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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DIAGNOSTICS AND REGULATION OF SPECIAL FLOW CASES IN OIL AND GAS PIPELINES

Specialty: 3354.01 – “Construction and Operation of Oil
and Pipelines, Storage Bases, and Facilities”

Field of science: Technical sciences

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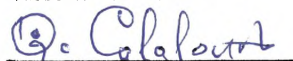
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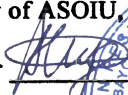
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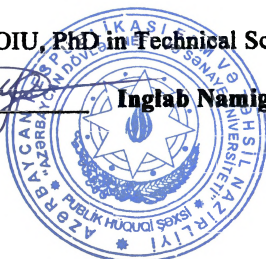
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GENERAL DESCRIPTION OF WORK

Relevance of the work. Practice shows that oil and gas extraction, gathering, and transportation processes, while occurring under various relief and thermobaric conditions, are observed with very diverse forms and structures of flow. In oilfield practice, single-phase and multiphase flows are widespread flow forms in the well-gathering system. Both single-phase and multiphase flows have laminar and turbulent movement regimes. The hydrodynamics of both flow forms has been a fairly broad subject of research and study. Nevertheless, practice demonstrates that special flow conditions also exist in single-phase and multiphase flows in oil and gas pipelines, to which increasing attention is essential. Dynamic loads, flows accompanied by hydraulic hammers, cavitating, obliteration laminar flows, the initial section of laminar flows, and flows under high pressure differentials belong to such flow conditions. It should be noted that the formation of such special flow conditions is also possible under certain operational cases in field technology pipelines. The diagnostics, hydrodynamic investigation, and regulation issues of the mentioned special flow conditions are highly relevant as they carry significant scientific and practical importance. Investigating the dynamics of such flow conditions and considering their hydraulic characteristics are crucial for increasing the efficiency of technological processes and solving problems related to equipment safety in oil and gas production and hydrocarbon transportation.

Object and subject of research. The object of research comprises special flow forms created during oil and gas gathering and transportation, while its subject consists of the development of methods for their diagnostics and regulation.

Objective of the research. To increase the operational efficiency and reliability of oil and gas pipelines based on the diagnostics and regulation of special flow conditions.

Main tasks of the research.

1. Analysis of flow forms and operational difficulties in oil and gas pipelines;

2. Investigation of special flow conditions;
3. Diagnostics of velocity-flow rate characteristics in laminar flows;
4. Dynamic loads in multiphase flows;
5. Investigation of the effect of condensate accumulation in the pipe on transportation pressure;
6. Diagnostics of cavitating flows and structural changes;
7. Regulation of dynamic loads and cavitating flows;
8. Diagnostics and regulation of hydraulic hammers in pipelines;
9. Regulation of multiphase flow zones;
10. Hydraulic study of obliteration laminar flows;
11. Diagnostics of the stabilization zone of laminar flows.

Methods of research. The problems posed in the dissertation were solved theoretically and experimentally through the mathematical processing of actual operational data, operational difficulties, and experimental indicators of oil and gas transportation pipelines, using computer software and digital tools.

Scientific novelties.

1. A method for diagnosing structural changes and critical parameters in cavitating flows has been developed;
2. A method for evaluating dynamic loads in multiphase flows considering a new physical flow model has been developed;
3. Methods for diagnosing and regulating the multiphase flow zone based on transportation parameters have been developed;
4. A method for evaluating and regulating hydraulic hammers in multiphase flows has been proposed.

Main propositions submitted for defense.

1. Method for diagnosing structural changes and critical parameters in cavitating flows;
2. Methods for evaluating and distributing dynamic loads in multiphase flows;
3. Methods for diagnosing and regulating multiphase flow zones;
4. Methods for diagnosing and regulating hydraulic hammers.

Theoretical and Practical Significance of the Study.

Diagnostic and control methods for dynamic loads are of critical

importance, as dynamic loads occurring in multiphase flows can be accompanied by significant hydraulic surge waves and exert destructive impacts, depending on the flow regime structure and which phase acts as the continuous medium (dispersion medium).

The developed method for the diagnostics and control of cavitating flows-one of the key factors contributing to premature failure in oil and gas gathering and field pipelines-holds substantial scientific and practical significance.

The diagnostic technique developed to determine the location and number of multiphase flow regimes generated in oil pipelines, based on the control of transportation parameters, was validated using a reference oil pipeline model, demonstrating the feasibility of controlling multiphase flow regimes. Furthermore, any methodology that enables the prevention of such flow regime formations carries high practical value.

Author's Personal Contribution. The practical results presented in the dissertation were accomplished directly by the author. The problem formulation, execution of tests, and the analysis, systematization, and generalization of results were carried out with the direct participation of the author.

Approbation and application. The principal statements and findings of the dissertation work were presented, discussed, and endorsed at the following international and national conferences and seminars:

1.XVIII Международная научно-практическая конференция «Трубопроводный транспорт – 2023», Уфа, 16–17 ноября, 2023;

2.Международная научно-техническая конференция «Транспорт и хранение углеводородного сырья», посвященная 60-летию ТИУ, Тюмень, 4–5 июня, 2024;

3.COP-29 Side Event – The Sixth Eurasian Conference RISK-2024 «Innovations in Minimization of Natural and Technological Risks of Climate Changes: Methodology and Practice», Baku, 27–29 November, 2024;

4.XVII Международная конференция «Рассохинские чтения – 2025», Ухта, 6–7 февраля, 2025;

5.7th Eurasian Conference on «Risk-oriented Design and Operation of Infrastructure Systems: Sustainability Paradigm», Baku, 21–23 October, 2025;

6.XI Международная научно-техническая конференция, посвященная памяти проф. В.К. Липского, Новополюцк, 27–28 ноября, 2025.

Publication of the Work. The main content of the dissertation has been published in 16 scientific articles and conference proceedings.

Scope of the dissertation with an indication of the volume of individual structural sections and the total volume of the work. The structure of the dissertation consists of an introduction (14 485 characters), Chapter I (25 351 characters), Chapter II (22 300 characters), Chapter III (31 476 characters), Chapter IV (84 104 characters), conclusions (1 723 characters), a list of references, and appendices. The total volume of the dissertation comprises 152 computer-typed pages, including 13 figures, 27 graphs, 12 tables, and a reference list of 152 titles, amounting to 179 439 characters excluding figures, tables, graphs, and the reference list at 156 pages of work.

The author considers it his duty to express his gratitude to the staff of the "Transportation and Storage of Oil and Gas" Department of Azerbaijan State Oil and Industry University PLE, where the dissertation work was carried out, for their support, and to his scientific supervisor, Doctor of Technical Sciences, Professor E.K. Iskandarov, for his valuable recommendations.

The author also expresses his gratitude to Doctor of Technical Sciences, Professor G.G. Ismayilov and PhD in Technical Sciences, Associate Professor F.B. Ismayilova for the advice they gave during the formulation, solution and discussion of the problems in the dissertation.

THE MAIN CONTENT OF THE WORK

In the introduction, the relevance of the dissertation is justified, the objective and main resolved tasks are presented, the scientific novelty, practical significance, and primary statements submitted for

defense are outlined, and a brief overview of the work's content is provided.

The first chapter is devoted to investigating specific flow regimes in oil and gas pipelines and analyzing the causes of their occurrence. Thus, flows accompanied by cavitation, obliteration, and hydraulic surge (water hammer), along with their formation mechanisms, diagnostic techniques, and control methods, are emphasized.

It is well known that during liquid transport in pipelines, changes in physical state can occur under certain conditions; namely, vaporization of the liquid as well as degassing (evolution of dissolved gas) take place. For instance, when a flowing liquid passes through a local constriction in a pipe, its velocity increases while the pressure decreases. If the absolute pressure drops to the vapor pressure at the given temperature or equals the gas evolution pressure (saturation pressure), intensive vaporization (boiling) and gas liberation occur at this localized point of the pipe (flow). Upon entering an expanding section, the flow velocity decreases, pressure rises, and the vapor-gas separation process ceases, with the liberated gas gradually redissolving into the liquid. This local disruption of flow continuity, characterized by the formation of gas and vapor bubbles (cavities) due to a localized pressure drop, is called cavitation, and such a flow is considered a cavitating flow. The inception and characteristics of cavitating flows are detailed, and given their undesirable nature, the necessity of preventing their occurrence in pipelines and other hydraulic systems is demonstrated. The importance of diagnosing and controlling cavitating flows is highlighted.

During fluid flow through capillaries and narrow clearances, phenomena sometimes occur that cannot be explained by classical hydraulic laws. Specifically, over time, the volumetric flow rate decreases despite a constant pressure differential and unchanged physical properties of the fluid. In extreme cases, fluid movement ceases entirely. This phenomenon is termed obliteration, and the corresponding flow condition is considered an obliterated flow. Obliteration is currently attributed to a reduction in the effective cross-

sectional area of the channel, explained by the surface adsorption (deposition) of polar-active fluid molecules. Since the thickness of such an adsorbed layer can reach several micrometers for oils, it can significantly restrict or completely block the flow cross-section.

In oil and gas production and hydrocarbon transportation practice, it is well established that sudden interruptions of single-phase or multiphase flows or rapid changes in flow velocity induce sharp pressure transients in pipelines. Such hydraulic surges (water hammer), accompanied by the generation and propagation of pressure waves in pipelines, cause compression of the transported medium (however minor) and alterations in its properties. Accounting for these effects is critical for technological processes, as well as for ensuring the safe and efficient operation of equipment. Therefore, taking scientifically and practically sound measures for the accurate diagnosis, evaluation, and timely mitigation of dynamic processes like hydraulic surges is of vital importance.

Numerous technological processes in oilfield operations accompanied by hydraulic surges can be cited as examples. In general, a body of literature exists describing the mechanics of surge processes during the interaction of liquid, gas, or multiphase media with hydraulic systems (including valves) and evaluating the resulting transient overpressure. However, protection methods against these surges remain insufficiently covered. It must be noted that any change (increase or decrease) in pipeline transport parameters can be considered a hydraulic surge, occurring either gradually or rapidly. The causes of surges include rapid valve opening or closure, pump startup or shutdown, and pipeline failures accompanied by medium release to the environment. As a consequence of hydraulic surges, pressure drops as well as pressure spikes can occur. In such cases, system pressure changes correspond to the rate of disturbance applied to the system. Specifically, a surge caused by instantaneous valve closure is positive, whereas instantaneous opening produces a negative (negative) surge. Positive surges are considered the most dangerous; during a positive surge, even an incompressible fluid must be modeled as a compressible medium. Hydraulic surge can induce longitudinal

pipe cracking and damage other system components, including heat exchangers, pumps, and other pressure vessels.

Field experience shows that the presence of air or gas pockets in pipelines is a frequent major factor initiating hydraulic surges. In multiphase flows, dynamic loads resulting from density differences between phases and transitions between flow regimes-occurring most prominently at pipe bends and direction changes-are accompanied by hydraulic surges. Pressure and flow velocity fluctuations under these conditions take a wave-like form, creating additional stresses. Pressure head and velocity in the system can experience both sharp spikes and sudden drops. Practice indicates that improper hydraulic regimes and abrupt cross-sectional transitions in pipelines create conditions where generated hydraulic surges are particularly hazardous, producing severe shock waves. If the peak transient pressure exceeds the maximum allowable operating pressure of the system, loss of pipeline structural integrity can occur.

The magnitude of a hydraulic surge depends on the rate of disturbance applied to the system and the distance from the point of impact. Analyzing the distribution of surge pressure parameters along the pipeline length enables the selection of appropriate system protection tactics and methods.

Characteristic quantities and evaluation criteria for various flow conditions have been investigated and systematized. For steady, incompressible fluid flow, the primary governing variables are flow velocity and pressure gradient. Considering equilibrium conditions for compressible and incompressible fluids, the interplay among pressure, inertial, and gravitational forces developed during flow has been analyzed for distinct flow regimes. Dimensionless parameters widely used in hydrodynamics have been systematized to study and evaluate flow conditions for fluids (systems) exhibiting diverse rheological properties. Additionally, accounting for interphase interactions and a new physical flow model, the necessity of incorporating the Bernoulli force-which shapes the gradient-velocity field in multiphase flows-

into hydrodynamic investigations is noted¹.

For steady viscous fluid flow in a pipeline, the distribution of forces acting on the fluid along the pipe axis and the key criteria used to evaluate these effects are emphasized. Friction, pressure, and inertial forces are expressed through dimensionless quantities characterizing the relative influence of viscosity, pressure gradient, and fluid density, respectively. According to dimensional analysis, considering that the number of variables governing fluid motion in a pipe can be reduced based on the fundamental dimensions of mass, length, and time, the complex impact of hydrodynamic similarity criteria on cylindrical flows is discussed. Furthermore, it is described that total pressure-the sum of static and dynamic (velocity) pressures-remains constant across the flow cross-section rather than static pressure alone. Consequently, in accordance with the new physical flow model for the case under consideration, static pressure and the pressure gradient vary across the cross-section.

In the second chapter, the hydraulic characteristics of laminar flow of viscous and visco-plastic fluids in pipes, as well as the transition process to a steady-state regime, are investigated. In oilfield practice, the laminar flow regime of fluids with diverse rheological properties is one of the most widespread motion patterns. On the other hand, from the onset of fluid motion in a pipe, a certain duration is required to establish flow steadiness-that is, the independence of its parameters from time.

Diagnosing steady-state characteristics during the laminar flow of both Newtonian and non-Newtonian fluids is of particular relevance. Determining velocity-flow rate characteristics for such flows, while taking into account the rheological properties of the fluid, is vital for developing hydraulic criteria.

In oil and gas production, many aspects of controlling technological processes and enhancing efficiency are closely tied to the diverse patterns and hydraulic characteristics exhibited by

¹ İsmayılov, Q.Q. Nəql fenomeni: Dərslik / Q.Q.İsmayılov, E.X.İskəndərov, F.B.İsmayılova. – Bakı: ADNSU, – 2021. – 212 s.

homogeneous and heterogeneous fluids with varying rheological and physicochemical properties during extraction, gathering, and transportation in pipes. Hydraulic calculation of pipelines and accurate forecasting of regime parameters, in turn, necessitate the diagnostics of steady-state fluid characteristics based on their rheological properties.

The multicomponent and multiphase nature of transported fluids significantly complicates their hydraulic behavior compared to homogeneous systems. During the transport of such systems, energy consumption increases, and the presence of diverse flow regimes substantially complicates hydrodynamic calculations.

Below, the governing laws controlling cross-sectional velocity distribution and flow rate determination in laminar flows for conventional and non-Newtonian fluids are investigated, accounting for rheological factors. The determination of the time required to reach a steady-state operating regime and the dependence of this duration on governing parameters are analyzed.

To this end, the analytical expression derived for determining flow rate in a pipeline was utilized, and the time-dependent variation of the flow rate ratio for viscous and visco-plastic steady flows was formulated respectively as follows:

$$\frac{Q}{Q_{st}} = \left(1 - e^{-\frac{8v}{R^2}t}\right) \quad (1)$$

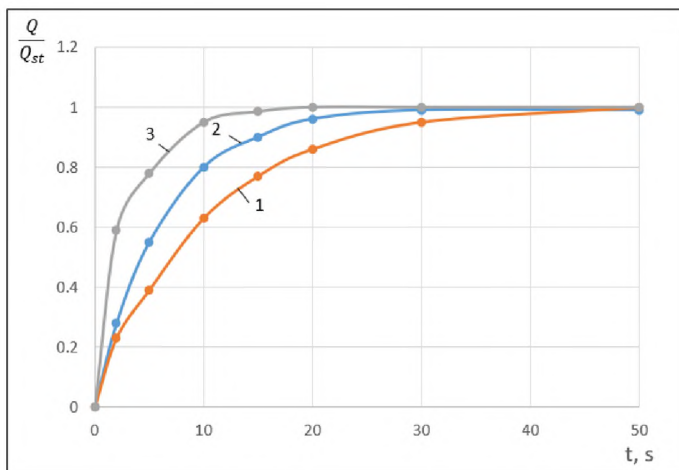
$$Q/Q_{st} = 1 - e^{-\frac{8v \cdot t}{R^2 \cdot \left(1 - \frac{4}{3} \frac{r_0}{R}\right)}} \quad (2)$$

Here: Q_{st} is the steady-state flow rate determined according to Poiseuille's equation;

v is the kinematic viscosity; R is the pipe radius;

r_0 is the radius of the plug flow core (yield-stress core) in visco-plastic flow.

As can be seen from equation (1), over time, the flow rate approaches the steady-state flow rate determined according to Poiseuille's equation.



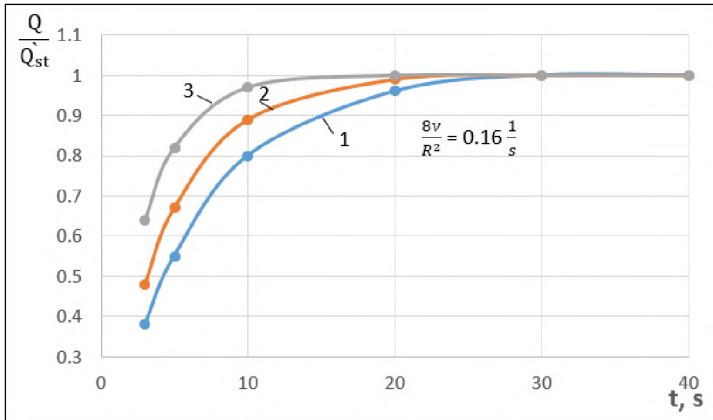
1–3 – corresponding to $8\nu/R^2 = 0,1; 0,16; 0,3$ 1/s respectively

Graph 1. Determination of the time required for a viscous fluid to reach a steady-state operation regime.

As shown in graph 1, derived from the calculations, at the inception of fluid motion, the flow rate undergoes unsteady variation before approaching a steady-state value after a certain period. Thus, it has been made possible to determine the time required to reach a steady-state operating regime during the laminar flow of viscous fluids in a pipeline.

The flow rate of a visco-plastic fluid was taken as the sum of the flow rate passing through the plug core and the flow rate through the outer shear zone. It was subsequently established that the flow rate magnitude for visco-plastic laminar flows differs from the rate determined by Poiseuille's equation for conventional fluids.

By accounting for pressure losses expended on inertial forces, a mathematical expression was derived for determining flow rate in laminar visco-plastic flows. Based on this expression, the steady-state rate ratios for visco-plastic flow were established, and the time-dependent variation of the flow rate ratio was investigated for various r_0/R values (graph 2).



1–3 – corresponding to $r_0/R = 0; 0,2; 0,4$

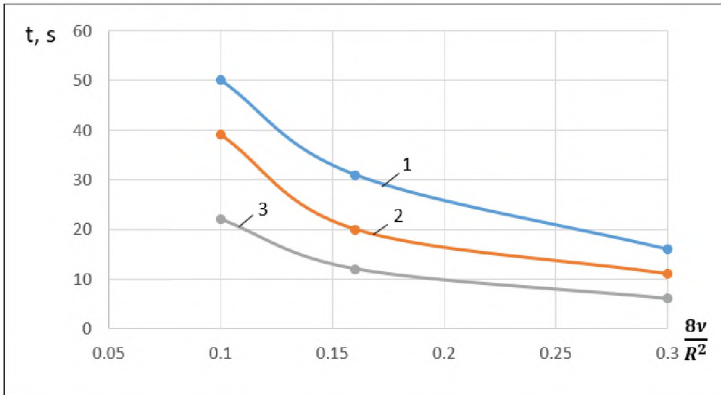
Graph 2. Determination of the time required for a visco-plastic fluid to reach a steady-state operating regime.

As shown in graph 2, during the laminar flow of visco-plastic fluids, the time required to reach a steady-state operating regime varies as a function of the parameters r_0/R and $8v/R^2$. The times to reach steady-state operation differ between viscous and visco-plastic fluids, decreasing as these parameters increase.

Thus, it was established that the duration to attain a steady-state regime for viscous fluids depends primarily on the parameter $8v/R^2$, whereas for visco-plastic flows, it additionally depends on r_0/R , which characterizes the formation of the plug flow core governed by the yield stress ($\tau=0$).

Additionally, specific cases of laminar flow-namely the hydrodynamic entrance length (initial stabilization zone), obliteration in narrow clearances, and thermodynamic effects under high pressure differentials-were comprehensively investigated, and their hydraulic criteria and characteristic parameters were refined. In the study, the influence of the initial stabilization zone (entrance length), where the parabolic velocity profile gradually develops at the pipe inlet, on flow parameters was analytically modeled. The distance over which the parabolic velocity profile develops due to near-wall viscous

retardation away from the pipe inlet was identified as a specific flow-regime zone. Based on analytical calculations and the critical Reynolds number threshold for laminar flow ($Re=2320$), it was established that the maximum length of the initial stabilization zone is $l^{max}(ent)=67.4 \cdot D$. It was proven that for a pipe diameter of $D=1m$, a fully developed laminar flow regime is established only after a distance of $67.4 m$. It was demonstrated that the length of the laminar hydrodynamic entrance zone is directly proportional to the flow velocity, inversely proportional to the kinematic viscosity, and varies primarily as a function of the pipeline diameter. To evaluate the influence of these parameters, the dependence of the stabilization zone length on pipe diameter (D) was calculated for various laminar flow velocities ($v=0.1 \div 1,0 m/s$) and kinematic viscosity values $\eta=5 \cdot 10^{-7}$; 10^{-6} ; $5 \cdot 10^{-6}$ and $10^{-5} m^2/s$ (Table 1).



1 – Viscous fluid; 2 – Visco-plastic fluid ($r_0/R = 0.2$); 3 – Visco-plastic fluid ($r_0/R = 0.4$).

Graph 3. Dependence of the time required to reach a steady-state operating regime on $8v/R^2$ during laminar flow.

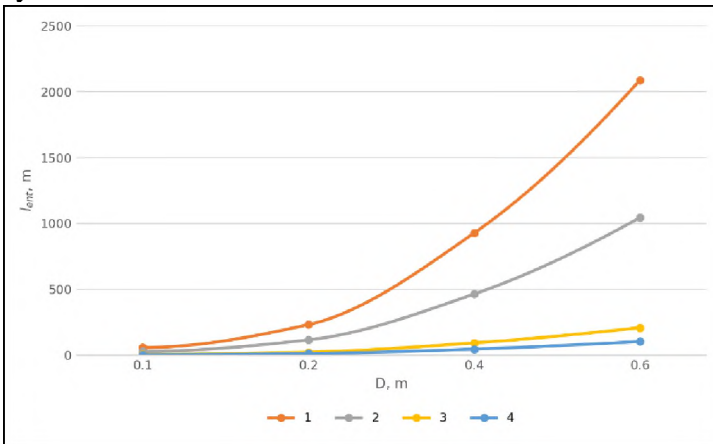
Depending on the pipe diameter, the hydrodynamic entrance length can reach several kilometers. It was proven in the research work that during the transport of high-viscosity fluids, the stabilization of the laminar regime occurs over a shorter distance, whereas for low-viscosity fluids, this zone expands significantly.

Table 1.

Calculated values of the entrance length for laminar flows
 $(l_{ent}, m), (D=0.6 \text{ m}).$

Flow velocity, $v, \text{ m/s}$	$\eta=5 \cdot 10^{-7}$	$\eta=10^{-6}$	$\eta=5 \cdot 10^{-6}$	$\eta=10^{-5}$
0.1	2088	1044	209	104
0.3	6264	3130	626	313
0.5	10440	5220	1044	522
0.7	12618	7306	1461	731
1.0	20880	10440	2088	1044

As seen from the plotted relationship graphs (graph 4), the length of the laminar flow entrance zone increases quadratically with an increase in pipeline diameter. This distance lengthens as flow velocity increases and decreases proportionally with an increase in kinematic viscosity.



1-4 corresponding to $\eta=5 \cdot 10^{-7}$; 10^{-6} ; $5 \cdot 10^{-6}$ and $10^{-5} \text{ m}^2/\text{s}$
Graph 4. $L_{ent} = f(D)$ dependence ($v=0.1 \text{ m/s}$).

Based on the hydrodynamic analyses conducted, it was substantiated that in the initial section of the pipeline ($l < l_{ent}$), the resistance is higher compared to the fully developed section due to near-wall viscous retardation. To accurately calculate the head loss in the entrance section, a correction coefficient $N=1.09$ based on

Schiller's relationship ($N = l_{ent} / (D \cdot Re)$) was applied, proving that the flow resistance at the pipeline entrance is 9% higher. It was demonstrated that in short pipelines, this discrepancy reaches even higher values.

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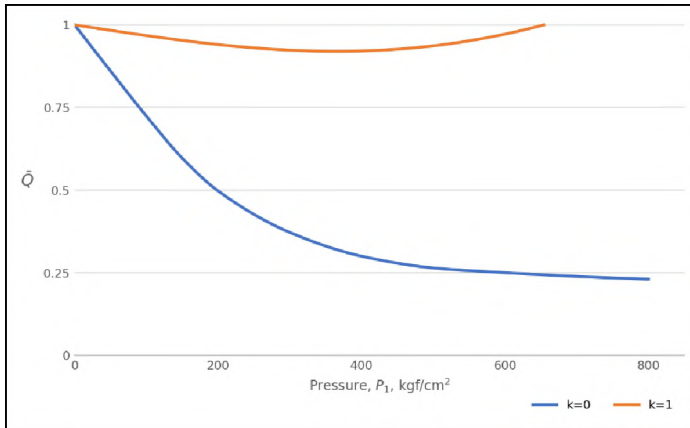
In the research work, another specific case of laminar flow-the phenomenon of obliteration in narrow clearances and capillaries, characterized by a decrease or total cessation of flow flow rate over time under a constant pressure differential-was analyzed from a hydrodynamic perspective.

During the investigation of laminar flows occurring under high pressure differentials, it was established that internal friction effects generated by the pressure drop raise the fluid temperature and reduce its viscosity. A dual variation mechanism for viscosity along the flow path-influenced simultaneously by the pressure drop and the temperature rise-was modeled. The opposing thermodynamic balance between the pressure increases (which reduces flow rate) and the temperature rise (which increases flow rate) was substantiated.

Based on expressions that account for the combined effect of pressure and temperature on viscosity, the flow rate variation mechanism was evaluated (graph 5).

As seen in graph 5, the variation in discharge is compared for both the adiabatic case where no heat transfer occurs through the pipe wall ($k=0$) and the isothermal case ($k=1$), where k represents the fraction of work done by viscous forces converted into fluid heating. The research demonstrates that the heat generated by internal friction

lowers the fluid viscosity, thereby facilitating discharge recovery at high operating pressures.



$k=0$ – heat transfer to the exterior does not occur; $k=1$ – for an isothermal process

Graph 5. Influence of pressure variation on flow rate.

Thus, the characteristics of laminar flows for viscous and viscoplastic fluids have been thoroughly investigated, and the transition process to a steady-state operating regime has been evaluated by taking into account the effects of inertial forces. Based on these investigations, a comprehensive methodology was developed to determine the time required to attain a steady-state regime. Furthermore, for visco-plastic fluid flow, the quantitative effect of the relative core radius (r_0/R) on both the discharge characteristics and the duration required to reach a steady state was established.

A thermodynamic viscosity–heat balance was modeled for fluid flow through narrow passages and capillaries under high pressure differentials, taking into account the temperature dependence of fluid viscosity. Based on this, the impact of temperature increases on viscosity, and subsequently the effect of viscosity variation on flow discharge, were established, providing a rigorous physical foundation for the mechanisms of obliteration and discharge fluctuations.

In the third chapter, specific flow phenomena in oil and gas gathering and field pipelines-namely cavitation induced by local resistances, structural regime transitions in the flow, and the diagnostics of critical parameters-were comprehensively investigated alongside the evaluation and control of hydraulic shock waves and dynamic loads in multiphase media.

The analyses conducted demonstrate that during the gathering and transportation of heterogeneous well fluids, cross-sectional constrictions caused by internal deposits (paraffin, sand, asphaltenes) or the partial closure of control valves (gate valves) increase local resistance and lead to the formation of cavitation inception zones. To diagnose cavitation regimes in gate valves, the valve cavitation index (σ) was utilized as the governing criterion:

$$\sigma = \frac{P_{out} - P_{sat}}{P_{inlet} - P_{out}} \quad (3)$$

In expression (3), the parameters denote the static pressures upstream and downstream of the valve, respectively, as well as the saturated vapor pressure of the transported crude oil. It was proven that when the current index falls below the critical index determined under laboratory conditions ($\sigma < \sigma_{crit}$), a latent and intensive erosion process is initiated within the valve body.

The onset of cavitation within a constricted section of diameter d in a crude oil pipeline of diameter D was modeled by incorporating Bernoulli's equation alongside the local resistance coefficient ($\zeta = 0.5$). From this formulation, the following analytical dependencies were derived for the critical cavitation parameter (σ_{crit}) and, via the continuity equation, the critical cavitation velocity (v_{crit}):

$$\sigma_{crit} = \frac{2 \cdot \Delta P}{\rho \cdot v^2} = \left(\frac{S}{S_1} \right)^2 - 0.5 \quad (4)$$

$$v_{crit} = v \cdot \frac{S}{S_1} \quad (5)$$

In the latter expressions, S and S_1 represent the cross-sectional area of the pipeline and the constricted section area, respectively. The calculated values for the critical velocity (v_{crit}) and the critical cavitation parameter (σ_{crit}) as functions of the pipeline constriction

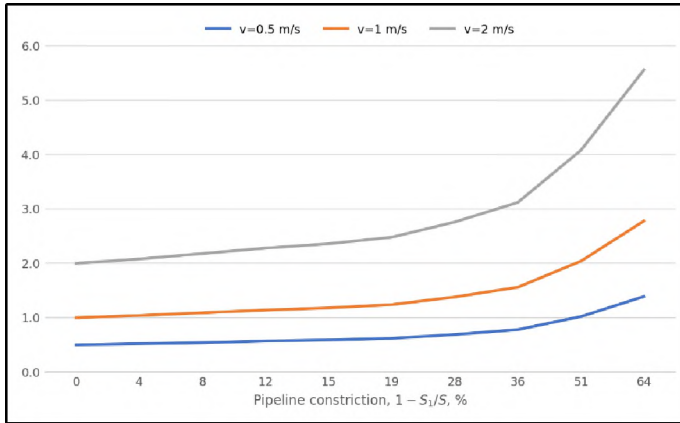
ratio at various flow velocities ($v = 0.5 \text{ m/s}$; 1.0 m/s and 2.0 m/s) based on our study are presented in table 2. An analysis of table 2 and the plotted relationship graphs (graphs 6 and 7) demonstrates that as the flow velocity increases and the cross-sectional area decreases, both the critical cavitation velocity and the critical cavitation number increase along a non-linearly ascending curve.

Subsequently, the hydraulic discharge characteristics of the pipeline were analyzed. By considering that the pressure loss ΔP varies proportionally with the square of velocity (v^2), a graph reflecting the hydraulic indicators in cavitating flows was constructed (graph 8). In the considered case, since the cavitation inception pressure is assumed to be the critical cavitation pressure ($P_2=P_{crit}$), the linear dependence breaks down at the characteristic point a with the onset of cavitation.

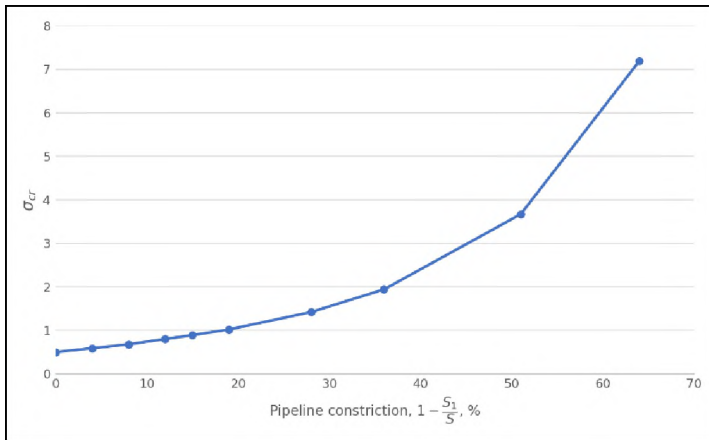
Table 2

Calculated Values of the v_{crit} and σ_{crit} Parameters Depending on the Pipeline Constriction Ratio.

d/D	S_I/S	$v_{crit} , m/s$			σ_{crit}	Kəmərin daralması, $I-S_I/S$, %
		Flow velocity				
		$v , m/s$				
		0.5	1	2		
1.00	1.00	0.5	1	2.00	0.50	0
0.98	0.96	0.52	1.04	2.08	0.59	4
0.96	0.92	0.54	1.09	2.18	0.68	8
0.94	0.88	0.57	1.14	2.28	0.80	12
0.92	0.85	0.59	1.18	2.36	0.89	15
0.90	0.81	0.62	1.24	2.48	1.02	19
0.85	0.72	0.69	1.38	2.76	1.42	28
0.80	0.64	0.78	1.56	3.12	1.94	36
0.70	0.49	1.02	2.04	4.08	3.67	51
0.60	0.36	1.39	2.78	5.56	7.19	64



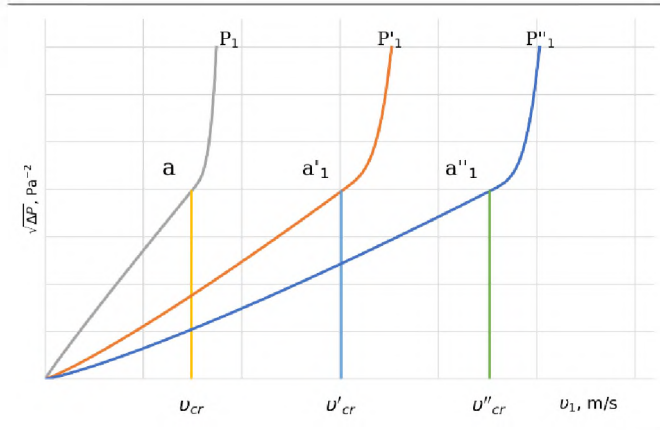
Graph 6. Dependence of critical velocity on pipeline constriction.



Graph 7. Dependence of cavitation number on pipeline constriction.

Due to the formation of gas-vapor cavities, the pressure loss increases sharply beyond this point, which has been substantiated as the primary diagnostic indicator of cavitation inception. Furthermore, it was proven that at a constant pressure P_l , an increase in the parameter σ_{crit} leads to a sharp decrease in the pressure corresponding to the cavitation threshold. These results are highlighted as key

indicators for preserving the net positive suction head (NPSH) margin in the suction lines of pumping stations and proactively mitigating vibration-induced failures.



Graph 8. Hydraulic characteristics in cavitating flows.

In the conducted investigations, hydraulic shock waves and dynamic loads arising from abrupt changes in flow velocity or direction within short time intervals in oil and gas gathering and transportation pipelines were comprehensively evaluated both analytically and numerically.

The hydraulic shock pressure $P_{h.s}$ generated in the system was modeled by considering the combined effects of the elastic compression of the transported medium and the elastic expansion of the pipe wall. Expressions were derived for the volumetric change due to the elastic compression of the transported fluid (ΔV_f) and the elastic expansion of the pipeline (ΔV_p):

$$\Delta V_f = \frac{P_{h.s} \cdot V}{E_f} \quad (6)$$

$$\Delta V_p = \frac{P_{h.s} \cdot \pi \cdot D^3 \cdot L}{4 \cdot \delta \cdot E_p} \quad (7)$$

Where: $V = \pi \cdot D^2 \cdot L / 4$ is the total volume of fluid in the pipeline; D and L are the diameter and length of the pipeline, respectively; δ is

the pipe wall thickness; and E_f and E_p are the elastic moduli of the fluid and the pipe material, respectively.

Taking into account the elastic deformation of the pipe wall, the shock wave propagation velocity c was determined by incorporating the continuity equation:

$$c = \left(\frac{E_f}{\rho_f} \right)^{0,5} / \left(1 + \frac{E_f \cdot D}{\delta \cdot E_p} \right)^{0,5} \quad (8)$$

As noted, since the hydraulic shock occurs when the valve closes instantaneously (t_v), the duration of the fluid volume change is equal to the duration of the shock phase, defined as $t_v \leq 2 \cdot L/c$. Otherwise, it is well known that the hydraulic shock is considered an indirect (non-direct) shock, and its magnitude is determined by the following expression:

$$P'_{h.s} = 2 \cdot v \cdot \rho \cdot L / t_v \quad (9)$$

As evident from the latter expression, to reduce the magnitude of the pressure surge resulting from hydraulic shock in the pipeline, the valve closure duration must be extended. It is therefore no coincidence that slow-closing gate valves or dampening surge vessels (air chambers) are widely deployed in pipeline operations.

This study further investigates the variation of hydraulic shock pressure surges induced by dynamic loads in multiphase flows, explicitly accounting for flow-regime structural patterns. To calculate the total hydraulic pressure, equation (9) above can be formulated as a function of the critical system transition across structural flow regimes as follows:

$$P_{h.s} = \rho_{mix} \cdot (v_{crit} - v_{ave}) \cdot c \quad (10)$$

Analytical expressions for the distribution of dynamic pressure loads have been developed for homogeneous, gas-dominant, and liquid-dominant flow regimes:

$$P_{dyn} = 0.217 \cdot \frac{(\rho_f - \rho_g)^2}{\rho_{mix}} \cdot g \cdot D \quad (11)$$

$$P_{dyn}^g = 0.217 \cdot \frac{(\rho_f - \rho_g)^2}{\rho_g} \cdot g \cdot D \quad (12)$$

$$P_{din}^f = 0.217 \cdot \frac{(\rho_f - \rho_g)^2}{\rho_f} \cdot g \cdot D \quad (13)$$

It was established that the capacity of entrained natural gas bubbles to absorb cavitation impacts and provide hydraulic damping directly depends on the phase velocity distribution within the pipeline. When the velocity ratio $v_g / v_l > 1$, gas plugs form along the upper crown of the pipe, causing the dampening effect to remain localized strictly within the upper zone while leaving the lower invert of the pipe vulnerable to cavitation and shock loads. Conversely, as phase velocities equalize ($v_g / v_l \rightarrow 1$) in a dispersed bubble-mist flow regime, the gas phase distributes homogeneously, expanding the absorption zone of shock waves and minimizing the rate of mechanical erosion on the pipe wall.

The results of the numerical calculations conducted for an oil pipeline with $L = 10 \text{ km}$, $D = 0.7 \text{ m}$, $\delta = 0.01 \text{ m}$, $V = 3846 \text{ m}^3$ are summarized in table 3.

Furthermore, to mitigate hydraulic shocks, a calculation methodology was developed focusing on reducing flow velocity, artificially extending valve closure duration ($t_v \geq 15$), and deploying dampening surge vessels (air chambers) (figure 1).

Upon valve closure, a fraction of the fluid enters the air chamber; due to air compression, the velocity deceleration occurs gradually rather than instantaneously, thereby dampening the shock.

In the performed calculations for an oil pipeline with $L = 5 \text{ km}$, $d = 75 \text{ mm}$, $\delta = 5 \text{ mm}$ ($Q = 9 \cdot 10^{-3} \text{ m}^3/\text{s}$, $v = 2.04 \text{ m/s}$, $c = 1170 \text{ m/s}$), the direct shock pressure under instantaneous closure was determined to be $\Delta P = 1.77 \text{ MPa}$. Given a shock phase duration of $T = 2L / c = 8.55 \text{ s}$, adjusting the valve closure time to $t_s = 15 \text{ s}$ was substantiated to suppress the surge pressure down to an allowable threshold of 1.0 MPa .

Table 3

Numerical Calculation Results for Hydraulic Shock and Multiphase Dynamic Loads.

Shock Wave Velocity (c)	<i>1181.25 m/s</i>	Velocity decreases from <i>1425 m/s</i> to <i>1181.25 m/s</i> due to the elastic deformation of the pipe wall.
Direct (Full) Shock Pressure ($t_v = 0\text{ s}$)	<i>2.20 MPa</i>	Maximum shock pressure generated in the pipeline during instantaneous valve closure.
Indirect (Partial) Shock Pressure ($t_v = 26\text{ s}$)	<i>0.144 MPa</i>	Extending closure duration to $t_v > 16.93\text{ s}$ attenuates shock pressure by a factor of 15.
Fluid Compression Volume (ΔV_f)	<i>0.332 m^3</i>	Volumetric change resulting from the elastic compression of crude oil at shock initiation.
Pipe Expansion Volume (ΔV_p)	<i>0.222 m^3</i>	Volumetric expansion of pipe walls driven by the elastic response at peak pressure.
Homogeneous Regime Dynamic Load ($\beta = 0.9$)	<i>12.3 kPa</i>	Gas elasticity in dispersed flow dampens shock energy ($\rho_{mix} = 88.7\text{ kg/m}^3$).
Slug Regime Dynamic Load ($\beta = 0.4$)	<i>364.8 kPa</i>	Increased mixture density ($\rho_{mix} = 517.2\text{ kg/m}^3$) elevates dynamic load by approximately 6-fold.

In another comparative calculation, the impact of pipe material elasticity on the shock wave was evaluated ($L = 20\text{ m}$, $d = 50\text{ mm}$, $\delta = 3.5\text{ mm}$, $v = 1.94\text{ m/s}$):

Steel Pipe ($E = 2 \cdot 10^{11}\text{ Pa}$): $c = 1320\text{ m/s}$, $\Delta P = 2.56\text{ MPa}$, radial deformation stress $\sigma = 18.1\text{ MPa}$;

Cast Iron Pipe ($E = 0.98 \cdot 10^{11}$ Pa): $c = 1240$ m/s, $\Delta P = 2.41$ MPa (the lower elasticity modulus of cast iron decreases both shock wave propagation velocity and peak surge pressure).

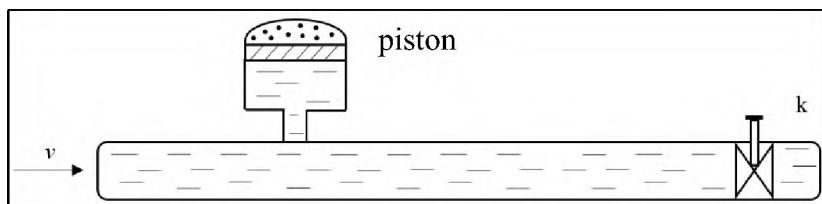


Figure 1. Schematic of a damping air vessel installed on a pipeline.

In this chapter, hydraulic shock phenomena in pipelines were modeled by incorporating both elastic volume variations (ΔV_f , ΔV_p) and dynamic loads (P_{dyn}) in multiphase media. It was established that in the slug flow regime of multiphase flows, the increase in mixture density escalates the dynamic load approximately 6-fold compared to the homogeneous regime (rising from 0.012 MPa to 0.365 MPa). A methodology for evaluating and controlling shock pressures was developed by calculating optimal valve closure times ($t_v \geq 15$ s) and sizing parameters for damping air vessels.

Chapter 4 addresses the enhancement of operational efficiency in oil and gas pipelines based on determining and regulating multiphase flow regimes and dynamic loads². It is well established that the co-current transportation of gas-liquid mixtures in pipelines is widespread in petroleum extraction, gathering, and transport systems. High flow velocities, strong corrosive and erosive activity, and continuous structural transformations place stringent demands on both the design and operational management of these systems. Experience demonstrates that design flaws frequently lead to critical operational issues-including severe vibrations, harmful pressure and flow

² İskəndərov, E.X. Neftin, qazın nəqli və saxlanması nəzarət-diaqnostika üsulları / E.X.İskəndərov. – Bakı: Elm, – 2023. – 327 s.

pulsations, accelerated erosion-corrosion of pipeline components, and even loss of mechanical integrity.

Multiphase gas-liquid flows fundamentally differ from single-phase regimes. Depending on phase mass flow rates, densities, viscosities, and surface tension, various flow structural patterns emerge, including bubble, stratified (smooth and wavy), plug, slug, annular, and dispersed-annular structures.

As gas velocity increases beyond the stratified regime, the flow bifurcates into slug and plug structures. In the slug regime, liquid slugs separated by large gas pockets generate severe hydraulic shocks, creating hazardous operating conditions. Under the physical model of the flow, dispersed phase particles (liquid droplets and solid particulates) are directed toward the flow core due to Bernoulli lift forces acting from the boundary layers toward the center. To mitigate erosion-corrosion wear in complex and vertical subsea offshore pipelines, hydrodynamic regulation of flowlines must be ensured alongside the optimization of pipe diameters and inclination angles.

In long-distance trunk pipelines, hydraulic calculations for multiphase mixtures differ radically from single-phase methodologies. This discrepancy is primarily driven by the progressive release of dissolved gas as pressure drops along the line, causing a non-linear expansion in total volumetric flow rate.

For multiphase oil-gas mixtures, the pressure loss due to friction within the pipeline is governed by the Darcy-Weisbach equation:

$$\Delta P_{fric} = \lambda_{mix} \cdot \frac{l}{d} \cdot \frac{\rho_{mix} \cdot v_{mix}^2}{2} \quad (14)$$

Where ρ_{mix} , λ_{mix} and v_{mix} are the density, hydraulic resistance coefficient, and flow velocity of the mixture, respectively. The Reynolds number is defined as $Re = \rho_{mix} \cdot D / \nu_{mix}$. For the kinematic viscosity of the mixture, the following empirical relationship is applied:

$$\frac{1}{\nu_{mix}} = \frac{\beta}{\nu_g} + \frac{1-\beta}{\nu_o} \quad (15)$$

Where $\beta = Q_g / (Q_g + Q_o)$ is the volumetric gas fraction (gas void fraction). The total pressure drops along the pipeline is expressed as the sum of friction (ΔP_{fric}) and gravitational (ΔP_{grav}) losses:

$$\frac{dP}{dr} = \frac{16 \cdot v^2 \cdot \rho_g \cdot \alpha \cdot (1 - \alpha^2)}{D} \quad (16)$$

The distribution of dynamic and hydrodynamic loads induced by multiphase flows in pipeline systems depends directly on the structural flow regime. Particularly in the slug flow regime, the high-velocity movement of large liquid masses followed by expanding gas pockets causes periodic momentum variations along the pipe walls.

The distribution of the static pressure gradient across the flow cross-section is expressed by the following equation³:

$$\Delta P = \Delta P_{fric} + \Delta P_{grav} \quad (17)$$

Where: v is the average volumetric flow velocity (m/s); ρ_g is the gas density (kg/m^3); D is the pipe diameter (m); and $\alpha = r / R$ is the relative coordinate with respect to the pipe radius.

Based on the critical condition where the static pressure gradient equals the difference in phase specific weights $g \cdot (\rho_o - \rho_g)$, the critical velocity (v_{crit}) ensuring the transition of multiphase flow to a homogeneous (dispersed) regime was analytically derived:

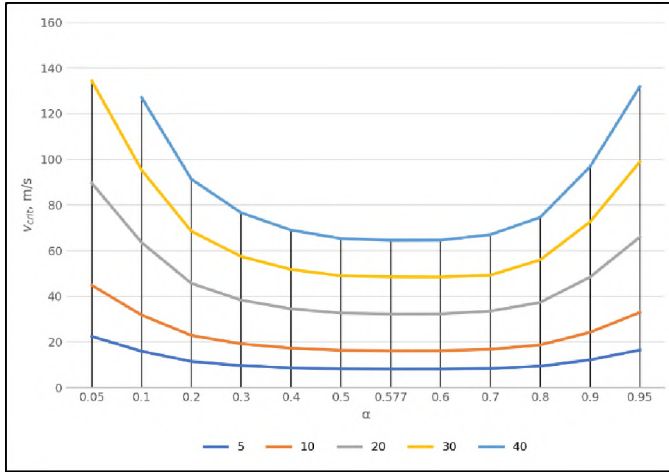
$$v_{boh} = \frac{A}{\sqrt{\alpha \cdot (1 - \alpha^2)}} \quad (18)$$

$$A = 0,25 \cdot \sqrt{\left(\frac{\rho_m}{\rho_q} - 1\right) \cdot g \cdot D}$$

At a relative coordinate of $\alpha=r/R=0.577$, the critical velocity reaches its minimum value, while the static pressure gradient attains its maximum value (graph 9). This specific relative coordinate has been substantiated as the critical zone inside the pipeline where the flow structure undergoes spatial destruction and where the pipe wall experiences the highest localized stresses.

³ Ситенков, В.Т. Теория градиентно-скоростного поля / В.Т.Ситенков. – М.: ОАО «ВНИИОЭНГ», – 2004. – 308 с.

The critical velocity decreases sharply with distance from the flow axis, reaches a minimum at $\alpha = 0.577$, and then increases again towards the pipe wall. Dynamic pressure loads for homogeneous and slug flow structures were modelled using expressions (11), (12) and (13) as functions of the flow density and the volumetric gas flow fraction (β).



Graph 9. Dependence of the critical velocity on α (at $A = 5, 10, 20, 30, 40$ m/s).

Calculations performed for a pipeline with $L = 10$ km, $D = 0.7$ m and $v = 2.16$ m/s (with gas as the continuous phase) yielded the following results:

In the homogeneous dispersed regime, the dynamic pressure load is $P_{dyn} = 12,337$ Pa.

In the slug flow regime, the dynamic pressure load rises to $P_{dyn} = 364,776$ Pa.

One of the principal causes of hydraulic shock waves and of the substantial pressure surges they produce in multiphase flows is the dynamic loads arising in such flows. Depending on the critical velocity and the density difference between the phases, these dynamic loads may be accompanied by significant hydraulic shock waves and may

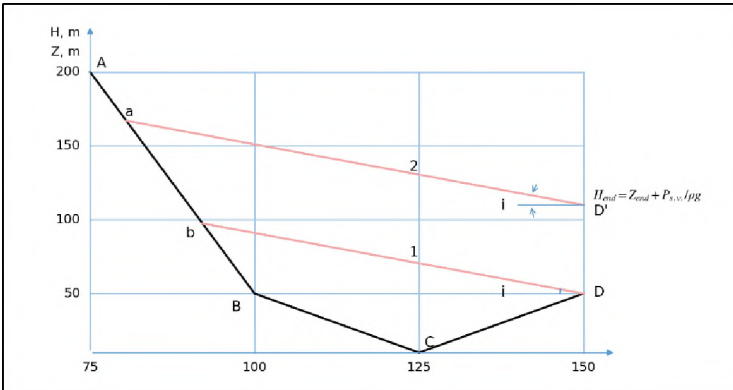
have a destructive effect, according to the flow structure and to which phase is dominant.

The study also examines how gas is released and multiphase flow zones form in oil pipelines over complex terrain downstream of summit (pass) points, where the piezometric head drops below the geodetic elevation. These zones, most frequent after operational shutdowns and accident-related spills, must be detected and located promptly. To identify them, i.e. to establish whether a summit point exists during operation, the hydraulic gradient is determined and its line is plotted on the pipeline's compressed profile.

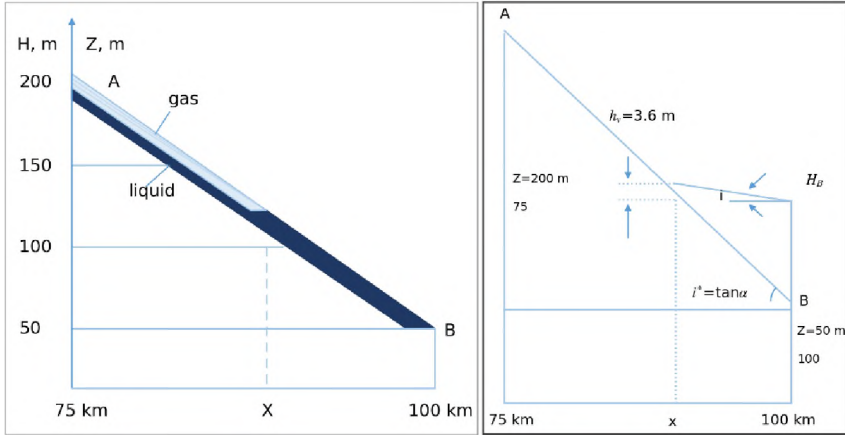
$$x = L_B - \frac{H_B - Z_B}{i^* - i} \quad (19)$$

$$l_{m.z} = x - L_A \quad (20)$$

Taking into account the vacuum head $h_v = P_{sat} / (\rho \cdot g)$ downstream of the summit point (A) on the compressed pipeline profile, the following equations were derived to determine the end coordinate (x) and the length ($l_{m.z.}$) of the multiphase flow zone, and graphs were constructed from the corresponding results (graphs 10, 11).



Graph 10. Formation of a multiphase zone in an oil pipeline downstream of the summit point (1 and 2 are the hydraulic gradient lines).



Graph 11. Multiphase flow zone in an oil pipeline and determination of its coordinates.

Where L_A , L_B are the coordinates of the summit point and of the end of the pipeline segment, respectively (km); Z_B is the geodetic elevation (m); H_B is the piezometric head at the end of the segment (m); i^* is the hydraulic gradient in multiphase flow; and i is the hydraulic gradient of single-phase oil flow.

The results of calculations performed for an oil pipeline with $L = 150 \text{ km}$, $D = 530 \text{ mm}$, $\rho = 850 \text{ kg/m}^3$ and $\nu = 15 \text{ cSt}$ are summarized in Table 4.

The control calculations have shown that when the transport flow rate is maintained at $Q_{min} = 511 \text{ m}^3/\text{h}$ ($v = 0.68 \text{ m/s}$) and the inlet pressure at $P_{in} = 1.38 \text{ MPa}$ (with $P_{out} = 0.1 \text{ MPa}$), the 9.89 km multiphase flow zone is completely eliminated and the pipeline changes over to a stable single-phase regime.

Table 4

Diagnostic and control parameters of the multiphase zone in an oil pipeline laid over complex terrain.

Calculated parameter	Calculated value	Physical interpretation and control effect
Coordinate of the summit point (L_A)	75.00 km	Geodetic summit on complex terrain where the multiphase zone begins
End coordinate of the multiphase zone (x)	84.89 km	End intersection point diagnosed on the basis of the head balance
Length of the multiphase zone ($l_{m.z}$)	9.89 km	Gas-filled zone causing imbalance and additional resistance in the pipeline
Minimum transport flow rate (Q_{min})	$511\text{ m}^3/h$	Minimum oil flow rate required to eliminate the zone completely
Required inlet pressure (P_{in})	1.38 MPa	Transport pressure that eliminates the multiphase zone at a hydraulic gradient of $i = 1.139\text{ m/km}$

Conclusion

1. The problems of evaluating and distributing dynamic loads in pipelines were considered for various structural regimes of multiphase flows, taking the critical velocity into account. It was shown that the dynamic pressure in separated slug flow patterns is several times higher than in flows with a dispersed structure. It was established that the dynamic loads arising when the gas phase is dominant (the continuous medium) are greater than those arising when the liquid phase is dominant, and that they increase with the ratio of the liquid and gas phase densities [1, 3, 12].

2. A method for evaluating and controlling dynamic loads in multiphase flows on the basis of a physical flow model has been developed [2, 12].

3. Methods have been proposed for the analysis and evaluation of hydraulic shocks arising in oil and oil product pipelines, and for the control of flows accompanied by such shocks [2, 9].

4. A numerical example has shown how the volume of the transported medium and of the pipeline changes during a hydraulic shock, taking into account the density of the transported medium [3, 5].

5. It has been shown that one of the major causes of the premature failure of field oil and gas pipelines is local structural changes associated with the presence of cavitating flows [4].

6. A method has been developed for diagnosing the structural changes and critical parameters in cavitating flows as functions of pressure and velocity variations [7].

7. Taking into account the resources of condensable petroleum gases, it has been established that in gas-condensate flows the transport pressure increases linearly with the equilibrium condensate fill fraction of the pipeline, regardless of the gas flow rate [11, 13].

8. On the basis of an analysis of the causes of multiphase flow zone formation during the operation of oil and oil product pipelines, a methodology has been developed for diagnosing the number and location of these zones and for controlling them, including preventing their formation, by means of the transport parameters [8, 15].

**The main content of the dissertation has been published in
the following works:**

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The author's personal contribution to the published works:

Works [4, 8, 11, 15] were carried out by the author independently.

In works [2, 3, 5, 7, 13], the applicant developed the research concept and the methodology, and carried out the processing of the results and the analysis of the data.

In works [1, 6, 9, 10, 12, 14, 16], the applicant carried out the processing of the results and the analysis of the data.



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