Simulation of repair and technical maintenance processes for power-generating equipment components at chemical factories

Nikolay S. Efimenko^{1,*}, Ildar A. Sabanaev¹, and Ilmur N. Madyshev²

¹Nizhnekamsk Institute of Chemical Technology, 423578, Nizhnekamsk, Stroiteley str., 47, Russia

²Kazan National Research Technological University, 420015, Kazan, Karl Marx str., 68, Russia

Abstract. Theoretical aspects and experience of using the mathematical modeling and computerized simulation technology for solving the problems of installation and repair of process equipment of chemical and petrochemical industries are considered in this scientific paper. Computational model of restoring process to working condition of pipeline section has been developed. It is shown that if you use the developed model, then the labor-intensive installation activities, related to the repair works on heat and power networks of chemical industries, can be performed in a more efficient way.

1 Introduction

The information technologies have found the greatest application in the field of mechanical engineering, and, in particular, chemical engineering, for calculation and simulation of processes and devices of chemical technology in order to find the optimal design-engineering solutions [1-8]. It is difficult to imagine the development of modern chemical and petrochemical equipment without using such software systems such as ChemCAD, Ansys, SolidWorks, WinMachine, Compass 3D. It is obvious that the information technologies can be extremely useful for solving the problems, related to the operation, maintenance, repair and installation of equipment and devices. Thus, for example, the scientific paper [9] shows the results of studies, which allowed to reduce the financial costs significantly during performance of repair works on large-dimensioned industrial heat exchangers. Just as in the case of simulating the processes and devices, here you can use a well-known modeling and CAD systems, or develop your own software solutions, as it is done in this scientific paper.

This scientific paper shows the results of simulation of process operations, associated with the recovery of proper operation conditions for the chemical-process equipment elements during the performance of repair works.

The study was carried out by means of specially developed computational model and full-scale experiment. The duplication of solutions was required in order to ensure the reliability of results.

* Corresponding author: v44444444@gmail.com

2 Description of the task and object of study

The pipeline element, which is a part of petrochemical production network, located in a horizontal plane with a total length of about 200 m and having a Π -shape, is installed on the pipe rack, formed by a number of reinforced concrete vertical structures. The pipe with a section of 325 mm and additional thermal insulation is fixed on the elements of pipe rack only by means of its own weight. The segments of U-beam No.18 with length of 250 mm, welded longitudinally to the bottom of pipe, are used as supports for the pipeline. Taking into account that the width of web of this profile is 70 mm, and then the height of support becomes equal to 40 mm.

Thus, the technical object under consideration can be simulated according to the scheme of multi-span continuous statically indeterminate beam with annular cross section. The main load, applied to the beam is the own weight of pipeline, which, at a given arrangement of supports, is insignificant and incapable to cause significantly dangerous stresses. The operation of pipeline shows that the influence of completely different factor requires stopping of its operation and performing the repair works. The pipeline is designed for transportation of hot water vapor under the pressure. In this case, the sufficient strength is provided. The problem appears due to the influence of kinetic energy of moving steam towards the pipeline angular sections. The load can cause the offset of entire structure by shifting the pipe supports over the surface of reinforced concrete columns. In addition, the peculiarity of steam supply can lead to some fluctuation of structure and vibration.

During the operation of pipeline, it was found that under the influence of loads, this section of pipeline was shifted in the horizontal plane by about 250 mm, i.e. the length of U-support along both coordinate axes. The shift led to the fact that the supports went off the reinforced concrete elements of pipe rack, and the pipe with heat-insulating material fell on the pipe rack. It is obvious that further operation of structure in this position can lead to the destruction of heat insulation of pipeline, as well as to worse offset, up to its fall from the pipe rack.

The task is to develop the procedure for returning the pipeline onto its supports. It is not allowed to cut the pipeline, as it will require additional permits from the relevant authorities after the reinstatement during the start-up. The task is complicated by the limited area for the use of hoisting cranes. Initial version with the use of three cranes with arrows of increased length to lift the whole structure at low height was rejected.

The problems to calculate the multi-span continuous beams, in relation to the solution of similar problems, arise quite often and a lot of researchers are working on them. The multi-span beams are common, statically indefinite systems and are widely used in civil engineering, for machinery and mechanisms, navigation equipment, etc. A lot of engineers and scientists contributed to the solution of this problem by means of their scientific works, and so far this topic attracts considerable attention of researchers [10]. Fryba [11] found an accurate solution for the dynamic reactions of simple, statically determinate and statically indeterminate continuous beam under the influence of dynamic load. Kai, Cheung, and Chan studied the dynamic reactions of infinite continuous beam, loaded with an axis-moving force, using the superposition method to find an accurate solution. Due to the development of information technologies, the numerical methods are widely used for solving such problems. Jumping Pu and PengLai [12] note that among the numerical methods, the finite element method becomes an ideal approach to solve such problems.

However, even with the use of analytical methods, the use of computational models remains necessary. The design-engineering method for the continuous beams, using the equation of three moments, belongs to the group of accurate methods. As stated in [13], the calculation of continuous beams with a large number of spans becomes a technically difficult task. To solve it, it is necessary to develop a computer program. The program shall

perform calculations for each span and then integrate the results for the whole beam. These ideas are implemented in an equation in the Matlab system [13]. The scientific paper [14] is devoted to the creation of algorithm for calculating the bending stiffness of arbitrary polygonal section, including the first derivatives of stiffness with respect to all input variables.

The coordinates of cross-sectional vertices are also included in these input variables. The algorithm is generally based on dividing the cross section into trapezoids, as well as on calculating the center point, the first and the second moments of area of these trapezoids, including the partial derivatives for all input variables, and then the compilation of all these sub-results into the final result. DLL, based on this algorithm, is then used in optimization program, based on the gradient minimization method. This program is used by the authors on a practical level to optimize the given characteristics of cross section in accordance with the given criteria. In this paper, the authors propose a solution, based on the application of analytical method, using a computational model with various algorithms, including those, based on numerical methods.

Since the number of supports is limited, it is proposed to consider the lifting of each support to a height of 60-70 mm sequentially and welding of steel plate with thickness of 20 mm and length of 350 mm to the base of support so that some of its part is lying on the element of pipe rack (Fig. 1).

Fig. 1. The scheme of returning the support into its design position:

1 – a part of pipe, 2 – weld joint for fixing the support, 3 – supporting U-shaped beam, 4 – weld joint for fixing the plate to the support, 5 – plate to be welded, 6 – a part of pipe rack, w – minimum required lifting height

After completion of such activities with all supports, it is necessary to shift the whole pipeline section in the horizontal plane sequentially in the direction of both coordinate axes. At the same time, due to the flat plates, the supports can be easily moved along the surface of reinforced concrete masts.

3 Mathematical modelling of pipeline lifting

The mathematical model of proposed solution shall take into account the necessity to solve two tasks: the lifting of pipeline section for the i -th support to the required height when there is no lifting of sections for the neighboring supports; voltage control at critical points to provide the required strength.

The mathematical model of the first task is limited to the calculation of deflection at the point of concentrated force application for a multi-support continuous beam with annular cross-section, taking into account its own weight. The problem is casted in the form of system of linear equations of three moments:

$$X_{i-1} \cdot \ell_i + 2 \cdot X_i \cdot (\ell_i + \ell_{i+1}) + X_{i+1} \cdot \ell_{i+1} = -6 \cdot \left[\frac{\omega_i \cdot z_{c_i}}{\ell_i} + \frac{\omega_{i+1} \cdot z_{c_{i+1}}}{\ell_{i+1}} \right] \quad (1)$$

where X_{i-1} , X_i , X_{i+1} – internal moments, on the respective supports $i-1$, i and $i+1$;
 ℓ_i , ℓ_{i+1} – length of spans i and $i+1$; ω_i , ω_{i+1} – areas of internal bending moment areas within the spans i and $i+1$; z_{c_i} , $z_{c_{i+1}}$ – distances to the gravity centers of bending moment areas within the spans i and $i+1$.

The equations of type (1) shall be generated as many as there are intermediate supports.

The obtained system of linear equations shall be solved by means of elimination method – a special case of the Gauss method, when the coefficient matrix of system has only 3 columns. Obviously, in the case of large number of equations, as in our case, the solution without computer program becomes extremely difficult and time-consuming task.

A computational model, simulating the process of lifting the pipeline by applying the force P_j at the point of support location, has been developed (Fig. 2). The solution result is the deflection of lifted section - the section above the currently lifting support to which the plate is welded.

Fig. 2. The calculation scheme

The uniformly-distributed load with an intensity q – is the weight of linear meter of pipe (taken from the reference book). The weight of thermal insulation is neglected. The concentrated force P_j is an effort with which the lifting is performed. The support under the force P_j is not shown on the calculation scheme, because in this case it is meaningless. The simulation includes the step-by-step build-up of force P_j with simultaneous calculation of deflection at the point of P_j force application, using the Mora integrals. The process continues until the calculated deflection reaches the required value of 60-70 mm or the bearing reactions, calculated by means of equation (1), for the supports i and $i+1$ become equal to zero. At this moment begins the lifting of sections on these supports, which is unacceptable. At the end of this part of simulation, the normal bending stresses at the extreme points of dangerous section are calculated. They shall not exceed the permissible value, calculated according to the yield strength of steel grade 20, taking into account the ultimate factor of safety.

The described procedure shall be carried out $n-1$ times – according to the number of intermediate supports, starting from the support 1 and finishing with the support $n-1$. In the first and the last cases, the load is increased up to the moment of reduction the support bearing reactions to zero on the extreme supports.

The multiple calculations have to be carried out because the distances between the supports are not regular. The program itself has been developed by means of Visual Basic For Application MS Excel. This choice is due to the convenience of providing the simulation results. Each worksheet of spreadsheet includes the solution for one support. In total, $n-1$ worksheets are required. The sheet shows the bearing reactions on each support for this case, the diagrams of bending-moments in the form of dotplot, the calculated deflection under the lifted section, the maximum stress. Another sheet – zero one is used to

form the initial data. The same macro program, reading the data from the zero sheet, displays the results on the corresponding separate sheet.

The calculation of deflections of beam section is carried out after the solution (1) and by using its results separately for each span, taking into account all the given loads, using the equation (2) and the boundary conditions for the supports (3):

$$y'' = \frac{d^2 y}{dz^2} = \frac{M(z)}{EI} \quad (2)$$

$$y_{(z=0)} = 0 \quad y_{(z=L)} = 0 \quad (3)$$

where $M(z)$ – equation for the internal moment within the arbitrary section, E – modulus of elasticity of beam material, I – axial moment of section inertia, z – longitudinal coordinate of beam.

The equation (2) is a second-order differential equation and is solved by means of finite difference method with approximating the second derivative to the central difference. This leads to the necessity to solve a system of $n-1$ linear equations of type (4):

$$Y_{i-1} - 2Y_i + Y_{i+1} = \frac{q \Delta z^3}{2EI} (\ell - i - \Delta z i^2) \quad (4)$$

The system of equations under the boundary conditions of type (3) is easily solved by means of elimination method – a special case of the Gauss method. The difficulty lies in the fact that the number of equations is large – this is due to the necessity to minimize the iteration step Δz , and the calculation procedure shall be fulfilled for each beam span, taking into account the results, obtained for the previous spans.

The developed program works in a simulation mode, sequentially forming the deflection diagrams by increasing the applied load value uniformly, and the program stops after obtaining the gap on the lifted support, sufficient for welding the cover plate to it. At the same time, the program monitors the dangerous values of calculated deformations and stresses. The simulation result for each support is shown on a separate sheet of spreadsheet. The number of sheets is equal, respectively, to the number of supports to be lifted.

4 Description of the experimental study

The experiment was carried out in order to confirm the results, obtained by means of computational model. The scale of physical model is 1:19.15. For example, the main straight section with a length of 110 m is simulated by a segment of 5730 mm.

The simulated pipeline is made of steel pipe with a diameter of 325 mm and a wall thickness of 8 mm. The calculated values of material properties are chosen as for the steel grade 20.

As a model of pipeline, the water supply pipe of PN20 type, made of PP-R 80 propylene, with the outer diameter of 20 mm and the wall thickness of 3.4 mm is used, having the following properties:

- density – 915 kg/m³;
- elastic modulus – 1.15 GPa;
- yield strength – 28 MPa;
- tensile strength – 34 MPa;
- relative elongation at break – 500%.

The scaling factor was calculated according the necessity to provide the similarity of simulated object and model. The similarity shall be provided in accordance with the stiffness of objects, calculated according to the scheme of beam. At the same time, the

section stiffness of initial and simulated pipes, taking into account the elastic properties of EI material, differs significantly, since it is required to relate them to different geometrical dimensions of simulated object and model.

The bringing of stiffness to geometric dimensions is performed by calculating the similarity of deformations – the maximum deflection of a two-support beam, loaded with a uniformly distributed load.

5 Results of calculation

The calculations show that with such section stiffness of object and model, the geometrical dimensions are provided at a scale factor $m = 19.15$. This coefficient value for the chosen pipe model will provide a geometric similarity of object and model, both in stiffness and geometrical dimensions. For example, if the maximum deflection of steel pipe with a diameter of 325 mm and a length of 10 m shall be 3.99 mm, then the model, made of propylene pipe with a diameter of 20 mm should have a length of 523 mm and obtain a maximum deflection of 0.21 mm.

The deflections are measured by means of dial indicators. The lifting force is measured by an electronic dynamometer with an accuracy of up to 0.01 N. The method of electronic strain measurement is used to measure the deformations and stresses. The strain gauges, connected to a 10-channel strain gauge station, shall be installed at those points of beam, which have the greatest tensile stress due to bending. The measured signal after digitization from this gauge via RS-232 channel is transmitted to the sequential port of PC and displayed in real time on the worksheet of spreadsheet.

6 Conclusion

As a result of study, an engineering procedure to perform the repair works on the pipeline section of power-generating infrastructure at a large petrochemical enterprise, has been developed. The developed computational model allows determining the accurate application points and the values of loads, required to solve the problem. The calculations and the physical model allow keeping the degrees of safe deformations and stresses under control during the works performance. In order to prepare the requirements for installation activities, the recommendations from managers shall be used [15]. The practical result of study is the successful restoration of pipeline operability with minimum labor and financial costs. All works on repairing the pipeline can be performed during one work shift, using one crane with the extended arrow, one caterpillar tractor, crew of welders and fitters.

The study was conducted with funding from the grant of RF President № MK-417.2019.8.

References

1. N.A. Merentsov, A.V. Persidskiy, V.N. Lebedev, M.V. Topilin, A.B. Golovanchikov, Advances in Intelligent Systems and Computing, *Modelling and Calculation of Industrial Absorber Equipped with Adjustable Sectioned Mass Exchange Packing*, **983**, 560-573 (2019)
2. A.V. Dmitriev, I.A. Sabanaev, O.S. Dmitrieva, J. Eng. Phys. Thermophy., *Rigidity of the Bearing Elements of the Contact Structures of a Mass-Transfer Apparatus*, **90(3)**, 715-720 (2017)

3. A.B. Golovanchikov, N.A. Merentsov, V.A. Balashov, Chem. Pet. Eng., *Modeling and analysis of a mechanical-draft cooling tower with wire packing and drip irrigation*, **48**, 9-10, 595-601 (2013)
4. O.S. Dmitrieva, I.N. Madyshev, A.V. Dmitriev, J. Eng. Phys. Thermophy., *Determination of the Heat and Mass Transfer Efficiency at the Contact Stage of a Jet-Film Facility*, **90(3)**, 651-656 (2017)
5. A.B. Golovanchikov, N.A. Merentsov, Advances in Intelligent Systems and Computing, *Modelling of Absorption Process in a Column with Diffused Flow Structure in Liquid Phase*, **983**, 635-644 (2019)
6. A.V. Dmitriev, O.S. Dmitrieva, I.N. Madyshev, Chem. Pet. Eng., *Optimal Designing of Mass Transfer Apparatuses with Jet-Film Contact Devices*, **53**, 7-8, 430-434 (2017)
7. O.S. Dmitrieva, A.V. Dmitriev, A.N. Nikolaev, Chem. Pet. Eng., *Distribution of circulating water in the work area of a vortex chamber with disk atomizer for the purpose of increasing the efficiency of the cooling process*, **50**, 3-4, 169-175 (2014)
8. O.S. Dmitrieva, A.V. Dmitriev, I.N. Madyshev, A.N. Nikolaev, Chem. Pet. Eng., *Flow dynamics of mass exchangers with jet-bubbling contact devices*, **53**, 1-2, 130-134 (2017)
9. D.V. Kozlyakov, I.A. Sabanaev, F.M. Almakaeva, *The use of CAD tools in the design of the dismantling unit at the site of dehydrogenation of butane*, Bulletin of the Technology University, **18**, 199-202 (2015)
10. A. Yavari, M. Nouri, M. Mofid, Advances in Engineering Software, *Discrete Element Analysis of Dynamic Response of Timoshenko Beams under Moving Mass*, **33**, 143, (2002)
11. L. Fryba, Workshop Bridges for High-Speed Railways, Faculty of Engineering, University of Porto, Porto, 137, (2004)
12. Junping Pu, Peng Liu, Engineering, *Numerical Calculation of Dynamic Response for Multi-Span Non-Uniform Beam Subjected to Moving Mass with Friction*, **2**, 367, (2010)
13. *The Three-Moment Equation for Continuous-Beam Analysis*, CEE 201L. Uncertainty, Design, and Optimization Department of Civil and Environmental Engineering Duke University, Henri P. Gavin, Spring, <http://people.duke.edu/~hpgavin/cee201/three-moment.pdf>, (2009)
14. J. Venclovský and P. Stepanek, Solid State Phenomena, *Calculation of Bending Stiffness and its First Derivatives Related to Optimization of a Steel-Reinforced Concrete Cross Section*, **249**, 253 (2016)
15. Correia M., Perneta H., Salta M., *Maintenance and repair of transport infrastructures – Technical guide. Part III – Steel structures. Vol. 4 – Repair methods*. (DURATINET project – WG A4. Lisbon: LNEC, (2012)