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Modeling Unsteady Processes in a Main Oil Pipeline under Conditions of Uncertainty

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Abstract: - This article explores the development of a model for technological processes in an oil trunk pipeline that operates in uncertain conditions. When considering technical modes, the major oil pipeline is considered as a complicated system with an adjustable structure and variable characteristics. A mathematical model that describes the temporary changes in the oil pipeline that happen when pumping begins or ends, when taps are turned on or off, when shut-off and control valves are operated, and during incidents such as pipe ruptures and blockages. The analysis focuses on the dynamic variations in pressure and flow within the pipeline as key factors in the oil flow. The Matlab/SimHydraulics program is used to calculate the state of the pipeline in terms of its fundamental distributed parameters and under non-stationary operation conditions. Subsequently, the suggested methodology is implemented to address the issue of modeling dynamic processes in the segment of the primary oil pipeline. Therefore, the knowledge acquired by constructing non-stationary (dynamic) models in the pipeline can be utilized to enhance the effectiveness of forecasting and control systems when operating the primary oil pipeline.

Keywords: Main oil pipeline, monitoring and control system, pressure and flow, unsteady processes.

I. Introduction

The operation of intricate technical facilities, such as the primary oil pipeline, has a complex relationship to the necessity of addressing the challenges of monitoring and predicting technological parameters in order to effectively regulate, optimize operational modes, guarantee seamless, environmentally friendly functioning, and conserve resources. To solve these objectives, it is necessary to upgrade the control system of technological parameters. This upgrade should focus on assuring the dependability of the parameters by employing advanced methods and tools for collecting, processing, and evaluating the information. Various developments in world practice focus on addressing different tasks related to the creation of monitoring and control systems in mainline pipeline transport. These tasks include evaluating the reliability of oil product supplies [1], detecting defects in assessing technical condition [2], analyzing the dynamics of corrosion processes [3], predicting hydraulic characteristics of flows [4], [5], hydraulic machines [6], and determining the design position of structures [7], etc.

Leakages in pipeline networks are a significant factor contributing to immeasurable losses for both pipeline operators and the environment. These leaks have the potential to result in severe environmental catastrophes, human fatalities, and financial setbacks. In recent decades, various techniques have been suggested to identify leaks in pipelines, employing diverse operational ideas and approaches. The current methods for detecting leaks include: acoustic emission [8]-[10], fiber optic sensor [11]-[13], ground penetration radar [14], [15], negative pressure wave [16]-[18], pressure point analysis [19]-[21], dynamic modeling [22], [23], vapor sampling, infrared thermography, digital signal processing, and the balance of mass and volume [24]-[28].

The main oil pipeline's characteristics, which include its complexity, distributed nature, potential for hazard, and significance to the national economy and the oil and gas industry's overall structure, determine the applicability of this kind of research [29]. The calculation and planning of technical modes, along with the monitoring of ongoing processes in the pipeline, play a crucial role in enhancing the efficiency of dispatching control and management.

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These activities are of great significance in both the theoretical development and practical implementation of this field.

The decision-making process during the operation of the main oil pipeline relies on comparing intended (forecasted) and actual (measured) values of various technological characteristics such as pressure, temperature, vibration indicators, and others. Technological process models are currently under active development to forecast the values of technological parameters in dispatch control and management systems. The existing methods and procedures for constructing models of technological processes in the main oil pipeline do not fully utilize the available information about the object and fail to account for its variability due to unknown or unaccounted factors. This adversely affects the precision of predicting the progression of technological procedures, and consequently, the appropriateness of judgments made in the operation of oil pipeline equipment.

The robust approach is one of the strategies used to develop models of technological processes in uncertain settings. This method primarily considers the inherent uncertainty and variability of genuine physical systems and their surrounding conditions. It acknowledges that these systems cannot be precisely described, since they may experience unforeseen changes and be affected by various disturbances. The robust technique aims to ensure the desired quality even in the presence of faults and changes in model parameters [30-32].

An algorithmic and software-technical support is crucial for effectively addressing practical challenges in monitoring technological parameters. This support enables real-time prediction of transient (unsteady) modes of operation in an oil pipeline [29]. Existing techniques for creating models and specialized software typically lack a balance between cost, accuracy, and speed. As a result, these algorithmic and software solutions are not in high demand or have limited applicability in oil pipeline transport firms.

Hence, it is crucial to devise novel techniques and algorithms to effectively utilize adaptive and simulation approaches for signal processing in pipeline controls, especially in uncertain conditions. Additionally, it is important to construct models of dynamic processes that occur in the primary oil pipeline. The established approaches and algorithms have a significant benefit in providing a comprehensive understanding of the object by considering both its stochastic and multi-connected characteristics.

This study aims to propose an alternate method for developing dynamic distributed models using the Matlab/SimHydraulics program [33]. The presence of uncertainties and unaccounted-for components hinders the straightforward construction of models using pre-existing modules, necessitating the inclusion of extra model configurations. Consequently, the resulting model no longer provided a comprehensive description of hydraulic processes using individual models. Instead, it became a macro-level model that underwent modifications by adjusting important parameters, typically resulting in a revised version of the model [29].

The article is structured in the following manner. Section 2 examines the main oil pipeline, which is regarded as an intricate system with an adjustable structure and variable characteristics. The text presents a mathematical explanation of dynamic processes in oil pipeline transportation and explores the potential for modeling nonstationary hydrodynamic regimes using the Matlab/SimHydraulics software package. Section 3 addresses the resolution of the issue of representing fluctuating processes in a main oil pipeline using the software mentioned in section 2. The efficacy of the proposed methodology is validated by the outcomes of simulating the system under investigation. Section 4 provides a concise summary of the key findings and implications of this article, as well as suggestions for further investigation.

II. Research Methods

When analyzing the primary oil pipeline within the context of technical modes, it is advantageous to conceptualize it as a sophisticated system with an adjustable structure and dynamic parameters. Let us examine a diagram illustrating the input and output parameters of the primary oil pipeline (Fig. 1), [29].

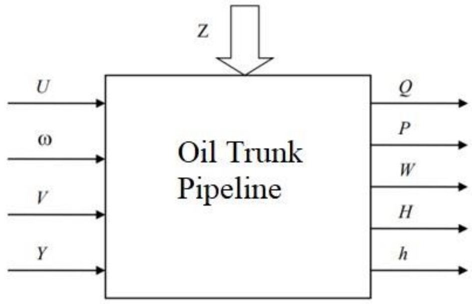


Fig. 1. Diagram illustrating the input and output parameters of the primary oil pipeline.

The system under investigation has two input parameters: U, which represents commands to turn on/off pumping units situated at oil pumping stations, and ω, which represents the setting for the pump speed at the pump station. V - commands, used to operate the secant valves that are fitted on linear sections. These commands can be used to open or close the valves. Y refers to the physical qualities of the pumped oil, including density and viscosity, which are determined through laboratory examination. When considering the technological process (Z), it is important to take into account additional aspects such as the variable configuration of the pipeline network, the types of pumps being used, and the alternatives for their activation. Environmental characteristics, such as ambient air or ground temperature, should also be considered. Additionally, there are intangible aspects that cannot be directly observed, such as the technical state of the equipment and the impact of deposits in the pipeline. The system's output parameters consist of two variables: Q, which represents the oil pumping capacity, and P, which represents the pressure values at specific points along the main oil pipeline. W represents the amount of power used by pumping units, H represents the pressure produced by oil pumping stations, and h represents the pressure decrease in linear sections.

Unsteady processes in an oil pipeline refer to situations when the properties of the oil flow vary not only across different sections of the pipeline, but also within each section over time. Among the varying attributes, it is essential to mention the pressure change process $p = p(x,t)$ and the flow rate $Q = Q(X,t)$ in the pipeline, which are expressed as functions of two variables: time t and the coordinates of the section x. Unsteady phenomena in pipelines occur at the initiation and cessation of pumping, the activation and deactivation of taps, the functioning of shut-off and control valves, as well as in other incidents such as pipe ruptures and obstructions.

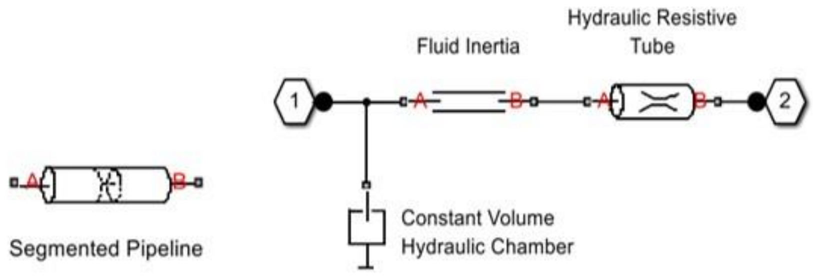
Partial differential equations [29] are used to represent unsteady flows in pipelines packed with weakly compressible liquids, such as oil and petroleum products:

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

where $p(x,t)$ is the pressure; $v(x,t)$ is the velocity of the liquid flow; ρ_0 is the density of the liquid; c is the velocity of sound propagation in the pipeline; g is the acceleration of gravity; $\alpha(x)$ is the angle of inclination of the pipeline axis to the horizon in section x . The system of differential equations (1) is solved under initial conditions characterizing the distribution of pressure $p(x,0)$ and flow velocity $v(x,0)$ at the initial moment of time $t = 0$; boundary conditions reflecting the processes at the ends $x = 0$ and $x = L$ of the pipeline, as well as interface conditions.

The hydraulic system model in Matlab/SimHydraulics consists of interconnected graphical elements that the user selects and connects to each other using a specialized graphical interface. The blocks are arranged in alignment with a variety of hydraulic components, including pipes, valves, tees, pumps, and so on. The package interprets the collection of interconnected blocks and presents it as a computational technique for solving the system of equations that describe the processes in the hydraulic circuit.

The SimHydraulics program incorporates differential equations of the form (1) into the model generated by visual modeling tools [36]. The basic Segmented_Pipeline block in SimHydraulics is utilized to depict the dynamic flow of liquid in a pipe segment (Figure 2a). A block is comprised of multiple segments, with each segment containing a group of blocks. The components mentioned are the Hydraulic_Resistive_Tube, Fluid_Inertia, and Constant_Volume_Hydraulic_Chamber, as shown in Fig. 2b [37].



a) b)

Fig. 2. Figure (a) depicts a visual depiction of the Segmented_Pipeline standard block, and Figure (b) shows a diagram that represents the segment included within it.

In order to enhance the stability of the computational process, the Segmented_Pipeline block incorporates two more blocks, namely the Hydraulic_Resistive_Tube and Fluid_Inertia, which are added sequentially to the existing sequence of similar segments (as seen in Fig. 2b). The Segmented_Pipeline standard block's structure is formed by these components (Fig. 3).

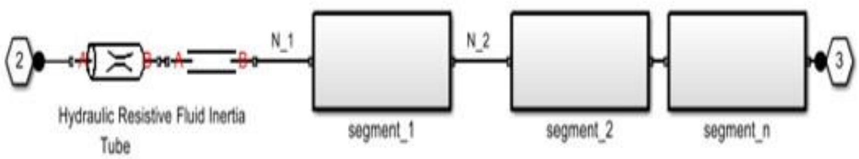


Fig. 3. Equivalent diagram of the Segmented_Pipeline block

The Hydraulic_Resistive_Tube block incorporates the pressure decrease caused by hydraulic resistance. The formulas from reference [29] are utilized to calculate the coefficient of hydraulic resistance in this scenario.

The Fluid_Inertia block characterizes the inertial characteristics of a liquid based on the ratio [37]:

$$p = \rho \frac{L}{A} \cdot \frac{dQ}{dt},$$

(2)

where p is the pressure difference in the initial and final sections of the pipeline segment; L is the length of the pipe segment; Q is the volume flow rate; p is the density of the liquid; A is the cross–sectional area of the pipeline; t is the time.

The Constant_Volume_Hydraulic_Chamber block considers the compressibility of the liquid and its related impacts based on the ratios [37].

$$\begin{cases} V_f = V_c + \frac{V_c}{E} p, \\ q = \frac{dV_f}{dt}. \end{cases}$$

(3)

where V_f is the volume of liquid in the pipe; V_c is the geometric volume of the pipe; E is the volumetric modulus of elasticity. If the pressure value computed using the model is negative, it indicates the presence of a mixture of liquid and gas instead of only liquid. The volumetric modulus of elasticity in equation (3) can be determined as follows [37]:

$$E = E_l \frac{1+\alpha\left(\frac{p_a}{p_a+p}\right)^{1/n}}{1+\alpha\frac{P_a^{1/n}}{n(p_a+p)^{n+1/n}}E_l},$$

(4)

where E_l is the volumetric modulus of a pure liquid; n is the ratio of heat capacities; and p is atmospheric pressure.

The Constant_Volume_Hydraulic_Chamber block takes into account the pipe's deformation at high pressures by utilizing the ratios [37].

$$V_c = \frac{\pi d^2}{4} \cdot L,\ d(s) = \frac{K_p}{1+\tau s} p(s),$$

(5)

where K_p is the Young's modulus of the pipe material.

III. Results And Discussion

We are going to look at one approach to solve the problem of modeling unsteady processes in a trunk oil pipeline. Here are the details we need to use to build a model of a pipeline section: L = 2000 м, D = 500 мм, δ = 7 мм, density = 850 кг/м3, and viscosity = 25 cSt. At first, the liquid was at rest, and it was thought that the pressure in the widest and narrowest parts of the tunnel was the same, at 3 bar. Then, at the start of the tunnel, the pressure rises slowly. Sliced_Pipeline is what we use to build the model (Fig. 4).

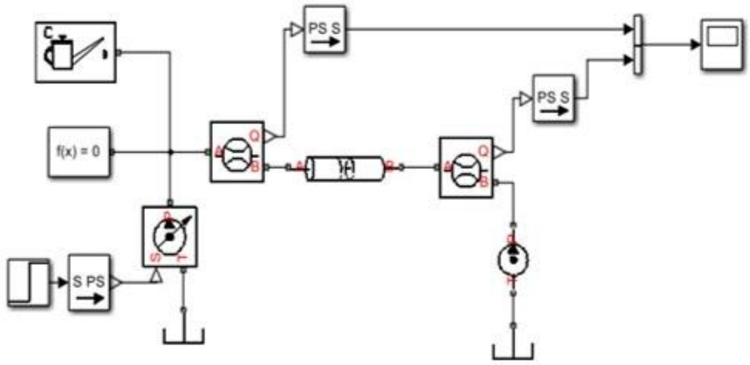


Fig. 4. Model of the pipeline section

Fig. 5 [33] shows how the flow rate changes over time in the first and last parts of the pipeline based on the results of building the model.

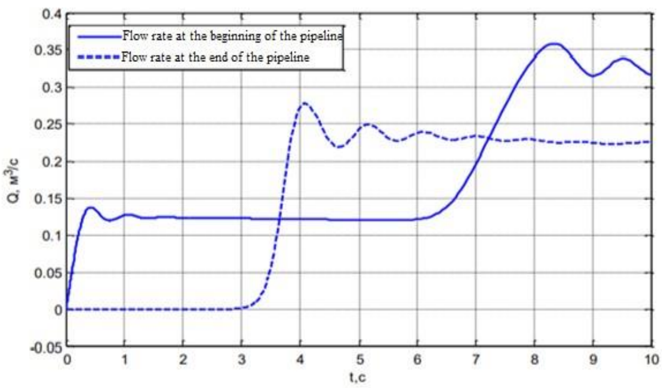


Fig. 5. Temporal variation of the flow rate in the starting and ending segments of the pipeline section

Let's suggest two changes to the Segmented_Pipeline block that was explained. The first one has to do with making the calculation method for pipe deformation better. The formula [38] is used to figure out how much the pipe has changed shape in the calculation methods:

$$\Delta d = \frac{d_0^2}{2E\delta}(p_1 - p_0),$$

(6)

where d_0 is the inner diameter of the pipe; $(p_1 - p_0)$ is the difference between internal and external pressures; E is the Young's modulus of the pipe material; δ is the wall thickness of the pipe.

Let’s modify the Constant_Volume_Hydraulic_Chamber block to incorporate the calculation of pipe deformation based on pressure as described in equation (6). Fig. 6 displays the representation of the newly introduced My_Chamber block, replacing the previous Constant_Volume_Hydraulic_Chamber.

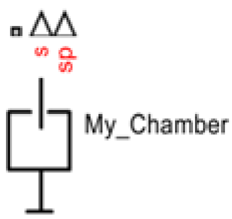


Fig. 6. My_Chamber block

Fig. 7 illustrates an instance of including the impact of changing the inner diameter of a pipeline based on pressure in a model utilizing the My_Chamber block. When applying conventional blocks, the model's features allow for the adjustment of the propagation period of disturbance waves. This refers to the duration it takes for a wave to travel a distance equivalent to the length of the pipe section. Nevertheless, varying the values of this parameter in the model did not yield a satisfactory outcome [33]. By utilizing the redesigned My_Chamber block, it becomes possible to rectify the description of deformation processes in the pipe segment model, hence eliminating this drawback [36].

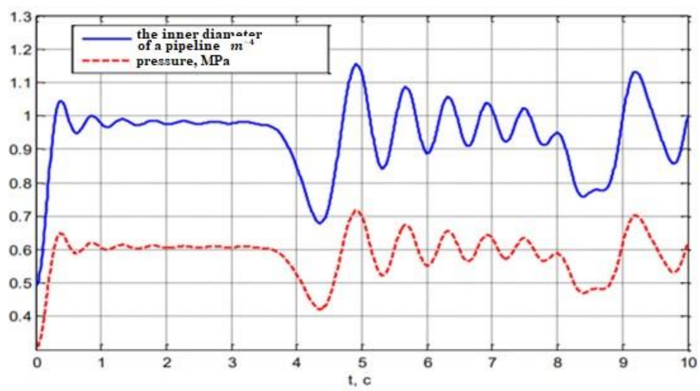


Fig. 7. The simulation results which depict the variation in the inner diameter of the pipeline section as a function of the operating pressure.

Consequently, specific guidelines have been formulated for utilizing and customizing the MATLAB/SimHydraulics software package in order to construct a prognostic model for operations in a main oil pipeline. This includes building the model using measured data of technological variables. The generated model can be incorporated into the algorithmic and software tools used for accurately predicting the flow of dynamic processes in the technological portion of the major oil pipeline.

IV. CONCLUSION

This article demonstrates the use of simulation modeling to analyze dynamic processes in an oil trunk pipeline using the Matlab/SimHydraulics package. The research aims to develop efficient calculation algorithms for anticipating technical modes in the dynamic operation of an oil pipeline utilizing novel modeling methodologies. This can greatly expedite the process of constructing models and enhance the accuracy of predicting crucial technological characteristics, such as the power consumption of pumping units. We are examining a mathematical model that describes unsteady dynamics in pipelines using partial differential equations. This text presents the capabilities of the Matlab/SimHydraulics software tool for simulating nonstationary hydrodynamic regimes. The building of the proposed model for the technological component is carried out utilizing a modified specialist software tool. Therefore, the concepts of the identification approach are integrated with the simulation technology of constructing models. Consequently, it is feasible to construct models of intricate and expandable pipeline networks.

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