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# Predictive model of the trunk oil pipeline technological section on the basis of results of transient conditions test

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**Abstract.** The paper deals with the problem of predicting the hydraulic parameters of the trunk oil pipeline (TOP) in transient operating practice. The requirements and assumptions for the model of the trunk oil pipeline are discussed. The basic differential equations describing hydraulic processes in the linear part of the TOP and pumping units are given. The paper analyzes the features of building models of trunk oil pipelines using the *Matlab / SimHydraulics* tool. As a result, a method for modifying standard *Matlab / SimHydraulics* tools for building TOP models was proposed. The TOP model "Omsk - Anzhero-Sudzhensk" was built using the modified features of the *Matlab / SimHydraulics* tool. A model quality criterion is proposed. Comparison of the results obtained in the TOP modeling with measurement data revealed the need to further adjust the model. Using optimization algorithms embedded in the *Matlab* package, the unknown parameters of the trunk oil pipeline model were adjusted according to the test of transient operating practice using the selected quality criterion.

## 1. Introduction

Continuous development of pipeline transport technologies, increasing requirements for energy efficiency and safety of operating the trunk oil pipeline cause an increase in the arsenal of tools and procedures for forecasting and management. Nowadays the creation of systems for monitoring and managing the processes in an oil pipeline is impossible without involving the apparatus of mathematical modelling of the control object, which takes into account its key features: distributed nature, uncertainty of parameters, etc.

Mathematical models of the processes occurring in the *trunk oil pipeline* (TOP) are needed to calculate the optimal modes and parameters of operation of process equipment, to develop protection systems and implement effective management of technological processes. Models make it possible to decrease the number of experiments on a working pipeline, which are often impossible to carry out due to their danger and high cost.

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Many phenomena in the pipeline can only be described in terms of dynamic models: the phenomenon of resonance, the propagation of pressure waves, water hammer. The lack of predictive models to detect these phenomena can lead to an unplanned stop and damage of equipment.

Particular models of fluid movement in the pipe can be developed using *computational fluid dynamics* (CFD) approach [1]. The main disadvantage of the approach is that it demands rather full information about physical parameters of the oil, explicit knowledge on pipeline geometry. This information is either unknown or not precise. Consequently, in practice the approach to describing processes in a pipeline in terms of dynamic models is not always used. Thus, during the use of the trunk oil pipeline by the “Transneft - Western Siberia” Joint-Stock Company, models are used in which the movement of oil and oil products is regarded as steady. On the basis of this assumption, the estimated throughput, pumping modes and other parameters are determined. However, during the operation of equipment, as a rule, 1-2 times a day there is a transition from one mode to another, which entails unsteady processes of fluid flow for several hours.

The paper considers one of the methods for building models of hydrodynamic processes in an oil pipeline using SimHydraulics - a modelling tool for hydraulic systems included in the Mat-lab package toolkit. The basic principles of building models in the selected package as well as the possibilities of their adjustment according to the measurement data of technological variables in transient modes are discussed.

## 2. Requirements for mathematical models and computational algorithms

Mathematical models of transitional (unsteady) modes in the oil pipeline must meet the following criteria:

- work in real time;
- meet the accuracy requirements of the forecast;
- have a relative ease of construction and configuration;
- correctly consider the boundary conditions;
- have the ability to be embedded into a unified system of dispatch control and management.

To build a mathematical model that meets the listed requirements, the Matlab application software package was chosen. This package is widely used in solving scientific and engineering problems; it is compatible with most operating systems and platforms for real-time computing [2].

The Matlab package implements an extensive functional for solving differential equations, including partial derivatives. This feature was used in the work to build a model of unsteady fluid flow in an oil pipeline.

The package provides the user with the opportunity to choose a numerical method for integrating differential equations. In the instrument under consideration, a set of numerical methods for solving equations, such as Newton's method, Runge-Kutta method, etc., is implemented.

## 3. Mathematical model of unsteady flow of oil in the pipeline

Transient operating modes of the trunk oil pipeline occur when starting and stopping the pumping, switching the taps on and off, shut-off and control equipment operation, as well as during various accidents, for example, pipe breaks and blockages. Pressure waves propagate along a section of the pipeline during transient operating modes, and the flow rate of oil in different sections of a pipeline with a constant diameter can take on different values.

Unsteady flows when the pipeline is completely filled with liquid are described by partial differential equations [3]:

$$\begin{cases} \dfrac{\partial p(x,t)}{\partial t} + \rho_0 c^2 \dfrac{\partial v(x,t)}{\partial x} = 0, \\ \rho_0 \dfrac{\partial v(x,t)}{\partial t} + \dfrac{\partial p(x,t)}{\partial x} + \lambda(\mathrm{Re},\varepsilon) \cdot \dfrac{1}{d} \cdot \dfrac{\rho_0 v(x,t)}{2} - \rho_0 g \cdot \sin\alpha(x) = 0, \end{cases} \tag{1}$$

where $p(x,t)$ is pressure; $v(x,t)$ is fluid flow rate; $\rho_0$ is fluid density; $d$ is the diameter of the pipeline; $c$ is sound velocity in the pipeline; $g$ is acceleration of gravity; $\alpha(x)$ is the angle of inclination of the pipeline axis to the horizon in cross section $x$; Re is Reynolds coefficient; $\varepsilon$ is relative pipe roughness; $\lambda$ is hydraulic resistance coefficient.

System (1) is a simplified mathematical description of processes in a pipeline section (one of the versions of the Navier-Stokes equations), which is based on numerous assumptions, such as linearization or immutability of key parameters. However, such a description seems to be quite sufficient for the express forecast of processes in the main pipeline.

It should be noted that when simulating transient modes for the oil pipeline section, it is necessary to take into account the compressibility effect of the “oil + pipe” system and the inertial properties of the flow. Oil itself has a low compressibility factor; however, the associated gas dissolved in oil can significantly increase it. A much greater effect on the properties of this system is produced by the deformation of the pipe under pressure, which in fact determines its compressibility characteristics. The total elasticity of the system is indirectly set by the parameter c in the given system of equations.

The system of differential equations (1) is solved under the initial conditions that characterize the distribution of pressure $p(x,0)$ and flow velocity $v(x,0)$ at the initial time $t=0$; boundary conditions, reflecting processes at the ends $x=0$ and $x=L$ of the pipeline, as well as interface conditions [4].

The oil in the pipeline is driven by the mainline pump assemblies (MPAs), which are, as a rule, high-performance centrifugal pumps with electric drive. The characteristics of centrifugal pumps, such as head, flow, efficiency, are usually represented by quadratic approximations [2]. The flow-pressure characteristic of *Q-H* and the characteristic of efficiency $\eta(Q)$ for mainline pumps are respectively presented by the formulas:

$$p=\left(H_0+a\cdot Q-b\cdot Q^2\right)\cdot\frac{\omega}{\omega_{ном}}\cdot\rho g\ , \tag{2}$$

$$\eta=\left(c_0+c_1\cdot Q+c_2\cdot Q^2\right)\frac{\omega}{\omega_{nom}}, \tag{3}$$

where $p$, $\eta$ are pump pressure and efficiency during flow *Q*; $H_0$, $a$, $b$, $c_0$, $c_1$, $c_2$ are empirical approximation coefficients of the pump; $\omega, \omega_{nom}$ are current and nominal shaft speed, respectively. Pumping and flow rate of the fluid are related by the following equation [3], [4]:

$$\upsilon=\frac{4Q}{\pi d^2}\ . \tag{4}$$

Equations of the form (2) are an example of boundary conditions for the system of equations (1). Their physical meaning lies, for example, in the influence of turning on or off the pump on the process of changing the oil flow in the linear part of the pipeline.

## 4. Building a model of the trunk oil pipeline in the Matlab / SimHydraulics software

In the publications [5] - [8] the possibility of building dynamic models of hydraulic systems for various purposes in the Matlab / SimHydraulics package was justified. However, the models of trunk oil pipelines implemented in this package have not been previously described anywhere in open sources.

The hydraulic system model in Matlab / SimHydraulics is a system of interconnected graphic objects, the selection and connection of which with each other is made by the user through a special graphic interface. The blocks are aligned with various hydraulic elements: pipes, valves, tees, pumps, etc. The set of interconnected blocks is interpreted by the package and is presented in the form of a computational algorithm for solving the corresponding difference equation system describing hydraulic processes in an equivalent pipeline.

A custom made block is used to describe the unsteady fluid flow in the pipeline in SimHydraulics. This block displays the model of the pipeline section, which is a discrete analogue of the system of equations (1). The set length of the section together with the number of segments in it determines the

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discreteness of the difference model along the coordinate. Accordingly, the wave propagation velocity in the model which depends directly on the relationship may deviate from the true value. In addition, the standard interface features of the block do not allow access to model variables with coordinates that lie "inside" the section, that is, for x not on its borders.

Thus, in the standard block implementation there is no possibility of tracking the current values of model variables (pressure and flow rate) from the coordinate of the pipeline section, as well as the functional of setting the wave propagation velocity. In [5], ways to overcome these limitations were discussed. As a result, the authors of the paper proposed a custom block, in which this flaw was eliminated.

The boundary conditions of the problem can be set using standard blocks — sources of constant pressure, flow - or blocks that are reservoir models. Also, boundary conditions are set by pump models represented by another self-made block. The disadvantage of the standard version of the block is the impossibility of setting the pump efficiency characteristic in the model for calculating its energy consumption. This paper proposes a modified model of a centrifugal pump developed by the authors that allows calculating and recording the current values of efficiency and head in accordance with relations (2) and (3). Additionally, a block implementing the serial connection of four pumps for a model representation of an *oil pumping station* (OPS) has been created.

The modified and new blocks were later used to build a model of the technological section of the trunk oil pipeline.

## 5. Model of the oil pipeline "Omsk - Anzhero-Sudzhensk"

The processes were modelled for the Omsk - Anzhero-Sudzhensk trunk pipeline section. The results of transient conditions tests on the indicated trunk oil pipeline with measured values of pressure at certain points over time were used as initial data. Additional information on the elevations at the points of installation of pressure sensors, the hydraulic characteristics of the main and supporting mainline pumps, and the number of pumps at each pump station was available.

The model was implemented in Matlab / SimHydraulics environment. A graphic representation of a single subsection within the Omsk - Anzhero-Sudzhensk trunk oil pipeline is shown in figure 1.

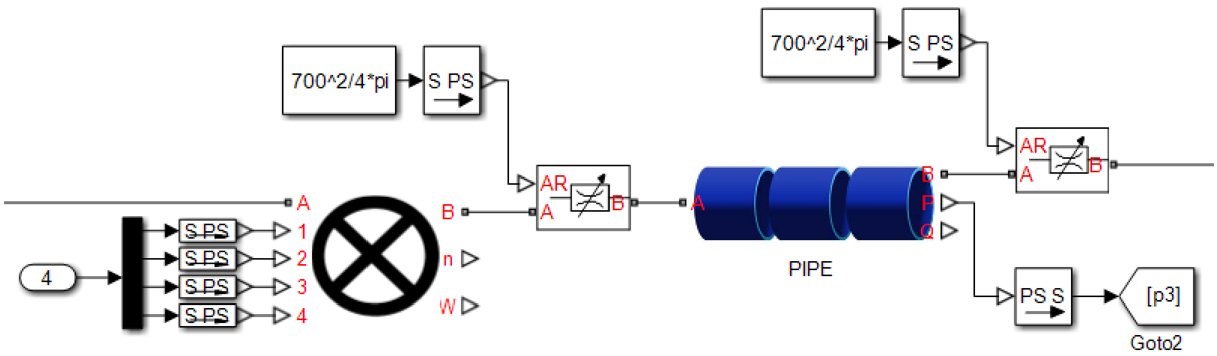


**Figure 1.** Subsection of the pipeline "Omsk - Anzhero-Sudzhensk" model in Matlab / SimHydraulics.

The model consists of alternating OPS blocks of the linear part of the pipeline, separated by blocks that imitate gate valves. Four control lines are connected to the block of each OPS to give signals on or off the pumps. The linear part of the pipeline is equipped with an interface for issuing a vector signal containing the information about the instantaneous values of the pressure profile. Modified blocks in which the most significant shortcomings of the standard blocks were eliminated were used in building the model.

The pipeline model was set up in stages. At the first stage an initial simulation model was created on the basis of the available a priori information about the technological section, including geometric, height characteristics, physical parameters of the pipeline, rheological characteristics of oil, parameters of pumping and locking-control equipment.

Further, a qualitative comparison of the response of the original model with the measurement data obtained during testing of unsteady operating practice was made. As a result, a discrepancy between the model response and measurement data was found (figure 2).

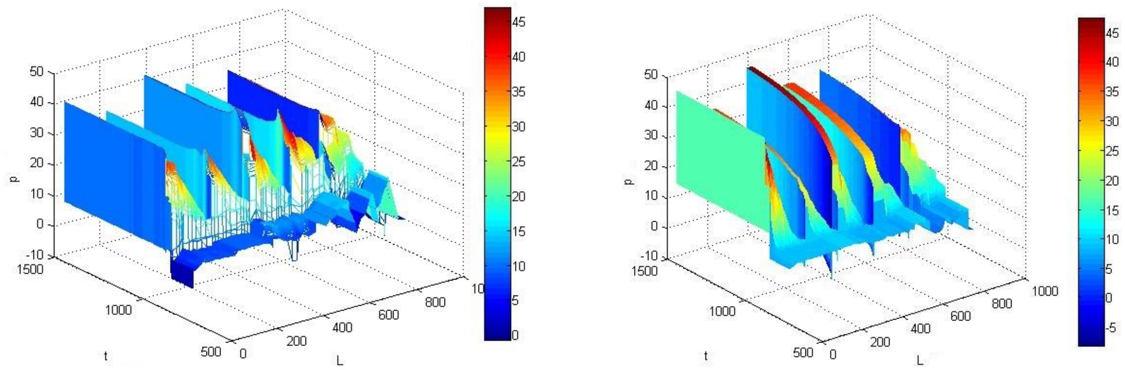


**Figure 2.** Dependencies of measured and calculated pressures: the measured dependence of pressures on the coordinate and time and the modeled dependence of pressures on the coordinate and time.

Analyzing the dependences presented in figure 2, one can observe the inconsistency of the qualitative representation of the functioning of the original simulation model in comparison with the measured pressure values in the transient mode. The main qualitative difference lies in the inadequacy of the model responses related to the nature of the resulting model damping. An assumption about the inaccuracy of the elasticity indicators calculation in the model of the "oil + pipe" system was made. The correction to the first equation of system (1), namely, the introduction of a correction weighting factor *a* was proposed as a means of solving the revealed problem:

$$\frac{\partial p(x,t)}{\partial t} a + \rho_0 c^2 \frac{\partial v(x,t)}{\partial x} = 0 , \tag{5}$$

Changing the balance between the terms in equation (5), this coefficient allows influencing the quality of the model and its adequacy in describing the hydraulic processes in the pipeline.

The next step in building the model was its optimization using the quality criterion with respect to the unknown parameter *a*. The relative error of the model response was taken as a criterion in the following form:

$$\varepsilon_p = \frac{1}{MN} \sum_{j=1}^{M} \sum_{i=1}^{N} \left| \frac{p_{pij}(a) - p_{uij}}{p_{\max}} \right| \cdot 100\% \to \min_a , \tag{6}$$

where $p_{pij}$ is calculated pressure corresponding to *j*-th section at the *i*-th moment of time; $p_{uij}$ is measured pressure corresponding to *j*-th section at the *i*-th moment of time; $p_{\max}$ is maximum measured pressure; $M$ is the number of sensors installed on the linear sections of the pipeline; $N$ is the number of time intervals.

The model was optimized using the algorithms built into the *Matlab* package. In particular, the internal point method and search optimization methods showed good results. The non-decreasing of the objective function within the specified tolerance value was chosen as a criterion for stopping the optimization algorithm.

The measured pressures on the linear part of the Omsk - Anzhero-Sudzhensk pipeline for March 30, 2015 were used as the initial data for optimization in the process of setting up and verifying the model.

The data corresponded to the transient mode (start of the trunk oil pipeline with the series switching on of oil pumping stations).

The calculated pressure values obtained using the optimized model and the corresponding measured values demonstrate a qualitative similarity in the process of analyzing the dependence of pressure on the coordinate and time. The value of the quality criterion calculated in accordance with the relation (6) was $\varepsilon_p = 7,8\%$.

The optimal model was verified on measured data for another transient mode to test its work. Thus, the model was tuned to the data of one transient mode (training sample), and its predictive accuracy was tested on the data of another mode (test sample). The selected test mode for model verification corresponded to the sequential shutdown of pumping stations as of 03/06/2015 at the same technological section of the trunk oil pipeline.

The value of the criterion (6) when comparing the model and the measured pressure values was $\varepsilon_p = 9\%$ which is a good indicator of the model quality for the transient mode according to expert technologists and allows judging the correctness of the chosen approach to building models of transient processes in the trunk oil pipeline.

## 6. Conclusion

The paper shows the possibility of building a model of unsteady processes in the trunk oil pipeline using the Matlab engineering calculations package and its tool for building models of hydraulic processes SimHydraulics. SimHydraulics tools have been modified to take into account the specifics of the processes in the trunk oil pipeline.

The paper paid greatest attention to setting up and verifying the models obtained. A quality criterion and a model optimization procedure are proposed. A model for the pressure measurements data in the implementation of transient modes on the section "Omsk - Anzhero-Sudzhensk" was built and the quality of the model constructed was evaluated. The relative deviation of the measured data and the data predicted using the model is 7.8–9%.

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## References

[1] Anderson John D 1995 *Computational fluid dynamics: the basics with applications* (New York: McGraw-Hill) p 547
[2] SimulinkTheMathWorks, inc. http://Matlab.ru/products/simulink
[3] Lourier M V 2003 *Mathematical modeling of the processes in oil, fuel and gas pipeline transport* (Moscow: Oil and gas) p 336
[4] Weinstock S M 2012 *Pipeline transport of oil* **1** (Moscow: Nedra-Business Center) p 406
[5] Mironov A G, Agafonov E D and Bezborodov Yu N 2015 Consideration of the velocity of propagation of pressure waves in simulating unsteady processes using Matlab / SimHydraulics *Vestnik of IrSTU* **3** 12–8
[6] Himr D 2013 Numerical simulation of water hammer in low pressurized pipe: comparison of SimHydraulics and Lax-Wendroff method with experiment *EPJ Web of Conferences*
[7] Hruzik L, Burecek A and Vasina M 2014 Non-stationary flow of hydraulic oil in long pipe *EPJ Web of Conferences*
[8] Hruzik L, Burecek A and Vasina M 2017 Effect of oil viscosity on pulsating flow in pipe *Mechanisms and Machine Science* **44** 137-43