The influence of the environment on the temperature state of structural elements of offshore stationary platform

I V Starokon
Russian state university of oil and gas named by I.M. Gubkin, Leninskiy pr. 65, Moscow, 119991, Russia

E-mail: starokon79@mail.ru

Abstract. Offshore fixed platforms (OFP) are exposed to solar radiation, which leads to their heating. In turn, a change in the thermal state (TS) of the structural elements (SE) of the support block leads to the appearance of different temperature stresses in direction and magnitude, the analysis of which was carried out by the author in the work. Previously, the author developed a technique that allows you to calculate the temperature of the SE of the reference block without taking into account the influence of the environment. This article provides an augmented technique that allows you to evaluate this effect both in conditions of free and forced convection. In addition, a correction factor is introduced into the formula for estimating the surface temperature of elements, taking into account their degree of blackness. On the basis of the developed methodology, an example of calculating the thermal state of the SE of OFP in the Black Sea is given. The difference between the TS columns, braces and horizontal elements is revealed.

1. Introduction
Oil and gas facilities operate in difficult environmental conditions and are exposed to various effects of corrosion, vibration, temperature) [1-20]. The problem of impact assessment is especially acute for a particular class of oil and gas production facilities, namely, offshore oil and gas production facilities. The most common object of this class are offshore stationary platforms. Today there are more than 4.500 of them.

Offshore stationary platforms are exposed to various influences affecting their stress state. One of these effects is temperature, causing variable temperature stresses in the cross sections of their structural elements. Earlier, the author proved this influence in the paper and substantiated the method of its numerical evaluation. However, this technique did not take into account heat transfer with the environment. The purpose of this article is to study the influence of the environment on the formation of the temperature of the outer wall of the structural elements of OFP. As an example, the thermal processes of the support blocks of offshore stationary platforms located in the oil and gas fields of the Black Sea will be considered. The analysis of the OFP projects showed that the structurally supporting blocks of the OFP are made of steel pipes of various diameters from 325 mm to 1020 mm. The OFP support block is exposed to solar radiation, which causes a change in its temperature state. The author developed a methodology that allows numerically assessing the magnitude of this effect, which consists in calculating the heat flux density acting on horizontal, vertical and inclined structural elements, and proposes a new formula for calculating the temperature of the outer wall of structural elements (SE) of
an OFP depending on the dynamics of density change heat flow. However, beyond the scope of previous studies, an assessment of the influence of the environment on the formation of the temperature of the outer wall of the studied object remained. This article studies this effect. From the classical theory of thermodynamics, we know that when a heat flux acts on a solid, part of the radiation is absorbed and heats the body, and part is reflected. The ratio between absorbed and reflected solar radiation is determined by the so-called "degree of blackness". What are the SE of OFP? These are steel pipes, coated with a paint and varnish coating that protects it from corrosion and has its own, in some cases very significant, reflective ability. However, as shown by the practice of operating the support blocks, the actual destruction of the paint coating (PC) occurs within one, two years after its application, depending on the brand and manufacturer. Due to the fact that the process of restoration of the paintwork is extremely expensive, it is carried out once every 10 years. In addition, in practice, the requirements for preliminary operations on the preparation of the surface of SE of OFP for applying paintwork (for example, surface cleaning) are not sufficiently met, which also reduces the resistance to damage of the paintwork. In turn, poor-quality paint coating leads to increased corrosion processes. The actual state of the elements of the support block can be described as "steel pipes with a highly oxidized surface", for which the reduced degree of blackness according to the reference data is 0.74, i.e. in other words, when solar radiation affects the elements of the support block, only 26% of this energy is reflected, while the remaining 74% is absorbed and heat the elements of the support block. In turn, the heated structural element radiates energy to the environment.

2. Methods
The heat transfer process occurs due to radiation and convection, which is divided into - free and forced. All these processes are characterized by heat transfer coefficients. During heat transfer by radiation, the heat transfer coefficient \( \alpha_l \) is calculated by the formula:

\[
\alpha_l = \frac{\varepsilon C \left( \frac{T_{wall}+273}{100} \right)^4 - \left( \frac{T_{air}+273}{100} \right)^4}{T_{wall}-T_{air}}
\]  

(1)

where: \( \varepsilon \) – degree of blackness for SE of OFP, accepted equal 0.74; \( C \) – the radiation factor is absolutely black body, equal to 5.67 W/(m\(^2\)K\(^4\)); \( T_{wall} \) and \( T_{air} \) the temperature of the wall of the SE of OFP and the air temperature in degrees Celsius. With free or forced convection, the heat transfer coefficient \( \alpha \) can be calculated by the formula:

\[
\alpha_k = \frac{Nu \lambda}{D}
\]  

(2)

where: \( \alpha_k \) – heat transfer coefficient, W/m\(^2\)K; \( Nu \) - Nusselt number; \( D \) – diameter of the structural element of the OFP, m; \( \lambda \) – thermal conductivity coefficient of air, 10\(^{-2}\) (W/mK). In turn, the Nusselt number is determined by the formula:

\[
Nu = C \cdot (Gr \cdot Pr)^n \cdot \left( \frac{Pr}{Pr_{wall}} \right)^{0.25}
\]  

(3)

where: \( C \) and \( n \) values selected from the table 1; \( Gr \) – Grashof number; \( Pr \) - Prandtl number at a certain air temperature; \( Pr_{wall} \) – Prandtl number of air, at a wall temperature of SE of the OFP.

Table 1. Value of coefficient c and indicator of degree n.

| Regime   | Gr·Pr      | C   | n   |
|----------|------------|-----|-----|
| Laminar  | 1·10\(^3\)÷5·10\(^2\) | 1.18 | 0.125 |
| Transition | 5·10\(^5\)÷2·10\(^7\) | 0.54 | 0.25 |
| Turbulent | 2·10\(^7\)÷1·10\(^12\) | 0.185 | 0.33 |

In turn, the Grashof number is determined by the formula:
\[ Gr = \frac{gD^3\beta(t_w - t_V)}{\nu^2} \]  
\[ (4) \]

where \( g \) – acceleration of gravity, \( g = 9.81 \text{ m/s}^2 \); \( D \) – the diameter of the SE of OFP in meters; \( \beta \) – temperature coefficient of volumetric expansion of air equal to \( \frac{1}{273 + t_v} \); \( t_w \) and \( t_v \) – the temperature of the SE wall of the OFP and air.

The Prandtl number is a reference value. The process of forced convective heat transfer has its own characteristics. An analysis of the data from the Black Sea climate reference books will allow us to state that the strongest storm winds that can seriously affect the formation of the temperature of OFP fall from November to March during the period of minimal solar activity. So, for example, in the coastal zone of the northeastern part of Black Sea range the average wind speed varies from 2.7–2.8 m/s in the south coast of Crimea to 6–7 m/s in the areas of the Kerch Strait and the Caucasus. On the other hand, from April to November, there is a weakening of wind activity, the wind speed decreases to 1.9–2.4 m/s and 3.3–5.3 m/s, respectively, while the intensity of solar radiation is significantly increased. Based on this, the author selected the period from April to November for consideration, as it is during this period that the most significant changes in the temperature state of the SE of OFP occur. It is quite obvious that when a wind stream flows around OFP elements, a complex heat exchange occurs, consisting of two components: forced convective heat transfer and radiation heat transfer. The orientation of the wind flow with respect to them is of great importance for the formation of the temperature of the SE of the OFP. Let us consider the case of a transverse flow around a wind flow of elements of a finite element OFP. The main criterion that determines the intensity of heat transfer is the heat transfer coefficient \( \alpha \). To calculate this coefficient, it is necessary to know the following initial data: the diameter of the structural element of the OFP, the speed of the wind flow, its direction with respect to the element under consideration. In calculating the Nusselt number, the orientation of the flow, determined by the angle \( \mu \), is of great importance. The perimeter average Nusselt number is determined taking into account the angle of attack \( \phi \) by multiplying by the correction factor \( \varepsilon_\phi \). For the conditions under consideration for the flow around the wind of OFP elements, the Nusselt number is determined from the conditions:

- When \( Re=10\ldots10^3 \) \( Nu = 0.43Re^{0.5}e_\phi \)
- When \( Re=10^3\ldots2*10^5 \) \( Nu = 0.216Re^{0.6}e_\phi \)
- When \( Re \text{ more } 2*10^5 \) \( Nu = 1.14CPr^{0.4}Re^m \)

In these conditions, the following notation: \( Re \) – Reynolds number, \( Nu \) – Nusselt number, \( e_\phi \) – coefficient depending on the wind direction and selected according to the table 1, \( C=0.023 \) and \( m=0.8 \) coefficients taken in accordance with work [2], \( Pr \) – Prandtl number taken in accordance with the table 2.

| Angle \( \phi \) | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|-----------------|----|----|----|----|----|----|----|----|----|
| \( e_\phi \)    | 0.42 | 0.52 | 0.67 | 0.78 | 0.88 | 0.94 | 0.98 | 1   | 1   |

In turn, the Reynolds number is determined by the formula:

\[ Re = \frac{\omega D}{\nu} \]  
\[ (5) \]

where: \( \omega \) – wind speed, m/s; \( D \) – diameter of the structural element of the OFP, m; \( \nu \) – kinematic viscosity of air \( \text{m}^2/\text{s} \), which is determined from the table 3.

| Air temperature | 0   | 10  | 20  | 30  | 40  | 50  | 60  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Kinematic viscosity, \( 10^6 \text{m}^2/\text{s} \) | 13.28 | 14.16 | 15.06 | 16 | 16.96 | 17.95 | 18.97 |
Based on the foregoing, the author calculated the Reynolds and Nusselt numbers, as a result of which the values of the heat transfer coefficient \( \alpha \) were obtained for the conditions considered by us. Currently, heat transfer processes between a uniformly heated pipe and the environment are well studied. However, the temperature state of pipes with unilateral heating has not been studied enough. The processes of temperature formation on the surface of the pipe wall and the dynamics of the propagation of this temperature on internal and external surfaces have not been studied. In connection with this, numerous experiments were carried out that made it possible to propose a solution to these problems. The first step in solving these problems is the study of the processes of temperature formation on the surface of the SE of OFP. Since exactly half the surface of the SE of OFP is exposed to direct solar radiation, it is proposed initially to determine the temperature of this surface to replace this heated part of the pipe with an equivalent sample equal to the mass of the entire element. Having determined the surface temperature, this value should be adjusted by calculating the heat sink to the environment. To correct the value of \( Q_{ke}^{cor} \) formula follows from the density of the heat flux created by solar radiation \( Q_{ke} \), subtract the density of the heat flux created by the wind. Then move on to the next formula:

\[
Q_{ke}^{cor} = Q_{ke} - q
\]  

(6)

Then you should calculate the density of the heat flux from the pipe wall to the colder environment of the incident wind flow according to the formula:

\[
q = \gamma \alpha (t_{wall} - t_{wind})
\]  

(7)

where \( q \) – heat flux density from the pipe wall to the incident wind flow, W/m\(^2\); \( \alpha \) – heat transfer coefficient, W/m\(^2\)K; \( t_{wall} \) – outer wall temperature of SE of OFP; \( t_{wind} \) – free wind temperature; \( \gamma \) – coefficient taking into account that in this case only half of the pipe is exposed to direct sunlight, the coefficient is assumed to be 0.5. The author proposed a technique that allows one to calculate the surface temperature of SE of OFP depending on the heat flux density arising from solar radiation:

\[
Q_{ke}^1 = \pi RLK(S_a + 2D_a)
\]  

(8)

where: \( Q_{ke}^1 \) – total heat flux of solar radiation, R and L – external radius and length of the structural element of the OFP in meters, \( S_a \) – heat flux density of direct solar radiation incident on the inclined surface of the structural element of the OFP, W/m\(^2\); \( D_a \) – heat flux density of scattered solar energy incident on an inclined surface of a structural element of OFP, W/m\(^2\); \( K \) – correction factor taking into account the heat flux reflected from the surface of the sea water. In addition, the author developed a formula that allows you to determine the temperature of the outer wall of SE of OFP exposed to solar radiation:

\[
T_{i+1} = T_i + 0.74 \frac{\pi RI}{mc} (Q_{i+1} - Q_i) \Delta t
\]  

(9)

where: \( T_i \) and \( T_{i+1} \) – the initial and considered at some point in time surface temperature of a structural element of OFP under direct solar radiation; \( R \) – outer radius of structural element of OFP, m; \( l \) – its length, m; \( m \) – mass of the considered section; \( 0.74 \) – correction factor, taking into account the degree of blackness of the pipe; \( Q_i \) and \( Q_{i+1} \) – initial and considered at some point in time density of the heat flux acting on the surface of the structural element of OFP.

Due to the fact that the initial and considered at some point in time surface temperature of the structural element of the OFP are unknown values, the author proposes the following methodology: 1) calculate the total values of the heat flux densities from solar radiation and determine the temperature of the outer wall of the SE of OFP; 2) knowing the data on the parameters of the wind flow (speed, temperature, etc.), calculate the density of the heat flux \( q \) created by the wind; 3) to adjust the value of the density of heat fluxes \( Q_{ke}^{cor} \); 4) using the obtained value \( Q_{ke}^{cor} \), determine the surface temperature of the structural element of the OFP.
3. Result
Consider an example. We investigate the process of heating and cooling of OFP using the example of August 14, 2010. Climatic conditions are obtained from the weather archive on the meteo.ua website. Consider the horizontal structural elements of OFP, made according to the project, from steel pipes with a diameter of 325x8 mm (the mass of the element under study is 312.5 kg) and the vertical elements of the OFP (columns), made according to the project, from steel pipes with a diameter of 720x20 mm (the mass of the element under study is 1739 kg). For a comparative analysis, we take the length of all elements the same and equal to 10 m. We take the atmospheric transparency coefficient $c = 0.38$, with no cloudiness.

Consider the heat flux density for a horizontal platform element. The heating process begins after sunrise at 5:00. The created heat flux density on horizontal elements (HE) by 5:00 has values of 13 W/m$^2$, which practically does not affect the formation of the surface temperature of the SE of OFP. Then, gradually increasing in the logarithmic dependence, the heat flux density reaches its maximum value of 1137 W/m$^2$ by 12:00.

Densities of heat flows from solar exposure to vertical elements (columns) are formed somewhat differently. It should be noted that the values of heat flux densities under similar conditions for columns are almost three times less than for horizontal elements. So, at the moment of maximum heat flux values of 12:00 in the considered example for horizontal elements, this value is 1137 W/m$^2$, and for columns only 348 W/m$^2$. Substituting the obtained values in formula (9) we obtain the following values (figure 1).

![Figure 1](image_url)  
**Figure 1.** The calculated values of the temperature of the horizontal and vertical elements of the support block of the OFP at various ambient temperatures in conditions of free convection.

4. Conclusion
The formation of the surface temperature of the SE of OFP depends on many factors. Obviously, the larger the diameter and the area of the irradiated surface, the higher temperatures should be formed on the surface of the SE of OFP. However, with an increase in diameter, the wall thickness of the SE of OFP also increases, and this leads to an increase in the mass of the element. And the greater the mass of the element, the less high temperatures it will reach when heated. It should also be noted one important feature of inclined elements, namely, that when they deviate with respect to the horizon to an angle of 250, an increase in the density of the heat flux of solar radiation occurs. So under the same conditions, the heat flux density of a horizontally located SE would be 1137 W/m$^2$, at the same time, for an element tilted at an angle of 250, this density is already 1254 W/m$^2$.

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