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MATHEMATICAL MODEL OF TIGHTNESS TESTS WITH THERMAL EFFECTS

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Abstract. *During oil exploration, tightness tests are performed to ensure the integrity of pipelines. They are carried out by pressurizing the line to the required pressure, sealing it and measuring the pressure over time. Some field engineers have reported excessive pressure drops during the tests that are not due to fluid leakages. Previous studies show that these pressure drops may be due to rheological and thermal effects. The current study proposes a mathematical approach based on the thermodynamic property changes during the fluid compression to predict temperature rise and pressure drops due to heat transfer to the surroundings. Common fluids properties are used to compute the maximum expected pressure drop after confinement. Results show that the temperature change due to the compression may cause significant pressure changes, depending on the fluid composition. The effect is negligible for water, but is noticeable for mixtures of water with oils and salts. For brines and drilling muds, the maximum expected pressure drop was in the range of 5% to 10% of the final compressed pressure.*

Keywords: *tightness test, pressure, temperature, heat transfer*

1. INTRODUCTION

Tightness tests are conducted on pressure vessels after maintenance or repair activities to indicate that all equipment is leak free (Petroleum Institute, 2006). These tests consist of pressurizing a line or component and registering the pressure over time. Safety norms define the maximum pressure drop over a certain time interval in order to approve the test. It is generally assumed that the pressure drop is caused only by fluid loss due to leakage. However, several studies show other factors that may influence the registered pressure changes. This is because oil rigs operate in complex systems, involving very long pressure lines, high temperature gradients and non-Newtonian fluids. In this field, two main effects on pressure changes are usually considered: rheological properties and thermal effects.

The rheological properties effects refer to the viscous nature of fluids. Since it is usually only measured at the pipe inlet, the pressure is assumed homogenous throughout the system. But it has been shown that pressure transmission throughout the whole pipe filled with high viscosity or yield stress fluids can be very slow or even incomplete (Galdino et al., 2019; Mitishita et al., 2018; Oliveira et al., 2012). Thermal effects, however, are usually neglected during tightness tests. Many studies consider thermal effects in other situations, such as in annular pressure buildup (APB), when a pressure increase takes place in confined fluids due to heat transfer (Alcofra, 2014; Halal & Mitchell, 1994; Oudeman & Baccarreza, 1995; Oudeman & Kerem, 2006). Since the underlying physical phenomenon is quite similar to that occurring in tightness tests, the effects of temperature on pressure changes have recently been considered (Knesebeck et al., 2020).

One thermal effect that has not been discussed in the literature is the increase of temperature caused by pressurization. As non-gases are often considered incompressible, this effect is usually disregarded. However, oil rigs operate at significantly high pressure changes that may affect temperature, so the volumetric behavior of fluids must be taken into account in order to avoid errors (Zamora et al., 2012, 2013).

This work aims at investigating the effects of fluid pressurization on temperature increase and how the heat transfer after pressurization affects the maximum pipe pressure. A model approach based on thermodynamic relationships is proposed. Material properties of common liquids are used to compute variations of temperature and pressure, showing changes can be significant, depending on the fluid composition.

2. MATHEMATICAL MODEL

The system (the confined fluid) at temperature T_0 and pressure P_0 (state 1) is considered initially in thermal equilibrium with the surroundings at T_0 . The initial condition is represented by the point 1 in Figure 1. The fluid is then pressurized to reach a specified test pressure P_{test} (state 2). The pressurization is assumed to change the temperature to $T_0 + \Delta T$. Considering the system at the new temperature transfers heat to surroundings, enough time is allowed to the system to reach a new equilibrium at T_0 and P_f (state 3).

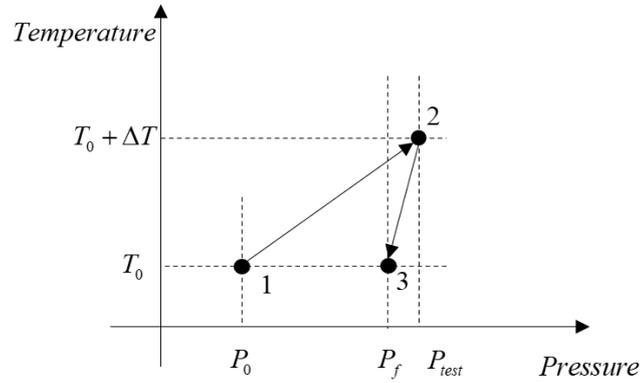


Figure 1. Three considered thermodynamical states

The following hypothesis are considered for changes between states 1 and 3:

- The fluid is weakly compressible;
- Properties are constant;
- Pressure and temperature are homogeneous throughout the system;
- The system is initially in thermal equilibrium with its surroundings at temperature T_0 ;
- The surroundings temperature is kept constant throughout the whole test;
- Heat transfer during pressurization is negligible;
- The pressurization is considered isentropic;
- The system's walls are rigid.

Figure 2 shows a schematic of the processes. The isentropic compression is considered between states 1 and 2 in order to obtain the highest possible ΔT and study it as the worst-case scenario, with the highest pressured drop between states 2 and 3, as the system returns to the surroundings temperature T_0 . In a real environment, heat transfer would occur during pressurization, making ΔT lower than in the isentropic case.

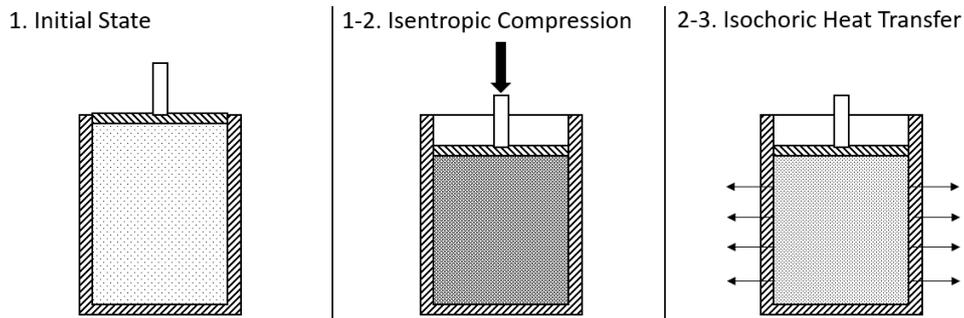


Figure 2. Processes between thermodynamical states

As the temperature increases with pressure takes place at constant entropy, the following Maxwell's relation can be obtained (Bejan, 2016):

$$\left(\frac{\partial T}{\partial P} \right)_s = \frac{\beta T}{\rho c_p} \quad (1)$$

where β is the thermal expansion coefficient, ρ is the density, c_p is the specific heat capacity and s denotes constant entropy. Considering small changes of temperature, ΔT_s can be approximated as a function of pressure variation during pressurization ΔP_s :

$$\Delta T_s = \frac{\beta T_0}{\rho c_p} \Delta P_s \quad (2)$$

After achieving the pressure at the end of the pressurization (state 2), the system loses heat to reach the final temperature T_0 . As the system walls are rigid, this process occurs at constant volume. Another Maxwell's relation can then be defined (Bejan, 2016):

$$\left(\frac{\partial P}{\partial T} \right)_V = \frac{\beta}{\alpha} \quad (3)$$

where α is the fluid compressibility and V denotes constant volume. The pressure drop due to the temperature decrease can then be computed by:

$$\Delta P_V = \frac{\beta}{\alpha} \Delta T_V \quad (4)$$

Assuming the system starts and ends in equilibrium, the initial and final temperatures are the same. Therefore, the temperature increase at constant entropy and decrease at constant volume are the same:

$$\Delta T_s = -\Delta T_V \quad (5)$$

Equations (2) and (4) can be combined to represent the ratio between the isochoric pressure drop and the isentropic pressure gain:

$$\frac{\Delta P_V}{\Delta P_s} = \frac{\beta^2 T_0}{\alpha \rho c_p} \quad (6)$$

This can be considered the maximum expected fraction of pressure loss due to heat transfer.

3. RESULTS AND DISCUSSIONS

By using equation (6), it is possible to estimate the maximum expected pressure drop due to temperature changes during pressurization. Properties of common fluids related to the oil exploration industry were used to compute the values. It is worth noting that the properties of some fluids can vary widely based on their compositions since they are made of mixtures of different materials. For instance, drilling fluids are very dependent on: type and ratio of base fluid, type and concentration of salt and amount of weighting material added. Since materials properties are usually measured at ambient temperature, the initial temperature T_0 is set to 300K.

Table 1 shows common materials found in literature, compiled by The Engineering ToolBox, (2001), while Table 2 shows properties of specific fluids obtained from the field or formulated in laboratory by Zamora et al. (2012, 2013). It is important to note that these properties may vary widely by fluid composition, temperature and pressure conditions. However, they may give a good estimate of the materials general behavior and provide a decent comparison.

Table 1. Properties of common materials related to the oil exploration industries
Obtained from The Engineering ToolBox (2001, 2004, 2009, 2010)

Material	$\alpha \times 10^{10} [\text{Pa}^{-1}]$	$\beta \times 10^4 [\text{K}^{-1}]$	$\rho [\text{kg/m}^3]$	$c_p [\text{J/kg.K}]$
Gasoline	7.69	9.50	721	2200
Glycerin	2.30	5.00	1249	2430
Mineral Oil	5.56	7.00	913	1670
Water (fresh)	4.65	2.14	999	4182
Water (sea)	4.27	2.57	1023	4066

Table 2. Properties of specific fluids in the oil exploration industries
 Obtained from Zamora et al. (2012, 2013)

Material	$\alpha \times 10^{10} [\text{Pa}^{-1}]$	$\beta \times 10^4 [\text{K}^{-1}]$	$\rho [\text{kg/m}^3]$	$c_p [\text{J/kg.K}]$
Brine (20% CaCl)	3.02	5.06	1172	3965
Brine (20% NaCl)	3.20	5.89	1152	3518
Oil (diesel)	6.74	7,58	827	2130
Oil (olefin)	6.82	9.28	788	2240
Oil (paraffin)	6,97	9.29	803	3260
Mud* (diesel based)	4.42	4.96	1917	1910
Mud* (olefin based)	5.04	6.03	1469	2274
Mud* (water based)	3.26	3.31	2042	2960

*barite was assumed to be weighting agent for muds, since the source did not specify

With the properties of Table 1 and Table 2, it is possible to compute equation (6) at the reference temperature of 300K. Figure 3 shows the expected dimensionless pressure drop for each fluid in ascending order. Water and water-based mixtures appear to have the smallest effects with noticeable effect only for brines with high salt concentrations. The type of salt also affects the pressure drop, as NaCl brine is more sensitive to thermal effect than the CaCl brine. On the contrary, oils and oil-based mixtures have very noticeable pressure drop, with the effect being diminished as the oils are diluted. The type of oil is also important, as olefin is more affected than diesel which reflects on olefin-based and diesel-based muds.

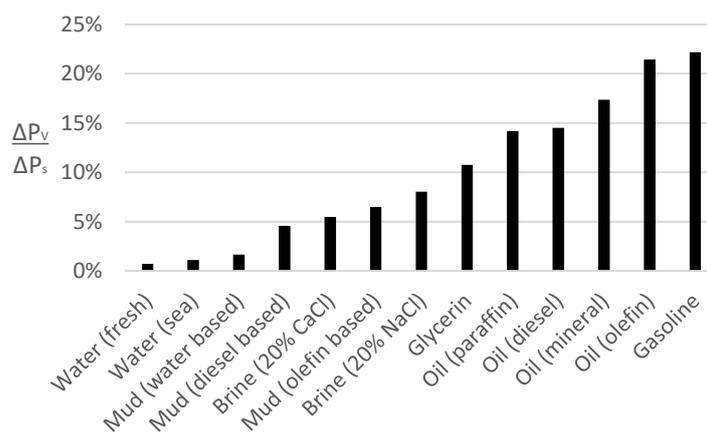


Figure 3. Expected pressure drop due to temperature loss after pressurization

Even though the used properties of drilling fluids are not exact, it is safe to assume that the behavior of the mixtures lies in between that of the components. Consequently, pressure drops in drilling fluids and brines will often be around the order of magnitude of 5% to 10%. It is important to note that the worst-case scenario is considered only as an estimate. In reality, the actual pressure drop should be smaller because the compression will never be completely isentropic. As the pressure drop may still be significant, the problem deserves further investigation.

4. FINAL REMARKS

A simplified model was used to estimate temperature increase due to pressurization in tightness tests. Results showed that, depending on the fluid's properties, this effect may cause significant pressure changes after confining the fluid.

The proposed relationship is limited to small changes in temperature. A more robust model must be developed for high temperature and pressure variations. Further studies are also necessary to verify if pressure may also have a significant effect on the fluid's properties and how that may change the expected pressure drop.

5. ACKNOWLEDGEMENTS

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