PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Numerical Approach for Temperature Estimation in Geothermal Drilling Operation

Heneka Yoma Priyangga, Auzan Abirama Soedarmo, Konark Ogra and Aliya Zhabagina

Graha PDSI Jln. Matraman Raya No. 87 Jakarta- Indonesia

heneka@utulsa.edu, heneka.priyangga@pertamina.com

Keywords: Temperature, Drilling, Numerical

ABSTRACT

Temperature affects various drilling considerations such as mud properties, wellbore stability, and bottom-hole assembly design. As opposed to an analytical solution, the numerical approach enables temperature profiling in wellbores involving complex trajectory, multiple tubular strings and formations, non-constant fluid properties, and Herschel-Buckley (YPL) rheology. The wellbore is discretized into grids in which piece-wise thermal hydraulics calculations are performed from top to bottom. Since fluid properties change with temperature, both annular and drill pipe fluid temperature have to be solved simultaneously. A wellbore trajectory and temperature profiling program is developed in C++. The program has been satisfactorily tested against arbitrary wellbore and data from reference publications.

1. INTRODUCTION

Wellbore temperature profile program is developed based on the conduction and convection heat transfer theory. The program extends available analytical solutions by considering complex wellbore trajectory, multiple casing strings and formations, and temperature dependent YPL fluid.

Wellbore temperature profile is developed using two main assumptions, namely: steady state heat transfer from wellbore wall to drilling fluids (Holmes & Swift, 1970), and transient heat transfer from the formation to wellbore wall (Kabir et al., 1996). In this work, formation temperature gradient, wellbore tubular design and thermal properties, drilling fluid properties (density and rheology) and circulation rate have to be known/ pre-calculated. Heat transfer equation is presented in three integrated parts, namely: between annulus and drill pipe, between annulus and wellbore wall, and between formation and wellbore wall.

Illustration of heat transfer layers involved during drilling operation is shown in figure 1 and 2.

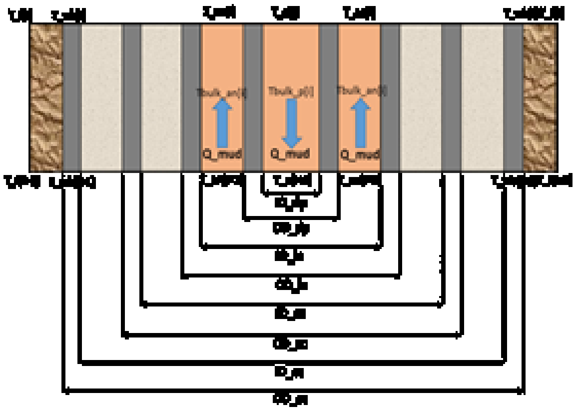

Figure 1: The figure above is Overall illustration of heat transfer layers involved during drilling operation

The governing energy equations between annulus and drill pipe fluid are shown in equation 1 to 3.

$$Q_{in} = U_{in}\,\pi\,OD_{dp}\,\Delta S\,\left(T^{i}_{b,an} - T^{i}_{b,p}\right) \tag{1}$$

$$Q_{in} = M_m\,Cp_{m,p}\,\left(T^{i+1}_{p} - T^{i}_{p}\right) \tag{2}$$

$$\frac{1}{U_{in}} = OD_{dp}\left[\frac{1}{h_p ID_{dp}} + \frac{\ln\left(\frac{OD_{dp}}{ID_{dp}}\right)}{2\,k_p} + \frac{1}{h_{an} OD_{dp}}\right] \tag{3}$$

Equation 4 to 6 describe heat balance equation between wellbore wall and annular fluid.

$$Q_o = U_o\,\pi\,OD_{cc}\,\Delta S\,\left(T_{wb}^i - T_{b,an}^i\right) \tag{4}$$

$$Q_o - Q_{in} = M_m\,Cp_{m,an}\,\left(T_{an}^{i+1} - T_{an}^i\right) \tag{5}$$

$$\frac{1}{U_o} = OD_{cc}\left[\frac{1}{h_{an} ID_{ic}} + \frac{\ln\left(OD_{ic}/ID_{ic}\right)}{2k_p} + \frac{\ln\left(ID_{sc}/OD_{ic}\right)}{2k_{cm}} + \frac{\ln\left(OD_{sc}/ID_{sc}\right)}{2k_p} + \frac{\ln\left(ID_{cc}/OD_{sc}\right)}{2k_{cm}} + \frac{\ln\left(OD_{cc}/ID_{cc}\right)}{2k_p}\right] \tag{6}$$

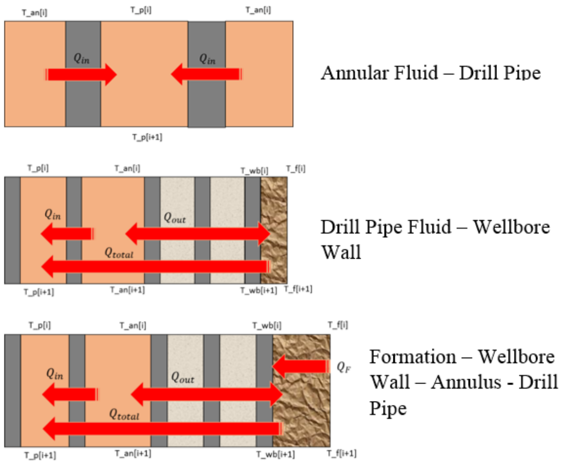

Figure 2: The figure above is Segmented heat transfer involved in drilling

Equation 7 to 8 describe the heat balance equation between formation and wellbore wall. The value of T_D is obtained from transient formulation from Hasan and Kabir (1994).

$$Q_F = U_F\,\Delta S\,\left(T_f^i - T_{wb}^i\right) \tag{7}$$

$$U_F = 2\pi k_e / T_D \tag{8}$$

Equation 9 to 11 describe the overall heat balance equation between wellbore fluid and formation.

$$Q_{ov} = \pi OD_{cc}\Delta S\,U_{ov}\left[\frac{k_e}{k_e + \frac{OD_{cc}}{2}U_{ov}T_D}\right]\left(T_f^i - T_{b,p}^i\right) \tag{9}$$

$$T_{b,p}^i = \frac{T_p^i + \frac{U_{ov}\pi\,D_{wb}\Delta S}{2\,M_m\,Cp_m}\left(\frac{k_e}{k_e + U_{ov}\,T_D\frac{D_w}{2}}\right)T_f^i}{1 + \frac{U_{ov}\,\pi\,D_{wb}\,\Delta S}{2\,M_m\,Cp_m}\left(\frac{k_e}{k_e + U_{ov}\,T_D\frac{D_{wb}}{2}}\right)} \tag{10}$$

$$\frac{T_{b,an}^i}{\pi\Delta S} = \frac{\frac{2T_{an}^i}{\pi\Delta S} + \left[\frac{U_{in}OD_{dp}\,T_{b,p}^i}{M_m Cp_m} + \frac{U_o D_{wb} T_f^i}{M_m Cp_m}\left(\frac{2k_e}{2k_e + U_{out}\,T_D D_{wb}}\right)\right]}{\frac{2}{\pi\Delta S} + \left[\frac{U_{in}OD_{dp}}{M_m Cp_m} + \frac{U_o D_{wb}}{M_m Cp_m}\left(\frac{2k_e}{2k_e + U_{out}\,T_D D_{wb}}\right)\right]} \tag{11}$$

YPL fluid hydrodynamics calculation is performed to obtain convective heat transfer coefficient. Empirical correlations are included to consider properties variation with temperature. Correlations included in this work are McMordie Jr. et al., (1982), Santoyo et al., (2001), and Santoyo et al., (2003). YPL fluid hydrodynamics in the annulus is solved using narrow slot approximation (Mitchell and Miska, 2011). The calculation procedures are shown in equation 12 to 14 for annulus and 13, 15, and 16 for drill pipe.

$$\frac{12v}{D_h} = \left[\frac{(\tau_w - \tau_y)^{\frac{(1+n)}{n}}}{K^{\frac{1}{n}}\,\tau_w{}^2}\right]\left(\frac{3n}{1+2n}\right)\left(\tau_w + \frac{n\,\tau_y}{1+n}\right) \tag{13}$$

$$Re = \frac{12\,\rho\,v^2}{\tau_w} \tag{14}$$

$$\mu_a = \frac{\tau_w}{\left(\frac{12v}{D_h}\right)}\frac{3n}{1+2n}\left[1 - \left(\frac{1}{1+n}\right)\frac{\tau_y}{\tau_w} - \left(\frac{n}{1+n}\right)\frac{\tau_y{}^2}{\tau_w{}^2}\right] \tag{15}$$

$$\frac{8v}{ID_{dp}} = \frac{(\tau_w - \tau_y)^{\frac{1+n}{n}}}{k^{\frac{1}{n}}\,\tau_w{}^3}\left(\frac{4n}{3n+1}\right)\left[\tau_w{}^2 + \left(\frac{2n}{1+2n}\right)\tau_y\tau_w + \left[\frac{2n^2}{(1+n)(1+2n)}\right]\tau_y{}^2\right] \tag{16}$$

$$\mu_a = \frac{\tau_{w\,D}}{8v}\left(\frac{4n}{1+3n}\right)\left[1 - \left(\frac{1}{1+n}\right)\left(\frac{\tau_y}{\tau_w}\right) - \left(\frac{n}{1+n}\right)\left(\frac{\tau_y}{\tau_w}\right)^2\right] \tag{17}$$

2. DATA AND METHOD

This calculation program is developed using marching algorithm from top to bottom. Simultaneous solution of drill pipe and the annular fluid temperature is required due to the temperature dependency of fluid properties. The overall algorithm is shown in figure3. Newton-rhapson method is used to solve YPL fluid hydrodynamics (equation 16 and 19). All the codes including wellbore trajectory code are written in C++.

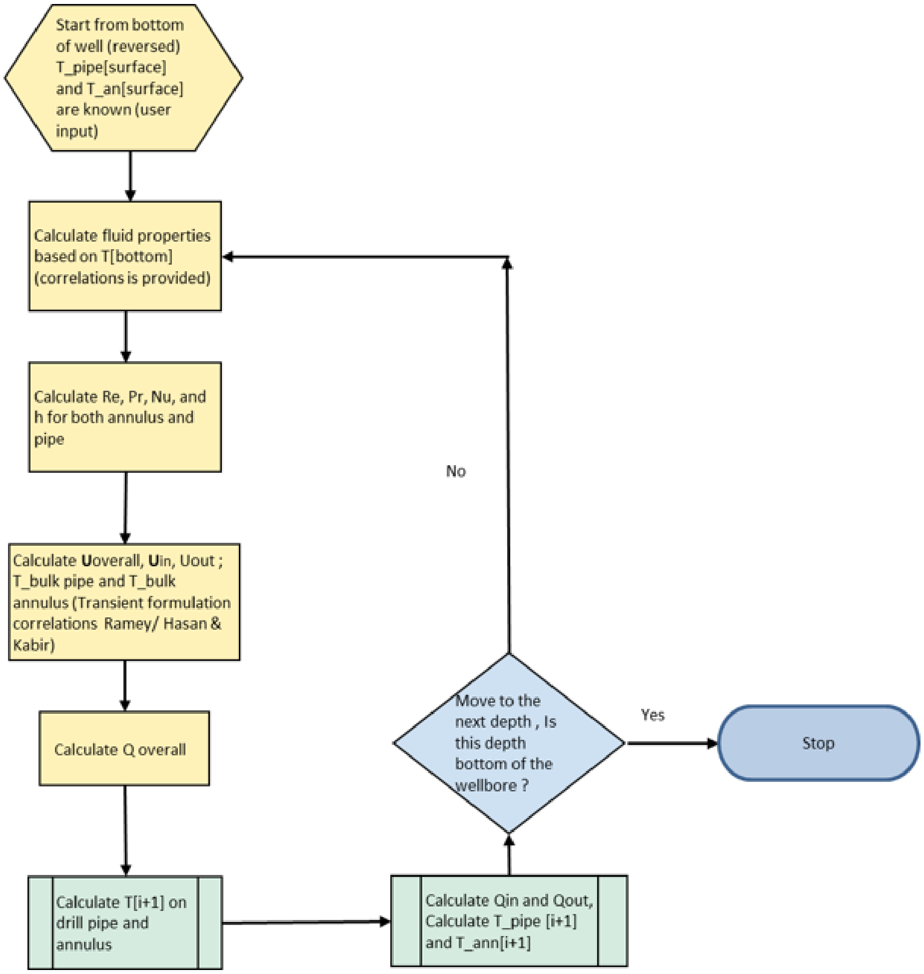

Figure 3: The figure above is Temperature Profile Algorithm

The temperature of the fluid both annular and drill pipe at the surface have to be specified in this algorithm. Over specification may result in bottom annular and drill pipe temperature discrepancy if the surface temperature inputs are completely arbitrary. The discrepancy is not significant if the input values are based on actual data. To minimize this discrepancy, the iterative approach is implemented to find best fit annular surface temperature value.

The program is tested against two type of wellbores. The first wellbore is a deviated shallow well, and the second one is an arbitrary deep vertical wellbore. The first wellbore trajectory is taken from Justad and Gaskin (1994) and shown in figure-4. Table-1 shows the formation, tubular design, and circulation data.

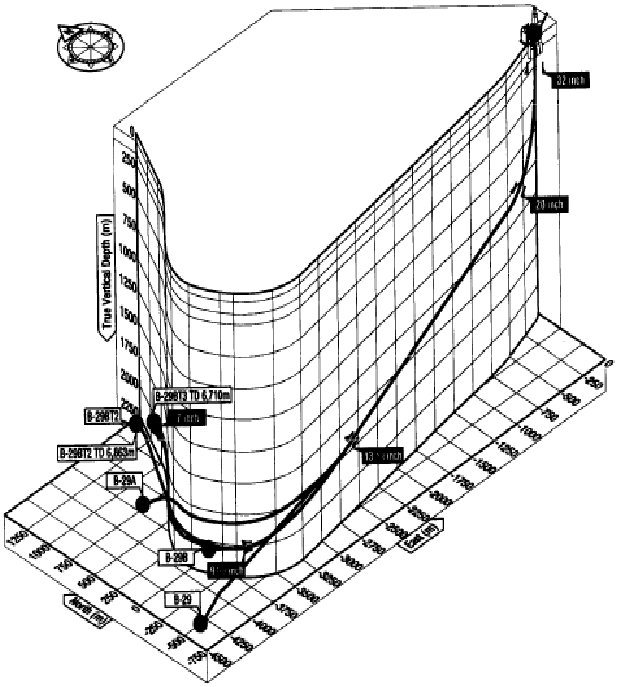

Figure 4: The figure above is Complex wellbore trajectory taken as reference data (Justad and Gaskin,1994)

Table-1. Formation, tubular design, and circulation data

Tubular Design Data		
Part	Depth (ft)	Size (OD x ID)
Conductor	200	20” x 18-1/8”
Surface	1500	13-5/8” x 13”
Intermediate	3200	9-5/8 ”x 8-3/8”
Drill pipe	6154	5” x 4.5”
Formation Data		
Layer	Type	Thickness (ft)
1	Sandstone	600
2	Dolomite	600
3	Shale	600
4	Limestone	600
5	Others	600
Mud Circulation Data		
Flowrate (US GPM)		750
Density (ppg)		13
Power law index		0.75
Consistency index		0.09
Pipe surface temperature (°K)		298
Annular surface temperature (°K)		303

3. RESULT AND DISCUSSION

Results of temperature profiling for both wellbore trajectories are shown in figure-5 and figure-6. The profiles show reasonable temperature profile pattern with following considerations:

- Drill pipe temperature is observed to be increasing over depth.
- Discontinuities are observed at the casing shoe depths or formation transitions.

- Observed regions where the annular fluid temperature is higher than formation, proving that possibility of two-ways heat transfer is considered in the program.
- Inflection point observed in the annulus, at the depth below which the heat transfer between formation and annulus is more dominant than heat transfer between the annulus and drill pipe.
- For deviated well, temperature profile at lateral section shows substantial change despite not having substantial TVD increment.

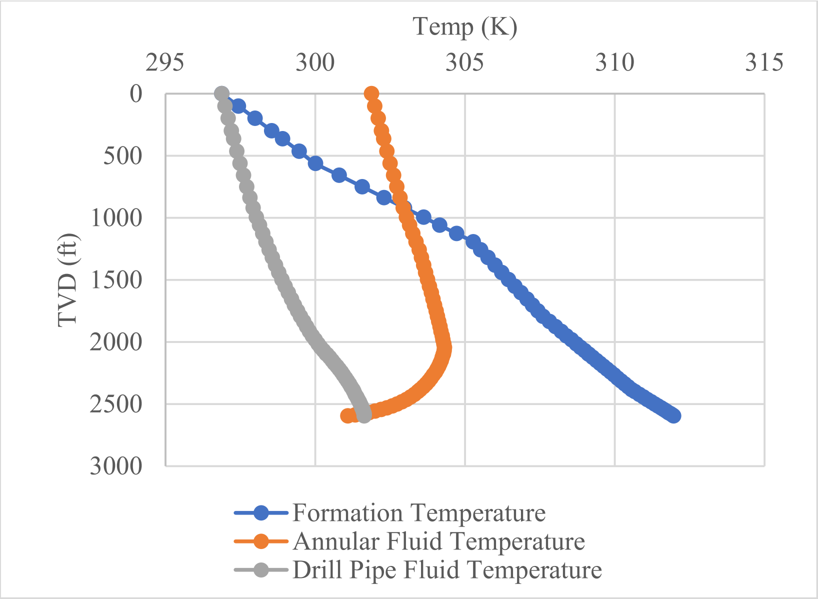

Figure 5: The figure above is Temperature profile results for deviated well

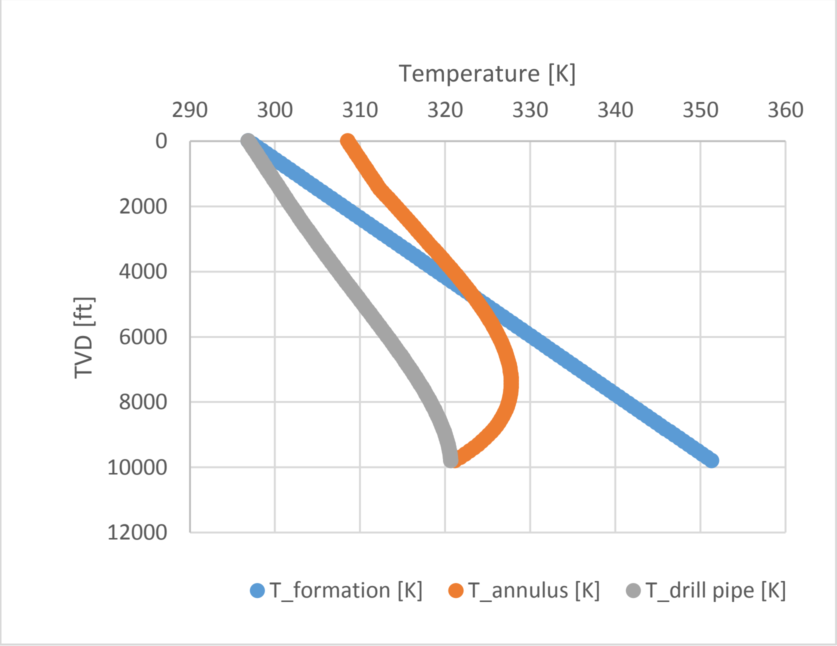

Figure 6: The figure above is Temperature profile results deep vertical well.

4. CONCLUSSION

- Wellbore trajectory and temperature profiling program are developed
- Extended analytical solutions for wellbore temperature profile
    - Complex trajectory and fluid rheology
    - Multiple formation and casing string
- Reasonable results obtained

  - Wellbore trajectory results are compared with paper and field data
  - Temperature profiles are obtained for complex deviated and deep vertical well
  - Inflection point for annular fluid temperature is observed
  - Regions where the temperature of drilling mud is higher than formation can be obtained
- Future improvements
  - Full flexible casing design, fluid properties correlation, and transient formulation

REFERENCES

Hasan, A., & Kabir, C., 1994, Aspects of Wellbore Heat Transfer During Two-Phase Flow, SPEPF, 211.

Holmes, C., & Swift, S., 1970, Calculations of Circulating Mud Temperatures. JPT, 670.

McMordie Jr., W., Bland, R., & Hauser, J., 1982, Effect of Temperature and Pressure on Density of Drilling Fluids. 57th Annual Fall Technical Conference and Exhibition of the SPE, Dallas.

Mitchell, R. F., & Miska, S. Z., 2011, Fundamentals of Drilling Engineering. Richardson: SPE.

Ramey Jr., H. 1962, Wellbore Heat Transmission. JPT, 427.

Santoyo, E., Garcia, A., Espinosa, S., Santoyo-Gutierez, S., & Gonzales-Partida, E., 2003, Convective Heat Transfer Coefficients of non-Newtonian Geothermal Drilling Fluids. Journal of Geochemical Exploration, 249-255.

Santoyo, E., Santoyo-Gutierrez, S., Garcia, A., Espinosa, G., & Moya, S., 2001, Rheological Property Measurement of Drilling Fluids Used in Geothermal Wells, Applied Thermal Engineering, 283-302.

NOMENCLATURES

Cp_m	Drilling mud Heat Capacity [J/kg-K]
D_h	Hydraulic diameter [m]
D_{wb}	Wellbore diameter [m]
h	Convective heat transfer coefficient [W/m^2-K]
M_m	Mass flowrate of the mud [kg/s]
k	Thermal conductivity [W/m-K]
ID_{cc}	ID of conductor casing [m]
ID_{dp}	ID of drill pipe [m]
ID_{ic}	ID of intermediate casing [m]
ID_{sc}	ID of surface casing [m]
k_{cm}	Cement thermal conductivity [W/m-K]
k_p	Thermal conductivity of drill pipe or casing material [W/m-K]
K	Drilling fluid consistency index
n	Drilling fluid power law index
OD_{cc}	OD of conductor casing [m]
OD_{dp}	OD of drill pipe [m]
OD_{ic}	OD of intermediate casing [m]
OD_{sc}	OD of surface casing [m]
Q_F	Heat transfer formation to wellbore wall [W]

Q_i	Heat transfer annular fluid to drill pipe fluid [W]
Q_o	Heat transfer annular fluid to wellbore wall [W]
Q_{ov}	Total heat transferred [W]
Re	Reynolds Number [-]
$T_{b,p}^i$	Bulk drill pipe fluid temperature in control volume [K]
$T_{b,an}^i$	Bulk annular fluid temperature in control volume [K]
T_f^i	Average formation at the control volume [K]
T_p^i	Drill pipe fluid temperature upstream of control volume [K]
T_p^{i+1}	Drill pipe fluid temperature downstream of control volume [K]
T_{an}^{i+1}	Annular fluid temperature upstream of control volume [K]
T_{an}^i	Annular fluid temperature downstream of control volume [K]
U_F	Heat transfer coefficient from formation to wellbore wall [W/m^2-K]
U_i	Heat transfer coefficient annular fluid to drill pipe fluid [W/m^2-K]
U_o	Heat transfer coefficient between annular fluid and wellbore wall [W/m^2-K]
U_{ov}	Overall heat transfer coefficient [W/m^2-K]
v	Fluid velocity [m/s]

Greek Symbols

ΔS	Change in measure depth [m]
μ	Fluid viscosity [Pa.s]
μ_a	Drilling mud apparent viscosity [Pa.s]
γ	Shear rate [1/s]
τ_w	Shear stress at pipe/ annulus wall [Pa]
τ_Y	Yield point of drilling mud [Pa]
τ	Shear stress [Pa]
ρ_m	Density of the mud [kg/m^3]