Wellhead Growth Analysis with Stiffness Method; and Onshore Gas Well Case Study

Ganesha R. Darmawan

1Bandung Institute of Science Technology
Email of Corresponding Author: ganesharinkudarmawan@gmail.com

ABSTRACT
One of the challenges in designing a production or an injector well is the potential of wellhead growth primarily because of casings thermal stress that are connected to the wellhead. Well integrity issue could occur if this movement was not addressed correctly. Casing thermal stress was created by temperature change in production or injection gas or fluids. That temperature change induces uncontrolled heat transfer from tubing to the casing strings in form of casing thermal stress.

One of gas well producing with formation water, was showing significant wellhead growth during production. The hazard noticed was the stiffness of the surface flowline equipment, as the wellhead moving upward, but the flowline is not free to move. The flange connection between the Christmas tree manifold to the flowline was the weak point, causing the well has to be shut in for further investigations.

Well constructions data collection continued with analysis was performed with stiffness method in multistring well thermal growth model as developed by Liang, Q.J., 2012 to calculate casing thermal stress and wellhead growth. Thermal growth is sensitive to the length of free moving casing sections, as the heat transfer laterally to the casing strings.

This paper will evaluate and analyze the cause of wellhead growth on gas production well with stiffness method in multistring casing, and estimating the cement column height on the casings that might cause the measured movement. A sensitivity of top of cements intermediate and production casing and how it affects the wellhead growth and thermal force. And also comparison forces between annulus pressure and temperature will also discussed in this paper.

Keywords: wellhead growth; temperature changes; stiffness method; thermal force

INTRODUCTION
One of gas well in X Field, Indonesia has shown a significant wellhead movement during the first production. The well has move upward around 10 – 11 cm after 24 days of production and had to be shut in because of the stiffness in the Christmas tree manifold to the flowline and could lead to integrity problem if the movement continued. Most of the gas production wells in the field were having a wellhead growth but steady at certain height and still within the movement range of flowline.

Several causes might create this wellhead movement, such as, bad cement bonding at surface area, cement channeling, not applying surface casing tension, annulus fluid expansion, etc. During casing installation and cementing operation, a tension on the casing was given to overcome the casing elongation due to change in temperature right after the cement about to harden (Liang Q. J., 2012 and Darmawan G.R., et al, 2017). Several cases recorded on growth or subsidence in deep onshore wells according to Anderson K.A, et al. 1999 and Baokui G., et al, 2016.

Wellhead growth usually occurred in in thermal wells and offshore self-standing platform wells (Baokui G., et al, 2016). Casing thermal stress was created by the temperature change in production or injection gas or fluids. The bigger diameter of casing, the bigger cross sectional area, and usually the cement return to surface (shorter uncemented section), the higher its stiffness value. That temperature change induces uncontrolled heat transfer from tubing to the casing strings in form of casing thermal stress. If the thermal force is low, there is a possibility of wellhead growth because cement column height is low and stiffness in the casing string is low too.

Heat transferred from outside of tubing to the casing thru annulus fluid. Annulus fluid expansion should be considered for high temperature wells as it will heats up and promote wellhead growth (Samuel, G. R., & Gonzales, A., 1999).
Potential gas production loss from this trouble well is around 12-14 MMSCFD. When the well was shut-in, the casing will shrink back and the wellhead slowly back to its original position, after the temperature back to surface original temperature. This thermal cyclic could cause wellhead fatigue that may have serious consequences to the well integrity (Reinas, L., 2012).

Evaluation and analyzing the cause of wellhead growth in this gas production well with stiffness method in multistring casing, and estimating the cement column height on the casings that might cause the measured movement. A sensitivity of Top of Cements (TOC(s)) intermediate and production casing and how it affects the wellhead growth and thermal force. Comparison forces between annulus pressure and temperature will also discussed in this paper.

**METODOLOGY**

The process of this study is described in flowchart below. Basic understanding on literatures on heat transfer and thermal force needed beforehand.

![Flowchart of wellhead growth Analysis](image)

**Heat Transfer and Thermal Force**

Heat transfer is a process of thermal heat energy exchange depending on the physical systems temperature and the properties of medium through which the heat is transferred. Thermal heat energy transferred from high temperature area through the medium to the low temperature area. On a production well, the surface temperature will change from the ambient to the wellhead temperature as reservoir fluids flow to surface. The heat transferred from the production tubing to the production casing via the packer fluid that is filled inside the A-Annulus. And from there, it transferred to the intermediate casing via the cement between those two casings string.

The basic physics of the heat transfer in producing wells are conduction, convection and radiation. Conduction [3] is the heat transfer between two elements that are in direct contact with each other. In this case are the tubing bowl and the wellhead connected to the casing strings. Convection [3] is a heat transfer in result of movement/flow/mix from the hot places to the cold places. In this case is the reservoir fluid with high temperature downhole flowing thru tubing to surface will create higher temperature at surface, especially if water is produced with gas. Radiation [3] is a heat transfer method that did not require any contact between the heat source and the heated object as in conduction and convection. In this case, tubing has an annulus with the casing production, and so on, where the heat transfer to the casings via the annulus medium, as the tubing temperature increases.

Thermal force is a force that occurs because of temperature change. Heat transfer to casing from the tubing will create the thermal force in casing. The higher the delta temperature will create higher thermal force. Another parameter affecting thermal force is modulus young, casing cross sectional area, annular fluid expansion, and the height of cement column. A good cement job will reduce the risk of thermal force. Cemented casing with good bond will create high stiffness value. This stiffness is another parameter that affecting the thermal force in every casing string.

In onshore wells, for casing that is cemented to the wellhead or surface, the thermal force on the wellhead will reach to the maximum level, this value is dependent on temperature and TOC (Top of Cement) level of casing and wellhead growth will be zero when the casing is cemented to wellhead (Liang Q. J., 2012).

In a well casing design, the deeper it gets, the smaller the casing string is. Intermediate casing has bigger cross sectional area compared to production casing, and have
less height of uncemented which create a higher stiffness value on intermediate casing. The thermal force on both intermediate and production casing is the same. Thermal force could be reduced by properly placing the TOC behind those casing strings. TOC of production casing if it is higher than the intermediate casing will not reduce the wellhead growth.

**Wellhead Growth Calculation**

To calculate the thermal force and wellhead growth, Liang Q. J., 2012 proposed and explained a stiffness method in multistring casing. Samuel, G. R., & Gonzales, A., 1999 proposed the multistring evaluation because it has better design process.

Parameters needed to calculate the wellhead growth is thermal expansion coefficient, stress, strain and modulus young. For calculating the thermal forces in each string at the wellhead due to temperature changes, the stiffness of all casing strings multiplied by the wellhead thermal growth subtracted by Fixed End Actions (FEA) caused by temperature.

Based on the data of casing and TOC presented in Figure 2, there are conductor, surface, intermediate, production casing to construct the well. Typical well schematic usually, consist of:

- Conductor to 100 m, cemented to surface but not connected to the wellhead
- Surface casing, cemented to surface but not connected to the wellhead.
- Intermediate and production casing, may be cemented to surface but could have some free section. Connected to the wellhead.
- Liner, it will not contribute on the wellhead growth.

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (mm)</th>
<th>Depth (ft)</th>
<th>TOC (ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>100</td>
<td>199</td>
<td>0</td>
<td>Cemented to surface</td>
</tr>
<tr>
<td>Surface</td>
<td>100</td>
<td>199</td>
<td>0</td>
<td>Cemented to surface</td>
</tr>
<tr>
<td>Intermediate</td>
<td>12.75</td>
<td>3930</td>
<td>0</td>
<td>Cemented to surface</td>
</tr>
<tr>
<td>Production</td>
<td>8.525</td>
<td>7213</td>
<td>0</td>
<td>Cemented to surface</td>
</tr>
<tr>
<td>Liner</td>
<td>2.76</td>
<td>8612</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Tubing</td>
<td>2.875</td>
<td>8612</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.** Well construction data on observed well

**Figure 3.** Static and dynamic temperature gradient

Since conductor and surface casing are not connected to wellhead, it will not contribute to the growth, so it will not be discussed further. The calculation will only be done to the casing strings connected to the wellhead, which is intermediate and production casing. The two layers of casings would grow up at the top wellhead end. The stiffness of intermediate casing is higher than the production casing. Growth on the wellhead caused by un-cemented/un-tension (free sections) intermediate casing that can move axially. Free section of intermediate casing could be caused by bad cement bonding/job. If the cement bonding is good, axial tension/movement will be solidified in the casing.

Thermal force will create the wellhead growth. High thermal force will create higher wellhead growth. If the thermal force is low, there is a possibility of wellhead growth because cement depth is deeper, and the stiffness value in the casing is low too. If one of the casing strings did not have good cement bonding, hence create low stiffness value, then the thermal force will be high. To reduce the growth, the TOC level of every casing string should be to surface. Bad cementing job (bad bonding) will ease the casing to grow.

All the casing string connected to the wellhead, which is the 13-3/8” intermediate casing and the 9-5/8” production casing. From the drilling report, the cementing design and operation was planned to surface for both casing. Both casing material was carbon steel.

Temperature change at surface area is important parameter in this evaluation. Static bottom hole temperature data was taken from the Electronic Memory Recorder(EMR), and
the surface temperature data was taken from the temperature gauge installed on flowline that is one meter away from the Christmas tree manifold.

During the start-up of production, the surface temperature gradually increased from 80 °F to 153 °F after twenty four days of production. This might create elongation on the tubing hence creating heat transfer to the surrounding casing strings (causing elongation as well). Most of the casing material used is carbon steel, but the tubing was duplex stainless steel which will create different thermal expansion.

The annulus pressure was increasing significantly from 0 psi to 3000 psi, then bleed off investigation and management is applied to know whether it is a thermal casing pressure or sustainable casing pressure. From the investigation, it was concluded that the annulus pressure was thermally induced, as the pressure decreased when the well is in shut in condition, and relatively constant at 1250 psi at a constant rate and temperature.

RESULT AND DISCUSSION
Stiffness method is used to calculate the thermal stress and wellhead growth (tubular buckling is neglected) as outlined step by step by Liang Q. J., 2012:
1. Calculate the stiffness of every casing strings that connected to wellhead, including tubing:
   \[ K_i = \frac{A_i E_i}{L_i} \]
2. Calculate the total stiffness
   \[ K_t = \sum K_i \]
3. Calculate the Fixed End Action (FEA) due to change in temperature
   \[ FEA_i = A_i E_i \gamma_i \Delta T_i \]
4. Calculate the total FEA in multistring due to thermal expansion
   \[ FEA_{thermal} = \sum FEA_i \]
5. Calculate the wellhead thermal growth
   \[ \Delta L_{thermal} = \frac{FEA_{thermal}}{K_t} \]
6. Calculate the thermal force on every casing string connected to wellhead due to temperature change
   \[ F_{i-thermal} = K_i \Delta L_{thermal} - FEA_i \]
7. Calculate the total thermal force acting on the wellhead
   \[ FEA_{total} = \sum F_{i-thermal} \]

Result of these analysis were combined, as:
1. To know the estimated cement (cracked, bad bond, etc.) failure depth on both of casing string evaluated by trying to matching the historic data of the flowing well to the maximum growth. Comparison between annulus pressure force and thermal force was also calculated to ensure which force contribute more on the growth.
2. TOC (Top of Cement) sensitivity on each casing string connected to the wellhead to avoid any forces that creates the growth. This TOC sensitivity used to analyze the force value and wellhead growth if there is a change in temperature. It could be reference between temperatures versus the growth in the future.

Wellhead Growth Calculation Based on Current Data
It is difficult to know the validity of bad cement depth based on calculation. The data taken from the well where the growth was around 10 – 11 cm (4.27 inch), calculations carried out to find the estimated cement breakdown on both of casing string. Both of intermediate and production casing are cemented to surface, which should reduce the thermal force, especially if the casing was given a tension at surface after setting.

From iteration, estimated cement damage depth at 840 ft on the intermediate casing and at 800 ft on the production casing. With these calculation simulations, the growth is matching the historic growth maximum before the well was shut in. From the calculations, estimated depth of the damaged cement is roughly the same, which allow the both casing connected to the wellhead to growth. Bad cement quality of the first casing connected to the wellhead is the root cause of wellhead growth in deep wells as concluded by Baokui G., et al, 2016.
Thermal force that occurred in the production casing was 362 Klbf. Thermal force in the intermediate was higher due to bigger cross section area, was 395 Klbf. The smallest thermal force occurred in the tubing. Tubing thermal force contributions at the wellhead is relatively low compared to casing strings, because its stiffness is very low (Liang Q. J., 2012).

Table 1. Wellhead growth calculations with Stiffness Method

<table>
<thead>
<tr>
<th>Parameter and Calculation</th>
<th>Intermediate</th>
<th>Production</th>
<th>Tubing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubular OD (in)</td>
<td>13.375</td>
<td>9.625</td>
<td>2.875</td>
</tr>
<tr>
<td>Tubular ID (in)</td>
<td>12.615</td>
<td>8.681</td>
<td>2.441</td>
</tr>
<tr>
<td>A (in^2)</td>
<td>15.54</td>
<td>13.57</td>
<td>1.81</td>
</tr>
<tr>
<td>E (lbf/in^2)</td>
<td>3E+07</td>
<td>3E+07</td>
<td>2.9E+07</td>
</tr>
<tr>
<td>Thermal expansion Material</td>
<td>6.56E-06</td>
<td>6.56E-06</td>
<td>1.66E-07</td>
</tr>
<tr>
<td>L (ft)</td>
<td>66</td>
<td>64</td>
<td>52</td>
</tr>
<tr>
<td>Length of fixed point from WH, LOFP (in) TOC</td>
<td>10080</td>
<td>9600</td>
<td>93283</td>
</tr>
<tr>
<td>Sopt(K) (B/ft/in)</td>
<td>46148</td>
<td>42852</td>
<td>563</td>
</tr>
<tr>
<td>Sopt(K) (B/ft)</td>
<td>198348</td>
<td>181539</td>
<td>605</td>
</tr>
<tr>
<td>Sum K (B/ft/in)</td>
<td>89103</td>
<td>830492</td>
<td>4.37</td>
</tr>
<tr>
<td>Sum FEA (lbf)</td>
<td>380492</td>
<td>380492</td>
<td>630951</td>
</tr>
<tr>
<td>Annulus thermal growth (Sum FEA/Sum K), in</td>
<td>4.37</td>
<td>4.37</td>
<td>5.99</td>
</tr>
<tr>
<td>Total force at wellhead, lbf</td>
<td>360951</td>
<td>360951</td>
<td>3009</td>
</tr>
<tr>
<td>Wellhead equipment weight, lbf</td>
<td>22000</td>
<td>22000</td>
<td>22000</td>
</tr>
<tr>
<td>Total WH load, lbf</td>
<td>738983.6</td>
<td>738983.6</td>
<td>738983.6</td>
</tr>
</tbody>
</table>

As intermediate casing is the first casing connected to the wellhead, a bad cement section depth could create axial movement. The subsequent casings string will also increase the possibilities of deepen of cement failure depth.

During production period, there will be an increase in the surface temperature systems, mostly due to connate water production. Increasing temperature must be monitored closely, as the higher the temperature, the more thermal forces occurred and lead to higher wellhead growth.

**Table 2. Thermal force compared to annulus pressure force**

<table>
<thead>
<tr>
<th>Thermal Force in production casing (Klbf)</th>
<th>Annulus Pressure Force (Klbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>363</td>
<td>34</td>
</tr>
</tbody>
</table>

**TOC Sensitivity to Thermal Force and Wellhead Growth**

TOC sensitivity analysis is divided by two, TOC sensitivity on the intermediate casing and production casing. Ballooning effect in this sensitivity is ignored since it did not give significant impact.

**Figure 4. TOC sensitivity in intermediate casing**

**Figure 5. TOC sensitivity for intermediate casing resulting wellhead growth**

**Figure 6. TOC sensitivity for intermediate casing with wellhead thermal force**

**Figure 7. TOC sensitivity in production casing**
Both of TOC intermediate and production sensitivity is created for four different TOC depths, at 100 m, 300 m, 600 m, and 900 m (Figure 4 and 7). From the sensitivity graphics of TOC depth to the wellhead growth in intermediate and production casing, the deeper the TOC, the higher the wellhead growth will be. This is because the deeper the TOC the stiffness will be smaller, hence casing freely to growth if there is a temperature change. In Figure 11 and 12, TOC of intermediate casing at 100 m deep will create growth of 6 cm, and for TOC intermediate casing at 900 m deep will create growth of 47 cm. To reduce or minimizing the risk of growth, the TOC should be high enough, close to surface.

From the figures of TOC sensitivity with force, there are two things that could be evaluated, first the effect of thermal force to the growth, and second, the effect of TOC to the thermal force. On the stiffness method, thermal force is calculated first to know the wellhead growth. Hence, analysis should be first on wellhead growth then TOC depths.

For analysis of TOC Intermediate at 600 m deep (Figure 10), the thermal forces needed to create a 5 cm wellhead growth is around 215 Klbf, and to create a 24 cm growth, 313 Klbf force is needed. This has shown a correlation where the more thermal forces created, the higher the wellhead growth will be. This correlation is only valid for one set of TOC depth.

TOC of 900 m and 100 m deep analysis, for 100 m TOC, thermal forces around 534 Klbf to lift the wellhead around 8 cm, and for 900 m TOC, to achieve the same of lift (wellhead growth), smaller thermal forces needed, 219 Klbf. The thermal forces different because the different TOC depth, which relates...
to different stiffness value. Stiffness value at lower depth of TOC (100 m) will be higher compared to the deeper TOC. And from this analysis, we can see that the wellhead growth will create different forces based on the TOC sensitivity.

From the calculations and analysis, it seems that a cement failure in the casing strings connected to the wellhead might create wellhead growth if the temperature changes. The wellhead growth could be avoided if the intermediate casing cement bonding is good because it is the first casing connected to the wellhead and have the possibilities to move axially if the cement is bad. It is also possible that the casing tension was not applied properly to prevent elongation.

CONCLUSIONS
As a result of evaluation and analysis for the case study in the field, there are some summaries could be derived:

1. Even though it is difficult to know the estimated cement failure depth, with some assumption to simulate it based on the movement recorded on the wellhead. From calculation using a stiffness method in multistring casing, cement failure (bad bonding) due to the thermal stress induced during production; the estimated cement failure depth is at around 840 ft (256 m) for intermediate casing. Bad cement bonding in the intermediate casing (first casing connected to wellhead) is the root cause of wellhead growth because the axial movement.

2. Annulus pressure increase might increase the exerted force in annulus, but the value is negligible to the thermal force.

3. TOC depth sensitivity has shown that to minimize the effect of thermal force on wellhead growth, intermediate casing should be properly cemented to surface. Shallower cement column on the intermediate casing, stiffness value is high, and the wellhead growth will be less.

ACKNOWLEDGEMENTS
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REFERENCES
NOMENCLATURE

- $A_i$: cross sectional metal area of string $i$ (in$^2$)
- $E_i$: Young’s Modulus of string $i$ (lbf/in$^2$)
- $L_i$: distance from bottom of wellhead to top of cement for string $i$ (in)
- $K_i$: stiffness of string $i$ (lbf/in)
- $K_t$: total stiffness (lbf/in)
- $F_{EA,i}$: fixed end action of string $i$ (lbf)
- $\gamma_i$: linear thermal expansion coefficient
- $\Delta T_i$: the temperature change from the installed condition for string $i$ (°F)
- $F_{EA,t}$: fixed end action due to temperature change (lbf)
- $\Delta L_t$: thermal growth (in)
- $F_{si}$: force in string due to temperature change (lbf, negative for compression)