Development of theoretical bases of analysis of reliability of marine oil and gas constructions with regard to temperature impact

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Abstract. Offshore oil and gas installations, located on the offshore fields are exposed to intense heat. The result is a change of temperature condition and having variable thermal stresses that cause fatigue damage and reduce resource. The paper proposes a method which allows to simulate the processes of heating and cooling offshore oil and gas installations in various environmental conditions, and proves the necessity of taking into account the thermal effects in the evaluation of their resource.

1. The stress state of offshore stationary platforms caused by temperature exposure

The Russian Federation has significant oil and gas resources located on the shelf. In recent years, our country has gained access to the existing and promising offshore oil and gas fields in the Black Sea, the extraction of which is carried out with the help of special hydraulic structures, called offshore oil and gas facilities. These structures are operated in difficult marine conditions, which brings to the fore the problems of ensuring their reliability and estimating the resource taking into account the negative impact of the environment [1]. To solve these problems, it is necessary to investigate all the factors affecting the stress state (NS) of offshore oil and gas facilities, since it is the periodic change in the NF that causes fatigue damage and directly affects the duration of their reliable operation (resource).

Stresses caused by thermal effects have a significant impact on the change in the NS of offshore oil and gas facilities (OOGF) [1]. The temperature of the OOGF elements depends on the density of the heat fluxes affecting them and the state of the environment. To estimate the values of heat fluxes, it is necessary to have data on the degree of transparency of the atmosphere, cloudiness, masses, and thermodynamic properties of the steel of OOGF elements, etc. [2, 3]. A change in the thermal state of the elements leads to a change in the stresses acting in them. The main value describing the radiation power, which affects a surface area of 1 m² on the boundary of the Earth's atmosphere, is called the solar constant, which is equal to 1395 W / m² [3, 4, 5, 6]. During the passage through the atmosphere, the density of the heat flux decreases due to [3, 4, 5, 6]: absorption by layers of clouds (17 ... 25% of solar radiation is absorbed as a whole by the atmosphere); scattering by molecules of dry air and dust, etc.
The thermal radiation is reflected to the surface of the sea. Thus, thermal fluxes affect the elements of OOGF, the density of which is the sum of direct and reflected radiations. In the thesis, Starokon Ivan a detailed procedure is given to calculate the total heat flux acting on elements of offshore oil and gas facilities. Analysis of OOGF designs showed that they are made of pipes with an outside diameter from 325mm to 1080mm. Calculation of the temperature of the elements of the OOGF cylindrical shape, which occurs when the heat flows, is carried out according to the formula obtained by the author:

\[ T_{i+1} = T_i + 0.74 \frac{\pi R l_m c}{m} (Q_{i+1} - Q_i) \Delta t, \]

where: \( T_i \) and \( T_{i+1} \) are the initial and considered at some instant time surface temperature of the structural element of OOGF, which is under the action of direct and reflected solar radiation, \([\text{K}]\); \( \pi \) is the \( \pi \) number of 3.14; \( R \) - outer radius of the OOGF structural element, \( [\text{m}] \); \( l \) - its length, \( [\text{meters}] \); 0.74 correction factor, taking into account the degree of blackness of the pipe; \( c \) - specific heat, \([\text{J} / (\text{kg} \cdot \text{K})]\); \( m \) - mass of the OOGF structural element \([\text{kg}]\); \( Q_i \) and \( Q_{i+1} \) - initial and considered at some instant of time heat flow density, \([\text{W} / \text{m}^2]\); \( \Delta t \) - duration of radiation, \([\text{seconds}]\).

2. Actual surface condition of offshore platforms

In addition to calculating the density of heat fluxes affecting the elements of OOGF, it is necessary to take into account heat exchange with the surrounding medium. It is known from the classical theory of thermodynamics [2, 3] that when a heat flow is applied to a solid body, part of the stream is absorbed and heated by the body, and a part is reflected. The ratio between absorbed and reflected solar radiation is determined by the so-called "degree of blackness". Elements of OOGF are steel pipes, with a paint coating applied to it, protecting it from corrosion and having its own, in some cases very significant, reflectivity. However, as the practice of operating support blocks has shown, in fact, the destruction of paint and varnish (LCP) occurs within one to two years after its application, depending on the manufacturer's brand and factory. Due to the fact that the process of restoration of the LCP is extremely expensive, it is carried out once every 10 years. In addition, in practice, the requirements for preliminary operations for preparing the surface of the OOGF for coating the LCP (for example, cleaning the surface) are not adequately observed, which also reduces the resistance of the paint to the destruction. In turn, low-quality LCP 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" (see figure 1), for which the reduced blackness level according to the reference data is 0.74 [4, 5, 6].

![Figure 1. The actual condition of the structural elements of the OOGF support block.](image-url)
3. Methods for calculating heat transfer between the surface of the offshore platform and the environment

In other words, when solar radiation affects platform elements, only 26% of this energy is reflected, while the remaining 74% are absorbed and heated elements of the support block. In turn, the heated structural element radiates energy into the environment. The heat transfer process is due to radiation and convection, which is divided into free and forced. All these processes are characterized by heat transfer coefficients. In the case of heat exchange by radiation, the heat transfer coefficient $\alpha_r$ is calculated by the formula (2):

$$\alpha_r = \frac{\varepsilon \cdot \varepsilon \cdot [(\frac{T_{st}+273}{100})^4 - (\frac{T_{air}+273}{100})^4]}{T_{st} - T_{air}},$$

(2)

where: $\varepsilon$-degree of blackness of element OOGF, taken equal to 0.74; $C$- is the emissivity of an absolutely black body, equal to 5.67 W / (m$^2$K$^4$); $T_{st}$ and $T_{air}$ the wall temperature of the structural element of OOGF and the air temperature in degrees Celsius. With free or forced convection, the heat transfer coefficient $\alpha$ can be calculated from the formula:

$$\alpha_k = \frac{N_{u} \cdot \lambda}{D},$$

(3)

where: $\alpha_k$-coefficient of heat transfer, W / (m$^2$K); $N_{u}$-number of Nusselt; $D$-diameter of the OOGF structural element, meters; $\lambda$-coefficient of thermal conductivity of air, $10^{-2}$ (W / mK). A detailed description of the calculation of the Nusselt number for the conditions of free and forced convection is given in the thesis by Starokon Ivan.

4. Practical example of estimating the wall temperature of elements of an offshore platform in the Black Sea

Analysis of data from the Black Sea climate guides [3] will make it possible to state that the strongest storm winds that can seriously affect the formation of the temperature of the OOGF fall from November to March in the period of minimum solar activity. For example, in the coastal zone of the the range of values of the average wind speed varies from 2.7-2.8 m / s on the South Coast to 6-7 m / s in the areas of the Kerch Strait and the Caucasus. On the other hand, from April to November, the wind activity decreases, 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 greatly increased. Proceeding from this, the author selected the period from April to November for review. it is during this period that the most significant changes in the temperature state of the OOGF occur. It is quite obvious that in the course of flow around the elements of the OOGF, a complex heat exchange takes place by the wind flow, consisting of two components: forced convective heat transfer and heat exchange by radiation.

At present, the processes of heat exchange between a uniformly heated pipe and the environment are well studied. However, the problems of the temperature state of pipes with one-sided heating have not been studied sufficiently. The processes of temperature formation on the surface of the pipe wall and the dynamics of this temperature propagation along internal and external surfaces have not been studied. In connection with this, the author carried out numerous experiments, which made it possible to propose a solution to these problems. The first stage in the solution of these problems is the study of the processes of temperature formation on the surface of the OOGF. Since exactly half of the surface of the OOGF surface is exposed to direct solar radiation, initially it is proposed to replace this heated part of the pipe with an equivalent sample equal to the mass of the entire element to determine the temperature of this surface. Having determined the surface temperature, this value should be corrected by calculating the heat removal to the environment. To correct the value of the formula, it follows from the density of the
heat flux generated by the solar radiation, subtract the density of the heat flux created by the wind action $q$. We proceed to the following formula

$$Q_{ce}^{cor} = Q_{ce}^1 - q,$$  \hspace{1cm} (4)

Where: $Q_{ce}^{cor}$-adjusted heat flux density, W / m$^2$; $Q_{ce}^1$-initial heat flux density; and the density of the heat flux from the pipe wall to the environment of the incoming wind flow by the formula:

$$q = \gamma \alpha (t_{wall} - t_{wind}).$$  \hspace{1cm} (5)

Where: $q$ - is the heat flux density from the pipe wall to the incoming wind flow, W / m$^2$; $\gamma$-coefficient, taking into account that in the case under consideration only half of the pipe is subjected to direct solar radiation, the coefficient is taken equal to 0.5; $\alpha$-coefficient of heat transfer, W / m$^2$K; $t_{wall}$-temperature of outer wall of CE OOGF; $t_{wind}$-temperature of the oncoming wind flow.

In the article the author proposes a technique that allows calculating the temperature of the surface of the OOGF, depending on the density of the heat flux arising from solar radiation. Due to the fact that the initial temperature and the surface temperature of the OOGF structural element considered at some instant of time are unknown values, the author suggests the following procedure: 1) Calculate the total values of heat flux densities from solar radiation and determine the temperature of the outer wall of the OOGF. 2) Knowing the data on the parameters of the wind flow (velocity, temperature, etc.), calculate the density of the heat flux $q$ created by the wind force. 3) Correct the value of heat flux densities. 4) Using the obtained value, determine the surface temperature of the OOGF structural element. Let's consider an example. Let us examine the process of heating and cooling of OOGF by the example of August 14, 2010. Data on climatic conditions are obtained from the weather archive on the website meteo.ua. Consider the horizontal structural elements of OOGF, made according to the project of steel pipes with a diameter of 325x8mm (mass of the investigated element 312.5 kg) and 530x12mm (the mass of the element being investigated is 767.7 kg). We will also analyze the vertical elements of OOGF (columns) made according to the project of steel pipes with a diameter of 720x20mm (the mass of the element being investigated is 1739 kg) and 1020x20mm (the mass of the investigated element is 2474 kg). For comparative analysis, we take the length of all elements to be the same and equal to 10 m. The heating process starts after sunrise at 5:00. Let us take the coefficient of atmospheric transparency $c = 0.38$, with no cloudiness. The created density of heat flow to horizontal elements (GE) by 5:00 has a value of 13 W / m$^2$, which practically does not affect the formation of the temperature of the surface of the OOGF. Already by 7:00 the heat flux density on the horizontal elements reaches 384 W / m$^2$, and by 9:00 the heat flux density is 845 W / m$^2$.

Then, gradually increasing in the logarithmic relationship, the density of the heat flux reaches its maximum value of 1137 W / m$^2$ by 12:00 o’clock. After that, the heat flux density begins to decrease, which is reduced to 845 W / m$^2$ by 15:00, is 384 W / m$^2$ by 17:00, and by 19:00 it is only 19 W / m$^2$. Densities of heat fluxes from solar influence on vertical elements (columns) are formed 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 values of heat fluxes 12:00 in the example under consideration for horizontal elements this value is 1137 W / m$^2$, and for columns only 348 W / m$^2$. The calculated values of the temperature of the horizontal and vertical elements of the OOGF under various environmental conditions are given in (see Table 1).

**Table 1.** The calculated values of the temperature of the horizontal and vertical elements of the OOGF support block under different environmental conditions.
### Time

| Parameter name                                | 7:00 | 8:00 | 9:00 | 10:00 | 11:00 | 12:00 | 7:00 | 8:00 | 9:00 | 10:00 | 11:00 | 12:00 |
|-----------------------------------------------|------|------|------|-------|-------|-------|------|------|------|-------|-------|-------|
| Density of heat flux of solar radiation, W/m² | 384  | 62   |      | 845   | 1014  | 1106  | 11   | 37   | 190  | 307   | 367   | 389   | 360   | 348   |
| Air temperature, °C                           | 28   | 29   | 30   | 30    | 31    | 32    | 28   | 29   | 30   | 30    | 31    | 32    |
| Wind speed, m/s                               | 1    | 2    | 1    | 2     | 1     | 1     | 2    | 1    | 2    | 1     | 1     | 1     |
| The temperature of the outer surface of the OOGF without taking into account the influence of the environment, °C | 56   | 79   | 100  | 115   | 124   | 12  | 7   | 29   | 32   | 34   | 35   | 33   | 33   |
| Coefficient of heat emission by radiation, α, W/(m²°C) | 5.3  | 7.1  | 6.8  | 7.3   | 7.6   | 7.8  | 4.6  | 5.7  | 4.8  | 4.8   | 4.8   | 4.8   | 4.8   |
| Coefficient of heat transfer at free convection, α, W/(m²°C) | 5.9  | 7.1  | 7.9  | 7.9   | 8.1   | 8.1  | 2.6  | 3.8  | 4.1  | 4.5   | 3.3   | 2.6   |
| Coefficient of heat transfer in forced convection, α, W/(m²°C) | 7    | 10   | 7    | 10    | 7     | 7    | 5    | 7.5  | 5    | 7.5   | 5     | 5     | 5     |
| Density of the outlet heat flux during heat exchange by radiation and free convection, W/m² | 157  | 35   | 5    | 566   | 707   | 793  | 81  | 4    | 14   | 18    | 23    | 8     | 4     |
| The temperature of the outer surface of the OOGF with allowance for heat emission by radiation and free convection, °C | 49   | 55   | 83   | 86    | 87    | 89   | 27   | 31   | 33   | 33    | 33    | 33    | 33    |
| Density of heat removal flow during heat exchange by radiation and forced convection, W/m² | 172  | 42   | 8    | 531   | 804   | 737  | 75   | 5    | 20   | 20    | 31    | 10    | 5     |
| The temperature of the outer surface of the OOGF with allowance for heat transfer by radiation and forced convection, °C | 47   | 45   | 73   | 60    | 80    | 82   | 27   | 30   | 33   | 33    | 33    | 33    | 33    |
| The temperature of the outer surface of the OOGF without taking into account the influence of the environment, °C | 44   | 59   | 73   | 83    | 89    | 91   | 29   | 32   | 34   | 35    | 33    | 33    | 33    |
| Coefficient of heat emission by radiation, α, W/(m²°C) | 5.0  | 6.5  | 5.8  | 6.0   | 6.2   | 6.4  | 4.6  | 5.7  | 4.8  | 4.8   | 4.8   | 4.8   | 4.8   |
| Coefficient of heat transfer at free convection, α, W/(m²°C) | 6.3  | 7.6  | 8.4  | 8.8   | 8.9   | 9.0  | 2.6  | 3.8  | 4.1  | 4.5   | 3.3   | 2.6   |
Coefficient of heat transfer in forced convection, $\alpha$ W/($m^2\cdot ^\circ C$)  
|   | 5.6 | 8.5 | 5.6 | 8.5 | 5.6 | 5.6 | 5 | 7.5 | 5 | 7.5 | 5 | 5 |

Density of the outlet heat flux during heat exchange by radiation and free convection, W/m²  
|   | 90  | 21  | 21  | 305 | 392 | 438 | 45 | 4  | 14 | 18 | 23 | 8  | 4 |

The temperature of the outer surface of the OOGF with allowance for heat emission by radiation and free convection, $C_0$  
|   | 36  | 41  | 47  | 50  | 52  | 53  | 27 | 31 | 33 | 33 | 33 | 33 |

Density of heat removal flow during heat exchange by radiation and forced convection, W/m²  
|   | 85  | 22  | 5   | 245 | 384 | 342 | 35 | 4  | 5  | 20 | 20 | 31 | 10 | 5 |

The temperature of the outer surface of the OOGF with allowance for heat transfer by radiation and forced convection, $C_0$  
|   | 37  | 40  | 52  | 51  | 60  | 61  | 27 | 30 | 33 | 33 | 33 | 33 |

5. Conclusion

As it can be seen from the table, the formation of the surface temperature of the OOGF depends on many factors. It can be assumed that the larger the diameter, and consequently the area of the irradiated surface, the higher the temperatures should be formed on the surface of the OOGF. However, as the diameter is increased, the wall thickness of the OOGF, as a rule, also increases, and this leads to an increase in the mass of the element. And the more 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 25°, the density of the heat flux of solar radiation increases. So under the same conditions, the density of the heat flux of the horizontally located would be 1137 W/m², while at the same time for an element inclined at an angle of 25° this density is already 1254 W/m². In the projects analyzed by the author, inclined elements such as braces are located at an angle of 570 with respect to the horizon, which in turn causes a decrease in the maximum density of the heat flux to 1072 W/m². This phenomenon of the influence of the angle of inclination of the plane on the density of the heat flux from solar radiation has been well studied in the field of designing solar energy installations and methods have been developed for selecting the optimal angles of inclination of the plane, which make it possible to accumulate the maximum possible density of the heat flux from solar radiation. The heat transfer coefficient (CT) also changes. At wind speeds of about 1 m/s, CTs are comparable to CTs with free convection, but with an increase in wind speed of up to 2 m/s, the heat transfer coefficients increase substantially. As a result of the calculations, it was found that, in contrast to columns, the temperature effect is insignificant.

As calculations have shown, when heat flows to elements of offshore oil and gas structures, a difference arises between their outer and inner surfaces. For example, for an element 325 mm in diameter with a wall thickness of 10 mm, the equivalent voltage at a temperature gradient between the outer and inner surfaces of $0.30C^0$ will be 23.9 MPa, and at a temperature gradient of $0.40 C^0$, the equivalent voltage will be 31.81 MPa. Similar calculations for an element with a diameter of 426 mm with a wall thickness of 12 mm have shown that at a temperature gradient between the inner and outer walls of the OOGF at $0.30C^0$, the equivalent voltage will be 26.3 MPa, and at a temperature gradient of $0.40C^0$, the equivalent voltage will be 35.1 MPa. These values are more than 50% of the endurance limit, and
therefore have a damaging effect, and should be taken into account when calculating the resource of elements of offshore oil and gas facilities. It is also necessary to take into account the diurnal temperature change, which together with the stresses from the temperature difference between the inner and outer surfaces of the elements, can create significant values of the amplitudes of the variable stresses. This condition, as shown by calculations, is fulfilled with the difference in the minimum nighttime and maximum daytime temperatures of the OOGF elements at 9.80 °C.

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