# Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 12 (23): 2484-2488, 2012
ISSN 1812-5654 / DOI: 10.3923/jas.2012.2484.2488


# Synergistic Evaluation of Production Tubing Heat Losses and Integrity of Oil Well

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**Abstract:** Oil production involves significant heat exchange between the wellbore fluid and its surroundings. During production, the hot fluid losses heat to the cold surroundings, continuously as it moves up the borehole. The heat transfer process impacts well-integrity and, in turn, the ability of the well to perform its required function effectively and efficiently whilst safeguarding life and the environment. One often overlooked heat transfer effect is increase in annulus pressure resulting from annular fluid thermal expansion, which can result in tubing collapse or casing burst. Damage due to high annular pressure can dramatically affect the well-integrity. During the design phase of a well, it is necessary to avoid risks and uncertainties and look at its planned life cycle. This study intends to investigate wellbore heat transfer and its impact on the well-integrity. Moreover; the results of the present work can be used for the preliminary design calculation of oil wells to estimate changes in some thermo-physical properties of the annular fluids. This study provides a baseline for temperature related well-integrity problems in oil wells.

**Key words:** Well-integrity, heat-transfer, oil wells, annular fluids, thermo-physical properties

## INTRODUCTION

Well-integrity is an important part of health, safety, and environment and quality assurance programs in the petroleum industry; it is a matter of protecting investment (Andersen, 2006). The efficient design and operation of an oil well requires an understanding of thermo-physical behavior of fluids in the annular space between tubing and casing. Longevity is a prime consideration in permanent tubing installation. In severe down hole environment, tubing materials must resist stress cracking, buckling, burst and collapse. Before selecting casing, tubing, it is necessary to understand down hole environments, in terms of thermo-physical properties of fluids in the annulus. One often overlooked thermal phenomenon in oil wells is increase in annulus pressure resulting from annular fluid thermal expansion which can result in tubing collapse or casing burst.

An oil well is usually constructed such that un-cemented annuli do not experience abnormal pressures. Under most circumstances, a proper design process will ensure that annuli do not experience abnormal pressures. By definition an annulus is a sealed volume and there should be no flow paths that cause migration of fluids into the annulus from its surroundings. In principle, given the annular configuration, all leak paths that can compromise its integrity should be identified. Figure 1 and 2 show the different kinds of annuli in a well bore.

The primary annulus (Type I) is formed by the production tubing and casing. It is bounded on the top and bottom by the wellbore seal assembly and completion hardware (including packers and seals), respectively. In addition, there may be an annular safety valve, gas lift valves and related equipment depending on the nature of the well. The secondary annuli can be of two kinds-Types II and III.

The Type II annulus is formed by two adjacent casing strings. It is bounded at the top by the wellhead seal assembly and at the bottom by the cement. The cement top in this instance is above the shoe of the outer string of the annulus. The type III annulus is essentially similar, except that its bottom is open to the formation.

The cement top lies below the shoe of the outer casing string, either by design or accident. The temperature across the wellbore increases (in comparison to its equilibrium initial magnitude); when the well is put on production. The temperature causes thermal expansion of the incompressible annular fluids. Since, the volume of the annulus does not expand to the same extent, the

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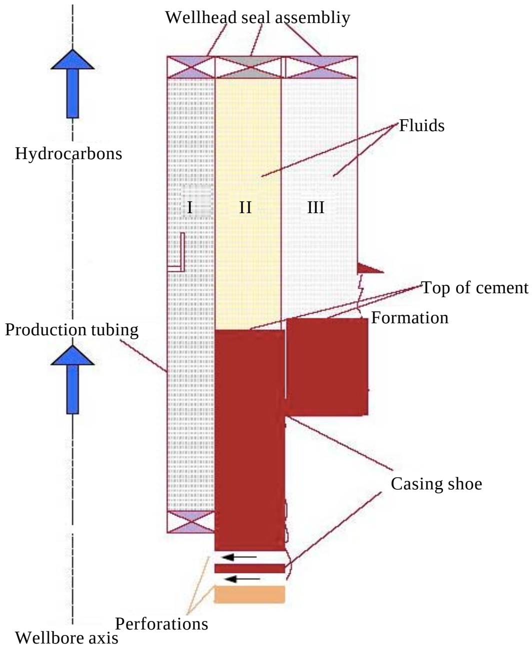


Fig. 1: Different kinds of annuli in an oil well

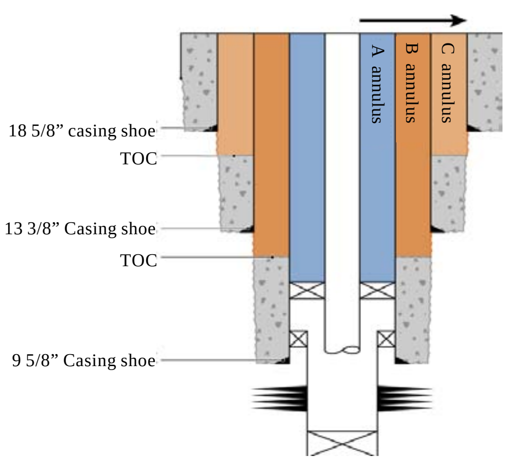


Fig. 2: Oil well architecture as a composite cylindrical wall

annular pressure increases. In designing for this load condition, care must be taken to include all the un-cemented annuli in the analysis.

Often, addressing the pressure build-up in one annulus may leave another annulus exposed to a failure-causing load. Such pressure abnormalities can typically accounted for in the well design process by most well designers. The procedures to do so are well documented in the oil field literature (Adams *et al*., 1992; Halal and Mitchell, 1994; Adams and MacEachran, 1994). Trapped annulus pressures are a natural phenomenon and do not arise due to a problem of design or construction. Of course, they cannot be ignored and must be considered when designing equipment to handle the expected loads.

The main objective of the present paper is to address the effect of the change of the annular fluid thermo-physical properties due to the variation of the temperature at various depths of the well. For the analysis, an in situ field data of the temperature-depth distribution was used. The results are presented in terms of thermal expansion coefficient, kinematic viscosity, and thermal diffusivity at various depth of the well.

## THE NAVIER-STOKES EQUATIONS FOR FLUIDS THE IN THE ANNULAR SPACE BETWEEN TUBING AND CASING

The Boussinesq approximation for steady laminar flow was employed in the present study. In the simulation, the conservation and the state equations were solved numerically for continuity, momentum and energy.

The following assumptions are totally true and applicable for the large aspect ratio annular fluid flow:

- The variation in the peripheral direction is negligible, $\frac{\partial}{\partial \theta} = 0$
- There is no velocity component in the peripheral direction, $V_\theta = 0$
- The flow is steady, $\frac{\partial}{\partial t} = 0$; Newtonian with constant viscosity and compressible

Hence, the governing equations in z and r directions are:

- Continuity equation:

$$\frac{1}{r}\frac{\partial(\rho r v_r)}{\partial r} + \frac{\partial(\rho v_z)}{\partial z} = 0$$

Momentum equation in r and z directions:

- For z-direction:

$$V_r \frac{\partial}{\partial r}(\rho V_z) + V_z(\rho V_z) = \frac{\partial p}{-\partial z} + \frac{1}{r}\frac{\partial}{\partial r} r\partial V + 0ZV + \mu + \partial g_2$$

- For r-direction:

$$V_r \frac{\partial}{\partial r}(\rho V_r) + V_z(\rho V_r) = \frac{\partial p}{-\partial z} + \mu \frac{\partial}{\partial r\left(\frac{1}{r}\frac{\partial}{\partial r}(rV_r) + \frac{\partial^2 V_r}{\partial Z^2}\right)} + \rho g_r$$

Energy equation in r and z direction:

$$C_p\left[V_r \frac{\partial}{\partial_r}(T\rho) + V_z \frac{\partial}{\partial_z(T\rho)}\right] = \frac{1}{r}\frac{\partial}{\partial_r}\frac{\partial T}{rk\partial_r} + \frac{a\left(k\frac{\partial T}{\partial Z}\right)}{\partial_z} + \varphi_{vis}$$

where, the viscous term φ is:

$$2\mu\left[\left(\frac{\partial V_r}{\partial r}\right)^2 + \left(\frac{V_r}{r}\right)^2 + \left(\frac{\partial V_z}{\partial z}\right)^2\right] + \mu\left(\frac{\partial V_z}{\partial r} + \frac{\partial V_r}{\partial z}\right)^2$$

Since, the flow is compressible, the state equation must be adopted in the model to relate the density change to the pressure and temperature:

$$\rho = \frac{p}{RT}$$

## NUMERICAL SIMULATION

The concentric vertical annulus with tubing outside radius 0.037 m, casing inside radius of 0.079 m and well-depth of 1632 m was modeled for two-dimensional flow using GAMBIT software. The well was segmented into $N_L$ segments; each segment has a height of 8.0 m. The surfaces temperatures of each segment were considered as an average of the temperature variation along ΔL. The temperature variation along the depth, L was adopted from the study of Sagar *et al*. (1991). Both; the flow and thermal behavior within the fluid field was solved numerically by computational simulated using FLUENT software. The buoyancy driven flow in the annulus was simulated as laminar since Rayleigh number is less than $10^9$, where the applicable correlations are limited to this Rayleigh number range. The Boussinesq approximation (Gray and Giorgini, 1976) for steady laminar flow was employed in the simulation. In the simulation, the conservation and the state equations were solved numerically for continuity, momentum and energy.

Governing equations were solved using SIMPLEC algorithm. At the different temperature range within the system, an 8 m depth part of the system was studied. The mesh generated for each 8 m segment is 80,000 structured cells with the following boundary conditions as can be shown in Table 1 and a no-slip condition for velocity and temperature on the walls.

Table 1: Tubing outside and casing inside temperature at different depths

| Well depth (m) | Average tubing temperature (K) | Average casing temperature (K) | Average annulus air temperature (K) |
|---|---|---|---|
| 0 | 304.111 | 297.444 | 300.778 |
| 152.40 | 306.889 | 299.111 | 303.000 |
| 304.80 | 308.556 | 300.778 | 304.667 |
| 457.20 | 309.667 | 302.444 | 306.056 |
| 609.60 | 310.778 | 304.111 | 307.444 |
| 762.00 | 311.889 | 305.778 | 308.833 |
| 914.40 | 313.000 | 307.444 | 310.222 |
| 1066.8 | 313.556 | 309.111 | 311.333 |
| 1219.2 | 314.111 | 310.778 | 312.444 |
| 1371.6 | 314.667 | 312.444 | 313.556 |
| 1524.0 | 315.222 | 314.111 | 314.667 |
| 1632.0 | 315.222 | 315.222 | 315.222 |

(Sagar *et al*., 1991)

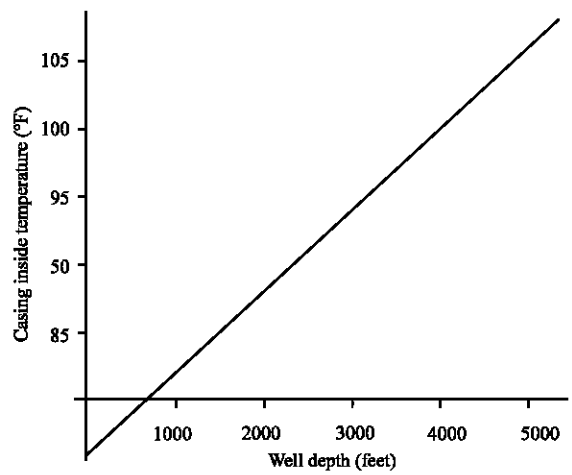


Fig. 3: Casing inside temperature

## THERMAL PROPERTIES OF THE ANNULAR FLUIDS IN SYSTEM

In the current study, wellbore temperature data provided by Sagar *et al*. (1991) from a 1632-meter-deep flowing oil well were used to calculate thermo-physical properties of the annular fluid, i.e., air. Table 1 reports the tubing outside and casing inside temperature at different depths (Sagar *et al*., 1991). The thermo-physical properties will be calculated at mean temperature of the tubing outside and casing inside temperature.

Figure 3 and 4 show the best-fit curve of the casing inside temperature and tubing outside temperature, respectively.

## RESULTS AND DISCUSSION

The design of oil wells and the ability to predict their performance depend on the availability of experimental data and conceptual models that can be used to describe

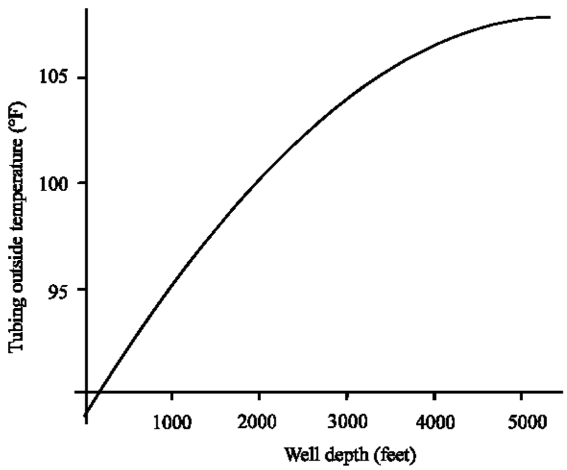


Fig. 4: Tubing outside temperature

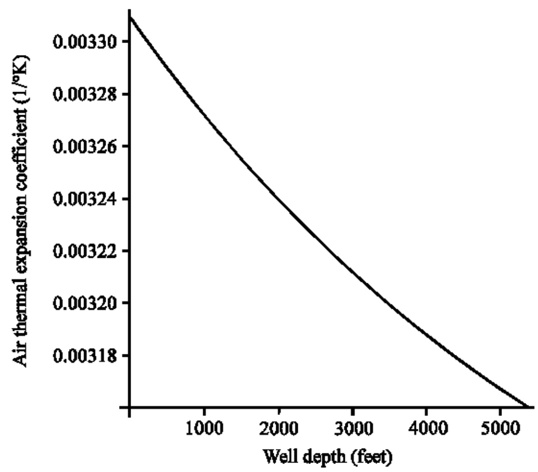


Fig. 5: Annular fluid thermal expansion coefficient

heat transfer process with a required degree of accuracy (Duns and Ros, 1963). From both a scientific and a practical point of view, it is essential that the various characteristics and properties of such conceptual models and processes are clearly formulated on rational bases and supported by field data. The correlations developed by Ierardi (2005) will be employed for calculation of thermo-physical properties of air.

One often overlooked temperature effect is increase in annulus pressure resulting from annular fluid thermal expansion, which can result in tubing collapse or casing burst. Damage due to high annular pressures can be prevented by annulus burst plates or relief valves, relieving expansion fluids to a catch tank or by leaving void space (gas) above annulus fluid. Required void space height depends on maximum expected temperature difference and fluctuating annulus pressures can be expected.

Figure 5 shows the annular fluid thermal expansion coefficient as function of well depth. The thermal expansion coefficient started at around 0.00334 on the surface of the wellbore and dropped gradually throughout the wellbore.

Figure 6 illustrates that annular fluid kinematic viscosity started at around 0.0000155 on the surface of the wellbore and increased gradually throughout the wellbore.

Figure 7 shows the annular fluid thermal diffusivity as function of well depth. The figure illustrates that air thermal diffusivity started at around 0.000018 on the surface of the wellbore and increased gradually throughout the wellbore.

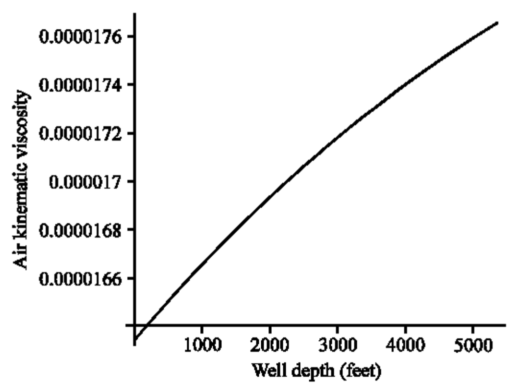


Fig. 6: Annular fluid kinematic viscosity

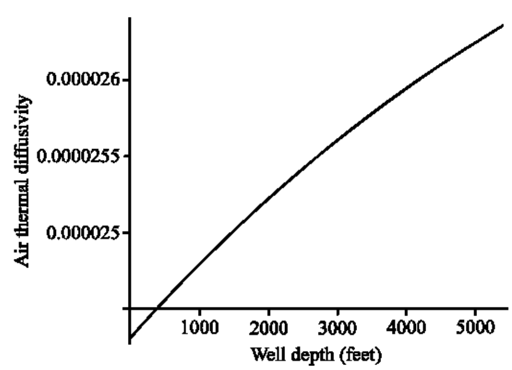


Fig. 7: Annular fluid thermal diffusivity

The pressure integrity of oil well depends on the thermo-physical properties of the annular fluids. Proper design ensures that the well can withstand the likely loads imposed due to sharp change in thermo-physical properties.

## CONCLUSIONS

Thermo-physical properties of the annular fluids of oil well as a function of oil well depth were studied here. The following conclusions can be drawn:

- The design of oil wells and the ability to predict their performance depend on conceptual studies that can be used to describe thermo-physical properties of the annular fluids with a required degree of accuracy
- One often overlooked heat transfer effect is increase in annulus pressure resulting from annular fluid thermal expansion which can result in tubing collapse or casing burst
- Pressure integrity of the production tubing is a function of tubing and casing mean temperature and annular pressure

## ACKNOWLEDGMENT

Authors would like to acknowledge the assistance of Universiti Teknologi PETRONAS (UTP), Malaysia for their support in conducting this research study and publication of results.

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