Evaluation of Effects of Trapped Fluid on Downhole Tool Deformation

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***Abstract**: During finite element analysis (FEA) of downhole tools, the fluid load acting on the tool chassis and completion system, such as hydrostatic pressure, reservoir pressure, or applied wellbore pressure, is simply represented by uniform static pressure. This approximation of fluid load has been shown to be effective and accurate enough for many applications and is widely accepted. However, this fluid load representation can be problematic in terms of trapped fluid because the pressure from trapped fluid, which is typically confined between seals in a closed or confined volume, changes with deformation or deflection caused by applied pressure or by axial tensile or compressive loads on surrounding structures. This paper uses a finite element algorithm to model trapped fluid, thereby accounting for the coupling between the deformation of the surrounding structure and pressure from the trapped fluid acting on the structure. The algorithm is applied to evaluate how the pressure of trapped fluid between sealing points in the annulus of a tubing string changes with surrounding pressure. Under a very high production flow, the tubing pressure decreases significantly; it is important to know whether or not the trapped fluid will cause tubing or a tool component to collapse. Conversely, during the setting process, it is important to know the amount of pressure increase from the fluid in the sealed-off section. Comparisons of predictions from models with and without fluid highlight the need to account for fluid structure interaction in evaluating the effect of trapped fluids.*

***Keywords**: fluid load, downhole tool, fluid structure interaction, trapped fluid.*

1. Introduction

One of the main functions of completion tools is to isolate various zones to facilitate production or other operations using packers or other type of seals. Fluid can be confined or trapped in this process. The trapped fluid pressure on the surrounding structure can change with ambient conditions. The contraction of the space trapping the fluid will lead to the increase of trapped fluid pressure, and the expansion of the space will cause the decrease of the trapped fluid pressure. The common approximation of fluid load on structure, the representation of fluid pressure by a uniform/constant pressure in finite element models, will not work for this scenario. The interaction between the trapped fluid and the surrounding structure, e.g., tubing and casing in many downhole applications, must be accounted for.

Two factors can lead to the change of the trapped fluid pressure. The first factor is mechanical load. For example, the change in ambient pressure or other loads acting upon the fluid containing structure will lead to the deformation of the structure, and consequently, the change in trapped fluid pressure. The second factor is thermal load, i.e., temperature change. Typically, when temperature increases, the trapped fluid pressure will increase because the coefficient of thermal expansion of fluid is an order of magnitude greater than that of steels and alloys. Consequently, the key physical properties of fluids for the trapped fluid analysis are fluid bulk modulus and the coefficient of thermal expansion. Fluid confined between sealing mechanisms (sealing points) for zonal isolation purpose is by design. There are scenarios in which fluids are unintentionally trapped within a complex multicomponent seal, for example, fluid trapped between the components of a V packing seal. In this paper, the focus is on the analysis of the effects of mechanical loads on trapped fluid between sealing points and its application in downhole operations.

In this paper, the approach to analyze the interaction between trapped fluid and structure will be described first in Section 2, along with the illustration of bulk modulus and coefficient of thermal expansion change with hydrostatic pressure and ambient temperature. A capped fluid-filled pipe will be used to illustrate the basic effects of trapped fluid on the burst and collapse of the pipe in Section 3. With proper engineering assumptions, the trapped fluid analysis method is applied to real-world scenarios in Section 4: 1) during production packer setting process, it is important to know the amount of pressure increase from the fluid in the sealed-off section to adjust operation parameters; 2) under a very high production flow, the internal tubing pressure decreases significantly; it is important to know whether or not the trapped fluid in the annular space between the production tubing OD and the casing ID will cause the tubing or a tool component to collapse. Section 5 includes a summary and concluding remarks.

2. The approach for trapped fluid–structure interaction analysis

The reason that the contraction of the space trapping the fluid will lead to the increase of trapped fluid pressure and that the expansion of the space will cause the decrease of the trapped fluid pressure in downhole applications is that fluid bulk modulus is small, but not negligible. When compared to bulk modulus of steel and alloys, e.g., the bulk modulus of water at room temperature and atmospheric pressure is approximately 3.12×10^5psi, and bulk modulus of the steel ranges from $22 \sim 24\times10^6$ psi. As shown in this paper, that effect of trapped fluid is appreciable.

Assume that the unpressurized fluid volume of the trapped pressurized fluid is V_f, the fluid cavity, i.e., the space that contains the fluid, has an initial volume of V_0, volume V when subject to external load F, but without fluid. For this problem setting (known external load F), there are two potential problems: 1) Given the magnitude of trapped fluid pressure P, what is the fluid volume V_f needed, and what is the equilibrium volume of fluid and the volume of fluid cavity? 2) For a given fluid volume V_f, what is the trapped fluid pressure P, and what is the equilibrium volume of fluid and the volume of the fluid cavity?

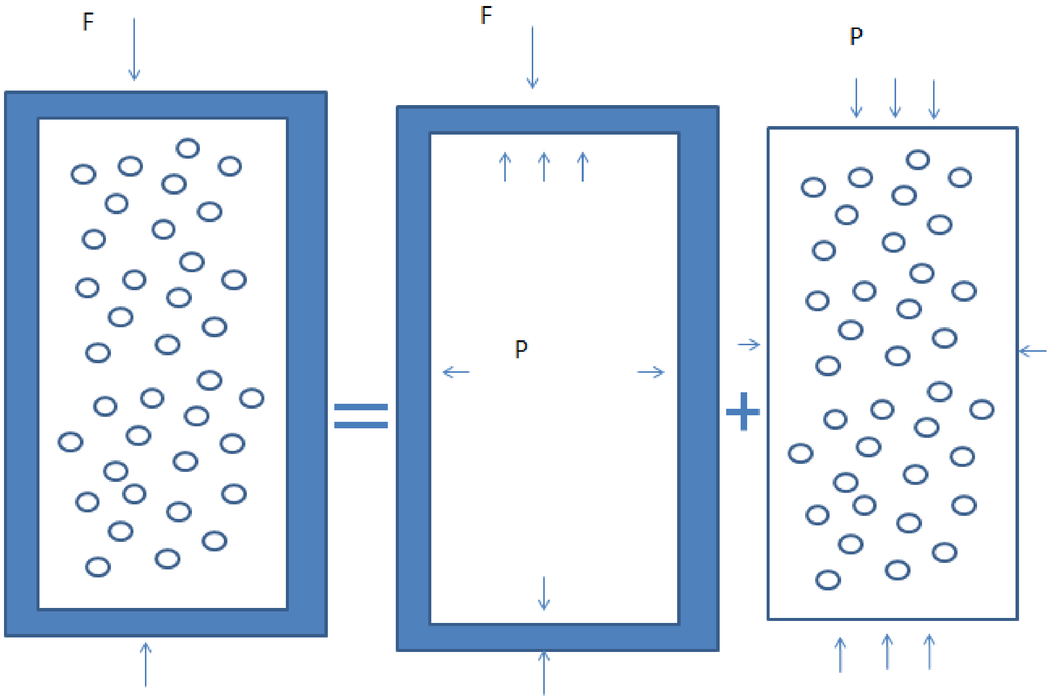

Figure 1. Illustration of a fluid containing structure.

Analytically the problem can be superimposed by two problems, as illustrated in Figure 1. The original problem is represented in the figure, on the left hand side of the equal sign: a container with filled fluid inside. The container is subject to external load F and internal pressure P from the trapped fluid. The two problems for the superposition are on the right hand side of the equal sign problem 1 is the deformation of the structure under external load F and internal fluid pressure P; problem 2 is about the fluid subject to hydrostatic pressure P . The connections between the two problems include the common fluid pressure P, and that the final equilibrium volume of the fluid and the cavity should be the same. The solution of problem 1 can be obtained with FEA; the solution of problem 2 is determined by Hook's law for bulk deformation *assuming that the fluid pressure is uniform*:

$$P = -K\frac{\Delta V}{V} \qquad (1)$$

Where K is bulk modulus of fluid, ΔV is fluid volume change under pressure P.

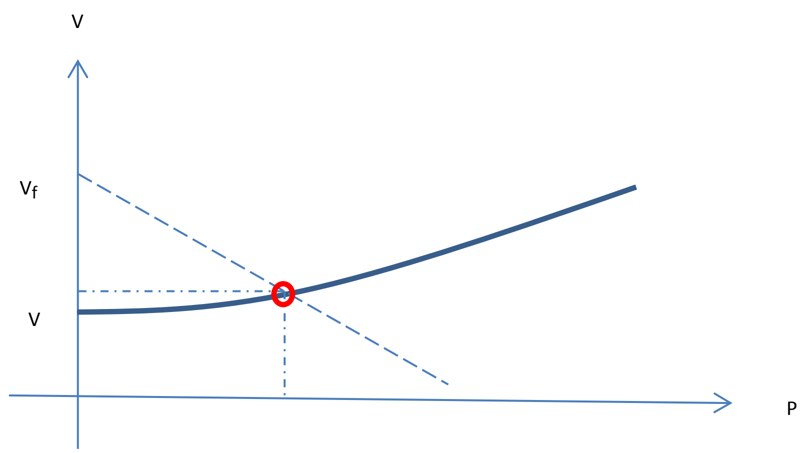

Figure 2. Illustration of the solution process.

Figure 2 shows the solution process. The solid curve corresponds to structural solution of problem 1, and the dashed line passing V_f is the P-V curve per equation 1. If the trapped fluid pressure is known, a vertical line can be drawn through (P,0), the intersect (the red dot) determines the equilibrium volume of the fluid and fluid cavity. The unpressurized fluid volume V_f is determined by drawing a line passing the red dot per equation 1. The intersect of this line and vertical axis determines $V_{f.}$ Conversely, if V_f is known, then trapped fluid pressure is determined by drawing a line passing (0, V_f) per equation 1. The intersection of this line and the solid curve (FEA solutions), the red dot, determines the trapped fluid pressure and equilibrium volume.

The previously described procedure can be implemented in standard finite element analysis code (Simulia, 2014), assuming uniform fluid pressure and uniform fluid density. In the finite element algorithm, a surface definition is provided for the coupling between the deformation of the fluid-filled structure and the pressure exerted by the contained fluid on the cavity boundary of the structure. The fluid cavities are represented by internal volume elements in the code. The coupled trapped fluid–structure interaction problem is solved in one run, rather than the two analyses previously described.

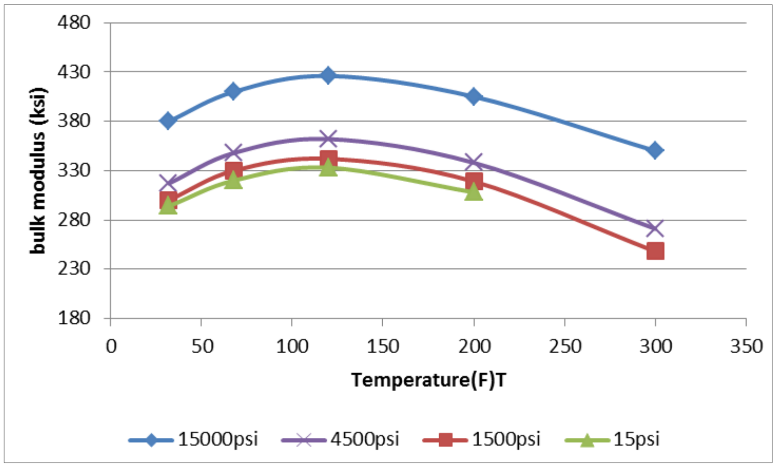

Figure 3. Water bulk modulus dependence on pressure and temperature.

Fluid bulk modulus and coefficient of thermal expansion depends on ambient pressure and temperature. Figure 3 shows an example of how the bulk modulus of water changes with temperature at various temperatures (McGraw Hill, 2000). It is obvious that the water modulus increases with temperature until it reaches maximum at 120°F. When the temperature is above 120°F, the bulk modulus decreases with temperature increase. The bulk modulus increases with increasing ambient pressure almost linearly (Figure 4).

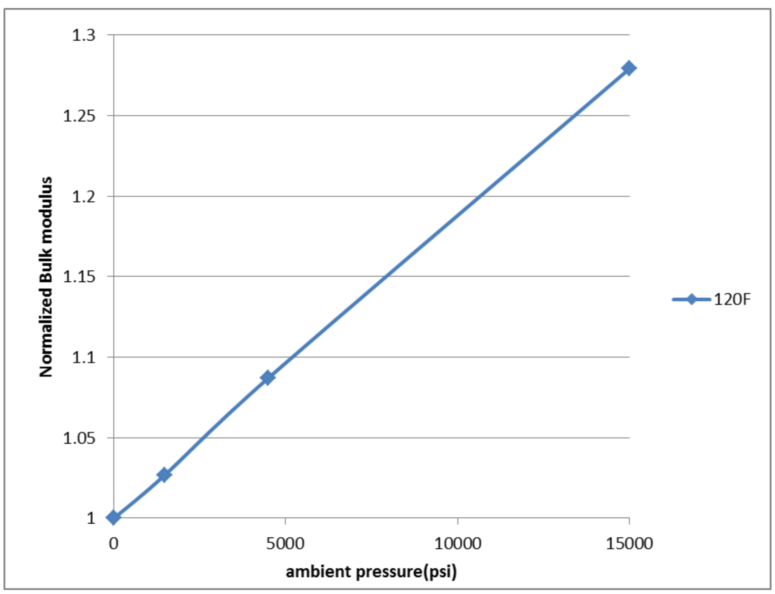

Figure 4. Change of water bulk modulus with respect to ambient pressure at 120°F.

The coefficient of thermal expansion (CTE) for fluid changes with temperature primarily and almost independently of ambient pressure. Typically, CTE increases with increasing ambient temperature.

3. Effects of trapped fluid on pipe burst and collapse

It is known intuitively that trapped fluid affects the burst and collapse of a capped pipe. For the burst of a capped pipe, the fluid pressure can be accurately represented by uniform pressure. Conversely, the filled fluid in the capped pipe should have a large effect on its collapse pressure rating. How large is the effect? A constant internal pressure will NOT work because the pressure from the trapped fluid changes with increasing external pressure; a fluid–structure interaction approach must be used to account for the effect. In the following example, a 12-ft. long 5.5 in. pipe with 5.1 in. inside diameter (ID) is analyzed for the two loading conditions with fluid in the pipe, for the burst pressure rating, and the collapse pressure rating. The ratings are compared to the ratings by typical FEA or API formula. The fluid is a type of oil with a bulk modulus of 21,7556 psi and a density of 0.0274 lb/in.^{3}. The pipe is made of L80 steel, with Young's modulus of 30 million psi, Poisson's ratio of 0.29, and a yield strength of 80 ksi. In the models, both ends of the pipe are fixed. The FEA model with fluid inside predicts a burst rating very near the modified API burst or the burst per thin wall theory (analytical solution). The difference between the two is attributable to the boundary conditions in the FEA model (Table 1). The added fluid volume for any given fluid pressure is also predicted from the FEA for the capped pipe with fluid.

Table 1: Comparison of burst rating per FEA model with fluid and thin wall theory

	FEA	Thin Wall	Difference
Burst (psi)	5,986	5,819	2.8%

As shown in Figure 5, the added fluid volume is proportional to the burst rating of 5,986 psi, and the relation becomes nonlinear at 6,412 psi. It requires 14.75 in.^{3} of additional volume fluid beyond the initial pipe volume to reach the burst rating.

In this case, the pipe is a thin wall pipe with (OD)/t=27.5 (OD is outside diameter, t is pipe wall thickness) and L/OD=26.2 (L is pipe length) ; this pipe will have elastic collapse (Zhong, 2011).

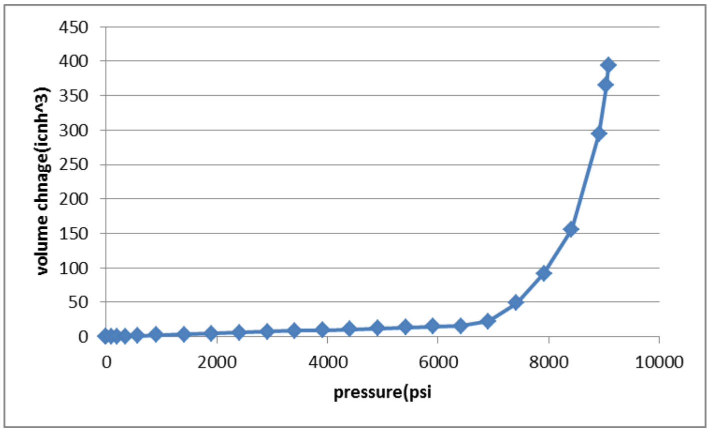

Figure 5. Additional fluid volume needed to reach a give fluid pressure.

A comparison of the FEA prediction for the collapse of this thin pipe without fluid inside the pipe and that for the collapse of a capped thin pipe with filled but unpressurized fluid inside (Figure 6) shows that the collapse mode for the two cases is essentially the same. The collapse pressures, however, are substantially different (Table 2). The support from the unpressurized fluid increased the collapse pressure of the thin pipe by 19%.

Without fluid

With fluid

Figure 6. Comparison of collapse modes for a 5.5-in. pipe with and without fluid in the pipe.

Table 2: Comparison of collapse per FEA model with fluid, without fluid FEA and analytical solution

	FEA with fluid	FEA without fluid	Analytical Solution without Fluid
Collapse (psi)	4,184.4	3,517	3,414

These simple analyses provide quantitative comparisons between predictions from two modeling approaches for a capped pipe with and without fluid inside; they demonstrate the effects of the trapped fluid. In real-world applications, the fluid cavities and loading conditions can be much more complex, and certain assumptions have to be made to perform a trapped fluid analysis. The following section presents two-real world scenarios involving trapped fluid.

4. Analysis of downhole operations involving trapped fluids

As previously discussed, fluid confined between sealing mechanisms (sealing points) for the purpose of zonal isolation is by design. There are times in which it is necessary to accurately evaluate the effect of trapped fluids between sealing points, for example, to adjust operation parameters to compensate for the change in the trapped fluid pressure, or to assess the integrity of the tubing string during a very high production flow situation when the tubing ID pressure can decrease significantly, potentially leading to tubing collapse.

4.1 Case 1: Trapped fluid between a seal assembly and a packer during setting process

In this case, a packer with a tailpipe is first stung into a polished bore receptacle (PBR) with seals during a running-in-hole process. For this particular tubing pressure set packer, the setting of the packer is enabled through the increase of tubing pressure. It is expected that when the packer element starts to set (STS), fluid between the packer element and the seals at the PBR is trapped in the annulus of tubing and casing. As the tubing pressure increases, the tubing will balloon, and the pressure of the trapped fluid will increase. This increase in trapped fluid pressure between the packer element and the seal assembly can affect the setting parameters. It is necessary to determine the annulus pressure increase from the STS pressure up to the full minimum setting pressure so that the setting parameters can be adjusted to compensate for this increase in annulus pressure.

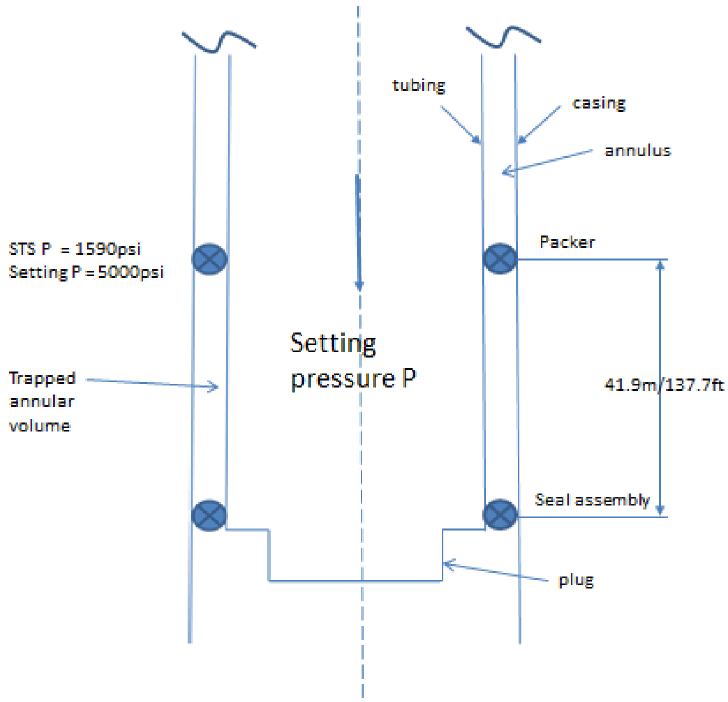

Figure 7. Illustration of design parameters.

Specific information related to this scenario includes the following: casing is 9 5/8 in. 53.5 lb L80 (ID: 8.535 in.); tubing is 7 in. 32lb VAM TOP HC 13%Cr 80MY. The packer depth is 8,692 ft (2650 m), and the hydrostatic pressure at the packer is 2,859 psi. The distance between the packer and the seal assembly is 137.7 ft (41.9 m). The setting fluid is an oil with density 0.0274 lb/in.^{3} and the bulk modulus 217556 psi. The downhole temperature at the packer is 212°F (100°C). The STS pressure is 1,590 psi, and the setting pressure is 5,000 psi.

The following assumptions are made: the movement of packer elements and seal assembly during the setting process is neglected, and the packer and seal assembly are assumed to be perfect seals at the STS condition. The fluid pressure and fluid density at the annulus between the packer and the seal assembly are assumed to be uniform. Based on the applications, it is assumed that casing is supported at OD by cement and wellbore. Numerically, all geometric details of packer elements and seals are neglected. Based on these assumptions, an axis symmetric FEA model for the trapped fluid problem is created, and casing and tubing are fixed at the top in the FEA model (Figure 8). It is noted that strength degradation at temperature is considered. *Hydraulic fluid in the annulus (red curve encircled area,) fluid pressure at STS pressure = 2,859 psi; tubing pressure increases from 2,859 to 4,449 psi (2859+1590) to 7,859 psi (assume set pressure 5,000 psi).*

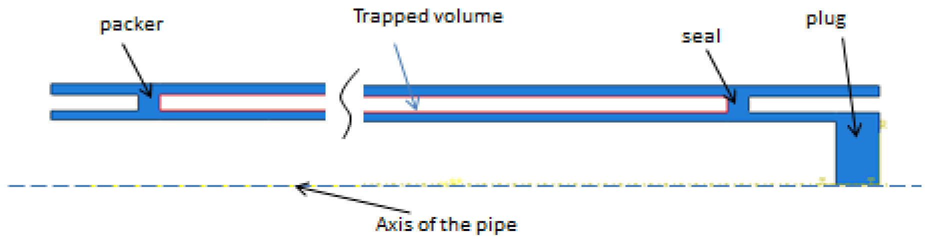

Figure 8. Illustration of the cross section geometry for the axis symmetric FEA model.

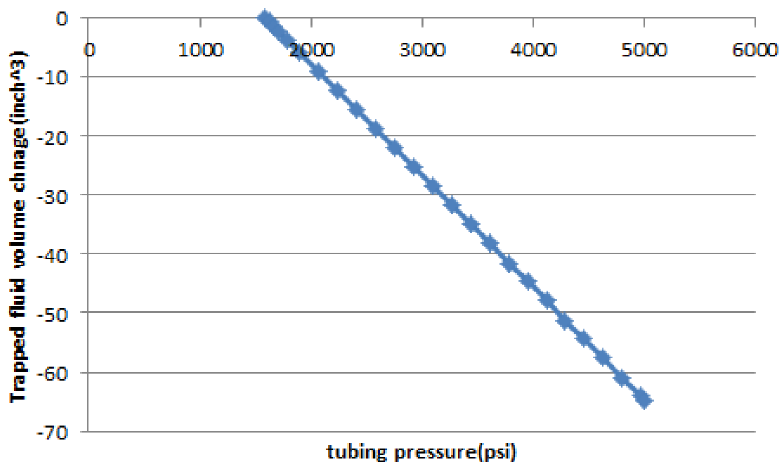

Figure 9. Annulus fluid volume change as a result of tubing pressure increase.

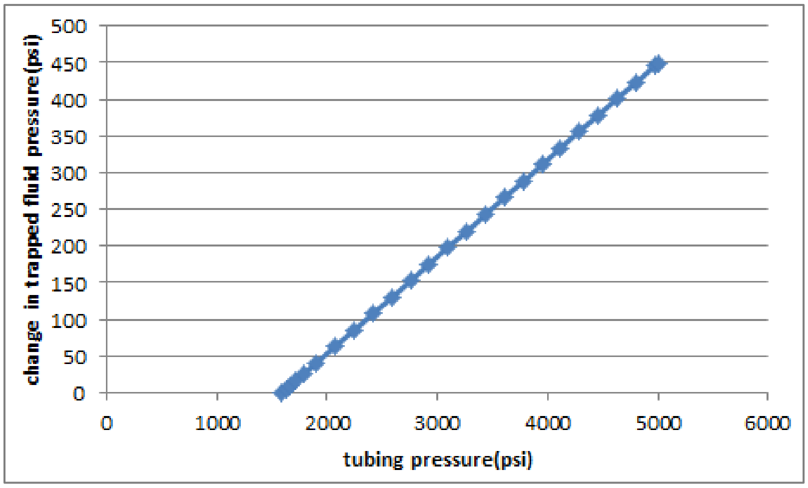

Figure 10. Increase of trapped fluid pressure as a result of tubing pressure increase.

It is predicted that, when the tubing pressure is increased from 1,590 to 5,000 psi, the annulus volume between the packer element and the seal assembly is reduced by 64.7 in.^{3} (Figure 9), and this contraction of the fluid-trapping cavity causes the trapped fluid pressure to increase. The **change** in the trapped fluid pressure is from 0 to 449.3 psi (Figure 10); i.e., 3,410 psi tubing pressure change caused a 449.3 psi increase in the trapped fluid pressure. It is also predicted that the stresses in the casing, tubing, and plug are all well below the yield strengths of the pipes at temperature (75.2 ksi) (Figure 11).

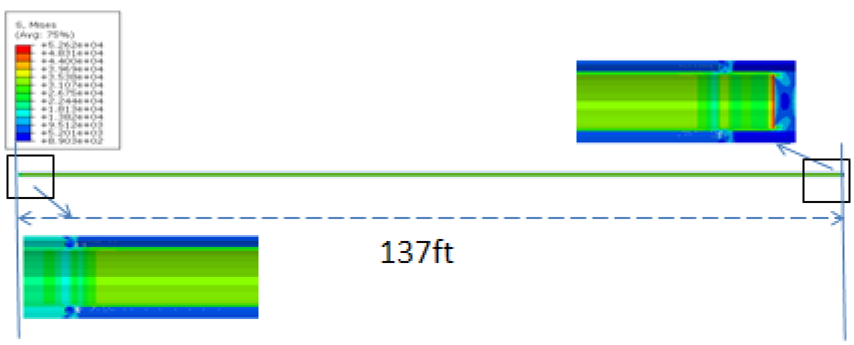

Figure 11. Stress in tubing and casing.

4.2 Case 2: Effect of Trapped fluid between two packers under very high production flow

Another scenario of interest includes the effects of pressurized trapped fluid pressure in the annulus when the tubing pressure is decreased to zero under extreme high production flow. In this case, pressurized fluid is trapped between a sump packer (18,491 ft depth) and a production packer (18,509 ft depth). The trapped pressure is 11,353 psi. Fluid density is 0.051 lb/in.^{3}, its bulk modulus is 508,000 psi, and the downhole temperature is 186°F. The pipe material is a low yield strength material (46.8 ksi, worst case, mock material), elastic modulus is 27.9 ×10^6 psi, Poisson's ratio = 0.3. Strength degradation is considered for the temperature. Assumptions are made similar to those made in Case 1, which yield the following axis symmetric FEA model for the trapped fluid (Figure 12).

Figure 12. Illustration of the cross section geometry for the axis symmetric FEA model.

Initially, the pressure of the trapped fluid in the annulus (the red curve encircled area) is 11,353 psi; tubing ID and casing OD pressure are also at 11,353 psi. It is desired to determine tubing deformation when the tubing ID pressure decreases to 0 psi, especially that at the 6-in. 20 lb LC pup joint near the sump packer.

As the tubing ID pressure decreases, the tubing OD will decrease, the annulus fluid-trapping cavity volume will increase as a result of trapped fluid pressure (Figure 13), and the increase in the fluid cavity volume will lead to the decrease in trapped fluid pressure (Figure 14). The annulus volume is increased by 10 in.^{3} when the tubing ID pressure decreases to zero from the hydrostatic pressure. In the meantime, the trapped fluid pressure is decreased from 11,353 to 8,563 psi. The differential pressure between the annulus and the tubing ID is 8,563 psi, rather than 11,353 psi, when the tubing ID pressure is zero.

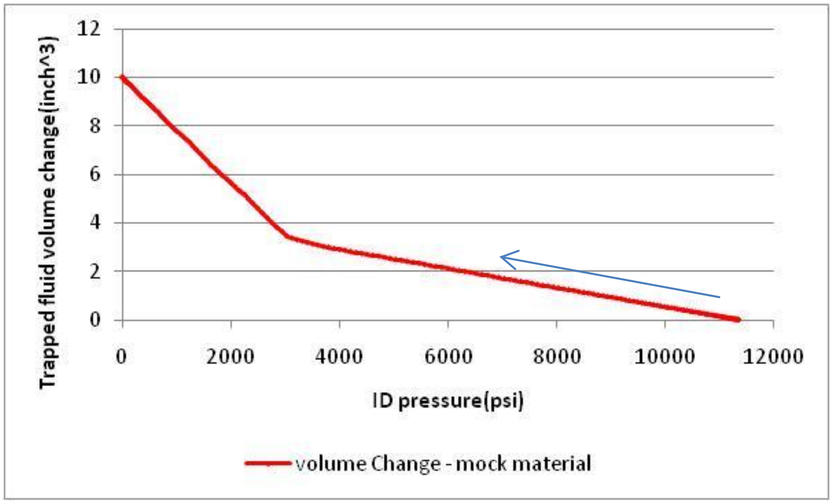

Figure 13. Annulus fluid volume change as a result of tubing pressure decrease.

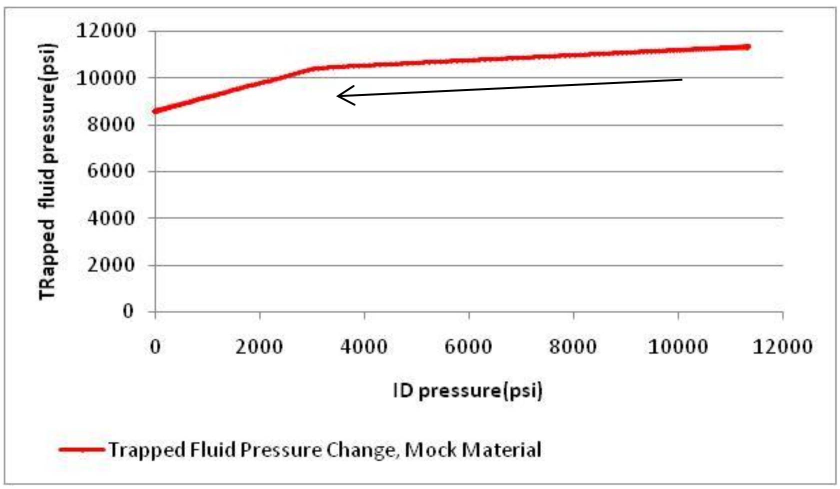

Figure 14. Decrease of trapped fluid pressure as a result of tubing pressure decrease.

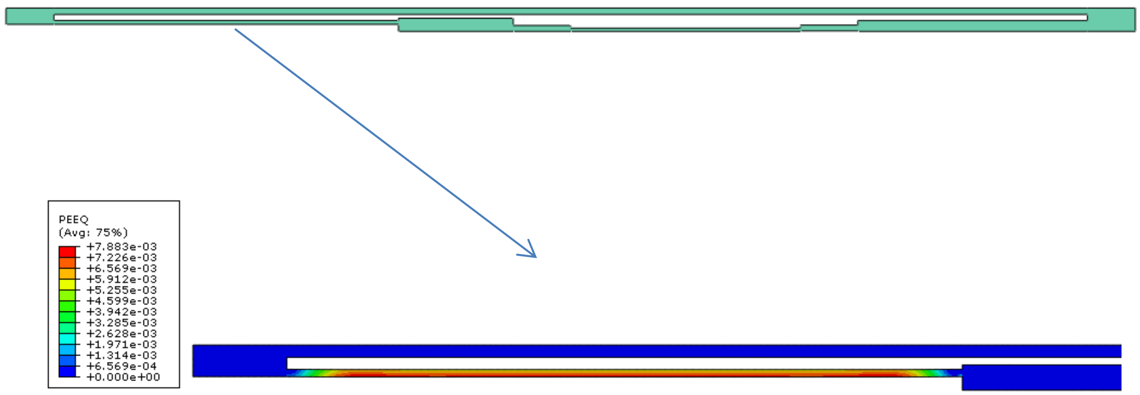

Figure 15. Pup joint yielded through when ID pressure decreases to 0.

It is also observed that for the mock material, the curves in Figure 13 and Figure 14 are no longer linear; there is a kink in the curve for both Figure 13 and Figure 14. The kink occurs at 3,409 psi ID pressure, corresponding to a differential pressure of 7,057 psi. The kinks in the curves indicate that a collapse of the weakest pipe joint, the pup joint, has occurred (Zhong, 2007).

For this case, when the tubing ID pressure decreases from 11,353 to 3,409 psi, the tubing collapsed under trapped fluid pressure; when the ID pressure decreases to 0, the tubing at the pup joint yielded through (Figure 15).

5. Summary and concluding remarks

The approach for trapped fluid–structure interaction analysis is studied and evaluated. With proper engineering assumptions, many realistic downhole operation scenarios can be analyzed and simulated using this trapped fluid analysis approach. It is shown that trapped fluid can significantly affect downhole tool deformation and the coupling between trapped fluid and tool and completion component structure must be accounted for to avoid unnecessary conservative calculation of tool rating, and to accurately predict tool performances.

6. References

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7. Acknowledgements

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