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EFFECTS OF INSULATION FOR THE STEAM STRING OF THE TS-1S EXPERIMENT

J. R. WAYLAND

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EFFECTS OF INSULATION FOR THE STEAM STRING
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ABSTRACT

The character of the steam quality at the production depth in the Laramie Energy Technology Center's Tar Sand steam injection field experiment is studied. A series of calculations were made using the BORE wellbore heat loss code. The results are given in graphical form along with simple functional fits for use in the field.

I. INTRODUCTION

The Laramie Energy Technology Center (LETC) is conducting a Tar Sand field experiment (TS-1S) to test steam injection enhanced oil recovery. This test is to be conducted at the Northwest Asphalt Ridge test site west of Vernal, Utah. The objectives of LETC's first steam in situ recovery experiment are to determine the technical and economic feasibility of using steam injection. Because this experiment is for surface steam generation the problem of wellbore heat loss had to be addressed. A series of calculations quickly established that, because of the low mass flow rate, substantial heat losses occur.¹ To reduce the heat loss, insulation has been added to the steam string. The purpose of this report is to characterize the steam quality at the production depth in terms of the proposed injection well configuration.

The TS-1S experiment injection well has a configuration as shown in Figure 1.² The steam string is 2 7/8-inch tubing with one inch of fiberglass insulation covered by 16 gauge steel sheet. The well is cased with 7-inch, N-80, 29 lb/ft. casing to a depth of 580 feet. A high temperature packer will be set at 480 feet. The steam will be injected into the Rim Rock sandstone member of the Cretaceous Mesaverde Formation between 500 and 540 ft. This zone has been perforated with 4 shots/ft. The outside of the casing has approximately a 1 1/2-inch cement shell. The maximum steam output from the generator is for 80% quality, 723 barrels (liquid) per day (B/D) at a pressure of 1000 psi. In transferring the steam from the generator to the well head, it is estimated that the quality will drop to about 75%. This geometry is summarized in Table 1, which also lists the needed input data for the simulation of wellbore heat losses.^{2,3} Appendix A gives a summary of empirical relationships that can be used to estimate many of the needed thermo-physical parameters.

The analysis was done with the computer program BORE.^{2,3} The one-dimensional steam flow is assumed to have quasi-steady heat transfer occurring only in the radial direction. The steam quality varies between zero and one-hundred percent. The basic geometry is as shown in Figure 1 with the formation assumed to be homogeneous and infinite in extent.

TABLE 1. INPUT PARAMETERS³

Parameter	Name	Value
Geometry		
Injection tube inner radius	R1	0.1017 ft.
Injection tube outer radius	R2	0.1200 ft.
Insulation outer radius	R3	0.2030 ft.
Casing inner radius	R4	0.2577 ft.
Casing outer radius	R5	0.2917 ft.
Cement outer radius	R6	0.4115 ft.
Thermal Conductivity		
Injection tube	C12	25.0 BTU/hr. ft. R
Insulation	C23	0.02 BTU/hr. ft. R
Casing	C45	25.0 BTU/hr. ft. R
Cement	C56	0.67 BTU/hr. ft. R
Formation	CINF	1.4 BTU/hr. ft. R
Thermal Differsivity		
Formation	ALPINF	0.04 ft ² /hr.
Heat Transfer Coefficient		
Steam-tube	HF	10 ⁶ BTU/hr. ft. ² R
Cement-formation	H6	10 ⁶ BTU/hr. ft. ² R
Infrared Emissivity		
Insulation	E3	0.9
Casing	E4	0.9
Friction Factor	FFAC	0.02
Surface Temperature	TS	515 R
Geothermal Gradient	GRAD	0.011 R/ft.
Initial Position	ZO	* ft.
Final Position	ZF	* ft.
Mass Flow Rate	FDOT	*lb _m /hr.
Initial Temperature	TO	* R
Initial Quality	CHIO	*

*As needed

FIGURE 1. BASIC WELLBORE GEOMETRY

Steam quality, temperature and enthalpy are computed as functions of depth for the input parameters given in Table 1. Note that it is assumed that the thin sheet plate over the insulation is not thermally important. The very small thermal mass of this sheet makes this assumption reasonable. Also it is assumed that the insulation covers the couplings between joints. About 20 feet of tubing will not be insulated in the 480 ft. above the high temperature packer. If one makes a first cut approximation to this by reducing the thickness of the insulation by 460/480 the impact is negligible.

II. CHARACTERISTICS OF THE PROPOSED INSULATION

Clearly after a sufficiently long time the system will come to thermal equilibrium. To be extra safe let us assume that steam has been injected for about a month (720 hrs.). Under these conditions it is possible to estimate the steam quality, X , at the top of the injection zone for steam of 80% quality at the well head. The results are shown in Areas A and B of Figure 2 as a function of the mass flow rate and injection pressures of 700 (curve A) and 1000 (curve B) psi. Little steam quality is gained for mass flow rates above 150 B/D but the penalty

FIGURE 2.

at rates of less than 20 B/D are severe. If we make the approximation that exposed (uncovered) links are equivalent to an reduction in insulation thickness, the impact of leaving about one half of the steam string uninsulated is shown in Curves AA (700 psi) and BB (1000 psi) of Figure 2. The effect is such that below about 30 B/D (compare curve BB to B), the steam quality becomes a problem.

The method of applying the insulation to the injection tube can cause some problems. A collar is attached to the bottom of the insulation package just above the end of each joint. The top of the insulation is open. Thus it is possible for the insulation to accumulate moisture. This will change the thermal conductivity. As a worst case the insulation can become water logged and the thermal conductivity will approach 0.35 BTU/hr.-ft.-R. This results in the steam quality reduction shown by curves AA and BB of Figure 3 for injection pressures of 700 and 1000 psi. Now the mass flow rate must be increased to about 100 B/D to maintain a steam quality of order 50% at the depth of 500 ft. Clearly something must be done to keep the fiberglass dry or use a non-wetable insulation,

FIGURE 3.

e.g., Calcium Silicate. If these problems are overcome, a workable system should exist. Let us now consider such an arrangement.

III. CHARACTERISTICS OF STEAM QUALITY FOR A WORKABLE SYSTEM

To estimate the conditions one might encounter in the field for a properly designed system, a series of simulations were performed. The range of injection pressures, all for an injection steam quality of 75%, included 300, 500, 700 and 1000 psi. The time dependence is shown in Figures 4, 5, 6 and 7 for mass flow rates of 50, 100, 150, 200 and 500 B/D at the midpoint of injection (520 ft.). The system is in equilibrium by the end of the simulation period of 100 hours (~4 days). For each case a linear fit of the form

$$X(\%) = a_1 t(\text{hr.}) + a_0$$

FIGURE 4.

FIGURE 5.

FIGURE 6.

FIGURE 7.

is given for each mass flow rate. Note again that rates ≥ 50 B/D are needed if steam quality losses are to be kept low.

The dependence of steam quality upon mass flow rate at equilibrium (100 hr.) is shown in Figure 8. If the goal is to keep steam quality losses to less than 5%, the injection rate of 100 B/D or greater should be required. This is, of course, upon the conservative assumption that we have an ideal system that performs perfectly. The field conditions suggest we should attempt the rather stringent goal of losses of less than 5%.

Another way of looking at the effects of varying injection conditions is shown in Figure 9. The steam quality is fitted to the functional form of

$$X(\%) = a_1 p \text{ (psi)} + a_0$$

for mass flow rates of 50 to 500 B/D at a depth of 520 ft. and $X_0 = 75\%$. Perhaps more useful in the field is the empirical expression for steam quality as a function of injection pressure and mass flow rate in

$$X(\%) = 64.59 \dot{m}^{(0.02478)} - 0.192 p \dot{m}^{(-0.8783)}$$

which reproduced the results of Figure 9 to within $\pm 2\%$ when $\dot{m}$ is in B/D and p in psi.

A different approach is given in Appendix B. In addition to providing a rough estimate of the amount of heat deposited into the formation, it is shown that the steam quality is given by

$$X = X_0 - \frac{(0.2031 T_0 - 111.86)l}{1318 \dot{m} P_0^{(-0.08774)}}$$

where l is the depth in ft. and T_0 and P_0 are the temperature (R) and pressure (psia) at the wellhead.

IV. CONCLUSION AND RECOMMENDATIONS

From the results reported in Figures 2 and 3, there appears to be possible problems associated with using fiberglass insulation if water

FIGURE 8.

FIGURE 9.

vapor is present in the annulus. The additional cost of using commercial insulation for 500 ft. of Conco Calcium Silicate is about \$10,000 and for Thermocase III about \$27,500. The Calcium Silicate has hot spot problems at the coupling between joints as does the fiberglass approach.

Because of the normal field conditions, it is important to have a goal of very low steam quality losses (Figs. 4 to 9). The dominant parameter here is the mass flow rate. It appears that, from the point of view of wellbore heat losses, this should be > 100 B/D.

APPENDIX A

Often it is not possible to have measured values of thermophysical properties of reservoir rocks and steam. S. M. Faroug Ali in the review monogram "Secondary and Tertiary Oil Recovery Processes"⁴ has given a number of empirical relationships that are useful for wellbore heat loss calculations.

The thermal conductivity of the reservoir rocks increases with density, liquid saturation, pressure, saturating liquid thermal conductivity and fluid velocity but decreases with elevated temperature and increased porosity. For water saturated rocks, Tikhomirov's equation is a useful guide to rock thermal conductivities ($k_h = \text{CINF}$).

$$k_h (\text{BTU/hr-ft-}^\circ\text{R}) = 6.36 \frac{\exp(0.6d + 0.6 S_w)}{(0.556T + 255.3)^{0.55}}$$

for dry rock density d (gm/cc) and S_w water saturation as a fraction of pore volume. Normally k_h is in the range of 1.0 - 1.4 BTU/hr. - ft.- $^\circ\text{R}$.

The thermal diffusivity ($D = \text{ALPINF}$) is related to the rock thermal conductivity by

$$D = \frac{k_h}{\rho C}$$

where the product ρC is the rock heat capacity per unit volume (BTU/ft.³- $^\circ\text{R}$). For most cases we will be interested in D is about 0.04 ft.²/hr.

Often the injection steam is described by a wellhead pressure, P_s and what is needed is the steam temperature T_s . One relationship that is valid to 1% for pressures up to 3000 psia is:

$$T_s = 115.1 P_s^{0.225}$$

The specific heat of sand usually follows the following linear function of temperature:

$$C = 0.2 + 10^{-9} T$$

where T is $^\circ\text{F}$.

APPENDIX B

Often it is helpful to have an estimate of the rate of heat loss to the formation. An examination of the results for the calculated heat loss rate $\dot{Q}$ shows that there is very little variation after equilibrium is established (less than 3% between $\Delta t = 2$ hr. and 50 hr.). Also the variation of $\dot{Q}$ with depth is small after equilibrium occurs (less than 2%). The dominant dependence is upon injection temperature (T_o) as shown in Figure 10. The linear relationship for injection steam quality (X_o) of 75% is

$$\dot{Q} = 0.2066 T_o(^{\circ}R) - 111.86 \quad (B-1)$$

The enthalpy at a depth l is given by

$$h(l) = h_o - \int_0^l \frac{\dot{Q}(x)}{\dot{m}} dx \quad (B-2)$$

where h_o is the injection enthalpy and $\dot{m}$ is the mass flow rate (lb/hr.) of the steam. At equilibrium $\dot{Q}$ can be replaced by an appropriate average value $[\dot{Q}]$, so that

$$h(l) = h_o - \frac{[\dot{Q}]}{\dot{m}} l \quad (B-3)$$

Hickox² has suggested that the enthalpy h_o can be estimated by

$$h_o = 1.113(T_o - 459.67) - 63.42 + x_o 1342.9 \left(1 - \frac{T_o}{1165.3} \right) 0.3674 \quad (B-4)$$

Then if we assume that all of the heat content in the steam at depth l , the top of the injection zone, is absorbed by the reservoir rock, the absorbed heat is

$$\Delta Q = h(l) \dot{m} \Delta t \quad (B-5)$$

during a period of time Δt . For example is $X_o = .75$, $T_o = 467^{\circ}F = 927^{\circ}R$ then $h_o = 1013$ BTU/lb. If $\dot{m} = 7350$ lb/hr. = 500 B/D the heat available for absorption in 24 hr. is 1.8×10^8 BTU.

FIGURE 10.

The above consideration allows one to develop a relationship for the steam quality at depth l , $X(l)$ as:

$$X(t) = X_0 - \frac{\dot{Q}l}{\dot{m}L} \quad (B-6)$$

where L is the latent heat of the steam. One can make an accurate estimate of L by

$$L = 1318 P_s^{-0.08774} \quad (B-7)$$

where P_s is the steam pressure in psia. Then from equations B-1, B-6 and B-7

$$X \cong X_0 - \frac{(0.2066T_0 - 111.86)l}{1318 \dot{m} P_0^{-0.08774}}$$

when l is in units of ft.

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