The study of the stress-strain state of the elements of the flange connection under the influence of internal pressure

R B Tukaeva, M I Bayazitov and A A Enikeeva
Technological machines and equipment chair, Ufa State Petroleum Technological University, Kosmonavtov str., 1, Ufa, The Republic of Bashkortostan, 450062, Russia
E-mail: annaenikeeva2020@gmail.com

Abstract. One of the main requirements that is presented to flange connections (FC) is to ensure uniform tightening torque of fasteners. Violation of this condition may lead to a decrease in FC reliability and an emergency. Regulatory calculations of FC for strength and tightness are carried out under the assumption of creating and maintaining during operation a uniform tightening force of fasteners. There is no information in the literature about whether and how the uneven tightening force affects the stress-strain state of a flange joint. In this paper, we propose such a study based on the method of modeling the stress-strain state of a flange connection. At the first stage, to select the initial data and develop the model, calculations were performed on the strength and tightness of the flat weld flange based on the PASSAT software package. Based on the analysis of changes in bolt loads and stresses, the FC parameters and loading conditions were determined, which are implemented during the development of the FC model and are described in our second article.

When designing and operating various technological systems and equipment, their reliability must be ensured. This fully applies to flange connections, since they make up the most numerous group of elements that are part of almost any equipment.

These connections, for example, in modern designs of cabinet equipment account for about 15-20% (and sometimes up to 70%) of the total number of connections (riveted, threaded, welded, etc.) [1-5].

Flange connections (FC) are used to interconnect parts of apparatuses and pipelines, fittings, devices, covers, etc.

To ensure reliable operation of the FC, in particular, it is necessary to strive to ensure that all bolts or studs are tightened with the same force, i.e. uniform tightening of the bolts was ensured. However, in practice, very often a situation arises when there is a deviation of the tightening force from the calculated value.

Two groups of factors can be distinguished that cause the appearance of unevenness of the tightening force of bolts and FC studs:

- technological (taking place directly in the assembly process);
- operational (arising during the operation of the unit).
Technological factors include errors in the methods and means of monitoring the tightening force, the mismatch between the calculated parameters and the actual ones (these include friction coefficients, geometric dimensions of the thread, ductility coefficients, etc.), force overvoltage in the joints during sequential tightening, human factor, etc. During installation, technological factors lead to a deviation from the required magnitude of the tightening force to a greater or lesser side (tightened or undershot connection). Also, during the installation of these units, the cause of the unevenness of the tightening torque of the bolts may be a large range of the torque recommended by the technical specifications. In addition, in the process of sequential tightening of threaded joints, redistribution of the tightening forces occurs [6]. The reason for this is that the tightening of each subsequent fastener of the group of threaded connections leads to a weakening of the tightening force in the previously tightened stud or bolt. Therefore, the installation of such connections should be carried out in several stages and in a certain sequence.

Operational factors include a decrease in the value of the tightening force in the threaded group due to deformation smoothing of the roughnesses of the mating surfaces in the joint of the parts and in the threaded joints (roughness sludge), residual deformations of the fastener rod, relaxation of the tightening stresses, self-unscrewing, etc. [7-9]. Thus, uneven tightening can be observed even if during installation the same tightening torque was ensured in all bolts or studs.

Uneven tightening can result in numerous negative consequences, such as, for example, FC depressurization, destruction of threaded joints, misalignment of parts, uneven compression of the gasket, plastic deformation of fasteners, and even rupture of bolts or studs (figure 1). All this can lead to an emergency [11].

![Figure 1. Destruction of a bolt when hauling.](image)

In addition, the uneven tightening of the bolts, apparently, causes a change in the stress-strain state of the flange connection and can affect the strength of the FC elements.

This question arises due to the fact that the analysis of the calculated dependencies given in the normative documentation (GOST 34233.4-2017) showed that they were obtained under the assumption of the same bolt tightening force for all fasteners.

Based on this, it is of interest to conduct a study of changes in the stress-strain state of the main elements of the FC in the event of uneven tightening of fasteners and how dangerous this situation is from the point of view of the strength of this connection.

Traditionally, such studies are carried out either on the basis of an analysis of the theoretical dependencies underlying the calculation of the FC, or by experimental methods. However, none of these methods allows these studies to be carried out, since the calculation formulas, as was said earlier, were obtained under the assumption of the same tightening force in all fasteners.
When artificially creating non-uniformity of the tightening force on one of the bolts on the experimental stands, firstly, the redistribution of the tightening force between the other fasteners takes place and it is impossible to distinguish the effect of the unevenness of the tightening force on the stress-strain state and, secondly, it is very difficult to technically measure stresses in design sections.

Thus, one of the methods by which it is possible to study the stress-strain state of FC, both with uniform and uneven tightening of fasteners, can be a modeling method in one of the software packages that was chosen in this paper.

To build a model and perform strength calculations using any computer-aided design system, it is necessary to select the object of simulation, the magnitudes and schemes of the application of loads, the limits of their change, the values of stresses that can occur in different sections, etc.

Therefore, this work was carried out in two stages, at the first of which the object of study was selected, initial data were determined, it was established how the values of bolt loads, bending moments, stresses and deformations change depending on pressure in various design sections of flange connections (figure 2) etc.

At the second stage, on the basis of the results obtained, a FC model was developed, a study of the stress-strain state for uniform bolt tightening efforts was carried out, and the model was checked for adequacy. Then, the same studies were conducted to create an uneven bolt tightening force.

This article presents the results obtained at the first stage of studies of the stress-strain state of a flange connection.

As an object of study, a flat welded flange on DN 250, PN 10 MPa from steel 20 with bolts M20, L75 from steel 35, which was under the influence of internal overpressure, was chosen.

We studied the method of strength calculation of FC according to GOST GOST 34233.4-2017 for strength and tightness and carried out the necessary calculations using the PASSAT software package at various internal pressures for the design sections shown in figure 2.

The initial data used for the calculations are given in tables 1-3.

### Table 1. Initial data for the calculation of flat welded flanges.

| Item                                      | Value  |
|-------------------------------------------|--------|
| Flange diameter, D, mm                    | 250    |
| Bolt circle diameter, D₀, mm              | 335    |
| Material of fasteners                     | 35     |
| Outside diameter, d, mm                   | 20     |
| Number of bolts, n                        | 12     |
| Gasket material                           | Paronite |
| Thickness, h₀, mm                         | 2      |
| Outside diameter, Dₜₜ, mm                 | 310    |
| Width, b₀, mm                             | 27     |
| Flange material                           | Steel 20 |
| Related items                             |        |
| Outer diameter of flange, Dₜ, mm          | 370    |
| Flange (ring) thickness, h, mm            | 21     |
| Wall thickness of adjacent element, mm    | 16     |
| Sum of increases, s, mm                   | 2.8    |

### Table 2. Initial data for calculation in the working conditions of flat welded flanges.

| Item                                      | Value  |
|-------------------------------------------|--------|
| Estimated temperature of connection elements, tₑ, °C | 20     |
| Nominal stress tolerances for bolt material (steel 35) at temperature T=20 °C, [σ]₀, MPa | 130 |
| Permissible stresses for the material of flanges and adjacent elements (steel 20) at temperature T=20 °C, [σ]₀, MPa | 147 |
Table 3. Gasket specifications.

| Type and gasket material | Paronite according to GOST 481 with a thickness of not more than 3 mm |
|--------------------------|------------------------------------------------------------------------|
| Coefficient, m           | 2.5                                                                    |
| Specific compression pressure, q_s, MPa | 20                                                                  |
| Permissible specific pressure, [q], MPa | 130                                                                |
| Compression ratio, K     | 0.9                                                                    |
| Conditional compression module, E_m, MPa | 2000                                                               |
| Effective Gasket Width, b_0, mm | 16.34                                                               |
| Working outer diameter of gasket, D_{imp}, mm | 310                                                                |
| Average effective gasket diameter, D_{e}, mm | 293.7                                                               |
| Gasket compliance, y_p, mm/H | 0.5273·10^{-7}                                                        |

Figure 2. Stresses in design sections of a flange connection: a) design flange sections; b) combination of stresses acting in elements 1 and 2. $\sigma_{0mm}$ – meridional membrane stress, $\sigma_{0mo}$ – circumferential membrane stress, $\sigma_R$ – radial stress, $\sigma_t$ – circumferential stress, $\sigma_\theta$ – meridional bending stress.

Figures 3-6 show the obtained dependences of changes in various loads and stresses in the FC elements on internal pressure.

Figure 3. Dependence of bolt load on internal pressure.
Figure 4. The dependence of the stresses in the bolt on the internal pressure.

Figure 5. Dependence of various types of loads on internal pressure.
Figure 6. The dependence of stresses in the flange on the internal pressure.

Table 4 shows the data on the test of the FC tightness (stiffness) at various values of internal pressure.

Table 4. Checking the stiffness of the flanges under operating conditions.

| Estimated internal overpressure, P, MPa | Flange angle, $\Theta$, ° | Permissible angle of rotation of the flange, $[\Theta]$, ° | The coefficient of increase in the permissible angle of rotation of the flanges, $K_\Theta$ | Flange stiffness condition, $\Theta \leq K_\Theta [\Theta]$, ° |
|---------------------------------------|---------------------------|---------------------------------------------------|-----------------------------------|----------------------------------------|
| 0.1                                   | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
| 0.5                                   | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
| 1.0                                   | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
| 1.5                                   | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
| 2.0                                   | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
| 2.25                                  | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
| 2.3                                   | 0.03569                   | 0.7448                                            | 1                                | 0.03569<0.7448 performed              |
An analysis of these values shows that the dependence of bolt loads and stresses on pressure is complex. In this case, the bolt loads and stresses from the internal pressure at pressure values up to 2 MPa practically did not change, and then began to increase significantly.

This is due to the fact that as a bolt load is selected:

- when tightening the maximum of two values \( P_{b\text{m}} = \max\{P_{b1}; P_{b2}\} \). Wherein up to 2 MPa prevails \( P_{b2} \), after 2 MPa – \( P_{b1} \);
- under operating conditions, only one value is calculated, \( P_b \) which is selected as the maximum.

In addition, the calculations showed that for the selected type of flange and the material of the elements, even at a pressure of 2 MPa in the flange in section \( S_0 \), the voltages are greater than the allowable ones. Therefore, at the first stage, the study of the stress-strain state in the model was carried out at a pressure \( P \) less than 2 MPa. The pressure \( P = 0.5 \) MPa was chosen as the initial value.

The summary stress values for this pressure are presented in table 5. The stress designations in the PASSAT and GOST 34233.4-2017 software systems differ from each other, therefore, table 1 shows the values used in these two cases.

| Parameter                          | Designation in PC «PASSAT» | Designation according to GOST R GOST 34233.4-2017 | Value   |
|------------------------------------|-----------------------------|--------------------------------------------------|---------|
| Operating bolt load, H             | \( P_b^\rho \)              | \( P_b^\rho \)                                     | 154600  |
| The meridional bending stress in the sleeve, MPa | \( \sigma_\rho^\rho \) | \( \sigma_\rho^\rho \)                               | 92,5    |
| The meridional membrane stress in the sleeve, MPa | \( \sigma_\rho^\text{mm} \) | \( \sigma_\rho^\text{mm} \)                         | 2,8     |
| The peripheral membrane stress in the sleeve, MPa | \( \sigma_\rho^\text{mm} \) | \( \sigma_\rho^\text{mm} \)                         | 5,1     |
| Radial stress in the plate, MPa    | \( \sigma_\rho^R \)         | \( \sigma_\rho^R \)                                 | 50,6    |
| Circumferential stress in a plate, MPa | \( \sigma_\rho^t \)  | \( \sigma_\rho^t \)                                | 14,2    |
| Equivalent stresses in a bolt, MPa | \( \sigma_{b2} \)         | \( \sigma_{b2} \)                                  | 57,25   |

Subsequently, these data were used in developing the FC model, selecting design parameters and external loads, performing calculations on the model, checking its adequacy, as well as studying the effect of unevenness of the fastening torque of fasteners on the stress-strain state, generalizing research results and issuing recommendations.

It is shown that flange connections constitute one of the many groups of elements used in almost all types of technological equipment operated at oil refineries and other enterprises. One of the main requirements for flange joints is to ensure uniform fastening of fasteners, the failure of which can lead to a decrease in FC reliability and an emergency. An analysis of the regulatory documents that describe the method for calculating the FC for strength and tightness showed that these calculations are carried out on the assumption that a uniform tightening force of fasteners is created and maintained during operation. The literature does not provide information on whether and how uneven tightening forces affect the stress-strain state of a flange connection. It is shown that such studies cannot be carried out using theoretical dependencies and experimental methods. Therefore, it is proposed to study the effect of uneven bolt tightening forces using PCS methods. To select the initial data and develop the model, at the first stage, calculations were performed on the strength and tightness of the flat welded flange based on the PASSAT software package. Analysis of changes in bolt loads and stresses showed that at a pressure greater than 2 MPa, the condition for the strength of the FC is not fulfilled. Therefore, initially, the calculations were carried out for internal overpressure \( P = 0.5 \) MPa. For this pressure, all data on the components of the bolt load and the stresses that arise in various sections and elements of the FC are systematized. The data obtained were used on the second ethane of the present studies to develop a FC...
model with a uniform and uneven torque of bolt tightening and checking its adequacy. The research results are presented in our next article.

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