New wellbore temperature control design for preventing failure and poor performance of logging tools in high pressure – high temperature wells

William Ejuvweyemer Odiete

Department of Petroleum Engineering, Delta State University, Abraka Oleh Campus, Oleh, Delta state, Nigeria

A R T I C L E   I N F O

Keywords:
Logging tools
Chilled oil-based mud
Temperature control
Heat transfer
Thermal drainage radius
Temperature-drop

A B S T R A C T

Failure and poor performance of logging tools in high pressure-high temperature wells; the associated technical consequences and the resultant high cost of logging operations are recurrent problems in the oil & gas industry worldwide. The aforesaid prompted this work to invent the “New Wellbore Temperature Control Design” for protection of logging tools against high bottom-hole temperatures. It hinges on the novel concept of thermal drainage radius and the temperature-drop effect of chilled oil-based mud to reduce bottom-hole temperature prior to logging. The methods applied include laboratory testing, mathematical modeling and design. The novel concept of “thermal drainage radius” quantified the radial extent of temperature-drop effect in the formation, away from the wellbore. Novel mathematical models were also invented. Laboratory results showed that the formation temperature-drop from bottom-hole temperature to thermal equilibrium temperature increased with bottom-hole temperature per chilled oil-based mud. The temperature-drop duration and temperature-rise duration increased with bottom-hole temperature per chilled oil-based mud. The temperature-rise duration increased with decrease in the temperature of the chilled oil-based mud per bottom-hole temperature. Job design results showed that when placed in the zone of interest in the wellbore the heat energy absorbed increased with quantity of the chilled oil based mud but the temperature rise duration decreased with increasing heat transfer rate from the formation and vice versa. Furthermore, results revealed that the higher the thermal conductivity of the formation, the longer the thermal drainage radius and vice versa. The logging operation should commence after placement of the chilled oil-based mud in the zone of interest (no circulation of the chilled oil-based mud) and be completed before the end of the temperature-rise duration. Oil-based mud is cheap and available in every country unlike the expensive vacuum flasks and thermal insulating jackets currently used for protecting logging tools against high temperature. The new wellbore temperature control design has global applicability.

1. Introduction

Failure and poor performance of logging tools in high pressure-high temperature (HPHT) wells coupled with the technical consequences and the resultant high cost of logging operations are recurrent problems in the oil & gas industry worldwide. Failure and poor performance of logging tools can lead to downtime, loss of revenue, high cost of logging operations, incomplete data acquisition; inaccurate data acquisition; bypassed oil & gas reserves; under-estimation or over-estimation of oil & gas reserves; under recovery, increased uncertainty in the estimation of oil & gas reserves in HPHT reservoirs.

Salim and Amani (2013) stated that HPHT projects increased during the past decade in the USA, Gulf of Mexico, Indonesia, North Sea, Norwegian Sea and Thailand but improved technologies are required to overcome the associated challenges. Yetunde and Ogbonna (2011) asserted that the continued depletion of conventional oil & gas reserves has pushed the Nigerian oil & gas industry into high temperature - high pressure environments but new technologies are imperative. Schlumberger (1998) stated that conventional logging tool electronics fail in HPHT wells, so new technologies are required to meet the ever-increasing demand of the HPHT hostile environment. Innovative Drilling (2007) stated that to develop and produce hydrocarbons from high pressure, high temperature reservoirs, the oil and gas industry requires new formation evaluation technologies designed to withstand the harsh environment. The adverse effects of hostile high bottom-hole temperature is not peculiar to logging tools as Elzeghaty et al. (2007) reported that high temperature variation in HPHT wells affects the expansion and contraction of casing and possibly resulting to the cracking of set cement.

E-mail address: williamodiete@gmail.com.

https://doi.org/10.1016/j.heliyon.2022.e09404
Received 22 July 2021; Received in revised form 31 December 2021; Accepted 5 May 2022

2405-8440/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
High pressure – high temperature wells have bottom-hole temperatures in the range of 300 °F (422.04 K) to 400 °F (477.59 K) and higher or bottom-hole pressures in the range of 10000 psi (68947600 Pa) to 20000 psi (137895200 Pa) and higher but this threshold is based on the behavior of standard elastomeric seals that must be replaced before re-using the tools in HPHT wells (Schlumberger, 2008). Relatively, considerable success has been recorded in containing the effect of high pressure on logging tools but equivalent progress has not been made in combating the hostile effect of high temperature on logging tools in the HPHT environment. This calls for research on immediate and long-term solutions to improve well logging measurements. Schlumberger (1998) stated that HPHT wells require formation evaluation services that push the limits of conventional logging tool technologies as conventional logging tool electronics fail and tool sensor responses are impaired at high temperatures. The urgency of the matter was re-echoed by Schlumberger (2008) when it wrote that limited capability in formation evaluation is currently being experienced in the HPHT environment of the oil & gas industry as electronic components, sensors and seals are particularly vulnerable at high temperatures and that the stability of the plastic and composite materials that provide modern electronics with structural integrity and insulation is also a major concern at high temperatures.

The current methods used to protect logging tools in HPHT wells include: (i) use of thermal insulating jackets and (ii) use of vacuum flasks (Schlumberger, 2008). Thermal insulating jackets and vacuum flasks are very expensive and not readily available, especially in developing countries. The use of vacuum flasks and thermal insulating jackets are also problematic. Therefore, alternative methods are required. Thermal insulating jackets are liable to damage, failure, corrosion, stress-cracking and heat leakage. Corrosionpedia (2015) stated that corrosion of steel caused by thermal insulation of pipes and other equipment are severe and it remains hidden under the thermal insulation jacket until it gets worse and causes equipment failure, accident or shutdown. Wikimedia Inc. (2021) stated that vacuum flasks are prone to failure, physical damage; implosion hazards and they can rupture due to differential thermal expansion between their inner and outer walls. EP1945094B1 (2017) stated that various approaches have been attempted to keep logging tool temperature below the maximum electronic operating temperature but no known technique has been adequately satisfactory including incorporating logging tools inside vacuum insulated Dewar flask e.g., the Boesn device.

To prevent failure and poor performance of logging tools, this research work invented the “New Wellbore Temperature Control Design” based on the novel concept of thermal drainage radius and the temperature-drop effect of chilled oil-based mud to reduce bottom-hole temperature prior to logging. It involves providing a chiller on the Rig or location to chill the oil-based mud to the required cold temperature before placing the chilled oil-based mud in the zone of interest; in the wellbore (no circulation of the chilled oil-based mud).

Oil-based mud with good rheology that ensures stability, easy mixing and pumping at surface, cold temperatures and the high bottom-hole temperature is required for the new wellbore temperature control design. Taugbol et al. (2005) stated that oil-based mud is used more often than water-based mud in the oil & gas industry because of its obvious advantages such as better lubricity, better hole-cleaning, hole-stability, cuttings-suspension property and better temperature stability when drilling at high temperatures. Nelson and Guillot (1990) wrote that a sound understanding of the rheology of drilling mud is required for evaluation of its ease of mixing and pumping, displacement rate design and optimum removal.

The novel concept of “thermal drainage radius” also invented in this work quantified the radial extent of the temperature-drop effect of the chilled oil-based mud in the formation, away from the wellbore. It is the fulcrum of the mathematical modeling done in this research work. The logging operation should commence after placement of the chilled oil-based mud in the zone of interest and be completed before the end of the temperature rise duration. The new wellbore temperature control design has global applicability. It can be applied in every country.

2. Materials & methods

The research methods adopted include laboratory testing, mathematical modeling and design.

2.1. Experimental

The wellbore, the wall of the formation and the bottom-hole temperature were simulated using the HPHT Filter Press in the Laboratory. Schlumberger (2008) stated that engineers simulate down-hole conditions when developing systems or structures for the protection of logging tools in HPHT wells. Materials used for the laboratory testing include oil-based mud, ice blocks and water. Equipment used also include Chan-35 Rheometer, stop clock, thermometer and water bath. The HPHT Filter Press and the water bath were used to conduct all the temperature-drop experiments. Ice blocks in water bath were used to cool the oil-based mud to required temperatures. Oil-based mud samples (1.91 SG) of 80 °F (299.82 K), 60 °F (288.71 K), 50 °F (283.15 K), 40 °F (277.59 K), 30 °F (272.04 K) and 20 °F (266.48 K) were used for the temperature-drop testing. The recipe of the oil-based mud includes: 0.538 bbl/bbl local base oil, 8 ppb primary emulsifier, 4 ppb secondary emulsifier, 4ppb Filtration reducer, 6 ppb lime, 19.46 ppb Calcium chloride, 0.102 bbl/bbl water, 7 ppb organophilic clay and 490 ppb Barite.

The procedure for the temperature-drop testing is as follows: Chill the oil-based mud to desired cold temperature e.g. 266.48 K using ice blocks and water bath (or preferably a Chiller). Turn the heater/thermal-stat knob full scale to heat up the filter press to the desired bottom-hole temperature (T1) of 477.55 K or desired bottom-hole temperature. Set the temperature at 477.55 K by turning the heater/thermostat knob backwards until the immediate glow of the pilot light. After a few minutes, check the thermometer to ensure that the temperature is not less than or higher than 477.55 K. The Filter Press cell body takes 0.000175 m³ of liquid only. Pour the chilled oil based mud of 266.48 K into the Filter Press cell body, cap it and put it back in the heating jacket. Start the stop clock. Record the temperature drop duration (t₁) as the time it takes the temperature to fall to the lowest temperature during the temperature decline, before it starts rising back to 477.55 K. Record this lowest temperature as the thermal equilibrium temperature (Tₑ), and record the time taken from thermal equilibrium temperature to bottom-hole temperature as formation temperature rise duration (t₂) from thermal equilibrium temperature to bottom-hole temperature. Record the total time taken from start of the stop clock to when the temperature increases back to the bottom-hole temperature as the formation temperature rise duration (t). For purpose of convenience, report the temperature drop duration and temperature rise durations in minutes per 0.001 m³ of chilled oil based mud by multiplying with a factor of 5.7143. Repeat the test at bottom-hole temperatures of 449.82 K, 422.05 K, 394.26 K and 366.48 K or desired bottom-hole temperatures. Follow same procedure with the other samples of chilled oil based mud at 477.55 K, 449.82 K, 422.05 K, 394.26 K and 366.48 K. The results are as presented by Figs. 3, 4 and 5.

2.2. Laboratory calculations

It is evident from the Laboratory tests that the temperature rise of the formation as simulated with the Filter Press involves two phases occurring simultaneously with the two phases involved in the temperature rise of the chilled oil based mud. The formation temperature rise involves temperature drop from bottom-hole temperature to thermal equilibrium temperature and temperature rise from thermal equilibrium temperature to bottom-hole temperature. The temperature rise of the chilled oil based mud involves temperature rise from its initial cold
temperature to thermal equilibrium temperature and temperature rise from the thermal equilibrium temperature to bottom-hole temperature.

The temperature drop phase of the formation occurs simultaneously with the temperature rise phase of the chilled oil based mud from its initial cold temperature to thermal equilibrium temperature. The formation temperature rise from thermal equilibrium temperature to bottom-hole temperature occurs simultaneously with the temperature rise of the chilled oil based mud from thermal equilibrium temperature to bottom-hole temperature.

From the Laboratory test:

Formation Temperature drop, \( \Delta T = T_i - T_e \)  

Formation temperature drop duration = \( t_1 \)  

Formation temperature rise duration from \( T_i \) to \( T_e \) = \( t_2 = t - t_1 \)  

Formation temperature rise duration, \( t = t_1 + t_2 \)  

Heat lost by a hot substance in contact with a cold substance is equal to heat gained by the cold substance (Engineering ToolBox, 2009). Therefore:

Heat lost by formation = heat gained by chilled oil based mud  

From Engineering ToolBox (2009); the heat up time, \( t \) (temperature rise duration) of the cold substance or heat loss time (temperature drop duration) of the hot substance depends on the amount of heat energy absorbed by the quantity of the cold substance. This can be explained by Equations (5), (6) and (7):

\[
Q = mC_p\Delta T \\
t = \frac{Q}{q} \\
t = \frac{mC_p\Delta T}{q}
\]

Therefore,

Formation temperature drop duration,

\( t_1 = \) temperature rise duration of chilled OBM from its initial cold temperature, \( T_m \) to \( T_e \)  

Formation temperature rise duration \((t_2)\) from \( T_e \) to \( T_r \) = Temperature rise duration of chilled OBM from \( T_e \) to \( T_r \)

Formation temperature rise duration,

\( t = \) temperature rise duration of chilled OBM from its initial cold temperature, \( T_m \) to \( T_e + \) temperature rise duration of chilled OBM from \( T_e \) to \( T_r \)

Formation temperature rise duration,

\( t = \) temperature rise duration of chilled OBM from its initial cold temperature, \( T_m \) to bottomhole temperature, \( T_r \)

Where,

\( t = \) Formation temperature rise duration  

\( t_1 = \) Formation temperature drop duration  

\( t_2 = \) Formation temperature rise duration from thermal equilibrium temperature back to bottom-hole temperature.  

\( T_e = \) Bottom-hole temperature  

\( T_r = \) Thermal equilibrium temperature

\[
\text{OBM} = \text{Oil based mud} \\
T_m = \text{Initial cold temperature of chilled oil based mud} \\
c_p = \text{Specific heat capacity of chilled oil based mud} \\
m = \text{mass of chilled oil based mud} \\
\Delta T = \text{Temperature change}
\]

2.3. Novel concept of thermal drainage radius

Originally, the chilled oil-based mud and the formation would be at different temperatures. The formation would be at the bottom-hole temperature \( (T_r) \) and the chilled oil-based mud at low temperature \( (T_m) \). When the chilled oil-based mud is pumped down-hole and placed in the zone of interest (no circulation of the chilled oil-based mud), heat transfer would occur from the formation to the mud principally by conduction until thermal equilibrium is attained between the formation and the chilled oil-based mud. Consequently, the temperature of the formation would fall from the bottom-hole temperature to the thermal equilibrium temperature, \( T_r \). The heat lost by the formation is equal to the heat gained by the chilled oil-based mud at thermal equilibrium.

The fact that the magnitude of formation-temperature drop is different per chilled oil-based mud and that the temperature drop increased with decreasing temperature of the chilled oil-based mud connotes that for a particular chilled oil-based mud placed in the zone of interest in the wellbore; there is a maximum distance into the formation, away from the wellbore, where the temperature-drop effect of the chilled oil-based mud terminates and it is hereby defined as the "thermal drainage radius" of the formation (see Fig. 1).

Thus, the novel concept of thermal drainage radius imposes an outer boundary in the formation (away from the wellbore) beyond which the temperature drop occasioned by the chilled oil-based mud is not felt by the formation. Hence, the temperature beyond this outer boundary is the normal geothermal temperature of the formation. Considering radial heat flow and the fact that the wellbore radius and the thermal drainage radius are both measured from the center of the wellbore; results in two concentric cylinders with radius \( r_m \) (wellbore radius) and \( r_{th} \) (thermal drainage radius) as shown in Fig. 2.

Mathematically, the initial and boundary conditions imposed by the novel concept of thermal drainage radius can be represented as follows.

**Initial condition**

The initial temperature of the formation is the same as the geothermal temperature:

\[
T_r (r, z, 0) = T_r + Gz
\]

The boundary conditions are:

i) Formation temperature beyond the thermal drainage radius is the same as the geothermal temperature

\[
T_r (r > r_{th}, z, t) = T_r + Gz
\]
ii) The formation temperature away from the wellbore up to the thermal drainage radius, \( r_{th} \) is less than the geothermal temperature during the temperature drop phase

\[
T_e (r \leq r_{th}, z, t) < (T_f + Gz)
\]

(14)

iii) Surface temperature is constant

Where, \( T_s = \) surface temperature \( T_e = \) temperature of the formation, \( z = \) True vertical depth (TVD), \( r_w = \) wellbore radius, \( r_{th} = \) thermal drainage radius, \( G = \) geothermal gradient and \( t = \) time.

2.4. Developing the thermal drainage radius mathematical model and other mathematical models

When the chilled oil-based mud has been pumped down-hole and placed in the zone of interest (no circulation of the chilled oil-based mud); the heat transfer from the formation to the column of chilled oil-based mud is principally by conduction. Iyagba (1997) wrote that heat transfer by conduction through two concentric cylindrical bodies as depicted by Fig. 2 can be represented by Equation (15) or (16):

\[
q = -kA \frac{dT}{dr}
\]

(15)

\[
q = -k(2\pi r h) \frac{dT}{dr}
\]

(16)

Therefore, rearranging and integrating Equation (16) in relation to the heat transfer from the formation to the column of chilled oil-based mud in the zone of interest in the wellbore leads to Equations (17) and (18):

\[
\frac{2\pi h k (T_e - T_s)}{\ln \frac{r_w}{r_{th}}} = \frac{T_s - T_e}{\ln \frac{r_w}{r_{th}}}
\]

(17)

\[
q = \frac{2\pi h k (T_e - T_s)}{\ln \frac{r_w}{r_{th}}}
\]

(18)

Where, \( q = \) heat transfer rate in watts, \( W \) (Joules per second), \( h = \) height of the zone of interest occupied by the chilled oil-based mud in the wellbore, in meters; \( k = \) thermal conductivity of the formation, \( W/m/K; T_e = \) bottom-hole temperature (BHT), in Kelvin, \( K, T_s = \) thermal equilibrium temperature in Kelvin, \( K. \)

Wu et al. (2018) stated as follows: (i) during drilling, the temperature of the fluid entering the drill pipe should be specified and the temperature of fluids in the drill pipe and the annulus should be same at the bottom-hole.

\[
T_p (z, t) = T_w (a_t z = 0)
\]

(19)

\[
T_p (z, t) = T_w (a_t z = H)
\]

(20)

(ii) At the wall of the wellbore, the heat flux from the formation is equal to the heat flux into the wellbore

\[
2\pi r_w h_w (T_f - T_s) = 2\pi r_w k \frac{dT_e}{dr} = r_w
\]

(21)

Where, \( r_w = \) wellbore radius, \( T_s = \) formation temperature, \( T_f = \) temperature of fluid in the annulus, \( K_\text{w} = \) thermal conductivity of the formation, \( T_p = \) temperature of fluid in drill pipe; \( T_m = \) temperature of fluid entering the drill pipe, \( H = \) total vertical depth, \( h_w = \) heat transfer coefficient between the fluid in the wellbore and the surrounding rock formation and \( t = \) time.

Jiang (2019) stated that during drilling of a well the heat balance in the annulus is given by Equation (22):

\[
\begin{align*}
\text{Heat entering the annulus} & + \text{Heat transferred from drill pipe to annulus} \\
= \text{Heat exiting the annulus} & + \text{Heat transferred from annulus to formation} & + \text{change in internal energy}
\end{align*}
\]

(22)

Therefore; considering the pumping and placement of the chilled oil-based mud in the zone of interest, the following boundary conditions apply:

- Controlled drilling fluid temperature at the surface

\[
T_p (0, t) = T_w
\]

(23)

- No heat transfers between drill pipe and fluid in the annulus

\[
T_p (L, t) = T_w (L, t)
\]

(24)

- No heat transfers between the drill pipe and the chilled oil-based mud

\[
T_p (L, t) = T_m (L, t)
\]

(25)

- No heat is exiting the drill pipe and annulus or wellbore at the surface

- Convective heat transfer between the formation and the chilled oil-based mud is zero or negligible

Where, \( L = \) vertical depth.

Relating the heat balance in Equation (22) to the pumping and placement of the chilled oil-based mud in the zone of interest, leads to the heat balance represented by Equation (26):

\[
\begin{align*}
\text{Heat transferred from formation to chilled oil based mud in the annulus} & + \text{Heat transferred from drill pipe to chilled oil based mud in the annulus} \\
= \text{Heat exiting the annulus at surface} & + \text{Heat gained by chilled oil based mud from the formation} & + \text{change in internal energy of chilled oil based mud}
\end{align*}
\]

(26)

After placing the chilled oil-based mud in the zone of interest and the drill string pulled out of hole (POOH) the heat balance becomes Equation (27):

\[
\begin{align*}
\text{Heat transferred from formation to the chilled oil based mud in the wellbore} \\
= \text{Heat exiting the wellbore at surface} & + \text{Heat gained by chilled oil based mud from the formation} & + \text{change in internal energy of chilled oil based mud}
\end{align*}
\]

(27)
The chilled oil-based mud did not undergo any phase change or chemical change. Hence change in internal energy is negligible or equal to zero. There is no heat loss from the wellbore at the surface. Therefore, the heat balance becomes Equation (28):

\[
\text{Heat transferred from formation to the chilled oil based mud in the wellbore} = \text{Heat gained by chilled oil based mud from the formation}
\]

\[
(28)
\]

From Equation (17), the rate of heat transfer by conduction from the formation to the chilled oil-based mud is given by

\[
q = \frac{2\pi h k (T_e - T_w)}{\ln \frac{r_w}{r_w}}
\]

But heat gained by the chilled oil-based mud during the temperature drop phase can be calculated from Equation (5) as:

Heat gained by chilled oil-based mud, \( Q = mc_p \Delta T \)

From Equation (1): \( \Delta T = T_e - T_w \). Substituting in Equation (5) leads to Equation (29):

Heat gained by chilled oil-based mud, \( Q = mc_p (T_e - T_w) \) (29)

\( T_e = \text{thermal equilibrium temperature, } T_w = \text{temperature of the chilled oil-based mud} \)

Therefore, the rate of heat gained by the chilled oil-based mud, \( q \) is given by Equation (30) as:

\[
q = \frac{Q}{t_{th}} = mc_p \Delta T / \ln \frac{r_w}{r_w}
\]

Where, \( t_{th} = \text{thermal drainage time (temperature drop duration), seconds} \)

At thermal equilibrium, the heat loss or rate of heat loss by the formation is equal to the heat gained or rate of heat gained by the chilled oil-based mud as represented by Equation (31):

\[
q = \frac{mc_p (T_e - T_w)}{t_{th}} = \frac{2\pi h k (T_e - T_w)}{\ln \frac{r_w}{r_w}}
\]

Solving for the thermal drainage radius leads to Equation (32):

\[
r_{th} = r_w \frac{e^{2\pi h k \Delta T / q}}
\]

Equation (32) is the thermal drainage radius mathematical model for calculating or predicting the thermal drainage radius of the formation, when other relevant parameters are given.

Solving for the thermal drainage time, \( t_{th} \) using Equation (31) leads to Equation (33):

\[
t_{th} = \frac{mc_p (T_e - T_w)}{2\pi h k (T_e - T_w)}
\]

Equation (33) is the thermal drainage time mathematical model for calculating or predicting the thermal drainage time of the formation when other relevant parameters are given.

It is evident from Equation (33) that the thermal drainage time increases with increase in the mass or quantity of the chilled oil-based mud placed in the zone of interest. The thermal drainage time is the time taken for the bottom-hole temperature to fall to the thermal equilibrium temperature when the formation is in contact with the chilled oil-based mud in the zone of interest. It is also known as the thermal depletion time or temperature drop time or temperature drop duration.

Rearranging Equation (31) and solving for thermal conductivity leads to Equation (34):

\[
k = \frac{mc_p (T_e - T_w) \ln \frac{r_w}{r_w}}{2\pi h k (T_e - T_w)}
\]

Equation (34) is the thermal conductivity mathematical model for calculating or predicting the thermal conductivity of the formation, when other relevant parameters are given.

From Equation (30):

\[
Q = mc_p (T_e - T_w) / t_{th}
\]

Rearranging and solving for thermal equilibrium temperature, \( T_e \) leads to Equations (35):

\[
T_e = T_w + \frac{Q h}{m c_p}
\]

Equation (35) is the thermal equilibrium temperature mathematical model for calculating or predicting the thermal equilibrium temperature between the formation and the chilled oil-based mud placed in the zone of interest.

Rearranging Equation (31) and solving for the temperature drop \( (T_e - T_w) \) of the formation, leads to Equation (36):

\[
T_e - T_w = \frac{mc_p (T_e - T_w)}{t_{th} \ln \frac{r_w}{r_w}}
\]

Equation (36) is the temperature drop mathematical model for calculating or predicting the temperature drop of the formation, when other relevant parameters are given.

Where, \( h = \text{height of the zone of interest occupied by the chilled oil-based mud in the open-hole, and } k = \text{thermal conductivity of the formation, } r_w = \text{wellbore radius, } r_{th} = \text{thermal drainage radius, } T_e = \text{bottom-hole temperature, } T_w = \text{thermal equilibrium temperature, } m = \text{mass of chilled oil-based mud and } C_p = \text{specific heat capacity of chilled oil-based mud; } T_w = \text{temperature of chilled oil-based mud and } t_{th} = \text{thermal drainage time, seconds.} \)

2.5. Application of the thermal drainage radius mathematical model

The novel concept of thermal drainage radius can be validated by using two formations of different thermal conductivities to check the trend of the calculated thermal drainage radius by imposing the same temperature drop as evidenced by examples 1 and 2. Labus and Labus (2018) stated that the thermal conductivity of sandstone is in the range of 2.50–4.20 W/m/K while the thermal conductivity of shale is in the range of 1.05–1.45 W/m/K.

2.5.1. Example 1

The thermal conductivity of a sandstone formation is 2.5 W/m/K. A sample of chilled oil-based mud having temperature of 266.48 K was placed in a wellbore at a depth (TVD) of 2743 m and the bottom-hole temperature dropped to a thermal equilibrium temperature of 428.15 K in 60 minutes. Calculate the thermal drainage radius of the formation, given a wellbore radius of 0.15239 m; height of zone of interest occupied by the chilled oil-based mud = 15.23926 m; mass of chilled oil-based mud = 50 kg; Bottom-hole temperature = 473.15 K. Assume specific heat capacity of chilled oil-based mud = 2500 J/kg/K.

Solution

Thermal equilibrium temperature, \( T_e = 428.15 K \)

From Equation (29): heat gained by chilled oil-based mud, \( Q = mc_p (T_e - T_w) \)

Putting values in Equation (29)

Heat gained by chilled oil-based mud, \( Q = 50 \times 2500 \times [428.15 - 266.48] = 20208750 \) J
Rate of heat gained by the chilled oil-based mud, \( q = 20208750 \text{ J} / 3600 \text{ s} = 5613.54 \text{ W} \)

From Equation (32): thermal drainage radius \( r_{th} \) is given by:
\[
r_{th} = r_w e^{2 \pi h_k \Delta T / q}
\]

Calculating the value of the term
\[
\frac{2 \pi h_k \Delta T}{q} = \frac{2 \times 3.142 \times 15.23926 \times 2.5 \times 45}{5613.54} = 91918
\]

Putting values in Equation (32):
\[
r_{th} = 0.15239 \times e^{91918} = 1.039 \text{ m}
\]

Therefore, the thermal drainage radius is 1.039 m into the formation, away from the center of the wellbore.

2.5.2. Example 2

The thermal conductivity of a sandstone formation is 3.0 W/m/K. A sample of chilled oil-based mud having temperature of 266.48 K was placed in a wellbore at a depth (TVD) of 2743 m and the bottom-hole temperature dropped to a thermal equilibrium temperature of 428.15 K in 60 minutes. Calculate the thermal drainage radius of the formation, given a wellbore radius of 0.15239 m; height of zone of interest occupied by the chilled oil-based mud = 15.23926 m; mass of chilled oil-based mud = 50 kg; Bottom-hole temperature = 473.15 K. Assume specific heat capacity of chilled oil-based mud = 2500 J/kg/K.

Solution

Thermal equilibrium temperature, \( T_e = 428.15 \text{ K} \)

From Equation (29):

Heat gained by chilled oil-based mud, \( Q = m c_p (T_e - T_m) \)

Putting values in Equation (29):

Heat gained by chilled oil-based mud, \( Q = 50 \times 2500 \times (428.15 - 266.48) = 20208750 \text{ J} \)

Rate of heat gained by the chilled oil-based mud, \( q = 20208750 \text{ J} / 3600 \text{ s} = 5613.54 \text{ Watts} \).

From Equation (32), thermal drainage radius \( r_{th} \) is given by:
\[
r_{th} = r_w e^{2 \pi h_k \Delta T / q}
\]

Calculating the value of the term
\[
\frac{2 \pi h_k \Delta T}{q} = \frac{2 \times 3.142 \times 15.23926 \times 2.5 \times 45}{5613.54} = 30320
\]

Putting values in Equation (32):
\[
r_{th} = 0.15239 \times e^{30320} = 1.525 \text{ m}
\]

Therefore, the thermal drainage radius is 1.525 m into the formation, away from the center of the wellbore.

Comments: The results of examples 1 & 2 validate the novel concept of thermal drainage radius. They show that for a particular chilled oil-based mud in the zone of interest in the wellbore, the higher the thermal conductivity of the formation (3.0 W/m/K in example 2), the lower the temperature gradient (or the thermal depletion gradient) with corresponding longer thermal drainage radius (1.525 m in example 2) but the lower the thermal conductivity of the formation (2.5 W/m/K in example 1) the higher the temperature gradient (or thermal depletion gradient) resulting to shorter thermal drainage radius (1.039 m in example 1).

2.6. Job designs (generic) – new wellbore temperature control design

The job design must be done prior to job execution in the field. The job design requires adequate proactive preparation to ensure that all required materials, data and equipment are available on the Rig and the Laboratory of the drilling mud company. Collaboration between the Laboratory Engineer, Mud Engineer and the Logging Engineer is required for a proper job design.

The new wellbore temperature control design involves using actual Rig samples of oil-based mud for laboratory testing. Quality assurance demands that laboratory tests should be repeated on the Rig or location before the job. The logging operation should commence immediately after placement of the chilled oil based mud in the zone of interest (no circulation of the chilled oil based mud) and be completed before the end of the temperature rise duration. The volume of chilled oil based mud required = 3 x volume of zone of interest in the wellbore. A chiller should be provided on the Rig or location to chill the oil-based mud to the required cold temperature under dynamic conditions (while being stirred at minimum shear rate). The new wellbore temperature control design requires the chilled oil-based mud to be placed in the zone of interest in the wellbore immediately after logging.

The job designs for five case wells are as presented in the supplementary content file named: New-wellbore temp-control-Job designs.

3. Results

The laboratory tests require fixed quantity of chilled oil based mud in the Filter Press. The following results were obtained:

i) the formation temperature-drop from bottom-hole temperature, \( T_b \) to the thermal equilibrium temperature, \( T_e \) increased with bottom-hole temperature per chilled oil-based mud but it increased with decrease in the temperature of the chilled oil-based mud at a particular bottom-hole temperature as evidenced by Fig. 3.

ii) The formation temperature drop duration increased with increase in bottom-hole temperature per chilled oil-based mud. The formation temperature drop duration also decreased with decrease in the temperature of the chilled oil-based mud at a particular bottom-hole temperature as evidenced by Fig. 4.

iii) The formation temperature rise duration from the thermal equilibrium temperature, \( T_e \) back to bottom-hole temperature, \( T_b \) also
increased with increase in bottom-hole temperature per chilled oil-based mud but it increased with decrease in the temperature of the chilled oil-based mud at a particular bottom-hole temperature as evidenced by Fig. 5.

Table 1 presents the formation (Filter Press) temperature rise duration (and other data) when in contact with the 266.48 K chilled oil-based mud in the Laboratory.

Table 2 presents the results of the heat transfer between sandstone formation thermal conductivity, 2.5 W/m/K and the chilled oil-based mud of 266.48 K pumped downhole and placed in the zone of interest in the wellbore as simulated with the job designs for five case wells.

Fig. 5 presents the rheology of the chilled oil-based mud samples. The rheology of the chilled oil-based mud revealed that the viscosity falls with increasing temperature and vice versa. This is a normal trend for oil-based mud.

---

**Table 1.** Formation (Filter Press) temperature rise duration (and other data) when in contact with the 266.48 K Chilled Oil Based Mud in the Laboratory.

| S/N | Depth of Open hole (TVD) | Bottom hole temperature | Actual volume of chilled oil based used in Filter Press | Formation Temperature rise duration, t = t1 + t2 as simulated with the filter press (Reported per 0.001 m³ of chilled oil based mud) | Heat transfer rate from Filter Press to chilled oil based mud (Actual) |
|-----|--------------------------|-------------------------|------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| 1   | 4876.56 m               | 477.55 K                | 0.000175 m³                                          | 42.7 min                                                                                                                      | 400 W                                                            |
| 2   | 4266.99 m               | 449.82 K                | 0.000175 m³                                          | 31.0 min                                                                                                                      | 400 W                                                            |
| 3   | 3657.42 m               | 422.05 K                | 0.000175 m³                                          | 20.43 min                                                                                                                     | 400 W                                                            |
| 4   | 3047.85 m               | 394.25 K                | 0.000175 m³                                          | 15.26 min                                                                                                                     | 400 W                                                            |
| 5   | 2438.28 m               | 366.48 K                | 0.000175 m³                                          | 12.87 min                                                                                                                     | 400 W                                                            |

**Table 2.** Job Deigns - New Wellbore Temperature Control Deign for Logging of Five Case Wells Showing Heat Transfer Results between Sandstone Formation of Thermal Conductivity, 2.5 W/m/K and Chilled Oil Based Mud of 266.48 K.

| Well | Depth of Open hole (TVD) | Bottom hole temperature | Volume of chilled oil based mud pumped downhole | Formation temperature rise duration, t = chilled oil based mud temperature rise duration in the zone of interest in the wellbore | Heat energy absorbed by chilled oil based mud in the zone of interest in the wellbore | Heat transfer rate from formation to chilled oil based mud in the zone of interest in the wellbore |
|------|--------------------------|-------------------------|-----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| 1    | 4876.56 m               | 477.55 K                | 16.755 m³                                    | 12.43hr                                                                                                                      | 1.68866817 × 10¹⁰ J                                                                                                                  | 377476.53 W                                                                                                                      |
| 2    | 4266.99 m               | 449.82 K                | 10.005 m³                                    | 13.10hr                                                                                                                      | 8758862243 J                                                                                                                     | 185694.92 W                                                                                                                     |
| 3    | 3657.42 m               | 422.05 K                | 3.351 m³                                     | 13.18hr                                                                                                                      | 2489279459 J                                                                                                                     | 52452.83 W                                                                                                                     |
| 4    | 3047.85 m               | 394.25 K                | 3.351 m³                                     | 12.60hr                                                                                                                      | 2044450964 J                                                                                                                     | 45078.70 W                                                                                                                     |
| 5    | 2438.28 m               | 366.48 K                | 3.351 m³                                     | 14.03hr                                                                                                                      | 1600102500 J                                                                                                                     | 31691.16 W                                                                                                                     |

Note: See supplementary content for job design calculations.
Table 3. Variation of Thermal Drainage Radius with Thermal Conductivity of the Formation.

| Formation  | Thermal conductivity (W/m·K) | Thermal drainage radius (m) |
|------------|-----------------------------|----------------------------|
| Sandstone A | 2.5                         | 1.039                      |
| Sandstone B | 3.0                         | 1.525                      |

Table 3 presents the variation of thermal drainage radius with the thermal conductivity of a formation using sandstone as case study and depicted by examples 1 & 2.

4. Discussion

The formation temperature-drop from bottom-hole temperature to the thermal equilibrium temperature at relatively short temperature drop duration and the corresponding long formation temperature rise duration to bottom-hole temperature are very significant and they constitute the technical basis for the application of the new wellbore temperature control design for protection of logging tools in high pressure – high temperature wells. The magnitude of the formation temperature-drop \((T_e - T_r)\) from bottom-hole temperature, \(T_r\) to the thermal equilibrium temperature, \(T_e\) is very important for the protection of logging tools in high pressure-high temperature wells. The thermal equilibrium temperature must be experimentally determined. It determines the magnitude of the temperature drop. The larger the temperature drop, the better the protection of the logging tools. The formation temperature drop duration (thermal drainage time) and the formation temperature rise duration from thermal equilibrium temperature to bottomhole temperature determine the total amount of protection time provided by the chilled oil-based mud for the logging tools and completion of the logging operation. Therefore, long formation temperature rise duration is preferred. It should be long enough to allow completion of the logging operation as evidenced by the formation temperature rise durations presented in Table 2.

When the chilled oil based mud is pumped down-hole and placed in the zone of interest in the wellbore, heat would be transferred from the formation to the chilled oil-based mud by conduction and from the chilled oil based mud to the logging tool. Equation (25) showed that heat lost by formation to chilled oil based mud = heat gained by chilled oil based mud. The chilled oil based mud of 266.48 K gave the best results among the chilled oil based mud tested in terms of temperature drop, temperature drop duration and temperature rise duration as evidenced by Figs. 3, 4 and 5. This prompted further work with this chilled oil based mud sample as presented in Tables 1 and 2.

The laboratory results presented in Table 1 are very significant. The results showed that when the quantity of chilled oil based mud and heat transfer rate from the formation are kept constant as simulated with the Filter Press, formation temperature rise duration or the temperature rise duration of the chilled oil based mud increased with bottom-hole temperature. Equation (9) showed that Formation temperature rise duration = temperature rise duration of chilled oil based mud from initial cold temperature to bottomhole temperature. Equation (7) showed that the temperature rise duration is an extensive property which depends on the amount of heat absorbed by the quantity of chilled oil based mud. Therefore, the short formation temperature rise duration obtained from the Laboratory test should not be a source of concern because the formation temperature rise duration for an actual logging job will depend on the amount of heat gained by the quantity of chilled oil based mud that will be pumped down-hole as evidenced by the job design summary for the five case wells in Table 2 and not the small quantity of chilled oil based mud (0.000175 m\(^3\)) used for the Laboratory test.

The job design results for the five case wells presented in Table 2 are very significant. They provide enormous insight into the actual down-hole heat transfer relationship between the formation and the chilled oil based mud. It is evident from Table 2 that the heat energy absorbed from the formation by the chilled oil based mud increased with bottom-hole temperature and the quantity of chilled oil based mud designed to be pumped downhole. Furthermore, the heat transfer rate from the formation increased with bottom-hole temperature while the temperature rise duration of the chilled oil based mud decreased with increasing heat transfer rate from the formation to the chilled oil based mud and vice versa. The very long formation temperature rise durations of 12.43 hr, 13.10 hr and 13.18 hr obtained at the bottom-hole temperatures of 477.55 K, 449.82 K and 422.05 K respectively showed that chilled oil based mud can provide enough protection for logging tools and completion of logging operation in high pressure – high temperature wells. The very long temperature rise durations 12.60 hr and 14.03 hr also obtained for the wells with bottom-hole temperatures of 394.25 K and 366.48 K respectively, showed that the new wellbore temperature control design can also be applied in wells with bottomhole temperatures below the high pressure – high temperature range, if required. It is evident from the aforesaid that the temperature rise duration of the chilled oil based mud upon which the protection of the logging tools depends is an extensive property which depends on the quantity of chilled oil based mud other than thrice the volume of the zone of interest in the wellbore; can also be used for the protection of logging tools provided that the temperature rise duration of the chilled oil based mud from its initial cold temperature to bottom-hole temperature as determined from the job design; is in excess of the required job time and long enough to enable multiple runs of the logging tool and completion of the logging operation. For example, if for an actual logging job, the temperature rise duration of the original chilled oil based mud volume (3 × volume of zone of interest); as determined from the job design is too short, other volumes of chilled oil based mud (e.g. 4 × volume of zone of interest) can be used for protection of the logging tool provided that the desired appropriate temperature rise duration is obtained at the job design stage.

The results of examples 1 & 2 presented in Table 3 are very significant as they validated the novel concept of thermal drainage radius. They show that for a particular chilled oil-based mud in the zone of interest, the higher the thermal conductivity of the formation, the longer the thermal drainage radius as evidenced by example 2 with Sandstone formation of thermal conductivity 3.0 W/m·K and thermal drainage radius of 1.525 m while example 1 shows sandstone formation of thermal conductivity 2.5 W/m·K and a thermal drainage radius of 1.039 m. This connotes that, the higher the thermal conductivity of the formation, the lower the temperature gradient (or thermal depletion gradient) with corresponding longer thermal drainage radius and vice versa. Iyagba (1997) wrote that good heat conductors have high values of thermal conductivity and low temperature gradients while poor conductors have low values of thermal conductivity and high temperature gradients.

Furthermore, it is evident from Fig. 3, that formation temperature drop increased with decrease in the temperature of the chilled oil-based mud, implying that for a particular formation, the thermal drainage radius \((r_{ch})\) increased with decrease in the temperature of the chilled oil-based mud. From Equation (18), the resistance to heat flow from the formation to the chilled oil-based mud is inversely proportional to
the thermal conductivity of the formation and the height of the zone of interest occupied by the chilled oil-based mud. The resistance to heat flow is also proportional to the open-hole size. Therefore, large open-holes or zones of interest will be better candidates for the application of the new wellbore temperature control design than narrow open-holes or zones of interest. Similarly, it is evident from Equation (5), that poor heat-conducting oil-based mud (with high specific heat capacity) will be better candidate for the application of the new wellbore temperature control design than good heat-conducting oil-based mud. Similarly, poor-heat conducting oils are preferred candidates for the application of the new wellbore temperature control design.

The comparison of the new wellbore temperature control design with the thermal insulating jacket and the vacuum flask is as follows:

i) Traditional methods of protecting logging tools against high bottom-hole temperatures in HPHT wells use thermal insulating jackets or vacuum flasks. The new wellbore temperature control design uses chilled oil-based mud to protect logging tools against high bottom-hole temperatures in HPHT wells.

ii) Thermal insulating jackets and vacuum flasks do not actually reduce the bottom-hole temperature of HPHT wells. They encapsulate the logging tools but thermal insulating jacket functions by thermal insulation while vacuum flask functions by using its internal silver lining and vacuum to reduce heat transfer to the logging tools. The new wellbore temperature control design uses the temperature-drop effect of chilled oil-based mud to reduce bottom-hole temperature prior to logging.

The new wellbore temperature control design applies the novel concept of thermal drainage radius. This is not applicable to the traditional methods.

iv) A design volume of chilled oil based mud can be used for multiple runs of logging tools because of its long temperature rise duration as evidenced by the aforesaid job designs for the case wells. Service charge per run is currently being paid by oil & gas producing companies for vacuum flask and thermal insulating jacket. Some oilfield service companies charge up to $2500 per run for either of them.

v) The thermal insulating jacket and vacuum flask are very expensive, each costing above $5000/unit. Oil-based mud is cheaper. The oil based mud to be used for the wellbore temperature control is part of the drill mud. The cost of the oil based mud used in this work is $434 per m³.

vi) The thermal insulating jacket and vacuum flask are not readily available except in the country of manufacture. So, they have to be imported by companies in other countries. Oil-based mud is available in every country.

vii) Wiring and other parts (as applicable) of thermal insulating jacket and vacuum flasks need to be checked and corrected (if required) before each run. If there is a problem, downtime and associated cost are inevitable. This concern is not applicable to the new wellbore temperature control design. Sarian and Gibson (2005) reported that serious complications occur in HPHT wells requiring costly redesign of sensors and related electronics.

viii) The new wellbore temperature control design require one-off purchase of a chiller by the responsible oilfield service company but this cost can be built into service charge to the oil & gas producing companies over time.

ix) Thermal insulating jackets and vacuum flasks are usually applied standalone. Each of them can be applied alongside the new wellbore temperature control design to improve their performance, if need be

The significance of the new wellbore temperature control design cannot be over-emphasized. Limitations encountered during this research include funding and equipment.

5. Conclusion

The down-hole temperature rise duration of the chilled oil-based mud from its initial cold temperature to the bottom-hole temperature determines the total amount of protection time available for the logging tools and completion of the logging operation.

The new wellbore temperature control design is especially suitable for wireline logging in high pressure - high temperature oil and gas wells. Application to logging while drilling (LWD) may require proactive replacement of spent chilled oil based mud.

The new wellbore temperature control design can also be applied to oil and gas wells with bottomhole temperatures below the high pressure – high temperature range to improve performance of logging tools. It has global applicability.

The thermal conductivity mathematical model, temperature drop mathematical model, thermal drainage radius mathematical model and the thermal drainage time mathematical model can be used for prediction of the applicable parameters when laboratory services or actual data are not available.

Application of the new wellbore temperature control design will reduce cost of logging operations; prevent or eliminate poor performance and failure of logging tools alongside the associated technical consequences in the oil and gas industry worldwide.

Declarations

Author contribution statement

William Odiete: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2022.e09404.

References

Corrosionpedia, 2015. Thermal insulation. https://www.corrosionpedia.com/definition/1882/thermal-insulation/. (Accessed 20 July 2021).

Wikimedia Inc., 2021. Vacuum flask. https://en.wikipedia.org/wiki/Vacuum_flask/. (Accessed 20 July 2021).

Elzeghaby, S.Z., Kinzel, H., Colvard, R.L., Cement Seal Units Eliminate Inter-zonal Communication. SPE paper no. 105770 presented at the 15th SPE Middle East Oil & Gas Show and Conference held in Bahrain International Exhibition Center, Kingdom of Bahrain, 11–14 March 2007.

Engineering Toolbox, 2009. Heating up applications - energy required and heat transfer rates. [Online]. Available at: https://www.engineeringtoolbox.com/heat-up-energy-d_1055.html. (Accessed 20 December 2021).

European Patent Office, 2017. Improved vacuum insulated Dewar flask. https://patents.google.com/patent/EP1945904B1/en/. (Accessed 20 July 2021).

Innovative Drilling, 2007. HPHT operations pose escalating challenges for operators, suppliers: expandables, MWD/LWD tools, completion systems offer potential solutions. Drill. Contract., 48–55.
Iyagba, E.T., 1997. Fundamentals of Transport Phenomena. Jita Enterprises Nigeria Ltd, Port Harcourt.

Jiang, M., 2019. A heat transfer model for accurate wellbore temperature prediction during drilling. Int. J. Pet. Petrochem. Eng. 5 (4), 1–9. https://doi.org/10.20431/2454-7980.0504001.

Labus, M., Labus, K., 2018. Thermal conductivity and diffusivity of fine-grained sedimentary rocks. J. Therm. Anal. Calorim. 132, 1669–1676. https://doi.org/10.1007/s10973-018-7090-5.

Sarian, S., Gibson, A., 2005. Wireline evaluation technology in HPHT wells. In: SPE Paper No. 97571-MS Presented at the 15th SPE High Pressure/High Temperature Sour Well Design Applied Technology Workshop Held in the Woodlands, Texas, 17–19 May 2005.

Taugbol, K., Fimreite, G., Prebensen, O.I., Svanes, K., Omiland, T.H., Svela P.E., Brevik, D.H., 2005. Development and Field Testing of a Unique High Temperature/High Pressure (HPHT) Oil-Based Drilling Fluid with Minimum Rheology and Minimum Sag Stability. Offshore Europe, Aberdeen.

Salim, P., Amani, M., 2013. Special considerations in cementing high pressure high temperature wells. Int. J. Eng. Appl. Sci. 1 (4), 120–143. Schlumberger, 2008. High pressure, high temperature technologies. Oilfield Rev., 48–60.

Nelson, E.B., Guillot, D., 1990. Well Cementing. Schlumberger, Sugarland.

Schlumberger, 1998. High pressure, high-temperature well logging, perforating and testing. Oilfield Rev., 50–67.

Wu, B., Liu, T., Zhang, X., Wu, B., Jeffrey, R.G., Bunger, A.P., 2018. A transient analytical model for predicting wellbore/reservoir temperature and stresses during drilling and fluid circulation. Energies 11 (42). https://doi.org/10.3390/en11010042.

Yetunde, S., Ogbonna, J. Challenges and Remedy for Cementing of HPHT Wells in Nigerian Operation. SPE paper no. 150751 presented at the Nigerian Annual International Conference and Exhibition held in Abuja, Nigeria, 30 July – 3 August 2011.