Optimization of Parameters of a Hydraulic Mobile Pumping Unit for Hydraulic Fracturing

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Abstract. As part of many units of the oil and gas industry, a manifold is used, which is an element of drilling equipment, included in the design of oil and gas fittings and represented by a whole block of pipelines and valves. Even though most of its components are formed by standard parts, the manifold is unique for each individual design due to the different arrangement of the equipment elements, which necessitates the study of the correctness of its functioning in each specific case. The purpose of this study is to check the strength of the attachment points of the manifold, which determine its overall performance. The objectives of the study are to carry out strength calculations of the fastening points of the manifold to determine their suitability for high-pressure operation, as well as automatic calculation of the flange connection. A 3D model of the manifold of a mobile pumping unit for hydraulic fracturing was used for the study. To determine the strength characteristics, the connection section of the high-pressure manifold transition coil with the pump by means of a flange connection was considered. For this unit, the strength calculation is performed according to Russian GOST 52857.4–2007. For the possibility of conducting the necessary studies in the design and optimization of the parameters of the flange connection, it is proposed to automate the calculation of the strength of flange connections. The computer-aided design system PTC Mathcad was used to automate the calculation. To find the coefficients presented in the standard in the form of graphical dependencies, they were translated into empirical formulae. The obtained results allow us to take the necessary coefficients in the calculation as input parameters and fully automate the calculation. The completed studies may be of interest to students and mechanical engineers who produce similar calculations.

Keywords: Manifold · Computer Mathematics System · Nomogram · Flange Connection

1 Introduction

The main oil deposits are contained in porous rocks. The efficiency of oil field development is largely determined by the high-quality and uninterrupted operation of producing wells [1–3]. During operation, the pressure in the reservoir decreases, excluding the independent gushing of the product, which necessitates the use of methods of intensification of mining. The most widespread are the basic methods [4–6], such as detonated rock rupture, acid treatment, hydraulic fracturing (FRACKING).

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Hydraulic fracturing technology consists in creating a highly conductive crack in the target formation under the action of a pressurized fluid supplied to it to ensure the inflow of the extracted fluid (natural gas, water, condensate, oil, or a mixture thereof) to the bottom of the well until the fluid pressure overcomes the stresses inherent in the rock, or exceeds the forces, holding the rock together [7–9]. Due to the stress concentration in the contact zone between the wedging substances and the rock and their difference in strength and stiffness, the wedging substances are embedded in the rock fracture surface [10]. Solutions with the use of high-molecular polymers (to reduce pressure losses) on a water basis are usually used as a working fluid [11–13]. In the process of hydraulic fracturing, a large amount of equipment is used, called a hydraulic fracturing fleet. The hydraulic fracturing fleet is a complex consisting of more than a dozen specialized installations, mounted on the chassis of trucks and semitrailers, and designed for hydraulic fracturing operations. The hydraulic fracturing fleet is represented by a complex of mobile units necessary for the technological operation of hydraulic fracturing, including pumping units, hydration units, mixers (blenders) for the preparation of working mixtures, manifold machines, automated control and control stations, tanks for storage and transportation of propanoate and working mixtures [14–18].

Hydraulic fracturing pumps liquid media under high pressure, so it is important to study the strength characteristics of the manifold of this system. Pumping units are equipped with manifolds for redistribution and direction of working fluid flows. They are an element of oil and gas fittings, represented by a whole block of pipelines and veins, used as part of many units of the oil and gas industry. This equipment is made of wear-resistant material and is calculated for high pressure according to a certain scheme and requirements, it is equipped with necessary shut-off and other fittings. Even dough most of the components are formed by standard parts, the manifold is unique for each individual design due to the different location of the equipment elements, which necessitates the study of the correct functioning of its operation in each specific case. The development of methods for automated calculation of the components of the manifold is an important topic for designers of this type of equipment.

Earlier in [11], 3 types of low-pressure manifold designs were considered, a hydrodynamic analysis was carried out when opening three suction valves for three design types of suction manifolds. During the study, the design of the suction manifold and the order of opening and closing the valves were varied. The controlled (output) parameters of the mixture movement according to three design types of manifolds are: the volume mass of the settled proppant in the manifold, the Reynolds number (Re), the flow rate of the mixture through the valve box. The method of 3D modeling "pustoty". The method used in the source [11] is like the one given by the authors in the studies [20, 21], where the frequency response of pressure pulsations and the identification of the source in the suction manifold were considered.

In the result of the analysis of the results of calculating the volume fraction of the settled proppant, with the sequential operation of valves for various designs, it was concluded that the design that most meets the technological requirements is the first variant, which is a "classic" ramjet model (see Fig. 1) [11]; this model will be used for further research.

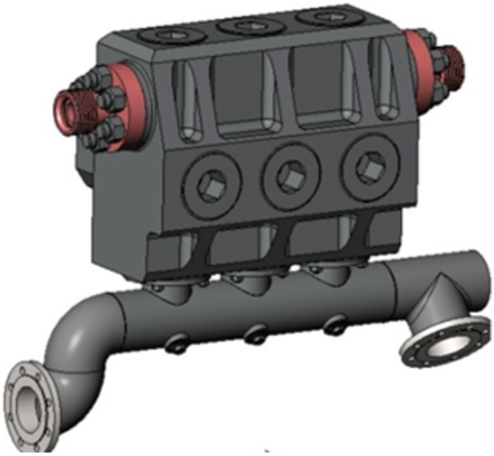

Fig. 1. Design of suction manifold ChecV ("classic" ramjet model)

It is important to test a strength not only specific components of the manifold, but also the places of their connection and attachment (in this case to the hydraulic block of the three-plunger pump), since they ensure tightness and maintain the necessary pressure, without which the efficiency of the equipment decreases and the probability of failure increases.

The purpose of the study presented in this paper is to check the elements of its fastening for strength. The subject of the study is the design element of the manifold of the pumping unit: flange connections, by means of which the elements of the suction and discharge lines of the manifold are attached to each other and connected to the pump. The objectives of this study are to carry out strength calculations of the attachment points of the manifold to determine their operability at high pressure, as well as automation of the strength calculation of the flange connection in a computer mathematics system.

2 Research Method

To carry out the strength calculation of the flanged ones, the methodology described in Russian GOST 52857.4 – 2007 "Norms and Methods of Strength Calculation. Calculation of the strength and tightness of flange connections". The standard is applied to the calculation of flange connections with butt- welded, flat-welded, and free flanges with flat, octagonal, and oval gaskets, which are completely, located inside a circle, bounded by holes for studs (bolts). It is used in conjunction with Russian GOST 52857.1—2007 "Vessels and Apparatuses. Norms and Methods of Strength Calculation. General Requirements".

The considered calculation method is applied to flange connections that meet the conditions:

$$\frac{D_{\text{out}}}{D} \leq 5; \frac{2h}{D_{\text{out}-\text{D}}} \geq 0.25,$$

where D_{out} is the outer diameter of the flange, mm; D is the inner diameter of the flange, mm; h is the flange plate thickness, mm. The slope of the sleeve of the butt-welded flange should not exceed 1:2.5 (0.4).

If the device operates in several different modes, the calculation must be carried out under conditions that ensure the strength and tightness of the flank joints in all modes.

Calculation of flange connections for strength and tightness consists of the following stages: (i) determination of the force, acting on the gasket under operating conditions, necessary to ensure the tightness of the flange connection, and the force, required for initial compression of the gasket; (ii) determination of the force in bolts (studs) under operating conditions and the tightening force required to ensure the tightness of the flange connection in working conditions; (iii) checking the strength of bolts (studs) and gaskets; (iv) calculation of the strength of the elements of the flange connection during tightening and under operating conditions and the action of pressure, forces in bolts (studs), necessary to ensure the tightness of the flange connection and other loads; (v) checking the angle of rotation of the flanges; (vi) calculation of the elements of the flange connection for low fatigue, if the loading is cyclical.

Automation of the calculation of flange connections was carried out in the automated design computer mathematics system PTC MathCad [21]. It contains arithmetic, logical, matrix operators, and has more than 700 built-in functions. There are many different categories that have program functions: Bessel functions, complex numbers, curve fitting, data analysis, differential equations, finance, Fourier transform, plotting, hyperbolic functions, image processing, interpolation, number theory, probability, sorting, statistics, trigonometry, vectors, and waves [22, 23]. When entering data and formulae in PTC Mathcad, the principle of "What you see is what you get—WYSIWYG" is used, which allows the engineer to immediately develop a document that is as similar as possible to the final report. On the PTC Mathcad worksheet, all expressions are not written in a computer formula language but have a familiar appearance for engineering perception. PTC Mathcad can interact with other programs, which simplifies calculations [24]. The Excel spreadsheet component greatly simplifies the transition to PTC Mathcad, since you do not need to start all over again. It is possible to use existing Excel spreadsheets in project calculations, as well as create new ones directly in calculations [25]. Two programs can work together, exchanging data bilaterally. The unknown coefficients of the regression equation calculation were determined by solving the matrix expression.

3 Results and Discussion

For research and the possibility of optimizing flange connections, the calculation of the strength of flange connections was automated in the computer mathematics program PTC Mathcad [14].

The initial data for calculating the forces, required to crumple the construction and ensure the tightness of the flange connection were set, namely the width and outer diameter of the gasket, in the computer mathematics system Mathcad program mode. The effective width of the gasket was calculated together with the force, required to crumple the gasket during tightening. The coefficients, specified in the appendix to Russian GOST 52857.4 $-$ 2007 were used in the calculation.

Further calculation of the flange connection includes the calculation of the force in the bolts (studs) of the flange connection during tightening and under operating conditions, checking the strength of bolts (studs) and gaskets, as well as the calculation of the flanges for static strength.

In the process of automating the calculation, it became necessary to choose the values of some coefficients by nomograms. In particular, the graph for finding the coefficient (see Fig. 2) β_F is one of the calculated coefficients depending on the ratio of the dimensions of the flange sleeve. Here S_0 is the thickness of the butt-welded flange at the place of welding to the shell (pipe), the thickness of the shell of the flat flange or the shoulder of the free flange, S_1 is the thickness of the butt-welded flange sleeve at the place of connection to the plate, l is the length of the conical sleeve of the butt-welded flange; l_0 is the parameter of the sleeve length.

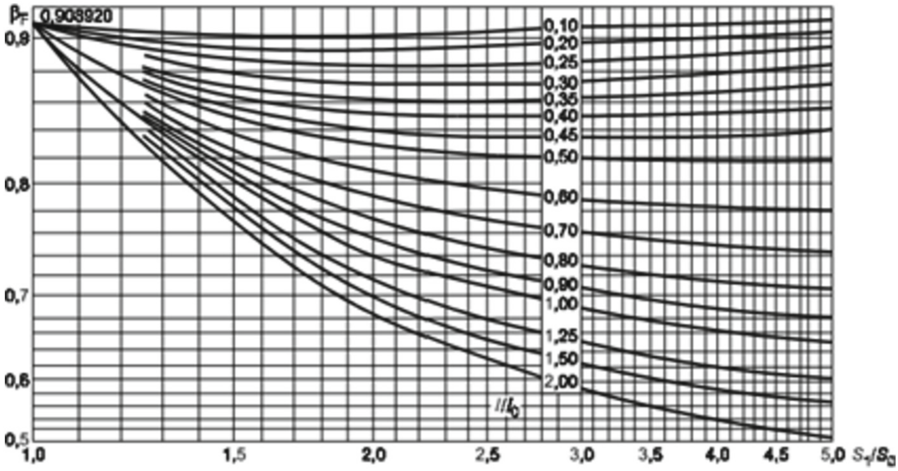

Fig. 2. Nomogram for finding the coefficient β_F, based on Russian GOST 52857.4

It is necessary to calculate the coefficient λ, which, in turn, is used to calculate the meridional bending stress in the sleeve of a butt-welded flange, the shell (pipe) of a flat flange or the shell of a free flange (since the calculation is valid for several types of flanges).

To find the coefficients, presented in the standard form of graphical dependencies, they were translated into empirical formulae. The analysis of the nomograms made it possible to obtain an array of points (three points for each curve due to the nonlinear dependence of the values) and process it using the method of multivariate regression analysis, since the effective feature (coefficient value) is influenced not by one factor, but by several different simultaneously acting factor features. As a result of qualitative analysis, factors (X_1, X_2,..., X_k) that affect the change in the predicted indicator Y are identified, unknown coefficients of the regression equation are determined and a regression dependence is constructed, which in this case will take the form:

$$y(X_1, X_2) = B_0 + B_1X_1 + B_2X_2 + B_3X_1BX_2 + B_4{X_1}^2 + B_5{X_2}^2 + B_6{X_1}^3 + B_7{X_2}^3$$

Based on the data, we obtain a graph of this dependence (see Fig. 3). The obtained coefficients of the regression equation were checked according to the Student's criterion, and the adequacy of the model was checked using the Fisher criterion, the hypothesis of the adequacy of the model was confirmed.

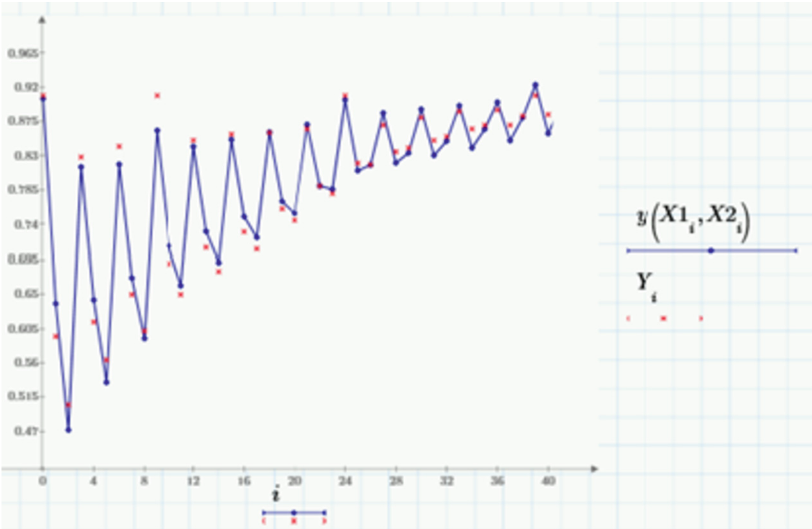

Fig. 3. Nomogram of coefficient β_F in PTC MathCad

Also, the correction factor for stresses in the flange bushing f was considered, which is determined by the nomogram (see Fig. 4). Since, we observe a linear relationship, we can define 2 points for each curve, 38 points for 19 curves. The coefficient also depends on the ratios S_1/S_0 and l/l_0.

Similar calculations were performed for the graph for determining the coefficient f. The results of the analysis of the nomogram in the form of an array of points were summarized in an Excel table. In the result of qualitative analysis, factors $(X_1, X_2, \ldots, X_k)$ that affect the change in the predicted indicator Y were identified, unknown coefficients of the regression equation determined, and a regression dependence was constructed (see Fig. 5).

The resulting regression equation has passed the adequacy test according to the Fisher criterion. Thanks to the computer mathematics program, it was possible to obtain an automated calculation for the strength of flange connections, corresponding to the declared Russian GOST.

The main feature of the performed study is the translation of the values of empirical coefficients, presented in the form of nomograms, into functional dependencies that allow calculating the values of the coefficients for the calculated case. This made it possible to fully automate the calculation of the flange connection. Similar studies that allow for the multidimensional optimization of technical objects, using the application package of the computer mathematics program MathCad, were carried out by the authors of works [14–16]. The paper [25] presents calculations performed in a similar manner, considering data for real drilling operations over the past few years. The calculation used data in the form of appropriate tables. The calculation of the flow rate in MathCad with three variants of flow and nozzle sizes to determine the gas flow rate in the annular channel corresponding to different locations of the CNBC was performed.

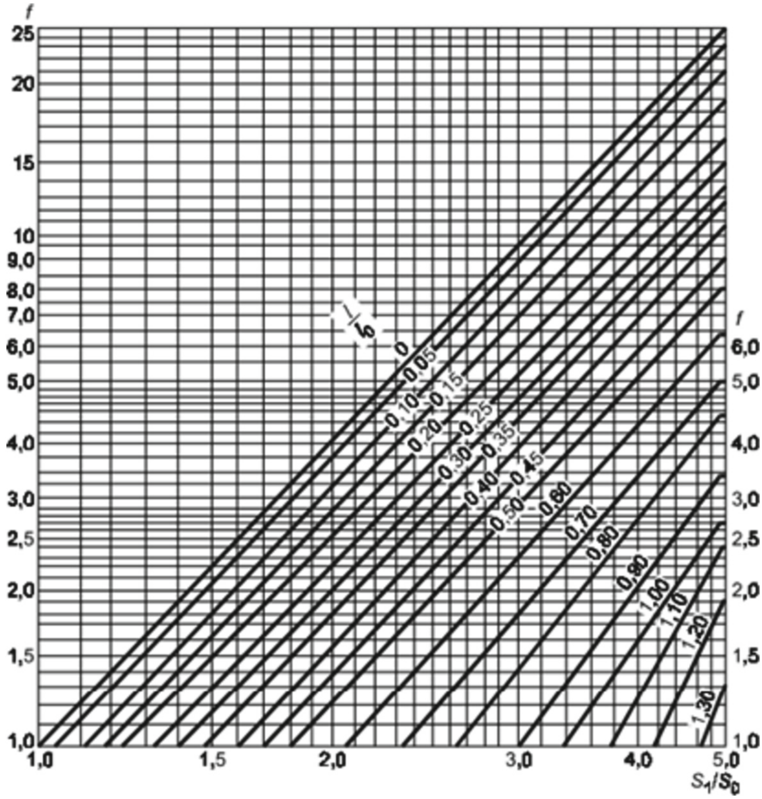

Fig. 4. Nomogram for finding the coefficient *f*, based on Russian GOST 52857.4 − 2007

The advantages of the presented automated calculation consist in its accessibility due to the prevalence of using the MathCad program for engineering and other calculations, in the convenience of determining the required coefficients without having to refer to the graph image, that is why the calculation is more optimized, as well as in minimizing the "human factor", the presented conclusion is consistent with the results of the work [26]. It can be used by students of mechanics and engineers to perform similar calculations since it eliminates mathematical difficulties, facilitates the understanding of the process under consideration and the study of the impact that input variables have on the solution.

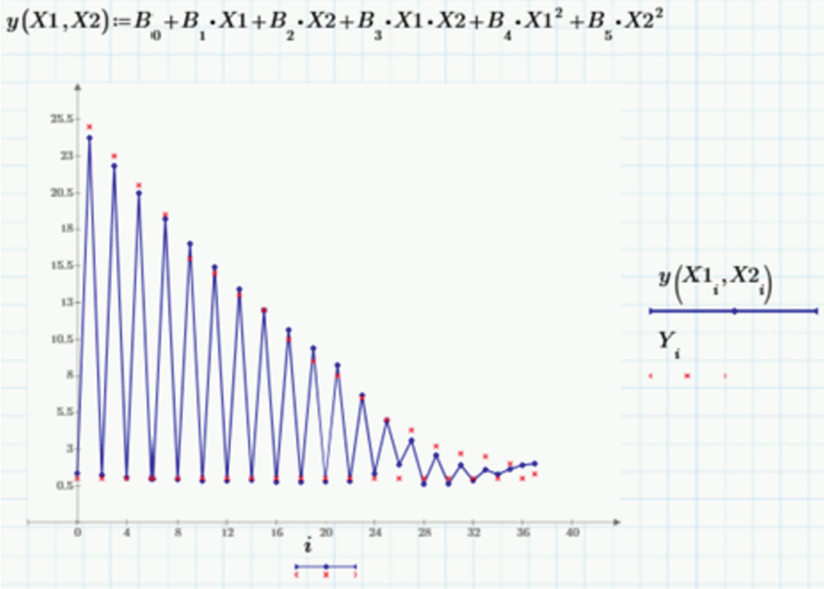

Fig. 5. Mathematical model and graph for determining the coefficient *f*

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