect of the heat transfer between well and formation.

2. ANTECEDENTS

There are several papers related to the heat transfer between wells and surrounding rock formations. The main differences among those works come from the degree of complexity used in the discretization of the several heat transfer surfaces usually found in a geothermal well.

Some of these works are referred to the oil industry (Moss and White, 1959, Ramey, 1962, Willhite, 1967) and related to secondary recovery activities. All those papers applied a modified version of the fundamental equations of fluid mechanics in order to estimate the temperature drop from surface to the depth of infiltration, due to the injection of liquids (cold water, hot fluids) and gases (air, natural gas). The formation temperature was estimated from the local-natural thermal gradient, assuming geothermal temperature is a linear function of depth. Also, the heat transmission is partitioned into two portions: a steady-state and an unsteady-state. In some of those cases, the global heat transfer coefficient is given as a known datum as part of input data file. The instant source solution (point and line source) is commonly used (Carslaw and Jaeger, 1946), but it is also common to use an approximate solution (Ramey, 1962) applicable just for long times (more than a week).

There are several non-commercial wellbore simulators for the geothermal industry, reported in the technical literature (Miller, 1980; Ortíz-Ramírez, 1983; Bjornsson, 1987; Hadgu, 1998; Battistelli, 2001) as well as some commercial simulators (e.-g.:

Wellsim). Few of them, utilize EoS of multi-component fluids, most using correlations to mainly estimate the pressure drop of the two-phase regimes (e.-g.: Orkiszewski, 1967; Barelli et al., 1994). Some of them also incorporate the global heat transfer coefficient as part of the input data file, and use punctual formation temperatures. In addition, some of them incorporate an isoenthalpic analysis, as alternative option.

3. WELLBORE CHARACTERIZATION

Wellbores' characterization is of key importance to the assessment of the potential of a high-enthalpy geothermal reservoir (Matín-Gamboa et al., 2015), but also to select the type, capacity and distribution of turbo-generator units (one or more flashes, back pressure, binary, hybrid, etc.) throughout the field. This, of course, is based on comprehensive exhaustive interrelated studies of geology, geophysics, geochemistry, and reservoir and production engineering.

Well completion design comprises the characteristics of production casing, liner (blind and slotted intervals), casing, hole, cementing and any other component included in its design (e.-g.: liner hanger or casing shoe). This information incorporates: the type or grade of material, internal and external diameters, length of production line (casing and liner) and casing (Halliburton, 1975). Also, it specifies the type of cement, and the diameters of the different holes.

Likewise, there are several methods to estimate the mass flow rate and specific enthalpy of a production well. The universal method, used by decades, is the James' that depends on the lip (or critical) pressure (James, 1962). It has been applied mainly to wells producing two-phase mixtures, but it also can be used to assess the discharge of critical saturated steam mass flow rate (Sánchez-Upton, 1986). Secondary elements such as sharp-edged-orifice plate, venturi pipe or nozzle are used for the evaluation of single-phase fluids (Sánchez-Upton, 1991). Sharp edged orifice plates have been used too for measuring two-phase flows (James, 1965; Sánchez-Upton, 1993). Most of these methods give reasonable results even on controlled pulsing flows.

From the particular point of view of production engineering, the evaluation of a production well usually comprises the estimation of production parameters such as mass flow rates (liquid, vapor, and even two-phase), specific enthalpy, gases and total dissolved solids (TDS) contents. All these parameters, as well as the wellhead temperature, are referred to the current wellhead pressures. In addition, downhole measurements of pressure, temperature and spinner (PTS), as well as, casing integrity logs must be included. From the interpretation of the spinner data registered, it is possible to estimate the partial mass-energy production of each feed zone located along a finite length permeable interval, along with the P-T data and other production parameters.

From the analysis of cores, taken during drilling, some other important data can be obtained such as, mechanical and thermo-physical rock properties among them resistance to compression, density, porosity, permeability, specific heat, thermal conductivity and diffusivity (Contreras, et al. 1988). Circulation losses while drilling indicate the location of permeable zones (feed zones) and the possible intersection to fault planes. Petrography studies allow identify high-temperature mineral such as amphiboles and epidotes (Gonzalez et al. 1990). Pressure transient tests are used to estimate the permeability-thickness product called formation conductivity (Sánchez-Upton, 1986), which is a relative measure of the well productivity. Temperature transient tests are used to estimate the stabilized temperatures (formation temperature) at specific depths (García-Estrada et al., 2001).

4. HEAT TRANSFER MATHEMATICAL MODEL

Following, the two parts of the one-dimensional conductive heat flow model are described. This model allows estimate the energy exchanges between a wellbore composed by a multiple-layer cylindrical walls and the surrounding homogeneous rock formation. This model assumes a steady-state in the wellbore (production pipe-casing-cement) and an unsteady-state in the rock formation, similar to that used by Ramey (1962).

For the radial steady-state part of the model we depart from the Newton's law of cooling and the Fourier's law (Kreith, 1970: Holman, 1972), and the heat flow through a radial-composed wall (Fig. 1) can be estimated using:

$$q = 2\pi h_f r \Delta z \Delta T = -2\pi k r \Delta z \frac{dT}{dr} = U A_t \Delta T \qquad (1)$$

where q is the heat flow; h_f is the fluid film conductance (convection heat transfer coefficient); k is the material thermal conductivity; r is the radius; Δz is the vertical length increment (perpendicular to the heat flow); T is temperature; and U is the global heat transfer coefficient.

Eq. (1) can be rewritten as:

$$T_f - T_H = \frac{q}{2\pi\Delta z} \left\{ \frac{2}{D_{ti,1} h_f} + \sum_{j=1}^{np} \frac{1}{k_{st}} ln\left(\frac{D_{to,j}}{D_{ti,j}}\right) + \sum_{j=1}^{np} \frac{1}{k_{c,j}} ln\left(\frac{D_{ti,j+1}}{D_{to,j}}\right) \right\} \qquad (2)$$

where T_f is the fluid temperature; T_H is the hole temperature (boundary between the well

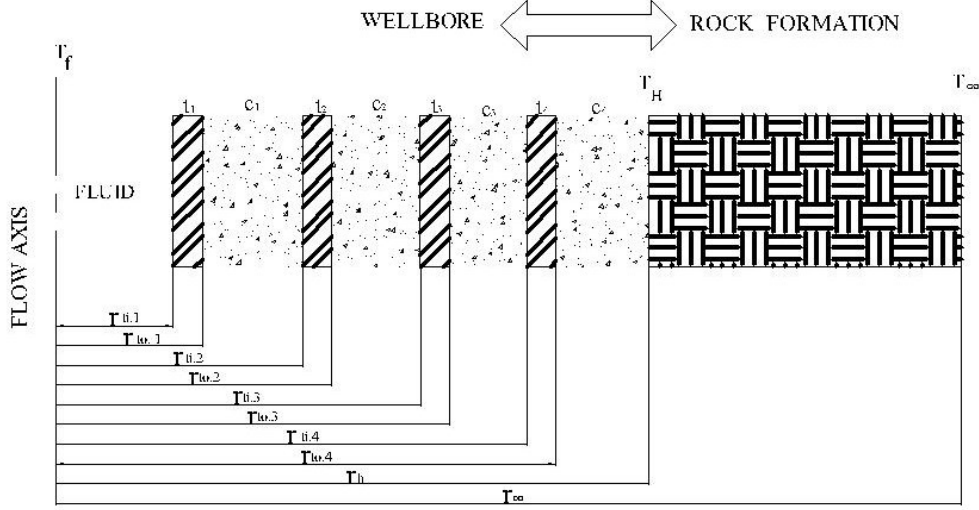ONE - DIMENSIONAL HEAT FLOW THROUGH MULTIPLE CYLINDRICAL WALLS

Figure 1. Schematic diagram showing a common arrangement of the upper part of a well (first interval defined below). It includes the flow axis, four different steel elements (production pipe and casings), the corresponding cement thicknesses and radii, and the surrounding rock formation. It also shows the fluid temperature (T_f); hole temperature (T_H) and the undisturbed rock temperature $(T_\infty$ at $r \to \infty)$.

and the rock formation); D_{ti} and D_{to} are the inner and outer diameter of the production pipe (or casing), subscript st stands for steel elements and subscript c for cement rings, respectively.

In relation to the film coefficient (h_f), there are several correlations in the technical literature that have been proposed for specific cases of pipe flows (Kreith, 1970; Holman, 1972). However, the number is shorter for the case of two-phase flow in rough pipes (Gao et al., 2017). Anyways, this term can be neglected in most of the practical cases, considering that the value of h_f is usually high (Ramey 1962).

$$Ч = \frac{2}{D_{ti,1}h_f} + \sum_{j=1}^{np} \frac{1}{k_{st}} ln\left(\frac{D_{to,j}}{D_{ti,j}}\right) + \sum_{j=1}^{np} \frac{1}{k_{c,j}} ln\left(\frac{D_{ti,j+1}}{D_{to,j}}\right) \tag{3}$$

where Ч is a pseudo-thermal resistance for conductive-steady-state radial heat transfer, in SI units [(m - °C)/W].

For the radial unsteady-state part of the model, the equation that describes the one-dimensional-radial transient heat flow by conduction through the rock formation is:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{\rho_f c_f}{k_f}\frac{\partial T}{\partial t} = \frac{1}{\alpha_f}\frac{\partial T}{\partial t} \tag{4}$$

where ρ_f is the density, c_f is the specific heat, k_f is the thermal conductivity, α_f is the thermal diffusivity, t is time. If we make a change of variable (Boltzman transformation), we have:

$$\psi = \frac{r^2}{t} \tag{5}$$

where ψ is the Boltzman's variable. Then, Eq.(4) can be rewritten as:

$$\frac{\partial^2 T}{\partial \psi^2} + \left[\frac{1}{\psi} + \frac{1}{4\alpha_f}\right]\frac{\partial T}{\partial \psi} = 0 \tag{6}$$

the solution to Eq.(6) is:

$$T_H - T_\infty = \frac{q}{4\pi k_f \Delta z}\left\{-\gamma - \ln(u) - \sum_{n=1}^{\infty} \frac{(-1)^n u^n}{nn!}\right\} = \frac{qE_1(u)}{4\pi k_f \Delta z} = \frac{q\Lambda}{2\pi\Delta z} \tag{7}$$

where

$$u = \frac{r^2}{4\alpha_f\, t}\,; \Lambda = \frac{E_1(u)}{2k_f} \tag{8}$$

where γ is the Euler's constant (0.5772…); $E_1(u) = \int_u^\infty \frac{e^{-x}}{x} dx$ is the exponential integral; and Λ is a pseudo-thermal resistance for conductive-unsteady-state radial heat transfer, similar to Ч. The variable u is dimensionless when a consistent set of units is used.

The result given by Eq. (7) is similar to that reported by other researchers (e.-g.: continuous line source-Carslaw and Jeager, 1946). Using Eqs(2), (3) and (7) we get:

$$T_f - T_\infty = \frac{q}{2\pi\Delta z}\{Ч + \Lambda\} \tag{9}$$

The undisturbed formation temperature (T_∞) can be assessed for wells of Los Azufres geothermal field with the polynomial function presented in Fig.4. This function is based on the data published by Garcia-Estrada et al. (2001) related to that geothermal field.

5. WELLBORE SIMULATOR MATHEMATICAL MODEL

Here, we briefly describe the wellbore simulator used in this study. It is a one-dimensional flow model based on the solution of the three fundamental equations of fluid mechanics (Wallis, 1969) along with the corresponding equation of state (EoS). The specific case of two-phase flow is considered as the transport of a homogeneous mixture. The fundamental equations are the following:

Mass conservation equation:

$$d\left(\frac{Av}{\nu}\right) = 0 \Rightarrow \dot{m} = \frac{Av}{\nu} = \text{constant} \tag{10}$$

where A is the flow cross section area; v is the mean flow velocity; ν is the specific volume of the homogeneous fluid mixture; and $\dot{m}$ is the mass flow rate.

Momentum conservation equation:

$$dP + \frac{f\nu}{2D}\left(\frac{\dot{m}}{A}\right)dz + \frac{g\cos(\theta)}{\nu} + \left(\frac{\dot{m}}{A}\right)^2 d\nu = 0 \tag{11}$$

where P stands for pressure; f is the friction factor (Colebrook-White); D is the internal pipe diameter; z is the flow (reference length) axis; g is the gravitational acceleration; and θ is the flow angle with respect to the z axis.

Energy conservation equation

$$dh + vd\nu + g\cos(\theta)dz - \frac{q}{\dot{m}} = 0 \tag{12}$$

where h is specific enthalpy; and q is the energy transfer (as heat) per unit of time.

Equation of state (EoS)

This wellbore simulator uses a three component ($H_2O - CO_2 - NaCl$) equation of state, and for the purpose of this work, it can be reduced to (Schmidt, 1979):

$$\nu = f(P, h) \tag{13}$$

We use an algorithm based on successive approximations to get the convergence of this equations' system.

6. CASE-STUDY

Following is a case-study with a set of data extracted from well Az-42 at Los Azufres Geothermal Field, Michoacán, Mexico. These data are used by the current wellbore simulator in order to study and evaluate an adiabatic process through the whole wellbore and the heat transfer between the wellbore and the surrounding rock formation.

The data include the well completion design, the undisturbed rock formation temperature; and a simultaneous-dynamic downhole P-T log along with the corresponding production parameters. Most of these data have been incorporated to Fig. 4, but the production data are given in Table 1.

The wellbore completion design comprises the dimensions and locations of production casing, liner, casings, holes and cement rings. Furthermore, the coefficients of the polynomial used to estimate the undisturbed formation temperature are given in the lowest part of Fig. 4.

Table 1. Production parameters registered and estimated during the running of a simultaneous P-T log.

Wellhead Pressure [bar]	Mass flow rate [kg/s]	Specific enthalpy [kJ/kg]
36.57	21.44	1303.6

6.1 Analysis of the Data

The downhole P-T log inside the well Az-42 was taken with a mechanical type element (Kuster). From both charts, 15 pairs of P-T data were read and recorded. The first pair of data was registered at 20 m depth and the deepest one, at 1800 m depth (Figs. 2 and 4). In order to start the analysis, we overlap this set of data on a P-T diagram (sometimes called "Clapeyron's diagram") for pure water (Fig. 2a).

It is notable that the first seven P-T data lie on the saturation line and the rest of deeper P-T data are located on the sub-cooled liquid region. This roughly means that the flashing point is near below 1200 m depth. Furthermore, this P-T path shows an "abnormality" below this same depth, which is characterized by the break of the "normal" trend of such profiles, as will be seen later. The temperature below 1600 m depth is almost invariant.

The P-Z (depth) diagram shows a non-linear path from wellhead up to 1200 m depth (Fig. 2b), and there is a nearly perfect linear distribution from 1400 m to bottom hole. It is typical of a hot liquid column (where flow velocity is low).

The temperature profile exhibits also an almost linear path from wellhead to 1200 m depth (Fig. 2c). Beyond this depth, there is an "unusual step" between 1200 and 1600 m depth. The temperature datum at 1400 m depth is an "outlier" in relation to the expected temperature trend. As mentioned before, temperature seems to be almost constant from 1600 m to bottom hole.

Fig. (2d) shows some detailed information about the production line (production casing and liner), including the possible flow path of a secondary feed zone (through the clearance at liner hanger).

Fig. (2e) presents the pressure gradient when the produced fluid travels as a two-phase flow, this is between 0 m and 1400 m depth. The liquid phase flow exhibits a pressure gradient of 0.075 bar/m approximately, from 1600 to bottom hole.

The temperature gradient increases slightly with depth in the region of two-phases, approximately 0-1200 m depth (Fig. 2f). It can be noted again the temperature datum at 1300 m depth is far from the usual trend. The liquid phase flow region is where the temperature gradient is almost zero.

Using the P-T data and the steam tables, we found the following values of specific enthalpy for 1400 and 1600 m depths, as reported in Table 2, corresponding to the "unusual step" of temperature mentioned before.

Table 2. Parameters measured and estimated at 1400 and 1600 m depths.

Depth [m]	Pressure [bar]	Temperature [C]	Enthalpy [kJ/kg]
1400	77.63	283.22	1253.12
1600	92.17	292.33	1301.28

These significantly different values of specific enthalpy suggest a probable secondary feed zone, which likely causes the "unusual step" between 1200 and 1600 m depth.

It is relevant to note at this point that the production parameters, such as total mass flow rate and specific enthalpy, were computed by using the James' method (James,1962; Karamarakar and Cheng, 1980). This method allows estimate the specific enthalpy of the mixture at stagnation condition, i.e., where flow velocity is zero. As it is known, the stagnation enthalpy is constant throughout an adiabatic process (no heat transfer). But its static and dynamic (kinetic) specific energy components depend on local properties such as temperature (pressure) and steam quality, but also the specific gravitational potential energy depends on the relative position, for two-phase flow. The flow velocity inside the well is usually low in such a way that the kinetic energy is almost always negligible, while the gravitational specific potential energy is 0.01 kJ/kg/m approximately. In contrast, al high speed flow velocity, i.e., at critical [sonic (C)] or lip pressure condition, the estimated specific kinetic energy (e_c) is given in Table 3.

Table 3. Estimation of kinetic energy per mass unit, assuming an adiabatic flow process.

Reference	C [m/s]	e_c [kJ/kg]	Reference	C [m/s]	e_c [kJ/kg]
Kieffer (1977)	280.0	39.2	Michaelides (1983)	250.0	39.2
	350.0	61.3	Homogeneous*	435.1	92.9

*calculated assuming a homogeneous mixture.

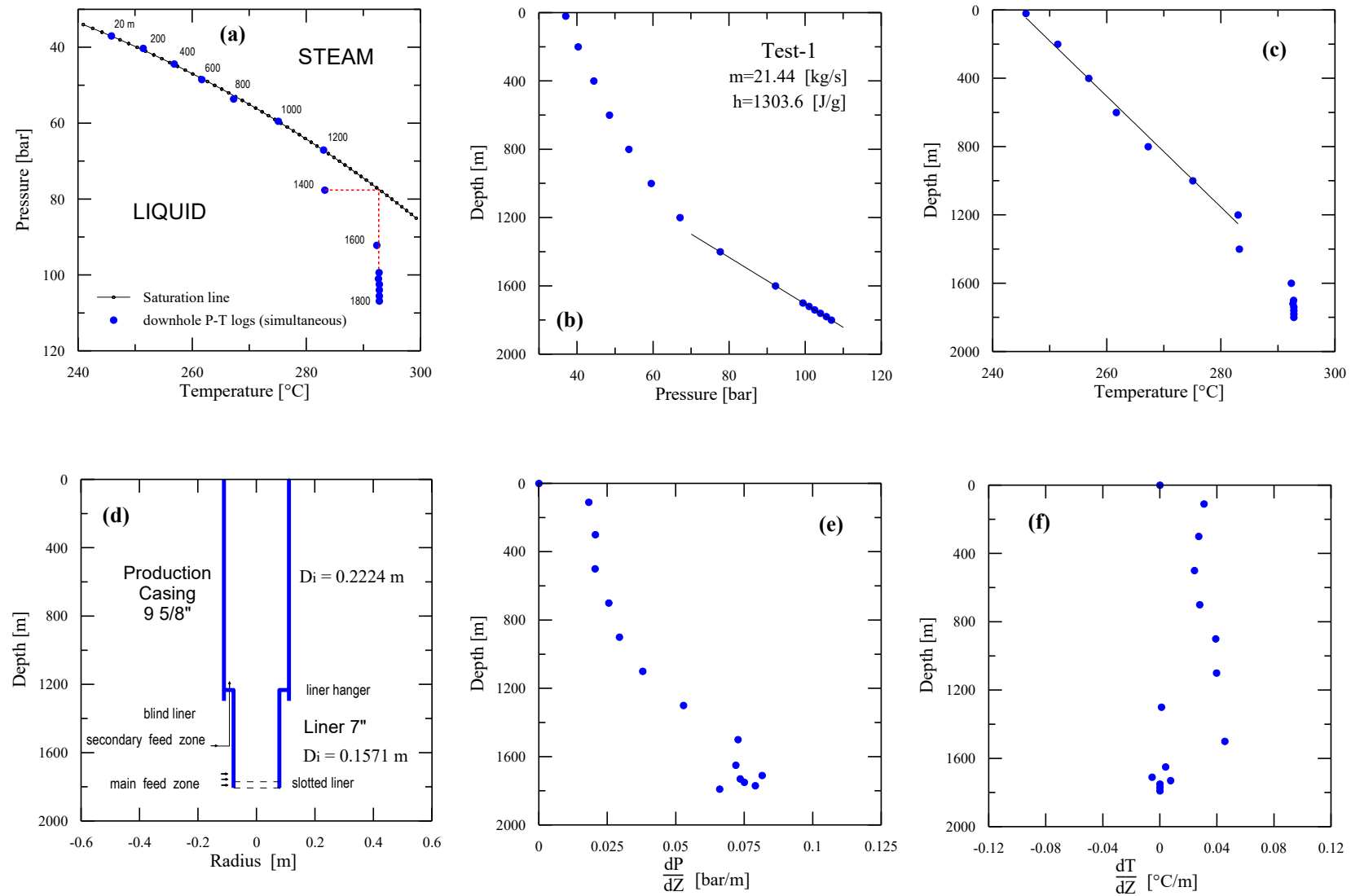# Well Az-42 (Los Azufres Geothermal Field, Mich., Mexico)

Figure 2. Different plots used to discover relevant phenomena registered by the run of the downhole log in well Az-42

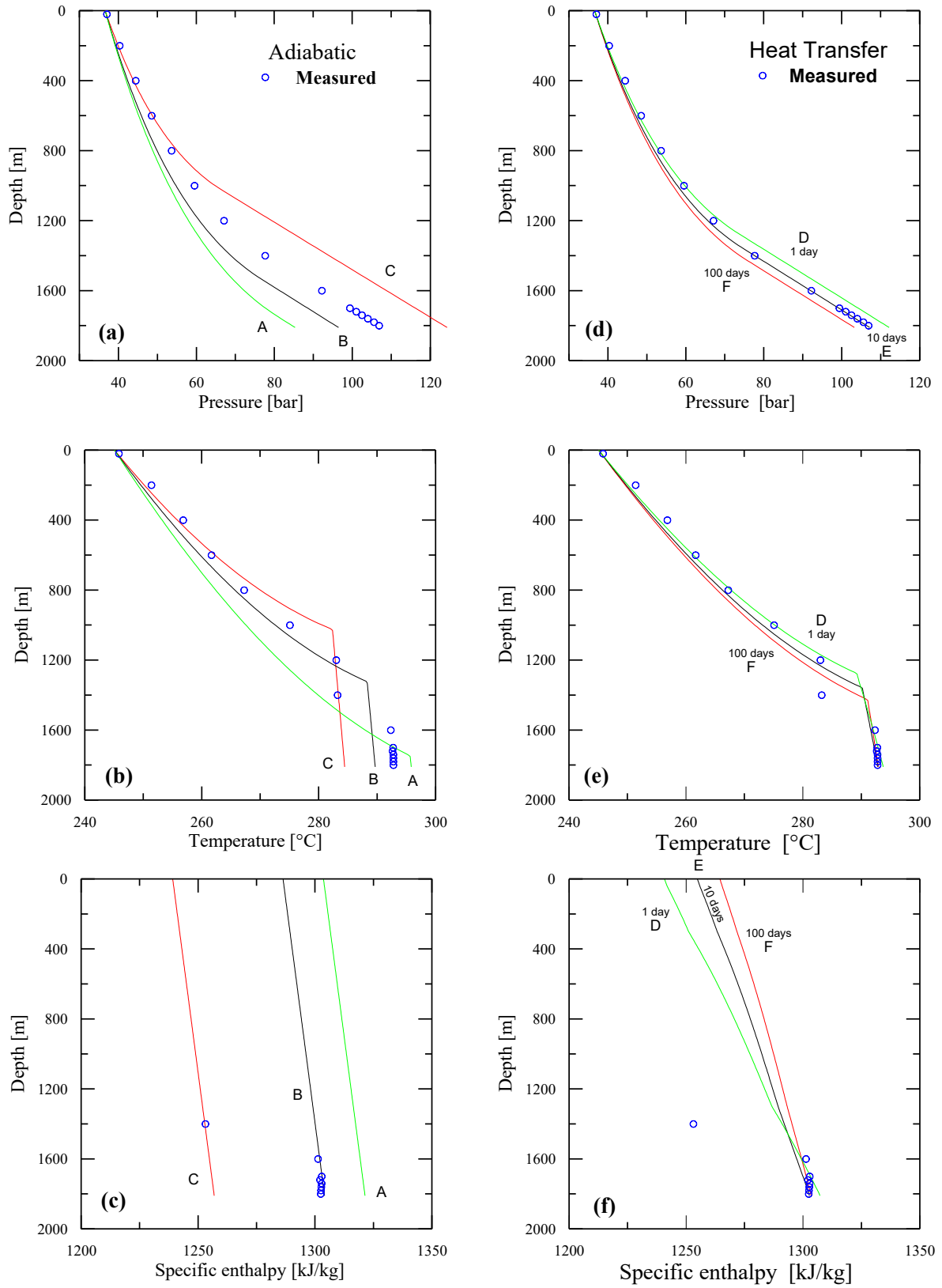# Well Az-42 (Los Azufres Geothermal Field, Mich.,México)

Figure 3. Results obtained by the wellbore simulator using different assumptions.

It can be noted that the specific enthalpy at 1600 m depth and below, where the flow velocity is near zero, is almost equal to the stagnation enthalpy reported within the production parameters. Thus, the P-T data measured at 1400 m depth is a potential outlier.

If it is true that the datum of T at 1400 m depth is an outlier, and if it is assumed an adiabatic process throughout the wellbore, the wellhead "static" specific enthalpy is a direct function of the length that separates the top and the bottom. This is, if we consider the total length of de well (1810 m), the specific enthalpy at wellhead would be 1303.6-17.7=1285.9 kJ/kg.

6.2 Use of the Wellbore Simulator

The results obtained by using a non-commercial geothermal wellbore simulator that forms part of GeothPack (Geothermal Package) are presented below. In order to have a global idea about this wellbore flow problem, we firstly used the simulator considering an adiabatic process throughout the well with the mentioned production parameters, and tried to fit separately the P-T log data. Then, we look at the most plausible solution to the current problem through other tentative scenarios, including heat transfer between the well and the surrounding rock formation. The properties of rock formation, cement, production pipe and casing were extracted from technical reports (Halliburton, 1975; Contreras et al., 1988; Santoyo, 1997).

We start plotting the P log data on a Z-P plane, incorporating the well simulator considering an adiabatic process and using the data presented in Table 1. These results correspond as case A in Figs. 3a-c, where the pressure and temperature are right only from 0 m to 200 m, and the differences between measured and calculated data increases gradually up to the bottom-hole.

Fig. 3c shows part of the data deduced from measured data (using the steam tables), and also the results of the simulator in relation to the distribution of the specific enthalpy. From the calculated distribution A on this figure, it is possible to estimate a specific enthalpy gradient of 0.01 kJ/kg/m, approximately. The estimated specific enthalpy of the possible outlier is also shown (1253.12 kJ/kg).

The second case (B) studied also considers an adiabatic process through the wellbore, but now the produced fluid has a wellhead specific enthalpy of 1286.3 kJ/kg, assuming a specific gravitational potential loss of 17.3 kJ/kg between the bottom and the wellhead. With this wellhead specific enthalpy, the calculated data close the measured data curves, especially noted on the temperature and enthalpy curve, but not enough (Figs. 3a-c).

In the third case (C), it is used a wellhead specific enthalpy of 1239.12 kJ/kg and the same other production parameters. This simulation corresponds to the case where a second feed zone would be located close to 1550 m depth. In this case, the temperature measured data is fitted well from wellhead to 1400 m depth, but the calculated pressure fits well only in the upper part of the well and diverges since 800 m depth. However, the calculated specific enthalpy is systematically lower regarding the lowest part of the measured data, this is, without considering the possible outlier.

On the other hand, we study the case when there is heat transfer between the well and the surroundings rock formation. Table 4 shows the parameters used in the following three cases studied.

Table 4. Parameters used in the three simulation cases with heat transfer between well and its surroundings.

Case	Production Time [day]	Wellhead specific enthalpy [kJ/kg]	Specific Enthalpy Drop [kJ/kg]
D	1	1240.77	62.83
E	10	1254.85	48.75
F	100	1264.48	39.12

The three cases under study fit well to the measured temperature and pressure, as it is shown in Fig. 3d-f. However Case E, in which the production time is 10 days, seems to be in general the best fitting to the measured data.

7. CONCLUSIONS

Figure 5 describes the main processes that are incorporated into the wellbore simulator to solve this type of fluid transport phenomena.

Main conclusions related to this study are as follows:

1. Heat transfer analysis must be carried out when all required data are available. This task makes possible to get the more reliable description and solution to the wellbore characterization.
2. Adiabatic analysis is acceptable only when there are not enough data for carrying out a heat transfer analysis. It could be a reasonable approach when the production time is more than a week. In the adiabatic case, the specific enthalpy loss between the stagnation position (well bottom) and the wellhead, is proportional to the specific gravitational potential energy between these two positions, this is, ≈0.01 kJ/kg/m.
3. This type of analysis can be used in order to detect the presence of different feed zones, determine its probable location, and estimate their partial productions. In this example, we conclude that the temperature measured datum at 1400 m depth is an outlier. In the lack of outliers, it would be easier to run the wellbore simulator from bottom hole to wellhead.

This exercise allows estimate the probable error when the simulation does not take into account the heat transfer mechanism. The wellhead specific enthalpies are as follows: h_{adia} = 1286.3 and h_{heat} = 1254.9 [kJ/kg], therefore the difference is |31.4| kJ/kg.

WELL COMPLETION	P-T (Kuster) log		
	Depth [m]	Press [bar]	Temp [C]
	20	37.00	245.82
	200	40.28	251.39
	400	44.40	256.82
	600	48.50	261.66
	800	53.61	267.24
	1000	59.49	275.07
	1200	67.06	283.00
	1400	77.63	283.22
	1600	92.17	292.33
	1700	99.36	292.73
	1720	100.99	292.62
	1740	102.46	292.77
	1760	103.96	292.77
	1780	105.54	292.77
	1800	106.86	292.77

WELL AZ-42 LOS AZUFRES GEOTHERMAL FIELD

Steel pipe   Cement

40" Ø Drillhole
FIRST INTERVAL
30" Ø Conductor (0-12 m)
SECOND INTERVAL
26" Ø Drillhole
20" Ø Casing (0-47 m)
THIRD INTERVAL
17 1/2" Ø Drillhole
13 3/8" Ø Casing (0-303)
9 5/8" Ø Production casing (0-1296.55 m)
FOURTH INTERVAL
Liner hanger at 1232.92 m
12 1/4" Ø Drillhole
7" Ø Liner
FIFTH INTERVAL
8 1/2" Ø Drillhole
Slotted Liner (1769.15-1806 m)
Not to any scale

Liner, Production Pipe and Casing Diameters (in/m) [Data from: Halliburton, 1975]									
7"/0.1778		9 5/8"/ 0.2445		13 3/8"/0.3397		20"/ 0.5080		30"/ 0.7620	
inner	outer	inner	outer	inner	outer	inner	outer	inner	outer
0.1571	0.1778	0.2224	0.2445	0.3204	0.3397	0.4857	0.5080	0.7300	0.7620

Polynomial function for calculating temperature distribution in the formation (Data from: Garcia-Estrada et al. 2001)

$$T_{for} = \sum_{n=0}^{5} a_n z^n$$

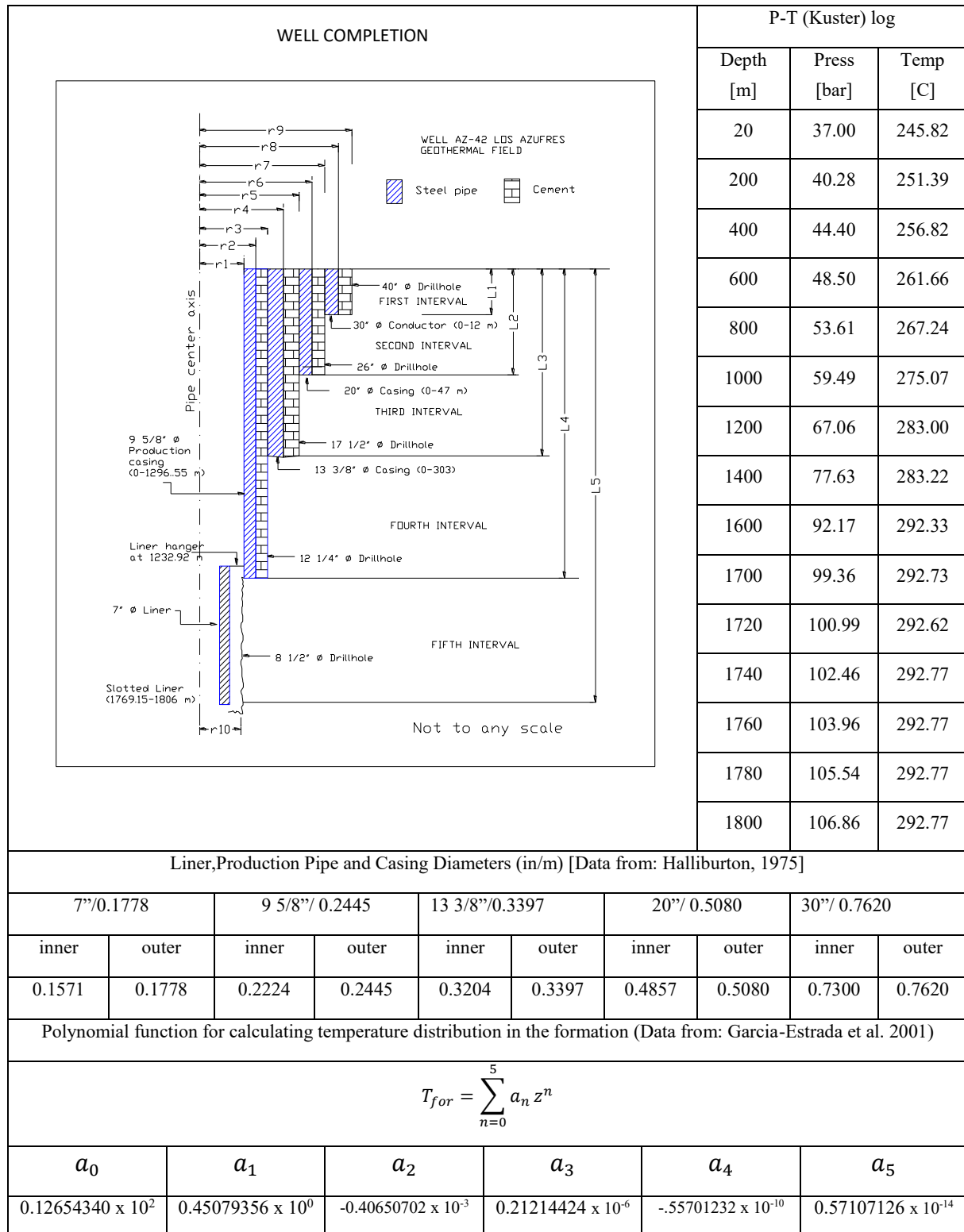| a_0	a_1	a_2	a_3	a_4	a_5
0.12654340 x 10^2	0.45079356 x 10^0	-0.40650702 x 10^{-3}	0.21214424 x 10^{-6}	-.55701232 x 10^{-10}	0.57107126 x 10^{-14}

Figure 4. Az-42 Well completion design; P-T log data; liner, production casing, casing and hole diameters; and coefficients of the fifth degree polynomial used to estimate the non-perturbed temperature of the rock formation.
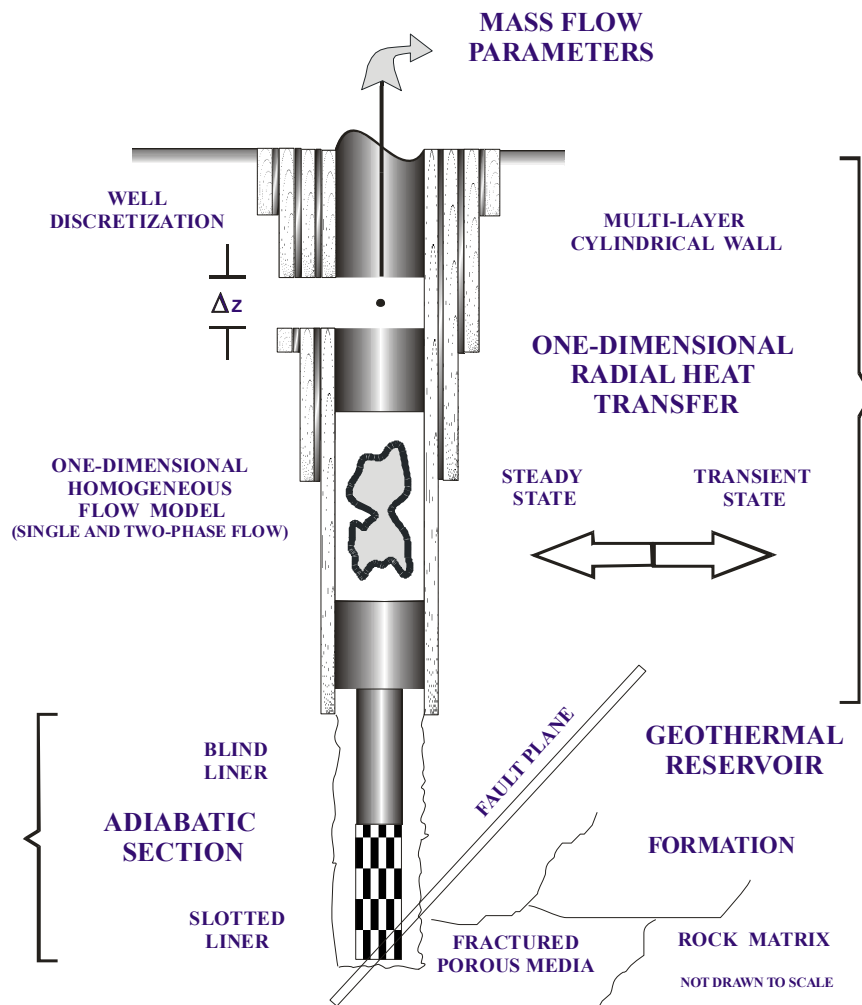
Figure 5. Main processes involved into the wellbore simulator for solving this type of flow problems.

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