Operating Modes Management of Oil and Oil Produkt Transport Systems Pipeline According to Acceptable Risk-Based Criterion

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Abstract. The paper discusses the solution to the problem of advanced risk management of oil and petroleum product pipeline systems (PS) based on calculating the level of stress-strain state of pipeline structures and reducing safety factors depending on the magnitude, rate, and frequency of pressure changes in the PS. The operating modes of some pipeline systems are characterized by unstaidness, accompanied by an increased level and frequent changes in the pipe wall stresses and, as a result, increased accident risks. The pipeline systems operating in an unsteady mode include the main oil and petroleum product pipelines (MP), characterized by very long distances. In this case, possible damages to the linear MP parts cause significant loss. Therefore, despite the high reliability of these structures, maintaining an acceptable level of safety margins and the risk of accidents is a rather urgent problem. The risks of accidents are calculated using models linking the process parameters of the PS operating modes and their design characteristics with the permissible stresses in the pipe wall and the pipeline valve installation places.

1. Introduction
The application of scientific and technical achievements in pipeline transport has brought certain positive results in ensuring the safe and efficient operation of pipeline systems. The pipeline system failures due to pipe corrosion and some other defects have been reduced. Herewith, failures caused by high stresses have not reduced, which are often accompanied by the pipe wall rupture and the release of the pumped product into the environment. New pipelines with severe operating conditions are being laid in areas with an increased mutual impact between pipeline systems and the environment. Also, at some facilities, process parameters of operating modes deviate from the design ones, leading to increased pipeline loads and, consequently, reduced safety margins and the increased risk of accidents.
The oil and gas industry pipeline system operating in the most complicated and harsh modes includes main pipelines pumping hydrocarbons (HC).

The safety of pipelines and equipment, the reliability and efficiency of the structures and equipment operation, the environmental safety of facilities, the development and implementation of measures to reduce the loss of HC's (oil, petroleum products, and gas), saving resources, and developing new equipment and technologies are fundamental conditions that should be ensured when operating the main pipelines (MP). To ensure reliable and safe pumping, process regulations for the MP operating modes, the pumping procedure including starting and stopping the MPs, individual oil pumping stations (OPS), and the pump units, switching from one mode to another when the pumping capacity changes, arranging the pumping modes under the reduced load conditions, pipeline and process control, etc. are being developed. Thus, changes in the pumping flow rate occur in pipelines with unsteady process parameters for various reasons.

From the effective MP operation point of view, ensuring the product pumping with the required capacity and the lowest operating costs is the process requirement. The main parameters and their values set by the pumping process mode are the MP capacity, the number of operating mainline pump units at each pumping station, operating pressure at the intake, upstream, and downstream of the pressure regulator, the maximum permissible pressure at the pump discharge, and the maximum permissible load on the pump unit motor.

In the process flow sheets for pumping oil through the MPs, the process sections are separated from each other by tanks creating the difference between the pumping process mode of one section and others.

Oil and petroleum product pipeline systems are potentially dangerous objects since, despite ensuring a sufficiently high level of their reliability, for various reasons, damage to pipelines and equipment occurs with the loss of tightness and release of the pumped product into the environment. The release of oil and petroleum products from the damaged pipelines and equipment creates a danger to the pipeline system (PS) elements and nearby facilities and causes significant damage to the environment.

In this regard, the problem of automating the control over the PS operating modes based on monitoring, forecasting the accident rate using models linking the process parameters of the PS operating modes and their design specifics with the permissible risks of accidents is urgent [1, 3-6, 10, 13-21].

Safety indicators are the intensity of accidents, the cost of a technical object exposed to an accident, losses from downtime, the lost product, etc. Assessing the accident risk in the analysis allows reducing heterogeneous indicators to a single one and quantitatively evaluating the hazard.

The accident risk \( R_a \) is taken as the product of damage in a single PS accident \( U \) and the rate of accidents \( \lambda \): \( R_a = U \cdot \lambda \). It is assumed that for the calculating period, the amount of damage has not changed during the PS operation. Therefore, the risk is managed by reducing the rate of accidents by maintaining process parameters within permissible limits determined by the pipeline stress-strain state.

The paper discusses the solution to the problem of advanced PS risk management based on calculating the stress-strain state of pipeline structures and reducing safety factors depending on the magnitude, rate, and frequency of pressure changes in the PS. Permissible pumping modes are ensured by the pump units (PU) equipped with variable-frequency drives (VFD) [12].

2. Application peculiarities

In pipelines, changes in the pumping flow rate with unsteady operating parameters occur for various reasons. In [9–12], it is noted that the longest possible oil pipeline operation in a given process mode should be ensured, while avoiding significant pressure fluctuations, i.e., the shutdown of one or two pump units or oil pumping. Despite these requirements, changes in the pumping mode or oil flow rate, sometimes quite sharp, occur in the main pipelines and their individual sections. Changes in the pumping mode most occur when considering the requirements for the oil pumping process mode to provide the specified MP capacity while ensuring the minimum product pumping costs. The number
of such changes in the pumping mode differs for each specific MP or its individual section. For some MPs and their sections, the pumping mode may change 350 times per year or more. Analysis shows that these changes in the pumping mode may be caused by not only changes in the MP capacity but also other process and operational factors such as the pump or pumping station shut down due to failures of the electrical equipment, power supply, mechanical parts, and the linear MP section [3, 4]. Therefore, considering the requirements for the pumping process mode in terms of the mainline pump and OPS equipment operating costs, there are also quite high requirements for their reliability and efficiency. These high requirements are best met by centrifugal pumps, which are widely used in main oil pipelines [9]. Currently, mainline centrifugal pumps of the NM type with a rated flow rate of 1,250 to 10,000 m3/h are most used at the OPS. The main types of electrical equipment for OPS are electric drives of pump units, power transformers, switches, etc.

Along with the above, one of the factors affecting the pumping mode and characterizing the operating conditions of the linear MP section and the OPS equipment is the change in the physical properties of the pumped oil (density and viscosity). Changes in oil properties occur with seasonal changes in air temperature and, consequently, oil temperature, as well as when pumping oil from different fields.

The reliable and safe operation of the main OPS equipment and the pipeline, in turn, substantially depends on the level and nature of the change in the pumping mode [16, 17]. Thus, the parameters of the oil pumping mode and the reliability of the OPS equipment and the MP linear section are interdependent.

Under the conditions of exposure to repeated loads during long-term MP operation with multiple changes in the pumping mode, low-cycle fatigue of the pipe and equipment metal is possible. Note that low-cycle fatigue is very sensitive to stress concentrators created by the pipe metal defects, welded joints, and cross-sectional shapes.

Changes in the pumping mode by switching additional pumps or also negatively affect the reliability of motors, transformers, and other electrical OPS equipment due to a sharp increase in the power grid current at the pump motor starting moment.

Significant causes of violating the PS integrity are a high level of stresses in the pipe metal and its changes due to the unsteadiness of process parameters [1, 13]. The main pipelines pumping hydrocarbons are operated with variable process parameters [7-9, 10, 14].

3. The Theoretical Basis for Calculating the Maximum Permissible Pipe Stress and Local Resistance

When calculating the static strength by the permissible rated stresses $[\sigma]_n$, the rated stresses $\sigma^*_n$ acting in the structural element should meet the inequality

$$\sigma^*_n \leq [\sigma]_n.$$  \hspace{1cm} (1)

The $[\sigma]_n$ value is determined by the yield strength $\sigma_{0.2}$ (or $\sigma_t$) and tensile strength $\sigma_b$, considering the yield and tensile strength margins $n_t=1.2 \pm 2.0$ and $n_b=1.7 \pm 2.5$, respectively [11]:

$$[\sigma]_n = \frac{\sigma_t}{n_t}, \quad [\sigma]_n = \frac{\sigma_b}{n_b}.$$  \hspace{1cm} (2)

According to [1, 2, 13], let us determine the dependencies of the pipe wall stresses and safety and durability margins in the boundary sections of the pipeline pressure change on the pipeline geometry, the pipe metal properties, the pressure change from the initial operating pressure $p$ to $(p + \Delta p)$ – increased pressure ($\Delta p$ is the pressure boost value), and the pipeline section length $\ell_o$, where the pressure changes from $p$ to $(p + \Delta p)$. When controlling the pumping mode, a smooth pressure decrease in the oil pipeline allows reducing stresses in the pipe wall and increasing its safety and durability margins. Moreover, the greater the length $\ell_o$ of the section where the pressure changes, the more significant the stress reduction and the increase in safety and durability margins.
Achieving acceptable safety margins improve safety and durability and reduce the risk of accidents to a permissible level [2, 11].

When switching the current pumping mode with a flow rate $Q_1$ and pressure $p_1$ to that with a flow rate $Q_2$ and pressure $p_2=p_1+\Delta p$, the geometry of a pipe section with a length $\ell_o$, where the median diameter D (or radius R) changes due to a change in pressure, and a pipe thickness $\delta$ can be linked with the permissible pipe material stress according to the standards, based on the limitation of the maximum equivalent stresses $\sigma_{eq.m}$ by the rated resistance $R^r_2$ equal to the pipe metal yield strength $\sigma_f$. The condition for preventing unacceptable deformations is

$$ \sigma_{eq} \leq R^r_2, \quad (3) $$

where

$$ \sigma_{eq} = \frac{pR^2}{\delta} \cdot \bar{\sigma}_{eq}. \quad (4) $$

Under the action of internal pressure $p$, the pipeline radius increases by the value [22]

$$ \Delta R = \frac{pR^2}{\delta E}, \quad (5) $$

where $E$ is the pipe metal elasticity modulus; $R$ is the radius of the median pipe wall surface; $\delta$ is the pipe wall thickness.

The resulting circular stresses

$$ \sigma_{cr} = \frac{E\Delta R}{R}. \quad (6) $$

With increasing pressure from $p$ to $(p + \Delta p)$ with $E$ and $\delta$ values unchanged, the pipeline radius increases in $\left(1 + \frac{\Delta p}{p}\right)$ times. In the cross-section of the junction of sections with internal pressures $p$ and $(p + \Delta p)$ and different geometry of interconnected pipes and equipment, a local pipe wall bending occurs, caused by a difference in the increase of the radius determined by (5). To estimate the impact of local bending and the resulting additional stresses on the strength and reliability of the entire MP, these additional stresses should be determined depending on the internal pressure $p$, its boost $\Delta p$, the pipe geometry, and the pipe metal strain-stress characteristics.

To solve the problem, let us use the thin-walled shell theory described in [22]. It is known that thin-walled cylindrical shells include pipes with a less than 1/30 wall thickness to radius ratio. Pipes with a rated diameter of 530 mm and more used in oil and gas pipelines have such dimensions.

![Figure 1. The Pipe Wall Bending Design Scheme for the Pressure Change from $p$ to $(p+\Delta p)$ in the section $\ell_o$](image-url)

Figure 1. The Pipe Wall Bending Design Scheme for the Pressure Change from $p$ to $(p+\Delta p)$ in the section $\ell_o$
The x-axis is parallel to the longitudinal axis of the pipeline and runs along the median pipeline wall surface, provided the pipe wall has no bending.

The differential equation of the pipe wall bending has the form

\[ \frac{d^4w}{dx^4} + 4\beta^4w = \frac{q}{d}, \]  \hspace{1cm} (7)

where \( w \) is the pipe wall bending, \( q \) is the internal distributed load acting on the pipe wall, for the problem being solved \( p \) and \( (p + \Delta p) \), \( D \) is the bending rigidity determined by the formula

\[ D = \frac{\frac{3^4E}{12(1-\nu^2)}}{}; \]  \hspace{1cm} (8)

\( \nu \) is the Poisson's ratio,

\( \beta \) is a parameter depending on the pipe geometry and its metal strain-stress properties, determined by the formula

\[ \beta = \frac{4\sqrt{3(1-\nu^2)}}{(R\sigma)^3}, \]  \hspace{1cm} (9)

where \( R = 0.5(D_{out} - \delta) \), \( D_{out} \) is the outer pipe diameter.

Solving equation (7) according to the provisions outlined in [22], to calculate the bending moment in the section \( x = 0 \), we have

\[ M_o = \pm \frac{\Delta p R \delta}{a_o} \sqrt{\frac{1}{12(1-\nu^2)}}. \]  \hspace{1cm} (10)

Then, considering the bending stress \( \sigma_{bn} = \frac{6M_o}{\delta^2} \) and using (10), we obtain

\[ \sigma_{bn} = \sigma_{cr} \cdot \tilde{\sigma}_{bn}, \]  \hspace{1cm} (11)

where

\[ \tilde{\sigma}_{bn} = \pm \frac{\Delta p}{p \delta} \sqrt{\frac{3}{1-\nu^2}} \Rightarrow \sigma_{cr} = \frac{p R}{\delta}. \]  \hspace{1cm} (12)

In section \( x = 0 \), the largest total circular stresses caused by an increase in the pipe radius under the action of internal pressure and longitudinal (bending) stress will be

\[ \sigma_{cr,s} = \sigma_{cr} \cdot \tilde{\sigma}_{cr,s} \]  \hspace{1cm} (13),

where

\[ \tilde{\sigma}_{cr,s} = 1 + \frac{\Delta p}{p} \left( 1 + \frac{1}{a_o} \sqrt{\frac{3\nu^2}{1-\nu^2}} \right). \]  \hspace{1cm} (14)

In the section \( x = 0 \), the pipe wall is simultaneously exposed to internal pressure and bending; the strength is checked according to the maximum-strain-energy of failure with the definition of equivalent stresses \( \sigma_{eq} \) by the formula

\[ \sigma_{eq} = \left( \sigma_{bn}^2 - \sigma_{bn} \cdot \sigma_{cr,s} + \sigma_{cr,s}^2 \right)^{0.5}, \]  \hspace{1cm} (15)

where \( \sigma_{bn}, \sigma_{cr,s} \) are, respectively, longitudinal (bending) and circular stresses, taken with their signs and therefore, according to (15), the maximum \( \sigma_{eq} \) will occur at different signs of \( \sigma_{bn} \) and \( \sigma_{cr} \).

Based on the foregoing, let us determine the equivalent stresses

\[ \sigma_{eq} = \sigma_{cr,eq}, \]  \hspace{1cm} (16)
where the dimensionless parameter
\[ \bar{\sigma}_{eq} = \left[ \bar{\sigma}_{bn}^2 + \bar{\sigma}_{bn} \cdot \bar{\sigma}_{cr.s.} + \bar{\sigma}_{cr.s.}^2 \right]^{0.5} \] (17)

Using (11)÷(17) and considering \( n = 0.3 \) for steel pipelines, to calculate \( \bar{\sigma}_{eq.m} \), we have
\[ \bar{\sigma}_{eq.m} = \left[ 1 + \frac{dp}{p} \right]^2 + 4,5824 \left( \frac{dp}{p \cdot a_0} \right)^2 + 2,9051 \frac{dp}{p \cdot a_0} \left( 1 + \frac{dp}{p} \right)^{1.2} \] (18)

where
\[ a_0 = \frac{1.2854 \ell_o}{(R \delta)^{0.5}}. \] (19)

Then, to ensure permissible deformations, the below condition should be met
\[ a_o \geq \frac{1.4526 \frac{dp}{p} \left( 1 + \frac{dp}{p} \right)^2}{B} \left( 1 + \left( 1 + \frac{2.1718E}{(1+\frac{dp}{p})^p} \right)^{0.5} \right), \] (20)

where
\[ B = \left( R \ell_o \right)^2 - \left( 1 + \frac{dp}{p} \right)^2; \quad R \ell_o = \frac{R^* \cdot \delta}{pR}. \] (21)

Considering (19) and (20) for the length \( \ell_o \), we have the condition
\[ \ell_o \geq 0.7780 \cdot a_o (R \delta)^{0.5}. \] (22)

On the other hand, the minimum permissible length \( \ell_o \) can be linked with the time \( t_R \) of the change in flow rate from \( Q_1 \) to \( Q_2 \) and the transition from pressure \( p_1 \) to \( p_2 \)
\[ t_R \geq \frac{\pi D_s^2 \ell_o}{2(Q_1 + Q_2)}. \] (23)

When the pumping mode changes, increased pipe wall stresses also arise in the cross-sections of the pipe connection with shutoff valves, thick-walled tees, couplings, and other equipment with load-bearing walls having the thickness several times larger than that of the pipe wall.

Determining the equivalent stresses according to the above method, for these pipe connections, equations (3) and (4) will have the form
\[ \bar{\sigma}_{eq} = 2.1407 \left( 1 + \frac{dp}{p \cdot a_0} \right). \] (24)

Using this equation, from condition (3), we find
\[ a_o \geq \frac{dp}{p} \cdot \frac{1}{0.4671 \cdot \bar{R}_2^{\ell_o - 1}}. \] (25)

Taking in (20) and (25) the values \( \phi_{bn} (\bar{\sigma}_b = \frac{\sigma_{pn} \delta}{pR}) \) or \( \bar{\sigma}_T (\bar{\sigma}_T = \frac{\sigma_T \cdot \delta}{pR}) \) instead of \( \bar{R}_2^{\ell_o} \), we have a condition for ensuring permissible safety margins and accident risk \( R_s \).
4. Algorithm application

The pipeline system safety and permissible risk level are ensured by reducing the level and rate of changes in the pipeline stresses due to the pressure change value and rate when switching from one mode to another, justified by calculations.

Under the conditions of changing process mode, pumping is controlled as follows.

1. By the equations (1)–(4) and (18)–(25), for the MPs, the minimum permissible time interval is determined for switching pressure (and the corresponding flow rates) from one mode to another. If the PS has several process sections, then the minimum pressure switching time is determined by the maximum time calculated for individual sections.

2. By the equations (3), (4), (24), and (25), the admissibility of changing pressure by Δp is checked based on the condition of maintaining the integrity of local connections. If the condition is violated, a lower pressure change is set, and the algorithm steps 1, 2 are repeated.

3. Pumps with variable-frequency drives are used as an executive system to control the pumping pressure.

Based on the pressure balance equation, to determine the shaft rotation frequency of the regulated VFD of the main pump, at a flow rate \( Q_2 \), we have

\[
\omega_2 = \omega_r F^{0.5}
\]  

(26)

where \( \omega_r \) is the rated speed; \( \omega_2 \) is the end speed, at which the flow rate \( Q_2 \) is ensured, \( F \) is the function defined as

\[
F = F(Q_2, N_m, N_b, H(Q), H_p, h_s, h_e, L, K),
\]

(27)

where \( N_m \) is the number of operating non-controlled mainline pumps, \( N_b \) is the number of operating controlled mainline pumps, \( N_b \) is the number of booster pumps connected in parallel, \( H(Q) \) is the set of pressure characteristics of mainline (controlled and non-controlled) and booster pumps, \( H_p \) is the residual pumping head at the process section end; \( h_s, h_e \) are the geodetic elevations of the process section start and end, \( L \) is the process section length, \( K \) is a complex parameter depending on the fluid flow pattern and its physical properties [9].

4. On the VFD controller (or the controller generating settings for the VFD controller) the time is programmed for switching the frequency from \( \omega_r \) to \( \omega_2 \), and the program starts.

As an example, let us consider a process section of an oil pipeline with an outer diameter of 1,020 mm and a wall thickness of 11 mm, running from an OPS, where mainline pump units of the NM 7000-210 type and booster pumps of the NPV 3600-90 type are installed. The section length is 150 km, \( \Delta z = – 50 \text{ m} \), \( h_s = 40 \text{ m} \), the pressure characteristics of the pumps and the oil properties are taken according to [9]. The pipe material is steel 17G1S with a yield point \( \sigma_y = 366 \text{ MPa} \). With two mainline (connected in series) and two booster (connected in parallel) pumps operating, the pumping capacity is 5,000 m³/h. Based on the calculation formulas given in [9] and considering formulas (26) and (27), it has been determined that to achieve the pumping capacity \( Q_2 = 6,000 \text{ m³/h} \), one mainline pump with VFD should be additionally turned on smoothly and its shaft rotation speed \( \omega_2 = 0.75 \omega_r \) ensured, where \( \omega_r \) is the rated speed of the mainline pump shaft. To significantly reduce the pressure boost due to a change in pumping capacity from 5,000 to 6,000 m³/h (or from 1.3889 to 1.6667 m³/s) and oil flow velocity from 1.78 to 2.13 m/s, according to the recommendations of [9] and considering the calculation formula (19), we have \( \ell_o \geq 0.7780 a_o (R \delta)^{0.5} \), and the length can be taken equal to 100 m. The change in the controlled pump unit shaft rotation speed and the oil pumping capacity should be made within 51 s provided that main oil pipeline safety is ensured. With an increase in the pumping capacity, the highest equivalent stress in the pipe wall will be 243.1 MPa, which is much less than the pipe metal yield point, and the safety margin \( n_r = 1.51 \). When the pumping capacity changes without the use of VFD, these stresses reach 310.0 MPa with a safety margin \( n_r = 1.18 \).
5. Conclusions
1. It has been established that under the conditions of changing pumping mode, the pumping capacity, the change in its value, and the time interval for changing the pumping capacity affect the level of the mainline pipe wall stresses and, accordingly, the risk of accidents.

2. The studies performed allowed obtaining the dependencies between the pumping parameters affecting the level of stresses in the oil pipeline wall and the risk of accidents. In particular, dependencies have been obtained between changes in the oil pumping capacity (flow rate) from $Q_1$ to $Q_2$, the flow rate change time interval $t_k$, and the length $l_o$ of the pipeline section where the flow rate changes, and their effect on the level and changes in stresses. The minimum process mode switching time has been justified, which ensures the permissible level of the stress-strain state of pipeline structures and, accordingly, the risk of accidents.

3. The design parameters of permissible pressure changes have been obtained for the pipeline sections of the junction with rigid elements, which ensure permissible safety margin and risk of accidents.

4. Based on the pressure change value and rate justified, implementation and an algorithm for switching the process mode to a given state using VFD have been proposed, at which a permissible risk of accidents is ensured.

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