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memorandum

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SYMBOL: ESS-4-83-399

SUBJECT: FURTHER RESULTS ON HEAT TRANSFER COEFFICIENTS
FOR THE EE-3 NITROGEN BLANKET EXPERIMENT

Summary

In previous memos on the heat transfer coefficient in the nitrogen filled annulus in EE-3, it was reported that the measured results were higher than theoretically estimated values by a factor of 2-3; measured value lying between 20-25 W/m²°C. The estimated values previously used were based upon natural (buoyant) convection heat transfer correlations involving Nusselt and Grashof numbers. In evaluating the latter we incorrectly evaluated the kinematic viscosity of nitrogen. Now, using pressure corrections for kinematic viscosity values we obtain theoretically estimated values between 20 and 70 W/(m²°C). The measured values agree with the lower end of this range.

To put these values in perspective, it is noted that if the annulus was filled with water instead of nitrogen, the heat transfer coefficient would be seven times higher. However, before readers conclude that nitrogen results in a system seven times as insulative, we point out that the heat transfer system is complex - heat is transferred from rock to casing, through the annulus to the drill pipe, and then to the flowing water in the drill pipe. At each interface there are contact or fluid film heat transfer resistances, and distributed resistances over the casing and pipe wall thicknesses as well as resistance in the rock itself. This latter resistance increases with time as the thermal boundary layer penetrates deeper into the rock. For comparison purposes the effective heat transfer coefficient across the casing and drill pipe is about 3000 W/(m²°C), and the film coefficient for the water inside the drill pipe

(which is in a state of forced, or pumped, convection) is about 2000 W/(m²°C). Their reciprocals, the heat transfer resistances, are negligible compared to that of the nominally static fluid, either water or nitrogen, in the annulus. However, the rock resistance is, because of low thermal conductivity, comparable to the annulus resistance after a period of several hours to perhaps a day.

The bottom line of these comments is that if it should be decided to resume fracturing in EE-3, and that, say, one million gallons will need to be injected at 20 BPM, then to avoid over stressing the EE-3 casing over its uncemented length from 0 to 5500 ft (which would occur if the mean casing temperature over this length was reduced by more than 15°C) the injected water must be heated to 50°C if the annulus is filled with nitrogen, 65°C if water is used.

Theoretical Estimates

Kreith and Black¹ suggest the following formula for enclosed spaces between parallel vertical boundaries:

$$\overline{Nu}_b = \frac{hb}{k} = \frac{0.065}{(L/b)^{1/9}} Gr^{1/3}; \quad 2 \times 10^5 < Gr < 10^7 \quad (1)$$

where $\overline{Nu}_b$ is the mean Nusselt number, Gr is the Grashof number, L is the vertical height of N₂ - filled annulus, and b is the radial gap of the annular space (0.051m), k is the N₂ thermal conductivity and h is the convective heat transfer coefficient. The Grashof number is

$$Gr = \frac{b^3}{\gamma^2} \frac{g \beta \theta}{\nu}$$

where

$$g = \text{acceleration of gravity} = 9.8 \text{ m/s}^2$$

$$\beta = \text{thermal expansion} = 2.5 \times 10^{-3} \text{ per } ^\circ\text{C}$$

$$\theta = \text{temperature difference} = 50^\circ\text{C}$$

$$\gamma = \text{kinematic viscosity} = 1.2 \times 10^{-7} \text{ m}^2/\text{s}$$

where properties have been evaluated at 100°C and 17 MPa (2500 psi). After evaluation it is found that $Gr = 1.1 \times 10^{10}$. For the situation pertaining to the N_2 blanket experiment

$$L = 1737 \text{ m}, \left(\frac{L}{b}\right)^{1/9} = 3.1885,$$

Thus $Nu_b = 45.7$, and $h = 27 \text{ W}/(\text{m}^2\text{ } ^\circ\text{C})$

It should be noted that our Grashof number is 1000 times greater than the upper limit of validity for Equation (1). There do not appear to be any correlations in the literature for the very high Grashof numbers our situation requires. However, the value of h predicted above appears reasonable in light of our measured values.

Researchers at the University of Waterloo in Canada have been studying natural convection in vertical and inclined closed spaces for about 10 years. In a recent summary (El Sherbiny et al 1983²), they suggest

$$Nu = [Nu_1, Nu_2, Nu_3] \text{ max} \quad ; \quad Gr < 10^8 \quad (2)$$

where

$$Nu_1 = .0605 Ra^{1/3} = 120, \text{ where}$$

$$Ra = Gr Pr, \text{ and } Pr = .7,$$

$$Nu_2 = 1 + (0.104 Ra^{.293})^{3/4} = 82.5$$

$$Nu_3 = .242 (Ra/A)^{.272} = 7, \text{ where}$$

$$A \text{ is the aspect ratio, } 1737/0.051$$

Thus, $Nu = 120$ and $h = 70 \text{ W}/(\text{m}^2\text{ } ^\circ\text{C})$

Once again, the Grashof number for our situation is 100 times larger than the upper limit of validity of Equation (2).

The large discrepancy between heat transfer coefficients predicted by Equations (1) and (2) probably stem from the ~ 100 fold extrapolations required in both cases, and points to the need for data in the Grashof numbers of interest.

References

1. Kreith, K and Black, W., Basic Heat Transfer, Harper and Row, 1980.
2. El Sherbiny, S. M., Rauthby, G. D., and Hollens, K.G.T., "Heat Transfer by Natural Convection Across Vertical and Inclined Air Layers", Journal of Heat Transfer, Volume 194, Feb. 1982, 96-106.

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