Computer Analysis of Durability and Leakproofness of Multilateral Junction of Wells

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Abstract. The paper considers method of computer simulation of well multilateral junctions corresponding to TAML Level-4. The base stages of algorithm of stress-strain condition calculation of cased main and side pipes are described. Durability of junction depending on internal pressure is established in a kind of functional dependences. The influence of side pipe thickness and whipstock angle on junction deformation is researched.

Introduction

Now in Russia construction of multilateral wells is promptly developing segment of oil and gas service. Technologies of multilateral drilling allow to increase considerably efficiency of development of oil and gas fields that has special importance for operation of oil-pool with hardly recoverable resources.

Today there are a lot of technical and technological decisions for a construction of multilateral wells which can be related to six levels in accordance with the standard international classification TAML (Technology Advancement for Multi-Laterals). Each TAML level is characterized by specific type of a junction design of side and main boreholes [1]. The most universal and economically justified decision for construction of multilateral wells on the land is the type of junction design corresponding to TAML Level-4 [2], which is characterized by the fact that the main and side boreholes are cased and cemented. This type of junction provides mechanical fixing of connection, but has not hydraulic isolation, therefore is characterized by insufficiently reliable bracing.

For the analysis of TAML-4 junction functioning in order to determine the directions of this technology development and identify the technical and technological restrictions of junction design authors developed the method of carrying out computing experiment for stress-strain condition estimation of multilateral junction in the conditions of a well.

1. Computer simulation

As the Lame’s formula [3] used for calculation of stresses in casing columns is applicable only to the infinite hollow cylinder and doesn't allow to consider assembly module, for the solution of this task it is reasonable to use a numerical method.

The Finite Element Method [4, 5] realized in ANSYS has the powerful capabilities for the solution of 3-dimensional tasks [6, 7]. This method is successfully applied for durability and reliability estimation of drilling [8, 9] and oil equipment [10].
As object of computer simulation the place of junction of the main and side pipes of a multilateral well was chosen because this element of module is the most difficult at construction and the least reliable at the subsequent operation. In the analysis process the five stages of modeling and calculation are realized.

Stage 1. The geometrical model creation.
To have an opportunity to research the influence of side pipe parameters on strength characteristics of module in whole, it is expedient to create its parametrical model in the ANSYS Parametric Design Language [11]. Therefore geometrical model is created with the help of Boolean operations [12].

The main case pipe was accepted steel (Strength grade E, yield strength is 552 MPas, tensile strength is 689 MPas) that corresponds to widespread conditions at multilateral wells drilling. The upper pipes of side pipe shank are made of an aluminum alloy (V95t1 aluminum, Russian State Standard 18482-79, yield strength is 400 MPas, tensile strength is 510 MPas). This feature of module is caused by a possibility of further drilling of cement and shank in the main column. Properties of materials were described by multilinear laws of deformation (Fig. 1).

Stage 2. Finite element meshing.
For model meshing finite elements SOLID95 describing elastic and plastic strains by quadratic functions were used. In order to decrease the random access memory size and to reduce the calculation time the sizes of elements in junction volumes were set small, and in constrained areas of model – larger [13].

Stage 3. The boundary conditions definition.
Because of symmetry of a model, only ½ its part was subjected to the analysis. On the section planes of model the symmetry boundary conditions were defined, upper and lower areas are constrained (Fig.2). As external loads the rock pressure equal 22 MPas was accepted, at junction position of the main and side pipes of well at depth 2000 m. As it was specified earlier, the TAML Level-4 junction has no hydraulic isolation and the cavity of case pipe and rock in junction place are connected. Therefore the internal pressure depending on degree of non-leakproofness of a junction, on rock properties and on the works performed in well, was varied during simulation.

Stage 4. Solution of the task.
For the solution of this task the Sparse Solver was chosen. Because of considering of elastic-plastic strains the task is characterized by physical nonlinearity, therefore for acceleration of nonlinear decision convergence the 4 substeps were set.

Stage 5. The results analysis.
During computer simulation eight calculations at different internal pressure values were carried out. For check of calculation model adequacy it is necessary to estimate the finite element grid quality [14]. The finite element grid quality estimation was realized similar to paper [8], in accordance with formula:

![Figure 1. Deformation curves of pipes materials](image)
\[ \Delta_1 = \frac{ESOL - NSOL}{ESOL} \cdot 100\% \tag{1} \]

where ESOL – element solutions; NSOL – nodal solutions. The estimation has shown quite satisfactory results presented in Table 1.

| Internal pressure, MPas | Maximum radial displacements, mm | Von Mises stress in steel, MPas | Grid quantity in steel, % | Von Mises stress in aluminum, MPas | Grid quantity in aluminum, % |
|-------------------------|----------------------------------|-------------------------------|---------------------------|----------------------------------|-----------------------------|
| 10.2                    | -1.777                           | 519.228                       | 521.679                   | 0.47                             | 368.967                     | 403.732                     | 8.611                        |
| 11                      | -1.651                           | 484.523                       | 486.803                   | 0.468                            | 358.578                     | 397.412                     | 9.772                        |
| 12                      | -1.4963                          | 441.549                       | 443.618                   | 0.466                            | 343.456                     | 372.118                     | 7.702                        |
| 13.6                    | -1.2537                          | 373.868                       | 375.606                   | 0.463                            | 318.646                     | 341.421                     | 6.671                        |
| 15.3                    | -1.003                           | 303.086                       | 304.478                   | 0.457                            | 271.454                     | 275.312                     | 1.401                        |
| 17                      | -0.877                           | 232.992                       | 234.025                   | 0.441                            | 203.995                     | 206.759                     | 1.337                        |
| 18                      | -0.856                           | 192.074                       | 192.911                   | 0.434                            | 164.482                     | 166.643                     | 1.297                        |
| 19                      | -0.8361                          | 151.295                       | 151.937                   | 0.423                            | 125.103                     | 126.711                     | 1.269                        |

The results of stress-strain condition estimation of multilateral junction at internal pressure 12 MPas are presented on Fig. 3. Deformations are magnified by a factor of 10. Contours of von Mises stress [15] the most illustrative for this task are shown on Fig. 4.
By results of computer simulation with the help of regression analysis following functions of displacements and stresses in pipes materials of pipes depending on internal pressure value were established. The obtained dependences are presented as polynomials.

Radial displacements:

$$ Ur(p) = -5.060313 + 2.230299 \cdot p - 0.244619 \cdot p^2 + 0.010638 \cdot p^3 - 0.0001621682 \cdot p^4 $$

Von Mises stress in steel pipe:

$$ \sigma_{EQV}^p(p) = 976.707 - 46.539 \cdot p + 0.164 \cdot p^2 $$

Von Mises stress in aluminum pipe:

$$ \sigma_{EQV}^p(p) = 208.641 + 38.991 \cdot p - 2.293 \cdot p^2 $$

Fig. 5 illustrates the computer simulation data showed by labels and plotted functions showed by solid curves.

2. Research of influence of multilateral junction geometrical parameters on its durability and leakproofness

The developed by authors algorithm of stress-strain condition estimation of multilateral junction realized in APDL language allows to research the influence of side pipe parameters (sidetracking angle and side pipe thickness) on distribution of displacement and stresses in module.
Now whipstocks of angles less than 3 degrees are generally presented at the market of oil services [9]. However in the carried by authors researches also larger angles were considered to estimate possible options of junction optimization. The results of calculations are presented in Table 2.

On Fig.6 contours of von Mises stress till yield strength for junction of angles 1.92 degrees and 3 degrees correspondingly are shown. Zones of plastic strain are marked by gray color. It is well visible that even small increase of sidetracking angle provides considerable shortening of plastic zone length. Authors of paper [16] recommend to choose the tools for sidetracking of angle 5 degrees to avoid big zones of the plastic strains capable to lead to column buckling. At the same time, researches of this paper showed that dependence of plastic strains zone length on whipstock angle has cubic character:

\[ L(\alpha) = 2573.914 - 1319.991 \cdot \alpha + 276.523383 \cdot \alpha^2 - 20.503049 \cdot \alpha^3. \]  

Table 2. The results of junction stress-strain condition estimation depending on whipstock angle

| Whipstock angle, degree | Maximum total displacements, mm | Length of plastic zone along side pipe, mm |
|------------------------|---------------------------------|--------------------------------------------|
| 1.92                   | 3.64765                         | 917                                        |
| 2.5                    | 3.37134                         | 670                                        |
| 3                      | 3.17468                         | 561                                        |
| 4                      | 2.85901                         | 402                                        |
| 5                      | 2.609                           | 325                                        |

The curve of established by polynomial regression dependence (5) is submitted on Fig. 7. Its well illustrates that increase of whipstock angle more than 3 degrees is ineffective. Moreover, use of whipstock of big angle can cause complications at well drilling and at subsequent shank descent in a side borehole.

Other way to increase the junction working capacity is magnification of side pipe thickness. Results of computer simulation have shown that side pipe thickness also has influence on working capacity of multilateral junction in whole. The established function of plastic strains zone length depending on side pipe thickness is quadratic, but is very close to linear: The curve of the function (6) is presented on Fig.7.

\[ L(t) = 2639.086 - 222.142857 \cdot t - 1.428571 \cdot t^2. \]  

Figure 6. Contours of von Mises stress for junctions of different angles
Results and discussion
Carried out computer experiment allowed to establish that the TAML Level-4 junction is subjected to extreme loads depending on difference between rock pressure and internal well pressure. At the same time high values of differential pressure apply stresses in pipes metal, close to material yield strength.

It follows that candidate wells for multilateral drilling must have the casing column of corresponding strength grade, and it is necessary to consider that casing column durability of old stock wells can decrease as a result of corrosion.

The obtained results testify that even at small pressure difference the junction is subjected to deformations. This factor will inevitably cause integrity violation of pipes and cement contact in the considered model. During operating in case of pressure decrease in well lower than limit pressure there is column displacement, violation of adhesion and cement integrity.

As a result at operation the prolapse of cement stone fragments and rock is observed that leads to frequent jamming and wear of pumps. Also at such operation the considered junction provides risk of intercolumn cross-flows and gas inrushes. This factor needs to be considered at design of construction of a multilateral well and to choose the place of sidetracking taking into account that the cement outside of main column and side borehole will be damaged on extended region.

Important design problem of multilateral well is quest for of reasonable compromise at the choice of whipstock angle and side pipe thickness, and also their combination with the purpose of multilateral well design optimization and increase of its reliability.

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