CHAPTER 1

INTRODUCTION

1.1 Background and Project Purpose

Over the last 20 years, intelligent well technology (including near-horizontal and multilateral wells) has become one of the oil and gas industry's main routes of production. Supported by vast improvement in electronic technology which ease the collection of data, was increase the number of long horizontal and highly deviated wells. Advanced completions with their ability to solve several of production problems are often installed in such wells. Instead of providing accurate data collection, these completions also allowing real-time data transfer from offshore to onshore, hence helping the engineers to have immediate information plan properly and come out with accurate decisions.

Predicting accurate temperature profiles in flowing wells is one of the benefits obtain from the horizontal well technology. The old technology use temperature measurement to understand inflow profiles (fluids enters and moving along the wellbore) in vertical wells which providing limited information solution and specified only for vertical well. Permanent downhole sensors used nowadays are the solution to predict temperature. They are used to measure temperature and pressure profiles, reliable and simple, can be operated at any deviation angle, and are capable of real-time response. Distributed temperature measurements using fiber optics, in particular, are becoming increasingly applied. Some of the temperature profiles functions are to calculate accurate two-phase flow pressure drop predictions, which in turn can improve an artificial lift system design.

In single well of multilateral wells temperature profile prediction was unlike with the conventional well as it was synonymy with 3 major sections which are the main wellbore (vertical), horizontal or lateral, and also the build-up section. [1]As Fluid temperature in the wellbore is governed by the rate of heat loss from the wellbore to the surrounding formation, which in turn is a function of depth and production/injection time, each section of well will have different heat transfer phenomena. Vertical profile is fairly easy to understand because the well is aligned with the geothermal gradient, while horizontal profile can be assumed constant as the well lying parallel with the depth which has same geothermal temperature.

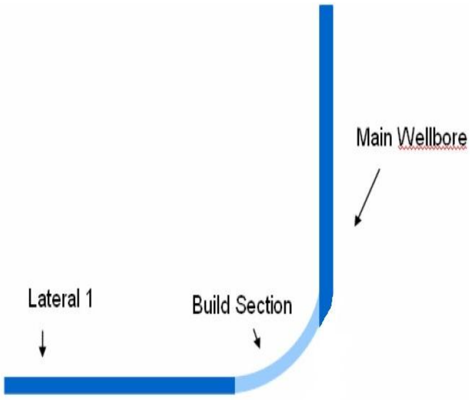

Figure 1: Sections of single well

However, at the build section, we wouldn't know whether the heat transfer rate is similar as in the vertical or horizontal.

Therefore in this study, liquid temperature at the build-up section for producing well is calculated in order to determine the temperature profile of heat transfer. By considering certain factors such as well inclination angle and velocity of flow production is examined to determine whether these factors are affecting the liquid temperature or not. Extended Ramey's method for single-phase incompressible liquid was used to calculate the fluid temperature and taking into account the overall heat transfer coefficient and geothermal temperature.

With the hope from this project, the knowledge from the study about temperature profile of wellbore is expected to helps engineer to be able to determine the suitability to run down the tool as for example temperature is subsequently affect the wellbore tool such as Electrical Submersible Pump (ESP), especially at high temperature condition. Thus, predicting temperature profile in flowing wells can greatly improve the design of production facilities in petroleum engineering.

1.2 Problem Statement

Build section can be defined as a section of wellbore that connects the productive lateral to the main wellbore or to another lateral. Build section is different from the vertical and horizontal, as it was in inclined condition. The assumption of fluid temperature in the build section cannot be directly calculated such as in vertical and horizontal. Basically, heat transfer occurs due to the temperature difference between producing liquid and geothermal temperature. In vertical we may assume that heat transfer occurs with respect to the geothermal temperature at specified depth.

While constant heat transfer is assume at the horizontal part as it lying at the same depth, so contact between liquid and geothermal temperature are in the same difference. On the build section is different; inclined wellbore have certain length depend on the deviation angle from the vertical well. Wellbore length at specified deviated angle theoretically put effect on the temperature of liquid inside the wellbore. In addition several parameters such as the liquid thermal properties, absolute value of temperature, geothermal gradient, inclination angle, liquid velocity, and thermal conductivity of materials use in the wellbore which also brings significant affect to the temperature profile.

1.3 Scope of Study and Objectives

Specifically, the study covers at the build-up section of single lateral well with single-phase producing liquid. Liquid temperatures at specified depth in the inclined wellbore are then calculated by using Extended Ramey's method. At depth of liquid, difference between the liquid and geothermal temperature brings to the occurrence of heat transfer and thus allowing to the prediction of temperature profile for the inclined wellbore. In order to see what factors influence the rate of heat transfer, two changing variables is examined. Therefore, the objective of this study is to calculate the liquid temperature at the build-up section of producing well with respect to various constant angles of build-up and in high and low flow rate condition.

Keeping the target depth for all constant angles is a must so that the initial liquid temperature at the bottomhole is similar for each well angle. By doing that, temperature profiles for each inclined wellbores can be compared and thus determining the rate of heat transfer as the liquid produced from the reservoir.

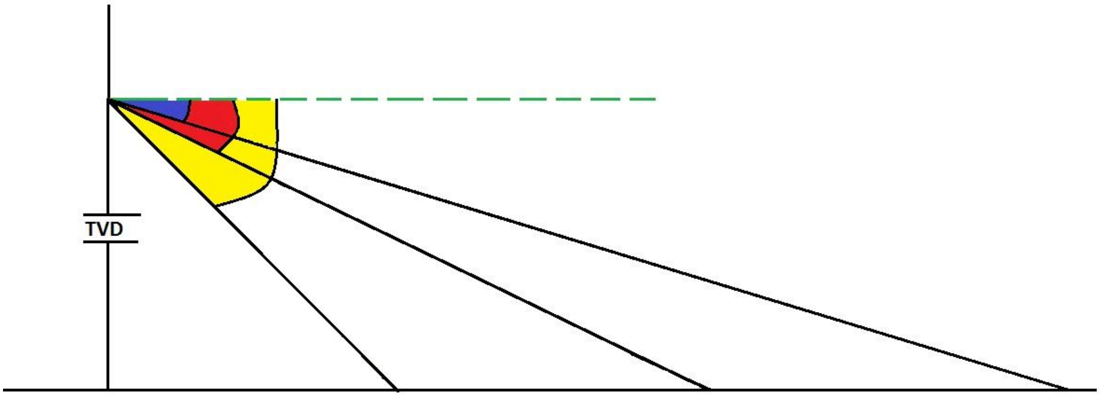

Figure 2: Constant angles with same target depth

CHAPTER 2

LITERATURE REVIEW

During the past few years, a lot of practical methods had been studied by several authors to model temperature profile base on the wellbore heat transmission. Heat transfer between fluids and the earth occur as a result of the variation between the liquid and geothermal temperature. Most researchers found several important parameters to be considered as the parameters may imply the temperature profile inside the wellbore. The parameters are as follows:

i. Thermal properties (liquid and formation)
ii. Absolute value of temperature
iii. Geothermal gradient
iv. Fluid flow rate in the wellbore
v. Trajectories of each build section.

[2]Ramey's method provides fundamental solution in predicting heat transfer in the well. The established solution for temperature distribution through the wellbore was used for injecting or producing wells either in single-phase incompressible liquid or single-phase ideal gas. Physical and thermal properties of the earth and wellbore were assumed to be constant with the temperature resulting in a steady-state condition. For liquid:

$$T_1(z,t) = aZ + b - aA + (T_0 + aA - b)e^{-Z/A} \qquad \text{………...………… (2.1)}$$

For gas:

$$T_1(z,t) = aZ + b - A\left(a + \frac{1}{778c}\right) + \left[T_0 - b + A\left(a + \frac{1}{778c}\right)\right] e^{-Z/A} \qquad \text{..…...… (2.2)}$$

Where

$$A = \left(\left(\frac{2\pi}{wC_p}\right)\left[\frac{r_{ci}Uk_e}{k_e + r_{ci}Uf(t)/12}\right]\frac{1}{86400\times 12}\right)^{-1} \qquad \text{………………………… (2.3)}$$

Time function of heat transfer is an important consideration as time will influence the rate of heat transfer. [3]Carslaw and Jaeger have come out with the estimation of time function for a cylinder losing heat at a constant temperature, a constant heat-flux line source, and a loss of heat under the radiation or convection boundary condition. The time function can be expressed by this equation

$$f(t) = -\ln\frac{r_{co}}{2\sqrt{\sigma t}} - 0.290$$

……..…………………….....…. (2.4)

[4]Sagar and Doty has make further approximation for the dimensionless time function for long times which can be expressed with this equation

$$f = -0.272\ (r_{wb}) + 3.53$$ ……….……...……………….. (2.5)

for wellbores ranging from 6.5 to 10 inch diameter and for times exceeding 1 week.

[5]Overall heat transfer parameter has been calculated accounting for all the resistances to heat flow presented by the fluid inside the tubing, the tubing wall, fluids or solids in the annulus, and the casing wall. Some ‘rule of thumb’ to calculate this variable is as follows:

i. Due to the higher thermal conductivity of steel, the thermal resistance of the pipe is neglected.
ii. The thermal resistance from liquid water or condensing steam can be ignored because of the high value of the corresponding heat transfer film coefficients.
iii. The resistance of cement must be considered because of its low conductivity.

Therefore, overall heat transfer can be calculated by using this equation:

$$U = \frac{12}{r_{ci}}\left[\frac{\ln(r_{wb}/r_{co})}{k_{cem}}\right]^{-1}$$

………………………………. (2.6)

It should be noted that the solution for determining the fluid temperature by Ramey is applicable for vertical well only. Therefore, [6]Romero Lugo has extended the basic equation by Ramey to determine the temperature profile of a build section where the well inclination is changing by applying an energy balance for a segment along the build section as a control volume. Thus, come out with these equations.

First segment of build segment:

$$T_f = T_{Gbh} - g_G \sin\alpha\left[(L-z)-\left(1-\exp\left(\frac{(z-L)}{A}\right)\right)A\right]$$

……………. (2.7)

Other build segments:

$$T_f = T_{Gi} + Ag_G \sin\alpha + \left\{ T_{f\,known} - T_{Gi} - Ag_G \sin\alpha \right\} \exp\left[\left(z - L \right) / A \right] \quad \text{………... (2.8)}$$

To calculate the temperature at certain depth on the build-up, the build-up needs to further divide into several segments. The temperature profile is then developed beginning with the lowest segment, which is connected to a horizontal lateral of known temperature. Moving up the build section, each lateral segment's temperature was based on the temperature of the previous segment. Each segment will have different constant angle which in turn differ the value of fluid temperatures.

CHAPTER 3

FUNDAMENTALS

3.1 Liquid Temperature at Specified Depth

Temperature profile in a build section can be obtained by using the extended Ramey's method to calculate the liquid temperature at specified depth. The equations describing temperature along the build section for single-phase liquid are described in Appendix A. The expression for single-phase liquid for the first build segment is:

$$T_f = T_{Gibh} - g_G \sin\alpha \left[(L - z) - \left(1 - \exp\left(\frac{(z - L)}{A} \right) \right) A \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

And for any other segment is:

$$T_f = T_{Gi} + A g_G \sin\alpha + \left\{ T_{f\,known} - T_{Gi} - A g_G \sin\alpha \right\} \exp\left[(z - L) / A \right] \quad \ldots\ldots\ldots\ldots\text{.. (3.2)}$$

Liquid temperature in the first segment is based on the changes of liquid temperature at the bottomhole as the liquid move at certain wellbore length. As liquid travel along the build section, each lateral segment's temperature was based on the temperature of the previous segment. The equation for liquid temperature in other segments will continue until the liquid reaches on the top of build-up section, means the liquid are entering the well inclination which is nearly vertical. After the top of build section, the well is in vertical and the equation 3.2 is no longer used. The first segment is started from below as the study is focus on producing liquid which means liquid flow are from bottom to top of build section.

3.2 Geometry of the Build Section

As the liquid flow from one segment to another segment, the liquid temperatures in the segment are influenced by the length of wellbore at each segment. Wellbore length at each segment is then related to the inclination of wellbore on the segment. To calculate the inclination geometry at each segment, the build-up section is further divided into several numbers of discrete wellbore increments of same length like shown from figure below:

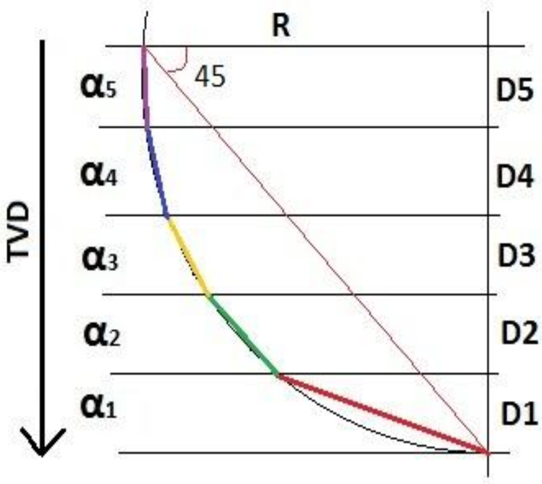

Figure 3: Segments with its wellbore inclination

Figure above show sample of build-up section with constant angle 45^o with several divided segments which have same height and with its own inclination geometry. The build section geometry is calculated by assuming a constant radius of curvature (R) between the horizontal wellbore and the main wellbore. By adapting the extended Ramey's method as shown above, inclination geometry for each segment is then computed into the equations to calculate the liquid temperature at specified depth. Other trajectories (build section with different constant angle) can be handled in a manner similar to that presented here. Refer Appendix B for calculation detail on inclination geometry.

3.3 Overall Heat Transfer Coefficient and Dimensionless Time Function

Determining liquid temperature at depth, several parameters related with wellbore condition is included in using the extended Ramey's method for producing single-phase liquid. Two main parameters which are the overall heat transfer coefficient and the dimensionless time function sets fix condition for heat transfer in the inclined section. Dimensionless time is to set the production time of flowing liquid, while overall heat transfer was focus on resistance of heat transfer. Thermal conductivity of cement were put into account in calculating the overall heat transfer because cement has low thermal conductivity which resist the heat conduction to the formation. However, thermal conductivity of steel for tubing and casing are neglected due to high thermal conductivity of steel, and the thermal resistance from liquid or condensing steam in the annulus can be ignored because of the high value of the corresponding heat transfer film coefficient. Figure below shows the travels of heat before it in contact with the formation:

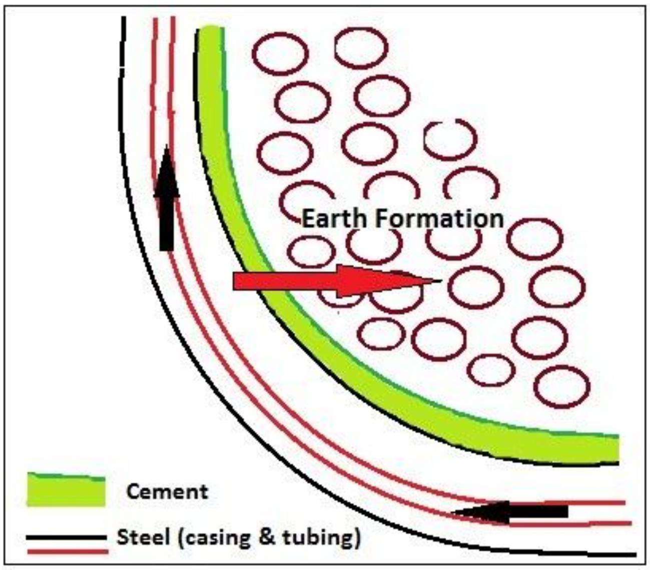

Figure 4: Heat transfer through tubing, annulus, casing and cement to earth formation

Flow of producing single-phase liquid was indicated with the black arrow. Temperature difference between liquid and geothermal temperature were allowing the transfer of heat, usually, geothermal temperature is lesser than liquid temperature, indicated by the red arrow shows the direction of heat transferred to formation.

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, results of temperature profiles along the build section with different trajectories are calculated. First, the inclination geometry of segments for each trajectory was obtained base on build section constant angle. Overall heat transfer coefficient and time function was also calculated to be used in the liquid temperature equation. Different flow conditions are tested while calculating the liquid temperature in the effort to find any factor that relates the rate of heat transfer between the liquid and geothermal temperature.

4.1 Inclination Geometry of build section for each constant angle

Segment	Depth, ft	Constant angle 45^o	Constant angle 25^o	Constant angle 10^o
1st	1400	10.52	1.98	0.68
2nd	1300	25.48	65.18	80.87
3rd	1200	33.40	67.13	81.55
4th	1100	39.85	69.05	82.23
5th	1000	45.51	70.95	82.91
6th	900	50.66	72.82	83.59
7th	800	55.45	74.68	84.27
8th	700	59.97	76.52	84.94
9th	600	64.30	78.34	85.62
10th	500	68.47	80.15	86.29
11th	400	72.53	81.96	86.97
12th	300	76.50	83.75	87.64
13th	200	80.40	85.54	88.32
14th	100	84.26	87.33	88.99
15th	0	88.09	89.11	89.66

Table 1: Inclination geometry for each constant angle of build section

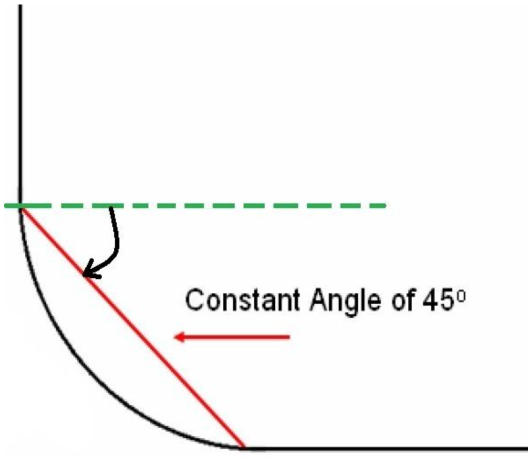

Figure 5: Build section with constant angle 45^o

Figure above shows constant angle 45^o of build section from positive x-axis line. Build section with constant angle is measured starting from the kick of point (KOP) until the first point of inclination become horizontal. Other constant angle (25^o and 10^o) can be handled in a manner similar to that presented here.

4.2 Temperature Profile along the Build Section with Different Trajectories under High flow rate

To determine the temperature profile along the build section with different trajectories, the target depth is fixed at 6742 ft and the depth of build section is between kick of point with the first lateral also maintain as showed by figure 6. This will provide same fluid temperature at the bottomhole so that we can see the difference of temperature profiles for each trajectory. Constant angle 10^o shows highest deviated well from the vertical and it also have the longest wellbore while 45^o constant angle is the least deviated among the three with the shortest wellbore length. Table 2 summarizes other important characteristics of the reservoir used. Temperature profiles for several constant angles (45^o, 25^o, and 10^o) were calculated under oil flow rate of 3000 STB/D, as shown in Figure 7, using equations 3.1 and 3.2.

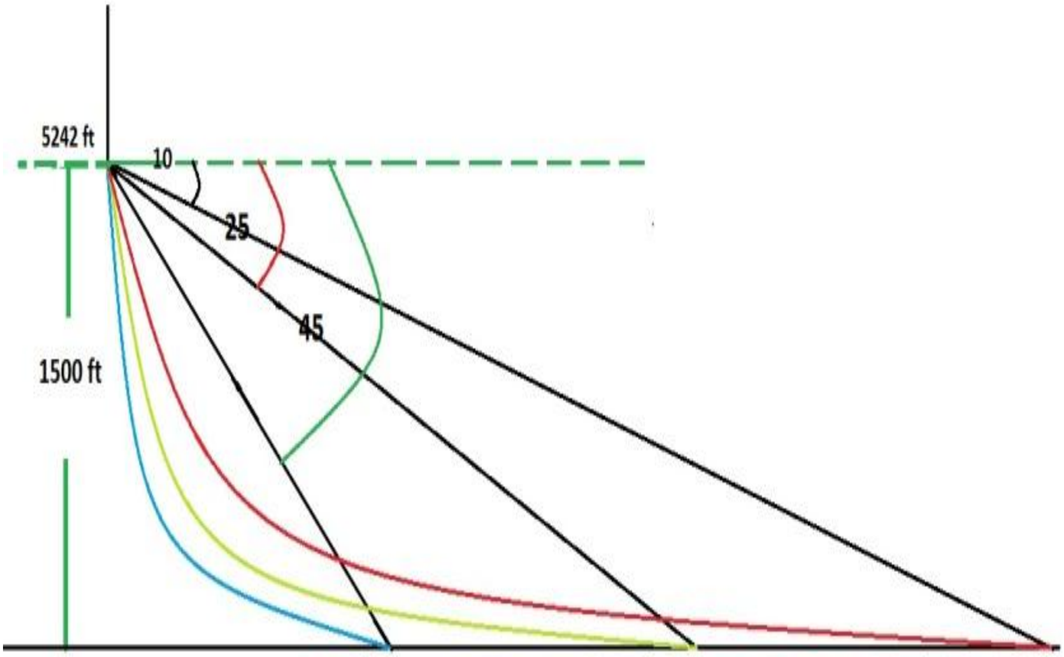

Figure 6: Constant angle 10°, 25°, and 45° at same target depth

Reservoir characteristic	**Values**
Geothermal gradient	0.0274 °F/ft
Oil heat capacity	0.485 Btu/lbm°F
Wellbore diameter	7.5 in
Outside casing diameter	5.5 in
Inside casing diameter	5.047 in
Thermal conductivity of cement	96.5 Btu/D ft °F
Thermal conductivity of earth	33.6 Btu/D ft °F
°API	35

Table 2: Main characteristics of the reservoir - Build section with different trajectories.

Temperature profile below shows that as the well deviation from the vertical increases, the temperature at the top of the build section decreases. This is because of the increased length of the wellbore in the build section as the deviation increases, which in turn increases the length of time for the relatively hot wellbore fluid to be cooled by the surrounding formation.

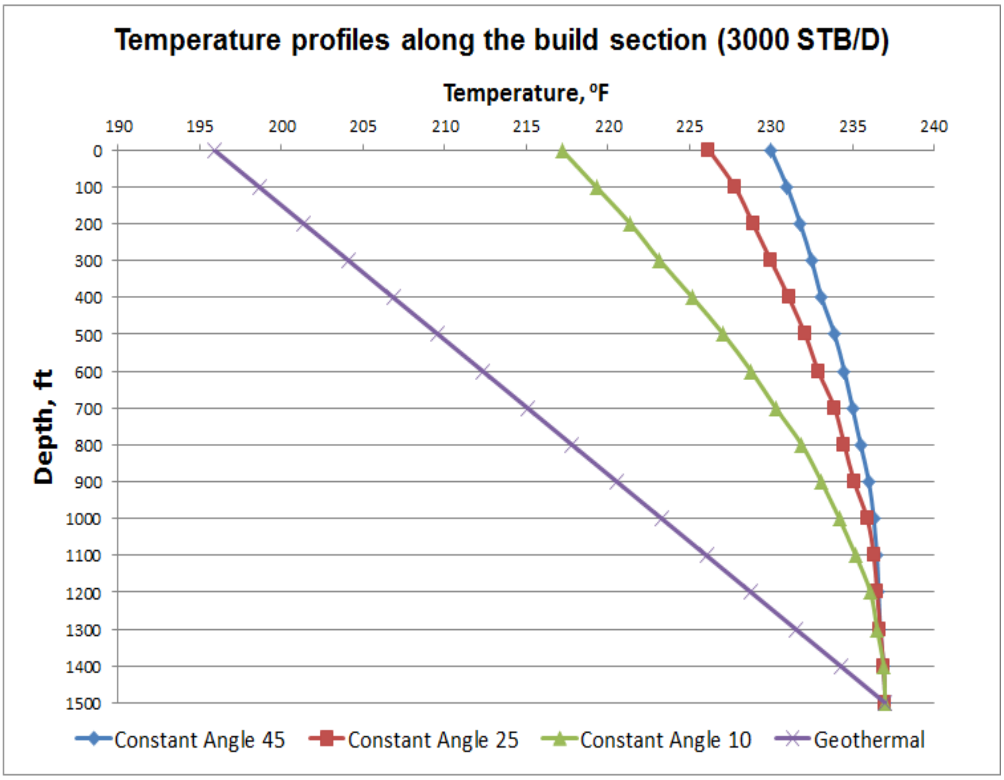

Figure 7: Temperature profiles for high production rate

Let see the difference of liquid temperature at bottomhole with the temperature at top of build section for each trajectory.

Depth location	Geothermal temperature (^{o}F)	45^o	25^o	10^o
Bottomhole (^{o}F)	237.2	237.2	237.2	237.2
Top of build section	196.01	230	226.2	217.2

Table 3: Comparison between liquid temperature at bottomhole and top of build section

Build section with constant angle 10^o with the longest wellbore gives more time for the liquid temperature to be cooled with surrounding contributing to highest rate of heat transfer. As a result, liquid temperature at the top of build section is the least among the three trajectories and shows highest heat loss to formation.

4.3 Temperature Profile along the Build Section with Different Trajectories under Low flow rate

To determine other factor which affects the temperature of fluid in the build-up, the rate of flowing liquid has reduced to relatively low rate condition. As a result, the temperature profile of low rate is shown on figure below:

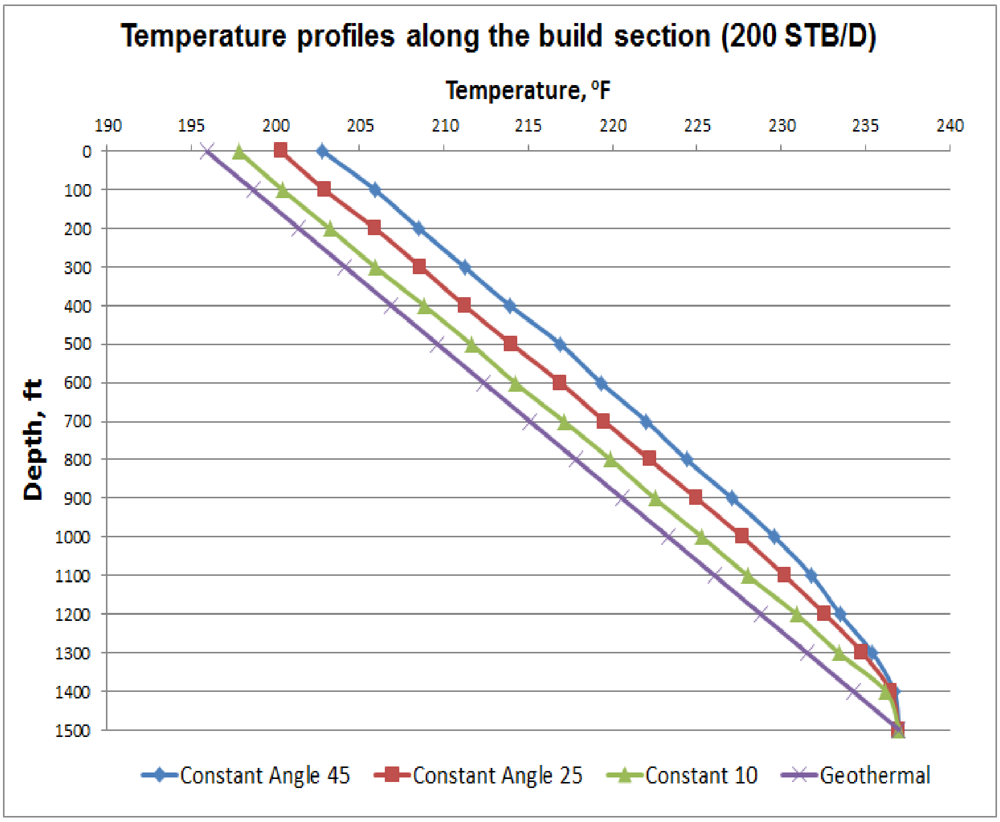

Figure 8: Temperature profile for low production rate

By changing the rate of production from 3000 STB/D to 200 STB/D, the temperature profile along the build section is significantly diminishes and approaching to the geothermal gradient. The differences between the initial liquid temperatures at bottomhole with the temperature at top of build section indicate that heat losses to formation are further when at the low rate. Regardless of well deviation factor, all observed well angle shows significant drop of fluid temperature at top of build section. This is due to the additional time for liquid temperature to be cooled with surrounding temperature. Low rate means the velocity of liquid to moving up is slower than liquid velocity at high rate, and contributes to extra time taken for the heat to transfer to the surrounding. Thus, reducing the temperature of liquid calculated in the build section. Higher heat transfer rate at high deviated well as the distance of wellbore on build section is longer.

4.4 Summary

Based on the results and discussions studied, several interesting observations are as follow:

i) When we consider the effect of deviation angles of the build section, we were able to calculate different temperature profiles for different constant angles in order to compare the effects of heat transfer due to length of wellbore factor and time travels.

ii) From the temperature profile too, effect of flow rate on the rate of heat transfer were also analyzed in this project. As a result, we were able to obtain different temperature profiles for high and low production rate. This means that the effect of different flow rates is significant and need to be taken into account.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The aim of this project to predict temperature profiles variable constant angle is achieved by calculating the liquid temperature in the build section. Extended Ramey's method has been used along with the consideration of overall heat transfer coefficient and time function has taken into account. Several assumptions on overall heat transfer and time function is based on the scope of this project that is single-phase liquid in production. Base on the results, it can be observed that the liquid temperature in the build section were influenced by two factors, which are the inclination angle of build up from vertical well and also the velocity of production flow rate. It can be conclude that, higher deviated well will have longer wellbore of build section, which then increase the time taken for heat transfer to loss into the formation. Velocity of flow rate also contributes to certain effect on the liquid temperature. High flow rate make less time for heat to transfer to surrounding, however, low rate provides more time for heat to transfer to surrounding, thus lead to less liquid temperature at the build section.

For future works in this project, the improvement and extension that author would suggest are:

i. Instead of using single-phase liquid to calculate the liquid temperature at the build section, we may also widen the scope of project to single-phase gas or even 2-phase production. In addition, the scope of project can also cover not only for production but also injection which lead to different consideration and assumptions on overall heat transfer.

ii. Determining the liquid temperature at the build-up section is a basic for further studies on heat transmission in multilateral well. Rather than calculating the liquid temperature in single well, the project can extend for dual-lateral that having a junction between the laterals. Temperature of mixed liquid at the junction can be studied base on several variables such as different flow rate at each laterals, different depth of each lateral and variety of well inclination. These factors were theoretically will affect the temperature of mixed liquids.

NOMENCLATURE

A = inverse relaxation parameter, ft

C_p = specific heat capacity, BTU/lbm^{o}F

$C1$ = integration constant

D = length of a discrete segment of build section, ft

$f(t)$ = time function, dimensionless

g = acceleration of gravity, 32.2 ft/s^2

g_c = conversion factor, 32.17 lbm-ft/lbf-s^2

g_G = geothermal gradient, ^{o}F/ft

H = enthalpy per unit mass, BTU/lbm

k_{cem} = conductivity of cement, Btu/hr-ft- ^{o}F

k_e = conductivity of earth or formation, Btu/hr-ft- ^{o}F

L = total measure of well depth, ft

p = pressure, psi

Q = heat transfer rate per unit length of wellbore, Btu/hr-ft

R = constant radius between the main wellbore and horizontal lateral,ft

r = radius, ft

t = production time, hr

T = temperature, ^{o}F

T_G = formation temperature at any radial distance, ^{o}F

T_{Gi} = formation temperature at initial condition, ^{o}F

T_{Gibh} = static formation temperature at the bottom hole, ^{o}F

T_f = fluid temperature, ^{o}F

$T_{f\,(known)}$ = last fluid temperature of final segment, ^{o}F

U = overall heat transfer coefficient, Btu/hr-ft^2- ^{o}F

v = fluid velocity, ft/s

w = mass flow rate of fluid, lbm/s

X = horizontal length of each discrete segment, ft

z = variable well depth from surface, ft

a = wellbore inclination with horizontal, degrees

g, l = angles between horizontals of each discrete segment, ft

r = density, lbm/ft^3

σ = thermal diffusivity, ft2/sec

SUBSCRIPTS

ci = casing inside

co = casing outside

to = tubing outside

wb = wellbore

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APPENDIX A

Derivation of liquid temperature at build section

In this appendix, derivation of equations describing the temperature in a variable angle build section was done by [6]Romero Lugo.

i) Build Section

To determine the temperature profile of a build section where the well inclination is changing, Ramey's[2] method has been extend to this flow geometry, as follows:

Applying an energy balance for a segment along the build section as a control volume as shown in figure below:

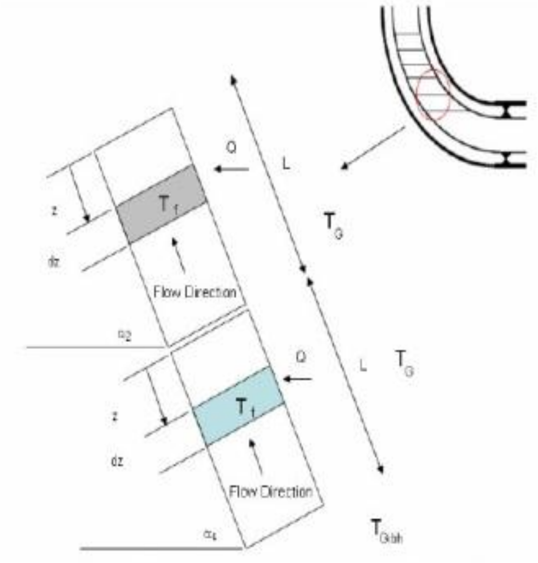

Figure 9: Control volume

yields

$$\frac{dH}{dz}+\frac{g\sin\alpha}{g_c J}+\frac{v}{g_c J}\frac{dv}{dz}=\pm\frac{Q}{w} \quad \text{……….. (i)}$$

the enthalpy is defined by

$$dH=C_p dT_f-C_j C_p dp \quad \text{………………(ii)}$$

by substituting equation (i) into (ii), become

$$\frac{dT_f}{dz}=C_J\frac{dp}{dz}+\frac{1}{C_p}\left[\frac{Q}{w}-\frac{g\sin\alpha}{Jg_c}-\frac{v}{Jg_c}\frac{dv}{dz}\right] \quad \text{……….. (iii)}$$

the heat flow through the completion can be represented as

$$Q = -2\pi r_{to} U_{to} \left(T_f - T_{wb} \right)$$ …………………….. (iv)

and the heat loss to the formation as

$$Q \equiv -\frac{2\pi k_e}{f(t)} \left(T_{wb} - T_{Gi} \right)$$ …………………….. (v)

combining equation (iv) and (v) yields

$$Q \equiv -\frac{wC_p}{A} \left(T_f - T_{Gi} \right)$$ …………………….. (vi)

Where A is define as

$$A = \left(\left(\frac{2\pi}{wC_p} \right) \left[\frac{r_{ci} U k_e}{k_e + r_{ci} U f(t)/12} \right] \frac{1}{86400 \times 12} \right)^{-1}$$ ………………….. (vii)

Substituting equation (vi) into (iii) becomes (viii)

$$\frac{dT_f}{dz} = \frac{\left(T_f - T_{Gi} \right)}{A} - \frac{g \sin\alpha}{C_p J g_c} - \frac{v}{C_p J g_c} \frac{dv}{dz} + C_J \frac{dp}{dz}$$ ……………… (viii)

ii) Single-phase liquid

The following assumptions were made in order to develop the equation for single-phase liquid

- incompressible fluids
- kinetic energy becomes negligible
- flowing friction becomes negligible
- radiation and convection coefficients are negligible and can be ignored for the calculation of overall heat transfer. In addition, steel has a high thermal conductivity, the thermal resistance of the pipe and casing are negligible as compared to the thermal resistance of the material in the casing.

For single phase liquid flow, the static head loss nearly equals the total pressure gradient.

$$\frac{dp}{dz} = \rho \left(\frac{g}{g_c} \right) \sin\alpha$$ ………………... (ix)

Liquid density variation with pressure is usually very small, so the Joule-Thomson coefficient can be defined as

$$C_j \equiv \frac{1}{C_p}\left[\frac{\partial H}{\partial p}\right]_T = \frac{V}{C_p} = \frac{1}{\rho C_p}$$ ……………………………….. (x)

and the final energy balance becomes

$$\frac{dT_f}{dz} = \pm\frac{\left(T_f - T_{Gi}\right)}{A}$$ ………………………………. (xi)

where

$$T_{Gi} = T_{Gibh} - \left(L - z\right)g_G \sin\alpha$$ …………………. (xii)

Substituting equation (xii) into (xi), the equation becomes

$$\frac{dT_f}{dz} = \frac{1}{A}\left\{T_f - \left[T_{Gibh} - \left(L - z\right)g_G \sin\alpha\right]\right\}$$ ……………. (xiii)

Solving the first-order linear differential equation with the integration factor method yields

$$T_f = T_{Gi} + A g_G \sin\alpha + C_1 \exp\frac{\left(z - L\right)}{A}$$ ……………. (xiv)

$$T_f = T_{Gibh} - \left(L - z\right)g_G \sin\alpha + A g_G \sin\alpha + C_I \exp\frac{\left(z - L\right)}{A}$$ ……… (xv)

iii) Boundary Conditions for Single-Phase Liquid

For fluid coming from the formation at the bottom hole location (z=L) fluid temperature and geothermal temperature are the same ($T_f = T_{Gibh}$). The integration constant for this boundary condition yields

$$C_I = -A g_G \sin\alpha$$ ……………. (xvi)

Substituting equation (xvi) into (xv), the equation becomes

$$T_f = T_{Gibh} - g_G \sin\alpha\left[\left(L - z\right) - \left(1 - \exp\left(\frac{\left(z - L\right)}{A}\right)\right)A\right]$$ ……………. (xvii)

For other segments, the initial fluid temperature is equal to the last fluid temperature of the last segment.

$C_I = T_f(known) - T_{Gi} - Ag_G \sin\alpha$ ……………. (xviii)

Substituting equation (xviii) into (xiv), the equation becomes

$T_f = T_{Gi} + Ag_G \sin\alpha + \left[T_f(known) - T_{Gi} - Ag_G \sin\alpha\right] \exp\frac{(z-L)}{A}$ .... (xix)

iv) Overall Heat Transfer Coefficient for Casing Flow

The radiation and convection coefficients are negligible and can be ignored for the calculation of overall heat transfer. Also, because steel has a high thermal conductivity, the thermal resistance of the casing is negligible as compared to the thermal resistance of the casing, so the heat transfer coefficient is

$U = \frac{12}{r_{ci}}\left[\frac{\ln(r_{wb} / r_{co})}{k_{cem}}\right]^{-1}$ ………………………….. (xx)

APPENDIX B

GEOMETRY OF THE BUILD SECTION

The build section geometry was calculated assuming a constant radius of curvature between the horizontal wellbore and the main wellbore by a number of discrete wellbore increments of same the length, each having a constant angle. As a result, the build section presents variable inclination geometry, as shown in Figure 10. Other trajectories can be handled in a similar manner to the one presented here.

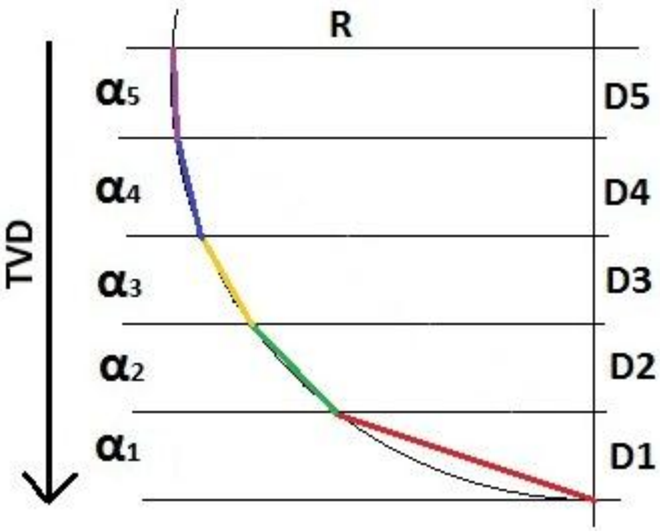

Figure 10: Geometry of build section

i) Angle from Each Segment

For the first discrete segment, in order to calculate the length of segment X1, the angle β was calculated using the equations (i) and (ii) from trigonometric definitions, as shown in Figure 11.

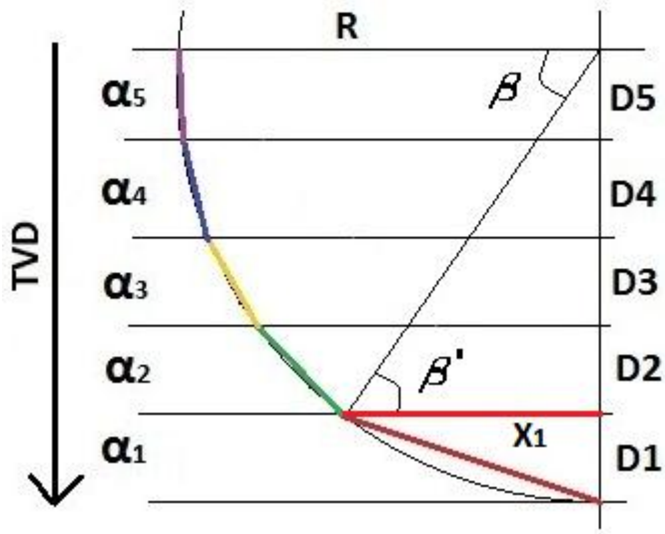

Figure 11: Demonstration on how to calculate segment X1

$$Sin(\beta) = \frac{D_6 + D_5 + D_4 + D_3 + D_2}{R}$$ ………………. (i)

$$\beta = \arcsin\left(\frac{D_6 + D_5 + D_4 + D_3 + D_2}{R}\right)$$ …………….. (ii)

Also, angles β and β’ are the same as that which is shown in Figure 11,

$$\beta = \beta'$$ ………………… (iii)

So, the length of X1 can be approximated by

$$X_1 = \cos(\beta') \times R$$ ……….. (iv)

After calculating the length of segment X1, the calculations necessary to obtain the angle γ are based on knowing both lengths X1 and D1, and on using the definition of a tangent as follows (and is illustrated in Figure12):

$$\tan(\gamma) = \frac{D_1}{X_1}$$ .... (v)

$$\gamma = \arctan\left(\frac{D_1}{X_1}\right)$$ …………….. (vi)

Knowing that the sum of the angles inside a triangle must be 180 degrees, and also knowing the value of two of the three angles (γ and 90 degrees), the angle λ can be calculated as follows:

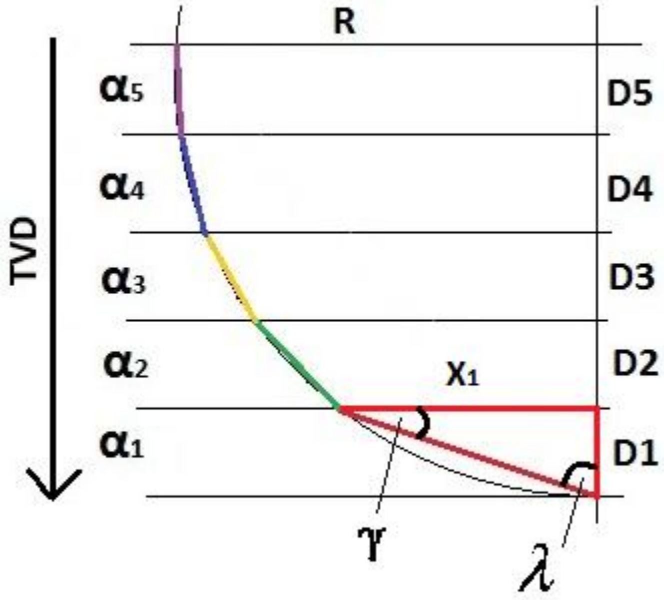

Figure 12: Demonstration on how to calculate angle λ

$\lambda = 180 - (\gamma + 90)$ ……………. (vii)

Yielding the solution for α_1 as

$\alpha_1 = 90 - \lambda$ ………………….. (viii)

For other discrete segments, the procedure to determine the length of segment X2 is the same as the one used to calculate the length of segment X1, but because the model was developed beginning with the lowest segment connected to a horizontal lateral, one of the distances of the triangle gets smaller as we move up. This can be seen in Figure 13. Also, the procedure is repeated in order to calculate the other lengths, X3, X4, etc. Until we get to the last segment.

$Sin(\beta) = \frac{D_6 + D_5 + D_4 + D_3}{R}$ ……………. (ix)

$\beta = \arcsin\left(\frac{D_6 + D_5 + D_4 + D_3}{R}\right)$ …………… (x)

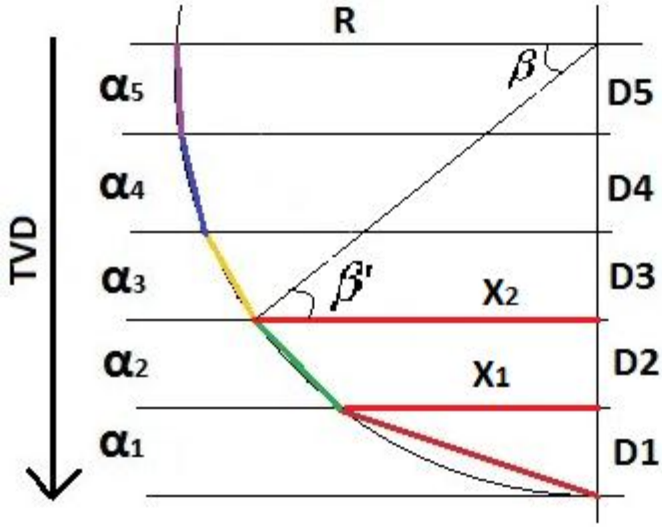

Figure 13: Demonstration on how to calculate segment X2

Also, angles β and β’ are the same, as shown in Figure B-4.

$\beta = \beta'$ ……… (xi)

So, the length of X2 can be approximated by

$X_2 = \cos(\beta') \times R$ ………….. (xii)

After calculating the length of segment X2, the calculations to obtain the angle τ_1 are based on knowing both lengths (X2-X1) and D2, and using the definition of a tangent as follows (and is illustrated in Figure 14):

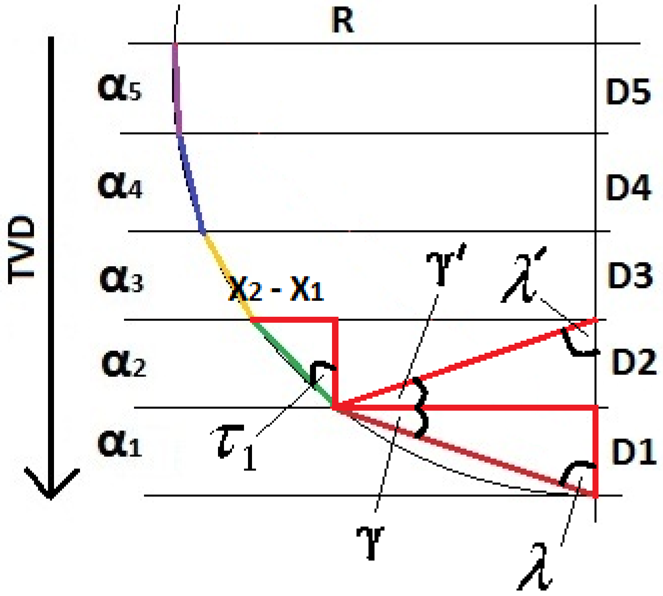

Figure 14: Demonstration on how to calculate the angle τ_1

$$\tan(\tau_1) = \frac{X_2 - X_1}{D_2} \quad \text{...............} \text{(xiii)}$$

$$\tau_1 = \arctan\left(\frac{X_2 - X_1}{D_2}\right) \quad \text{...............} \text{(xiv)}$$

Yielding the solution for α_2 as,

$$\alpha_2 = (90 - \tau_1) \quad \text{........................} \text{(xv)}$$

This procedure was repeated for all discrete segments until we reached the final segment.

VITA

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