A Method for Calculating Circulating Temperatures

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ABSTRACT

A method has been developed to calculate wellbore temperatures during mud circulation and the actual cementing operation to aid in the design of cement slurries. The method agrees within 10F with previously measured values. The calculation technique provides temperatures, as functions of time, at varying depths in both the casing and annulus. The technique also provides this information if a relatively cool cement slurry is pumped into the well immediately following circulation of hot mud. Circulating bottom-hole temperatures of brine and a bentonite mud were measured.

INTRODUCTION

As wells are drilled deeper, greater demands are being made on all phases of the industry, and new technology has been developed to provide satisfactory well completions. However, little or no work has been conducted on accurately determining bottom-hole, static and circulating temperatures.

In designing a cement slurry, such factors as density, fluid loss control, viscosity, deterioration from temperature, compressive strength and pumping time must be considered. Individual well conditions often make it necessary to include still other factors. Pumping time is a primary consideration and, as wells are drilled deeper, encountering higher bottom-hole temperatures, this property becomes even more important. Cement slurries must be designed with sufficient pumping time to provide safe placement in the well; however, the slurry cannot be overly retarded as this will prevent the development of satisfactory compressive strength.

The pumping time of a specific cement is currently obtained by subjecting the cement to simulated conditions of temperature and pressure. A reasonably accurate bottom-hole pressure may be obtained by considering hydrostatic heads of fluids, friction pressure and wellhead pressures. However, accurately determining bottom-hole temperatures is much more difficult. Bottom-hole static temperatures are estimated by considering several sources of information, including logging temperatures, published temperature gradient maps and field experience. This information is usually questionable due to disagreement of data from the various sources.

Temperature gradient maps were constructed based on temperatures recorded many years ago while running bottom-hole pressure tests. These thermal gradients then represent an average of well conditions and cannot always apply to a specific well. Also, logging temperatures may be affected by the time since fluid was last circulated, rate of penetration, circulating rate and many other factors. Therefore, even though logging temperatures are available, the question still exists as to the correction factor that should be applied to obtain an accurate static temperature.

After obtaining static bottom-hole temperature, it is then necessary to relate this to circulating temperatures actually encountered by the cement slurry. This is accomplished by selecting a test schedule from the API RP-10B corresponding to the estimated well conditions.[2]

The API-recommended practice for testing oilwell cement provides testing schedules for various well depths and conditions. These schedules are intended to simulate down-hole conditions during cementing. They provide a rate at which both temperature and pressure are increased until the estimated circulating conditions are reached. These testing schedules represent circulating temperatures for an average well and, although there is flexibility in choosing the test schedule that most accurately simulates the temperature of an individual well, it still is not possible to consider all the well conditions that will affect the bottom-hole temperature.

Many factors affect cement temperatures; for example, the length of time a well has remained static prior to running casing and cementing, the circulation time, the temperature of fluids used in cementing, fluid density and flow properties of fluids. The pumping time for a typical retarded cement could vary from 2 to 4 hours with a 10F change in testing temperature. Variations in pumping time are the most critical in highly retarded cements used in deep, hot wells; yet, predicting bottom-hole circulating temperatures is more difficult in these wells.

This work was conducted to develop a means of calculating circulating temperatures as a function of well depth, casing and hole size, pumping rate and time, fluid and reservoir physical properties and thermal status of the well.

PREVIOUS WORK

In 1941 Farris reported on a study to develop information leading to a more practical laboratory evaluation of oilfield cementing mixtures and performance.[1] It was then recognized that the pressure factor was being neglected,

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[1]References given at end of paper.

and that the temperature did not simulate completely the conditions existing during cement jobs. Farris' study developed a chart showing the circulating bottom-hole temperatures during cementing operations, and this chart has formed a basis for tentative standards for testing oilwell cements.[2]

Farris' observations, which showed a direct relation between well depth and circulating bottom-hole temperature, have served as a guide in the past. It is well known that static geothermal gradients may range from 5 to 25F/1,000 ft; the circulation rates and pipe and hole sizes may vary appreciably; the weights and thermal properties of the fluid and rock may vary; and other factors may affect cementing temperatures actually existing in the well. Farris showed that the bottom-hole temperature of a well may change 45F or more within 2 hours after cooled mud has started circulating.

The work of Edwardson *et al.*[3] on drilling mud temperatures indicates that the maximum temperature achieved by a cementing slurry does not occur at the bottom of the hole, but may occur on returning about 40 percent of the distance up the annulus.

CALCULATION PROCEDURE

Because many factors influence the temperature of a cementing slurry during placement, a study has been made to calculate transient cementing temperatures for various operating conditions. Factors to be taken into consideration are well depth; casing ID, OD and steel thermal properties; hole size, pumping rate and fluid viscosity; fluid specific heat, thermal conductivity and density; rock specific heat, thermal conductivity and density and thermal status of the well, which may include the initial wellhead and bottom-hole temperatures just prior to cementing.

HEAT TRANSFER EQUATIONS

The heat transfer rate from the annulus through the tubing is given by

$$q = UA\Delta T \quad \ldots \quad (1)$$

The value of U is calculated by

$$\frac{1}{U} = \frac{A_1}{h_i A_1} + \frac{L_m A_1}{k_m A_{avg.}} + \frac{A_1}{h_a A_2} \quad \ldots \quad (2)$$

For turbulent flow the basic equation for h is[1]

$$\frac{hD}{K} = 0.027 \left(\frac{DG}{\mu}\right)^{0.8} \left(\frac{c\mu}{k}\right)^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad \ldots \quad (3)$$

For streamline flow the basic equation for h is[4]

$$\frac{hD}{K} = 1.86 \left[\left(\frac{DG}{\mu}\right)\left(\frac{c\mu}{k}\right)\left(\frac{D}{L}\right)\right]^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad . \quad (4)$$

The heat flow into the rock formation is given by

$$q_f = k_r \left(\frac{\partial T}{\partial r}\right)_{r=r_w} \quad \ldots \quad (5)$$

where the temperature potential for the case of a thermal film is given analytically by Carslaw and Jaeger.[6]

For each increment in tubing depth and time, the change in temperature for the fluid in the tubing and annulus was required to satisfy the heat balance: net heat gain in annulus fluid increment = heat flow from tubing fluid increment minus heat flow into the formation. The foregoing group of equations may be solved and checked by use of the heat balance.

Knowing the pumping rate, fluid properties, casing and hole sizes, the Reynolds number of the fluid can be calculated for flow in the casing and annulus. With the pertinent value of the Reynolds number and the conduit length-to-diameter ratio, values of the thermal film coefficients at the fluid-solid interfaces can be obtained.[4] The film coefficients and thermal properties of the pipe permit calculation of an over-all heat transfer coefficient between the fluid in the pipe and the fluid in the annulus.

The radial heat flow from the formation into or from the annulus is provided by Fourier's equation in cylindrical coordinates. This equation has the same form as the water influx equation, solutions for which have been presented by van Everdingen and Hurst.[5] A thermal film coefficient is calculated for the rock and annular fluid interface and made a part of the computation.[6]

The net heat flowing from the rock into the annulus depends on the thermal history and status of the well. This is accounted for by use of superposition as previously described.[5,6] To initiate calculations, well depth was divided into from 5 to 40 increments; however, 20 increments were found to be the maximum required. For long cementing times, 10 increments might give satisfactory answers, i.e., less than 1F difference from the 20-increment calculation at any point in the well.

Calculations began with Edwardson *et al.*'s simplified temperature profile method.[3] This assumes the geothermal gradient is a straight line to within about 5 percent of the bottom; a 7F temperatures rise is then anticipated. Edwardson *et al.*[3] suggest that for most engineering purposes their procedure can be used to approximate the temperature profile of a well after stopping mud circulation. This may require one temperature measurement at the bottom of the hole and a second measurement about 300 ft off bottom. Alternate methods are described in their paper; but whenever possible their technique was used with Farris' data.

The static mud temperature at the wellhead was usually set about half-way between a normal surface temperature of 75F and the mud pumping temperature. This alters the geothermal gradient from the true gradient; however, it was believed permissible since it is known that the static mud temperature will fall between the two temperatures, depending on length of time after stopping circulation. Farris' data indicated that equilibrium should be approached very soon after restarting circulation; therefore, small errors in the geothermal gradient may not cause large errors in the final circulating temperatures.

RESULTS

Farris presented data on observed bottom-hole circulating temperatures, and mud suction and discharge temperatures for five wells ranging in depth from 5,310 to 10,925 ft. The static bottom-hole temperatures ranged from 136 to 244F. Mud suction temperatures ranged from 96 to 128F except in one case where a volume of the cooled mud (80F) equal to the casing volume was circulated. Transient or time-dependent temperature data were presented only on Well 2 by Farris. Comparisons of calculated and observed temperature data on this well are shown on Fig. 1.

Well 2 was 8,160 ft deep. The static bottom-hole temperature was 195F and circulating bottom-hole temperature was 122F. Referring to the detailed work of Farris, it is seen that after circulation ceased the bottom-hole temperature could range along the dotted line within the above limits. The bottom-hole temperature was about 156F 34 hours after the test period began. This 156F was used in calculations as the starting bottom-hole temperature. The mud was pumped in at 110F and observed bottom-hole and discharge temperatures were 122 and 115F, respectively. Calculated results were 125 and 123F, respectively. Maximum annulus temperature was about 3F hotter than bottom-hole temperature. The pumping rate was 4.17 bbl/minute and fluid viscosity was arbitrarily set at 10 cp.

At a rate of 8.34 bbl/minute (immediately following the 4.17 bbl/minute test) the bottom-hole temperature and circulating discharge temperature were 121.5 and 116F, respectively. This compares with calculated values of 125 and 117F (using 156F as the starting bottom-hole temperature for each rate). In separate calculations the fluid viscosity was increased to 25.0 cp and calculations were repeated. The resulting bottom-hole and circulating discharge temperatures were about 116 and 110F, respectively. Actual observed values were 5 to 7F higher.

In a separate experiment Farris reported that two casing volumes of mud at 80F resulted in a bottom-hole temperature of 94F. (The first casing volume was pumped at 4.17 bbl/minute, and the second at 8.34 bbl/minute an hour later.) A bottom-hole temperature of 93 to 92F was calculated (for two casing volumes at 4.17 bbl/minute). The API-schedule temperatures for an 8,000-ft well are 125 and 159F for casing and squeeze schedules, respectively, while the actual bottom-hole temperatures experienced in this case are 31 and 65F less than shown on API schedules.

For Well 3, observed bottom-hole and circulating discharge temperatures were 127.5 and 121F, respectively. After 2.5 hours of circulation, calculated values were about 135 and 130F and were still cooling slowly. Farris did not report the time at which his measurements were observed. Table 1 summarizes Farris' observed values and those calculated in this work.

TABLE 1 — COMPARISON OF EXPERIMENT AND CALCULATED FLOWING TEMPERATURES

				Circulating Temperatures, °F				
				Observed		Calculated		
Well	Depth (ft)	Rate (bbl/min.)	Assumed Viscosity (cp)	Bottom Hole	Discharge	Bottom Hole	Discharge	Maximum Annulus
1	5,310	10.15	10	109.5	105	104	103	106
2	8,160	4.17	10	122	115	125	123	128
2	8,160	8.34	10	121.5	116	125	117	127
2	8,160	4.17	25	122	115	116	110	135
2	8,160	8.34	25	121.5	116	122	116	126
2	8,160	4.17	25 (80° in)	94	—	92	—	132
3	8,300	12.10	10	127.5	121	135	130	138
4	9,923	9.65	10	137	121	140	127	145
5	10,924	9.73	10	156	133	160	142	165

DEVIATIONS, °F

	Bottom Hole		Discharge	
	10 cp	25 cp	10 cp	25 cp
	−5.5	−6	−2	−5
	3	+0.5	8	0
	3.5	−2	1	—
	7.5	—	9	—
	3	—	6	—
	4	—	9	—
Average deviation	(+2.5)	(−2.5) =	(+5.2)	(−2.5)
Average absolute deviation	4.6	2.9	5.9	2.5

For the assumed 10-cp mud (Farris did not give fluid properties) the average deviations in bottom-hole and discharge temperatures were +2.5 and 5.2F respectively. For

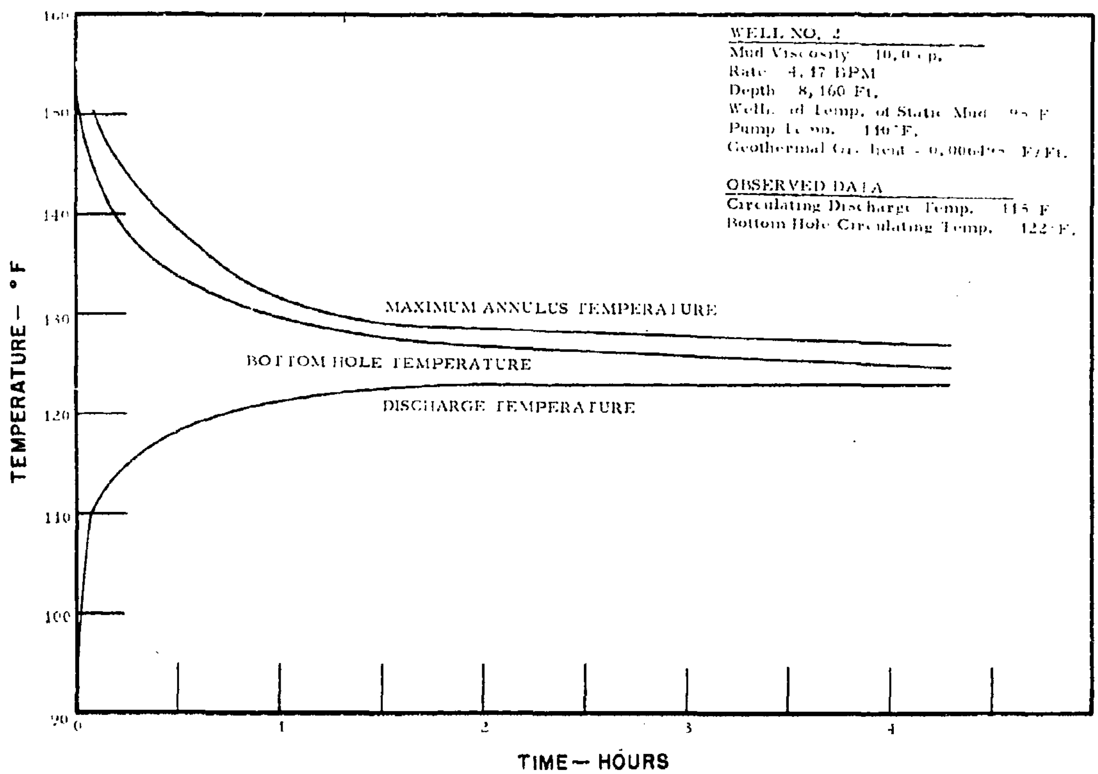

FIG. 1—CEMENTING TEMPERATURES, WELL 2.

TABLE 2 — WELL AND CEMENTING CONDITIONS

Well depth, ft	10,000
Casing ID, in.	4.892
Casing OD, in.	5.50
Hole size, in.	9.00
Pumping rate, bbl/minute	10.0
Cement temperature, °F	70
Fluid viscosity, cp	25.0
Fluid specific heat, Btu/lb, °F	0.94
Fluid thermal conductivity, Btu/ft, °F	0.37
Fluid density, lb/gal	10.0
Rock specific heat, Btu/lb, °F	0.21
Rock thermal conductivity, Btu/ft, °F	1.30
Initial wellhead temperature just prior to cementing, °F	135
Bottom-hole temperature just prior to cementing, °F	187

a 25-cp fluid these deviations are both −2.5F, indicating that the actual apparent viscosity of the mud used by Farris was in the 10- to 25-cp range.

EXAMPLE

To provide insight into information that can be obtained from this study, the data shown in Table 2 were used in producing the temperature profiles given in Table 3. The temperature history of a given element of fluid, as well as a given location, is provided. Table 3 also shows that maximum temperature experienced by the fluid may be one-third of the depth up from the bottom in the annulus.

FIELD TESTS

Although calculated temperatures for various well conditions agreed closely with those taken by Farris in 1938, it was felt that additional data should be studied using fluids of different flow properties and flow regime so that variations of bottom-hole temperature changes might be observed as forecast by the calculations. However, a search of the literature showed the only published data on actual measured bottom-hole circulating temperatures were those taken by Farris.

To obtain additional circulating temperature, a well was selected in Matagorda County, Tex. It had been drilled and cased with 5½-in., 17 lb/ft casing, and 2½-in. tubing was hung without a packer at 8,650 ft. Tests were conducted measuring bottom-hole static temperatures and circulating temperatures at pump rates of 2 and 6 bbl/minute using field salt water, and at 2 bbl/minute using a bentonite mud. It was felt that 2 and 6 bbl/minute circulating rates would approximate cement squeeze and casing cementing conditions, respectively.

The well was not disturbed for approximately 72 hours prior to starting tests. A high-resolution temperature tool was positioned approximately 5 ft above the bottom of the tubing. A static temperature of 250F was measured at this point. This gave a calculated temperature gradient of 2.03F/100 ft, which compares well with a 1.75F/100 ft gradient shown for the area on published gradient maps. The well was then circulated with 8.4 lb/gal salt water at 2 bbl/minute for 2 hours and 40 minutes. Temperature of the water was constant at 76F. A plot of temperature measured at the bottom of the tubing is shown on Fig. 2. Measured fluid temperature at start of circulation was 250F. After circulating at 2 bbl/minute for 2½ hours, the temperature of the fluid dropped 37°, cooling to 213F. This measured temperature of 213F agreed within 3F of the temperature calculated by the program. At the end of the circulating period a temperature profile was taken from 8,650 to 25 ft; approximately 1 hour was required to log the profile.

The temperature tool was run back to bottom and measurements were again taken while the well was circulated with salt water at 6 bbl/minute. The observed temperature when circulation began was 224F. Therefore, the well was 26F cooler than at the initial start of circulation. The well was circulated 56 minutes at 6 bbl/minute. Circulating temperature at the end of this period was 196F, or a further reduction of 28F and a total reduction of 54F below the observed static temperature.

After being adjusted for this specific bottom-hole static temperature, the API testing schedules reflect a circulating temperature of approximately 163F. The final measured temperature after circulating 2 hours and 40 minutes at 2 bbl/minute and 56 minutes at 6 bbl/minute was 33F higher than the temperature predicted by the published schedules. The water flow pattern at both 2 and 6 bbl/

TABLE 3 — CASING AND ANNULUS TEMPERATURE DURING CEMENTING

	Pumping Time (0.0 hours)		Pumping Time (0.194 hours)		Pumping Time (0.388 hours)		Pumping Time (0.77 hours)	
Percent Depth	Casing Temp. (°F)	Annulus Temp. (°F)	Casing Temp. (°F)	Annulus Temp. (°F)	Casing Temp. (°F)	Annulus Temp. (°F)	Casing Temp. (°F)	Annulus Temp. (°F)
0	—	—	—	128.7	—	124.1	—	118.8
5	137.2	137.2	75.9	132.7	75.4	128.0	74.9	122.5
10	139.5	139.5	81.6	136.5	80.7	131.8	79.6	126.0
15	141.7	141.7	87.2	140.2	85.8	135.5	84.3	129.4
20	144.0	144.0	92.6	143.9	90.9	139.1	88.8	132.5
25	146.2	146.2	97.6	147.4	95.8	142.6	93.3	135.5
30	148.5	148.5	103.1	150.8	100.6	146.1	97.6	138.2
35	150.7	150.7	108.2	154.0	105.3	149.4	101.7	140.6
40	153.0	153.0	113.1	157.3	109.9	152.7	105.8	142.7
45	155.2	155.2	118.0	160.3	114.4	155.7	109.6	144.4*
50	157.5	157.5	122.5*	163.7	118.8	158.5	113.3	145.6
55	159.7	159.7	148.6	166.0	123.0	160.9	116.7	146.5
60	162.0	162.0	150.8	168.4	127.1	162.7	120.0	146.9
65	164.2	164.2	153.1	170.9	131.0	164.0	123.0	146.8
70	166.5	166.5	155.4	173.1	134.7	164.7	125.7	146.4
75	168.7	168.7	157.7	174.6	138.1	164.9	128.1	145.6
80	171.0	171.0	159.9	174.9	141.3	164.7	130.2	144.5
85	173.2	173.2	161.9	174.0	144.2	164.0	132.1	142.9
90	175.5	175.5	163.8	172.2	146.7	162.9	133.6	140.9
95	177.7	177.7	165.3	169.7	149.0	161.4	134.8	138.6
100	187.0	187.0	166.5	—	150.8*	—	135.6	—

*Cement-mud interface.

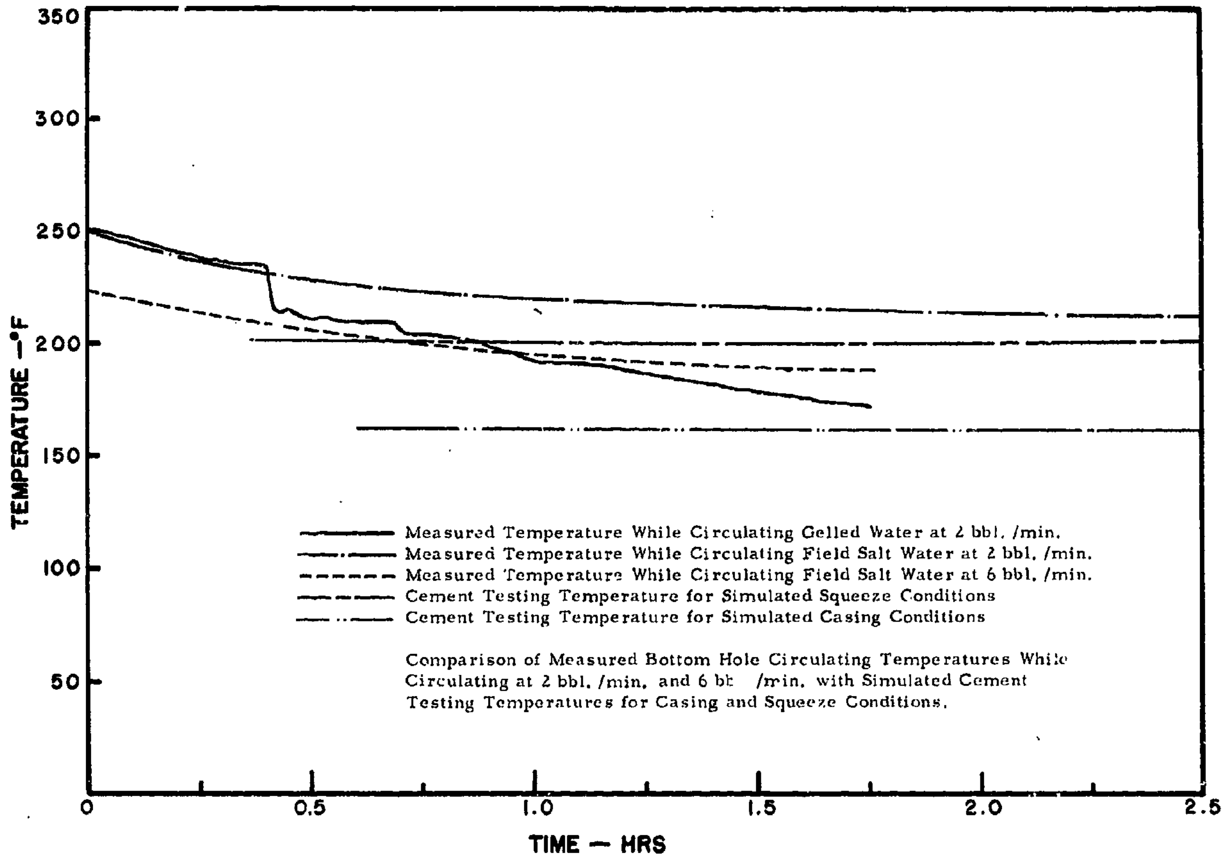

FIG. 2—OBSERVED CIRCULATING TEMPERATURE.

minute was turbulent. A temperature profile was again logged out of the hole at the end of the second circulation period.

The well fluid was not disturbed for 12 hours, and again a temperature profile was logged from surface to the bottom of the tubing. The bottom-hole temperature had returned essentially to static condition. Bentonite mud was then circulated for 1 hour and 46 minutes at 2 bbl/minute to observe the effect of changing fluid properties. The final observed circulating temperature was 173F (178F was calculated). The bottom-hole temperature decreased 77F from 250 to 173F in 1¾ hours. The bottom-hole temperature was 216F at the same time period while circulating at the same rate with salt water.

Test schedules for squeeze cementing again adjusted to this static temperature would be 202F. The bottom-hole circulating temperature was 215F when the gelled water reached the temperature tool. The fluid then cooled to 173F during the remaining 81 minutes of circulating time. The temperature of the fluid was observed to be 13F higher when it reached the bottom of the tubing than the predicted testing temperature. Although further cooling to 173F did occur during the remainder of the circulation period, this probably would not have occurred on an actual squeeze since the pump rate is reduced and usually stopped for short periods after the cement reaches the bottom of the tubing and starts out the perforations.

A 20F temperature decrease was noted when mud reached the temperature tool. The tubing was filled with salt water prior to pumping the gelled water. The large decrease in temperature that occurred when mud reached the tool confirms the significant role of fluid properties in circulating temperatures. A change in these properties is not considered in currently published data on circulating temperature.

CONCLUSIONS

A method has been developed for calculating transient temperatures during a cementing operation. Comparison with what data are available in the literature indicates agreement within a few degrees. Maximum temperatures occur in the annulus. This annulus temperature is several degrees higher than the bottom-hole temperature for all cases studied, but it is some 20 to 35F hotter when the pumping rate is about 4 bbl/minute. This low rate provides a viscous flow regime for the fluid properties used.

Bottom-hole temperature decreases if a higher viscosity (or relatively cool) fluid is pumped into the well. This change in temperature significantly affects the setting time of most cement slurries.

The scarcity of data on bottom-hole circulating temperatures emphasizes the industry's need for additional data to insure better engineered completions of hot, deep wells.

NOMENCLATURE

q = heat transfer rate

U = over-all heat transfer coefficient

A = area perpendicular to heat flow

T = temperature

h = film coefficient

k = thermal conductivity

D = effective conduit diameter

G = mass velocity

μ = viscosity of fluid

μ_w = wall viscosity

c = specific heat

r_w = radius of well

L_m = thickness of metal pipe

L = length of increment of pipe

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