Modeling the influence of variable temperature fields on the stressed state of offshore facilities

I V Starokon

Russian State University of Oil and Gas named after I.M. Gubkin, 65, Leninskiy ave., Moscow, 119991, Russia

E-mail: starokon79@mail.ru

Abstract. The article considers the influence of temperature fields on the stress state of offshore facilities using the example of fixed offshore platforms for oil and gas production. It is noted that there is no theory for offshore oil and gas facilities that would allow a numerical description of the nature and mechanism of action of both conventionally stationary and variable temperature fields. An analysis of various literature sources showed that currently there are solutions for the dynamics of propagation and stress state for an axisymmetric temperature field, for a non-axisymmetric case, characteristic of the operating conditions of the support blocks of offshore platforms, there is no such solution. The author notes that a change in the thermal state of the elements of offshore facilities as a result of various factors leads to a change in their stress state. In some cases, in the presence of significant defects, these defects act as stress concentrators, thereby increasing the nominal strain. A numerical-analytical modeling of the effects of both variable and conditionally stationary fields was carried out, which made it possible to identify a number of patterns.

1. Introduction

Throughout the entire life the FOPs are exposed to various sources of heat, causing changes in their stress state. Variable temperatures cause alternating strains. Currently, this phenomenon with respect to FOPs has not been practically studied, therefore, the study of the influence of temperature fields on the development of fatigue cracks is an important and urgent task [1-20]. Offshore structures are exposed to two different types of temperature fields:

1) A conditionally stationary temperature field is applicable to offshore oil and gas pipelines and is characterized by the thermal field of the product pumped through them, varies slightly over time, causing long-term constant stresses due to the difference between the temperature fields of the inner and outer walls of the pipe . A feature of this field is that most often it is axisymmetric;

2) The variable temperature field is applicable to those structural elements of the FOPS, for which oil and gas are not pumped, for example, the support block of an offshore stationary platform, and whose temperature field is determined only on the basis of environmental conditions. The variable temperature field is characterized by its frequent changes, and by the alternating strains caused by it.

This field can also be axisymmetric, but most often it does not appear, because to a large extent depends on the solar radiance, wave action, the influence of sea currents, wind speed and direction, ambient temperature, convection conditions into the environment, etc. In the case of complete calm, weak wave action and low flow velocities, heat transfer occurs under conditions of free convection and depends on the Grashof and Prandtl criteria [10-13].

Otherwise, heat change occurs by forced convection and is determined by the Reynolds criterion. As it is shown in the work, the thermal regime at wind speeds of about 2 m / s significantly affects the temperature field of the pumped product. In addition, a change in the lighting conditions of the structural elements of the FOPs associated with both meteorological and their design features, lead to the alternation of lowering and increasing temperature. For example, the difference in the required capacity for pumping oil through pipelines exposed to solar radiation in daytime and nighttime is 10%. It is necessary to note that the temperature regime of pipelines is affected by the geometric shape and pressure change of the transported product.

The author investigated a section of a gas pipeline under a pressure of 55 atm., 1.17 m long and consisting of four adapters successively welded to each other with a diameter of 108x159mm, 159x219mm, 219x273mm, 273x325mm. As a result, it was found that the temperature of the outer surface of the gas pipeline at the beginning in the section of the adapter with a diameter of 108 mm is 1.6 ° C different from the surface temperature in the section of the adapter with a diameter of 325 mm. This can be explained by the throttling effect, which is also confirmed by the numerous cases of gas pipeline icing occurring even at an ambient temperature above + 35 ° C in the areas where pressure regulators exit when the pressure is 55 atm. decreased to 1.7 atm.

The first step that needs to be done to determine the magnitude of temperature stresses is to determine the temperature field of the structural element of the FOPs (both the element of the support block of the FOP and the sea pipeline). The analysis of a large number of specialized literature sources showed that at the moment there is no solution to the problem that would take into account the uneven heating of the FOPs structural elements, the influence on the distribution of the temperature field of the paint coat and the corrosion layer. Solutions to the problems are reduced to determining the thermal fields that occur when the temperature difference between the outer and outer walls of the pipe when exposed to an axisymmetric temperature field (ATF). A detailed description of these solutions is given in [10-13]. That is why, the author has developed a technique that allows establishing the law of the dynamics of the temperature field spreading over the entire surface of a structural element of an FOP in the presence of corrosion layers and a layer of paint and varnish coating, and also take into account the influence of environmental influences.

In this article, the author focuses on the stresses arising from exposure to heat fluxes on offshore stationary platforms.

2. Materials and methods

2.1. Temperature distribution over wall sections of elements of marine facilities

The author proposes to adopt the logarithmic law of temperature distribution over the wall thickness of the FOPs structural element for a conditionally stationary axisymmetric temperature field, and use the linear law for a variable axisymmetric temperature field. In mathematical terms, it looks like this:

$$f[T(r)] = \begin{cases} T_1 - (T_1 - T_2)\dfrac{\ln\left(\dfrac{r}{r_1}\right)}{\ln\,(r_2/r_1)}\,, \\ T_1 - (T_1 - T_2)\dfrac{r - r_1}{r_2 - r_1} \end{cases} \quad (1)$$

where: $f[T(r)]$- temperature distribution function over the cross section of structural elements og FOPs; T_1 and T_2 - the temperature on the inner and outer surfaces of the FOPs structural element, respectively, $r -$ the considered coordinate located inside the section of the studied structural element of the FOPs, r_1 and r_2 - inner and outer diameters.

2.2. Assessment of the influence of thermal fields in various areas of the platforms

The author considers the support block of the offshore platform, dividing it into the following conditional zones: uncovered, variable wetting and underwater. Let us analyze the surface zone. At first glance, it would seem that the temperature field in this zone is determined by the temperature of the atmosphere. However, as it is shown by measurements taken at the FOP, the temperature of the structural elements of the FOPs is highly dependent on solar radiation, and their actual temperature at the top of the cycle (i.e., the maximum temperature) in the hottest period of the year is about + 70.5° C. In addition, the wind effect has a significant effect. In addition, the wind action has a significant effect. It should be noted that the actual state of the FOP has numerous through damages, which makes it possible to take measurements from both the external and internal surfaces of the structural elements of the FOP. The measurements were carried out using an infrared pyrometer AR 330, with a measurement accuracy of 0.1 C. The data obtained from the measurements indicate that the difference in the temperature field between the inner and outer surfaces of the structural elements of the FOP at a certain point in time reaches 0.4 C.

In the absence of exposure to solar radiance and significant wind exposure, the temperature field of the FOP is determined by the state of the atmosphere of so-called heat exchange occurs under the conditions of free convection. The analysis of archival data showed that the maximum temperature in the area of the Subbotinsky deposit reached + 31.5 C, and the minimum recorded -13.5 C.

For the underwater part of FOPs, the most powerful fluctuations are observed at depths of up to 50 meters; practically no temperature changes occur below this mark. According to the project, starting from a zone with a depth of 50 meters, the temperature practically does not change and is within + 8C. And to a depth of 1500 meters, the temperature is approximately within + 9 ° C. This suggests that the influence of variable temperature fields takes place only in areas above sea level. The results of their calculation will be given below. This suggests that the influence of variable temperature fields takes place only in areas above sea level. The results of their calculation will be given below.

2.3. Methods for assessing stresses from temperature effects in the initiation of a temperature difference between the inner and outer surface of the walls of elements of marine facilities

Let us proceed to the solution of the problem of determining the stresses caused by the temperature difference between the inner and outer surfaces of the structural element of the FOPS, which has a tube shape, with the outer and inner radii. In such a structural element of the FOP under the temperature conditions of operation described above, a temperature field T (r, t) arises, accompanied by a strain in the event of a temperature difference between the inner and outer walls. The temperature field is determined based on the equations described above. The stresses caused by the variable axisymmetric temperature field are determined by the formulas:

$$\sigma_r = \frac{\alpha\Delta TE}{3(1-\mu)(r_2 - r_1)}\left[r - \frac{r_1^3}{r^2} - (1 - \frac{r_1^2}{r^2})(\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2})\right] \quad (2)$$

$$\tau = \frac{\alpha \Delta T E}{3(1-\mu)(r_2 - r_1)}\left[2r + \frac{r_1^3}{r^2} - (1 - \frac{r_1^2}{r^2})(\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2})\right] \quad (3)$$

$$\sigma_z = \frac{\alpha \Delta T E}{3(1-\mu)(r_2 - r_1)}\left[3r - 2(\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2})\right] \quad (4)$$

where:$\sigma_r, \sigma_\theta, \sigma_z$- radial, ring and longitudinal stresses; α - is the linear expansion coefficient of the pipe metal; E - modulus of elasticity of the pipe material; ΔT - calculating temperature difference; r_2 and r_1- inner and outer radius of the tube; μ – Poisson's ratio. In the case of a conditionally stationary axisymmetric temperature field, the emerging stresses are determined by the formulas:

$$\sigma_r = -\frac{\alpha \Delta T E}{2(1-\mu)\ln(\frac{r_2}{r_1})}\left[ln\frac{r_2}{r} + \frac{r_1^2}{r_2^2 - r_1^2}(1 - \frac{r_2^2}{r^2})ln\frac{r_2}{r_1}\right], (5)$$

$$\tau = \frac{\alpha \Delta T E}{2(1-\mu)\ln(\frac{r_2}{r_1})}\left[1 - ln\frac{r_2}{r} + \frac{r_1^2}{r_2^2 - r_1^2}(1 + \frac{r_2^2}{r^2})ln\frac{r_2}{r_1}\right], (6)$$

$$\sigma_z = \frac{\alpha \Delta T E}{2(1-\mu)\ln(\frac{r_2}{r_1})}\left[1 - 2ln\frac{r_2}{r} - 2\frac{r_1^2}{r_2^2 - r_1^2}ln\frac{r_2}{r_1}\right], (7)$$

where the measurements are the same, as in formulas 2 - 4.

Since a flat stress state is realized when a temperature gradient arises between the walls of the SE FOPs, the value of the principal stresses can be calculated by the formula:

$$\sigma_{max,min} = \frac{\sigma_r + \sigma_z}{2} \pm \sqrt{\left(\frac{\sigma_z - \sigma_r}{2}\right)^2 + \tau^2}, \quad (8)$$

Having obtained the values of the principal stresses, we can proceed to the calculation of equivalent stresses by the formula:

$$\sigma_{экв} = \sqrt[2]{0{,}5\left(\sigma_{max}^2 + \sigma_{min}^2 + (\sigma_{min} - \sigma_{max})^2\right)}, \quad (9)$$

Depending on what temperature will be higher on the inner or outer wall of the pipeline, the stresses that arise will change their sign and direction. With a positive temperature difference ΔT, points on the inner surface of the pipe are dangerous, with a negative ΔT on the outside.

2.4. Methods for calculating variable stresses in a daily alternation of temperatures

The daily change in temperature and the resulting alternating strains are determined by the formula:

$$\Delta\sigma = \pm E\alpha\Delta T, \quad (10)$$

Where: $\Delta\sigma$ - is the measure of variable strains, E – modulus of elasticity; ΔT- daily temperature difference.

3. Discussion

Let us move on to practical calculations. Here are some characteristics of the steels used in the structural elements of FOPS (table 1).

Having performed the corresponding calculations using formulas (2) - (9), we find that for an element with a diameter of 325 mm and a wall thickness of 10 mm, the equivalent strain at a temperature gradient between the external and internal surfaces of 0.3 ° C will be 23.9 MPa, and with a temperature gradient of 0 4 C equivalent stress will be 31.81 MPa. Similar calculations for an element with a diameter of 426 mm and a wall thickness of 12 mm showed that with a temperature gradient between the inner and outer walls of the SE FOP at 0.3 ° C, the equivalent strain will be 26.3

MPa, and with a temperature gradient of 0.4 ° C the equivalent strain will be 35.1 MPa, which is slightly higher than the endurance limit, which means that there is some damaging effect. However, the situation may be aggravated by the presence of cracks, corrosion caverns, or other stress concentrators in the elements of FOPs, as a result of which stresses caused by temperature changes can multiply.

Table 1. Properties of some steel grades depending on temperature

Steel	Operational temperatures of FOP										$\alpha, 10^{-6}$ $1/^0C$	μ
	-40	-30	-20	-10	0	10	20	30	40	50		
	Module of elasticity E, GPa(10^4 H/mm^2)											
Bst3sp5, St10, St20	20.6	20.1	20.4	20.3	20.2	201	20	19.9	19.8	19.7	11.5	0.28
09G2S, 17G1S	21.6	21.5	21.4	21.3	21.2	21.1	21	20.9	20.8	20.7	11.5	0.30

The daily change in temperature and the resulting alternating strains directly depend on environmental conditions. Strong heating relative to thin-walled elements in the daytime in sunny weather will necessarily be replaced by cooling at night, in rain, wind or other weather events. However, the frequency of such changes itself relates this phenomenon to the section of low-cycle fatigue. Assessing the daily temperature effect, it can be noted that despite the fact that the temperature effect has a low frequency of cycles, nevertheless it creates significant variable strains. The damaging effect of variable stress amplitudes should be at least 22.5 MPa. It is quite obvious that the temperature stress range for damaging effects should be equal to 55 MPa, which for known values of Young's modulus (approximately 200,000 MPa for steel 09G2S depending on the ambient temperature) and the coefficient of linear thermal expansion ($11.5 * 10^{-6}$) is achieved with a daily temperature difference of the structural element of approximately 19.6C. This condition is fulfilled, for example, with the corresponding daily temperature fluctuation. So, for example, for a horizontal element with a diameter of 325 mm with a wall thickness of 8 mm and a mass of 312.5 kg, this condition can be fulfilled at a heat flux density of 384 W / m^2. It is well known that under the conditions of the Black Sea with a degree of transparency of the atmosphere of 0.38, the values of the heat flux density of less than 384 W / m^2 are reached in the period of December 3 (337 days counted from January 1) to January 6. Those. when calculating the fatigue life in the example we are considering, we should not take 365 cycles per year, but 331. Further research by the author showed that, taking into account the influence of variable stresses caused by thermal stresses, all other things being equal, the resource decreases from 21.3 years to 20.96 years, i.e. decreases by approximately 4 months.

4. Conclusion

The magnitude of the emerging temperature stresses of the FOPs depends on the characteristics of the elements of offshore structures (material, mass, diameter, etc.) and the conditions of interaction with the environment.

1. With a decrease in the operating temperature of the FOP, the value of temperature stresses increases, which is explained by an increase in the elastic modulus, which also depends on the operating temperature.
2. The most significant alternating strains are formed during a daily change in temperature.
3. When a temperature difference occurs between the inner and outer walls of the structural elements of the FOP, ring, longitudinal and radial stresses arise, the largest values of which take ring stresses. The picture of the stress state with this effect has the following features:
4. The magnitude of the occurring temperature stresses of the FOPs depends on the characteristics of the elements of offshore facilities (material, mass, diameter, etc.) and the conditions of interaction with the environment, which allows them not being taken into account in the future.

Ring stresses in the case of a conditionally stationary temperature field uniformly propagate over the cross section of the structural element of the FOP, changing only depending on the value ΔT. In the case of a variable temperature field, ring stresses linearly vary along the cross section of the FOP structural element, increasing or decreasing from the inner surface to the outer, depending on the value of ΔT. With an increase in diameter, but with an equal wall thickness and the same environmental conditions, the magnitude of the ring stresses decreases for both a conditionally stationary and variable temperature field. With a decrease in wall thickness, but with the same diameter and the same environmental conditions, the magnitude of the ring stresses increases for both conventionally stationary and variable temperature fields. Longitudinal stresses, both in the case of a conditionally stationary and variable temperature field, linearly propagate along the cross section of the structural element of the FOP, tend to zero values in the middle of the wall of the structural element of the FOP, and reach their maximum values in sections close to the outer and inner surfaces. Moreover, they have opposite directions.

5. Longitudinal stresses, both in the case of a conditionally stationary and variable temperature field, linearly propagate along the cross section of the structural element of the FOPS, tend to zero values in the middle of the wall of the structural element of the FOPS, and reach their maximum values in sections close to the outer and inner surfaces. Moreover, they have opposite directions. The magnitude of the longitudinal stresses depends on the value of ΔT. With an increase / decrease in diameter, but with an equal wall thickness, just as with a decrease / increase in wall thickness, but with an equal diameter, and under the same environmental conditions, the magnitude of the longitudinal stresses does not change much for both a conditionally stationary and an alternating temperature field. The magnitude of the longitudinal stresses depends on the ΔT value.

References

[1] Henning A and Jan B 1993 Fatigue Life of Repair-Welded Tubular Joints in OffshoretructuresIbso Proceedings of the Third *International Offshore and Polar EngineeringConference Singapore* pp 62-69
[2] Boersheim E, Reitenbach V and Albrecht D 2019 Summary of an experimental investigation toevaluate potential technical integrity issues in porous UGS containing hydrogen *EAGE/DGMK Joint Workshop on Underground Storage of Hydroge*
[3] Panfilov M, Reitenbach V and Ganzer L 2016 Self-organization and shock waves in underground methanation reactors and hydrogen storages *Environmental Earth Sciences* **75(4)** 313
[4] Pudlo D, Flesch S, Albrecht D and Reitenbach V 2018 The impact of hydrogen on potential underground energy reservoirs *Geophysical Research Abstracts* 20 (EGU2018-8606)
[5] Reitenbach V, Ganzer L, Albrecht D and Hagemann B 2015 Influence of added hydrogen on underground gas storage: a review of key issues *Environmental Earth Sciences* **73** 6927–6937 DOI: 10.1007/s12665-015-4176-2
[6] Reitenbach V, Ganzer L and Albrecht D 2014 Influence of Hydrogen on Underground Gas Storage *Research Report* (Hamburg)
[7] Ganzer L, Reitenbach V, Pudlo D, Albrecht D, Singhe A, Awemo K, Wienand J and Gaupp R 2014 Experimental and numerical investigations on CO2 injection and enhanced gas recovery effects in Altmark gas field *Acta Geotechnica* (Central Germany) **9(1)** 39-47
[8] Pudlo D, Flesch S, Albrecht D and Reitenbach V 2018 The impact of hydrogen on potentialunderground energy reservoirs *Geophysical Research Abstracts* **20** (EGU2018-8606)
[9] Teodoriu C and Asgharzadeh A 2017 A novel model for catenary drilling and drill string induced stresses *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering* (OMAE-2017)
[10] Shadravan A, Schubert J, Amani M and Teodoriu C 2015 Using fatigue-failure envelope for cement-sheath-integrity evaluation *SPE Drilling and Completion* **30 (1)** 68-75

[11] Waltrich P, Zhang H and Teodoriu C 2014 Remote real-time experimental diagnostics for well challenges Proceedings *SPE Annual Technical Conference and Exhibition* pp 4926-4936

[12] Bär F and Teodoriu C 2013 Approaches for determination and reduction of non-productivetimes of drilling rigs for deep wells *Logistics Journal*

[13] Yuan Z, Schubert J, Esteban U, Chantose P and Teodoriu C 2013 Casing failure mechanism and characterization under HPHT conditions in south texas *Society of Petroleum Engineers International Petroleum Technology Conference IPTC 2013: Challenging Technology and Economic Limits to Meet the Global Energy Demand* **3** 2207-2217

[14] Teodoriu C 2012 Selection criteria for tubular connection used for shale and tight gas applications *Society of Petroleum Engineers SPE/EAGE European UnconventionalResources* Conference and Exhibition pp 865-870

[15] Raza M, Salehi S, Ghazal S, (...), Cokely E and Teodoriu C 2019 Situational awareness measurement in a simulation-based training framework for offshore well control operations *Journal of Loss Prevention in the Process Industries* **62** 103921

[16] Starokon I and Golovachev A 2019 Method of Determining the Sizes of Corrosion Defects of Elements of Marine Oil and Gas Industrial Constructions on the Basis of Data on Temperature Contrasts (Vladivostok) **272** 032089 DOI: 10 1088/1755-1315 272(3) 032089

[17] Starokon I 2019 Methods for solving the problems of extending the resource of offshore stationary platforms: case study Journal of Physics *Conference Series* **1399** 055087 DOI:10.1088/1742-6596/1399/5/055087

[18] Starokon I 2019 Development of theoretical bases of analysis of reliability of marine oil and gas constructions with regard to temperature impact *Journal of Physics: Conference Series* (Krasnoyarsk) **1399** 055066 DOI:10.1088/1742-6596/1399/5/055066

[19] Starokon I and Ermakov A November 2019 Assessment of jacket-type platform stress state in corrosive environment *2nd Conference of Computational Methods in Offshore Technology and First Conference of Oil and Gas Technology (COTech & OGTech 2019) Materials Science and Engineering* (Norway: Stavanger) **700** 012018 DOI:10.1088/1757-899X/700/1/012018 27–29

[20] Srivastava S and Teodoriu C 2019 An extensive review of laboratory scaled experimental setups for studying drill string vibrations and the way forward *Journal of Petroleum Science and Engineering* **182** 106272