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# ANALYTICAL CRITERION FOR THE STRENGTH OF BONDED-DISPERSED GELS DURING PIPELINE TRANSPORTATION

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**Abstract**. Modern pipeline systems, both main and industrial, allow transporting a wide range of liquid and gaseous substances, including a variety of solid bulk materials, minerals, building materials and mixtures. However, the development of pipeline transport systems today is hindered by the lack of theoretical developments in the implementation of practical engineering projects for the creation of both main and industrial product pipelines for various purposes. Therefore, the further development of the theory of flows of various substances in pipelines and the creation of universal methods for engineering calculations of design parameters of pipeline systems based on this theory are priority tasks for the further development of product pipeline transport. The studies were carried out in accordance with the condition of stochastic transformation of the coagulation-thixotropic structure of the gel flow into sol. Such a stochastic transformation of the coagulation-thixotropic structure can be observed both when reaching the mode that determines the turbulent motion of a viscous colloidal solution, and somewhat earlier – at the stages of the laminar flow regime of the solution. Based on the formal phenomenological analysis, it has been determined that during the transition of the laminar mode of motion of the Newton fluid flow in a cylindrical tube to the turbulent mode, the transported structured gel flow is guaranteed to collapse into a colloidal sol. Based on the example of a typical design calculation of a technological (production) pipeline for the transportation of motor oils of the SAE-10 and SAE-40 grades, the optimal conditional internal diameters of the product pipeline were determined. The compliance of the design structural parameters of the pipelines with the corresponding physical and mechanical properties of the transported liquids was established. The proposed methods of engineering calculations of design parameters for technical objects of pipeline transport should expand and supplement the regulatory documentation for the preparation of projects for the construction of both main product pipelines and technological "interoperable" production pipelines

**Keywords**: pipeline, flow, gel, laminar mode, turbulent mode, pipeline design parameters

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## INTRODUCTION

The accelerated development of pipeline transport systems in the second half of the 20th century is conditioned by its technical efficiency and significant operational advantages compared to other technologies for transporting various materials [1-3]. In particular, these are such advantages as: large capacity due to the continuity of the transport process [2]; the absence of intermediate operations that require the creation of special equipment and training of qualified support personnel [1; 3]; the absence of transport losses of material [2]; transport and environmental safety for the implementation of the transportation process and minimisation of landscape and destruction violations [2]; independence from weather and climatic conditions [3].

At the same time, the improvement of the technical capabilities of pipeline transport, the appearance and technical improvement of hydraulic transport systems [3] facilitated the significant expansion of the range of transported substances and materials [4; 5]. Modern pipeline systems, both main and industrial, allow transportating various solid bulk materials [2; 4], minerals [6], building materials and mixtures [2], industrial and household waste [3], chemical raw materials and substances [2; 7; 8], etc. However, prolonged stay in pipelines and changes in transportation modes lead to changes in the properties and characteristics of the transported substances and materials [7; 9; 10]. At the same time, these changes can both worsen and improve the quality of not only the materials transported by pipelines, but also the liquid "technological carrier of the transported material" [6; 11]. It is stochastic changes in the quality indicators of substances and materials transported in pipelines that necessitate in-depth experimental studies aimed at developing theoretical foundations and practical recommendations for the optimisation of the motion of pressure and gravity flows of gels and sols in pipelines [6; 11; 12].

During the operation of main oil pipelines, deposits in the form of resinous-paraffin compounds accumulate on the internal surfaces of pipes, and intense corrosion and stratification of metal is observed [12]. This leads to a decrease in the working cross-section of the pipeline, an increase in the absolute roughness of the inner walls of pipes, and consequently, to an increase in hydraulic resistance, a decrease in the service life of pipelines, and a reduction in the volume of petroleum products pumped [2]. To prevent these negative processes, from the moment the pipeline is put into operation and during the entire period of its service life, there is a need for periodic cleaning of the internal surfaces of pipes of main oil pipelines [1; 3; 13-15]. The use of so-called "gel pistons" has become widely used for cleaning the internal surfaces of product pipes [13; 15]. The basis for the manufacture of the gel piston is polyacrylamide (PAA), which is able to form a branched spatial structure, which gives viscoelastic properties to the "gel separator of petroleum products". As a result, the so-called gel piston creates a proppant effect and when it moves through the pipeline, it completely covers the internal working section of the pipe and all deposits of dirt and resinous-paraffin compounds are collected in the tail part of the piston in the course of its motion [12; 13; 15].

However, theoretical developments in the field of hydrodynamics of complex colloidal flows today are mostly semi-empirical [2; 12; 14] and are far from exhaustive and complete. It significantly complicates the application of these theoretical developments in the implementation of practical engineering projects for the creation of both main and industrial product pipelines for various purposes. As for experimental studies of hydrodynamics of complex colloidal flows, including methods of physical modeling of the dynamics of these flows, and corresponding engineering and technological equipment, such studies require significant capital expenditures [4; 6; 11] and fail to provide generalised universal results [2; 3].

Thus, the further development of the theory of dispersed flows of gels and soles in pipelines and the development of universal (generalised) methods of engineering calculations of design parameters of systems and individual technical objects of pipeline transport based on the appropriate analytical studies are priority tasks for the further development of product pipeline transport.

*The purpose of the study* is to ensure stabilisation of the quality indicators of substances and materials transported by pipeline transport systems.

## MATERIALS AND METHODS

The study considers the motion of a viscous fluid between two parallel layers, which is caused by some infinitesimal shear stress (Fig. 1).

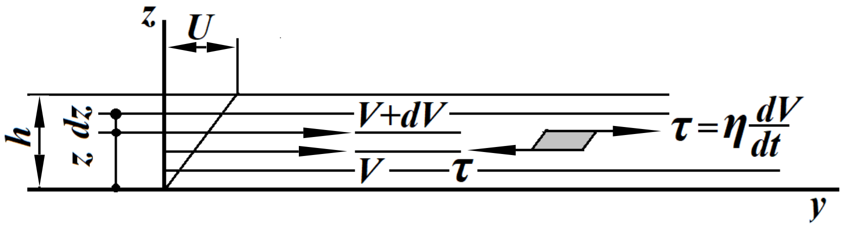

***Figure 1**. Motion of a viscous structured liquid between two parallel layers*

Assume that the velocity of a liquid at a certain zdepth is v, which means that the change in this velocity over depth $z$ (velocity gradient) will be $dv/_{dz}$. In general (see Fig. 1) the velocity gradient will be defined as [13; 14]:

$$\frac{dv}{dz} = \frac{v}{h} = \frac{1}{h} \cdot \frac{du}{dt} = \frac{d\left(\frac{u}{h}\right)}{dt} \qquad (1)$$

In equation (1), the value $u/_{h}$ is the offset gradient, which we will later denote as $\gamma$. And then it follows from equation (1) that the time derivative of the offset gradient $\dot{\gamma}$ is equal to the velocity gradient $dv/_{dz}$:

$$\dot{\gamma} = \frac{dv}{dz} \qquad (2)$$

Therefore, the tangential stress $\tau$ that occurs between the liquid layers will be proportional to the ratio of the velocity difference in the liquid layers to the distance $dz$ between these adjacent infinitely closely located thin layers. Within each of these layers, it is assumed that the velocity in the liquid layer is a steady-state value and changes by a value $dv$ only when crossing the boundary between neighboring layers. Then:

$$\tau = \eta \cdot \frac{dv}{dz} \qquad (3)$$

where: $dv$ – velocity difference in adjacent liquid layers; $dz$ – distance between the midpoints of the adjacent liquid layers under consideration (layer thickness); $\eta$ – dynamic viscosity, which is essentially a tangential stress, which is necessary to cause the liquid layers to move relative to each other at a speed equal to 1.

Given equations (3) and (1), the dynamic viscosity has the dimension of the product of tangential stress and time. Taking into account equation (2), the following is obtained:

$$\tau = \eta \cdot \dot{\gamma} \qquad (4)$$

The resulting equation (4) is essentially a formalised expression of Newton's law of viscosity, which models (Fig. 2) phenomenological properties of a viscous rheological body [5; 12] and determines the dynamics of motion [5] of a viscous liquid in a cylindrical tube (Fig. 3).

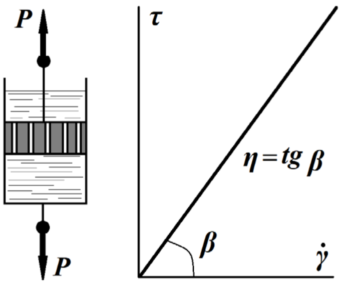

***Figure 2**. Model of a Newtonian rheological body (viscous fluid flow):*

$P$ – shear forces applied to the model; $\eta$ – dynamic viscosity of the liquid; $\tau$ – tangential stresses between the liquid layers; $\dot{\gamma}$ – derivative of the displacement gradient between the liquid layers

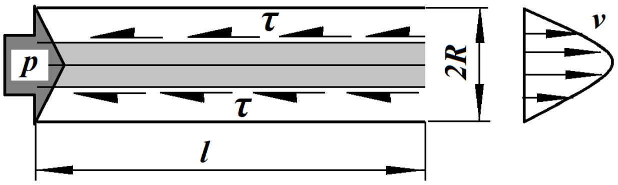

***Figure 3**. The motion of a viscous Newton fluid in a cylindrical tube*

Consider a cylindrical liquid column with radius $r$ and length $l$. The side surface of such a column will be $2 \cdot \pi \cdot r \cdot l$, and the total resistance to fluid motion will be $2 \cdot \pi \cdot r \cdot l \cdot \tau$ ($\tau$– tangential stresses between the liquid layers, see Fig. 2). If the specific pressure on the considered column of liquid with a radius $r$ is $p$ and, accordingly, the total pressure is equal to $p \cdot \pi \cdot r^2$, then the equilibrium condition for the considered column of liquid will be:

$$p \cdot \pi \cdot r^2 - 2 \cdot \pi \cdot r \cdot l \cdot \tau = 0 \qquad (5)$$

from where:

$$\tau = \frac{p \cdot r}{2 \cdot l} \qquad (6)$$

In equation (1), the value $z$ is substituted with the radius $r$ of the liquid column under consideration:

$$dv = \dot{\gamma} \cdot dr \qquad (7)$$

From equation (3) and taking into account (6) and (7), the following is defined:

$$dv = \frac{p}{2 \cdot l \cdot \eta} \cdot r \cdot dr \qquad (8)$$

and after integrating expression (8), the following is obtained:

$$v = \frac{p}{4 \cdot l \cdot \eta} \cdot r^2 + \mathrm{C} \qquad (9)$$

An arbitrary constant $C$ can be determined if the boundary conditions for (9) assume that the liquid layer that is directly in contact with the inner wall of the pipe has a velocity $v = 0$. And then, if $r = R$ (Fig. 3) the following is obtained:

$$C = -\frac{p}{4 \cdot l \cdot \eta} \cdot R^2 \qquad (10)$$

and, as a consequence:

$$v = -\frac{p}{4 \cdot l \cdot \eta} \cdot (R^2 - r^2) \qquad (11)$$

The sign "–" in equation (11) means that the motion of fluid occurs in the opposite direction to the increase in pressure $p$. Therefore, it follows from equation (11) that the distribution of the fluid velocity over the longitudinal section of the cylindrical flow is delineated by a parabola with an extremum (maximum) lying on the longitudinal axis of the section. Assuming that $r \to 0$, then:

$$v_{max} = \frac{p}{4 \cdot l \cdot \eta} \cdot R^2 \qquad (12)$$

$v_{max}$ determines the flow rate of the fluid (productivity of the product pipeline $Q$) by the formula for the paraboloid of rotation (Poiseuil equation) [12]:

$$Q = \frac{1}{2} \cdot \pi \cdot R^2 \cdot v_{max} \qquad (13)$$

From where, taking into account (12), the following is obtained:

$$Q = \frac{\pi}{8} \cdot \frac{p}{l \cdot \eta} \cdot R^4 \tag{14}$$

Thus, the obtained equation allows analysing the flow volumes in pipelines and the critical value of the flow rate in terms of the transition of the laminar flow regime to the turbulent one, determined by the Reynolds number:

$$Re = \frac{\rho \cdot v \cdot D_h}{\eta} = \frac{v \cdot D_h}{\nu} = \frac{Q \cdot D_h}{\nu \cdot A} \tag{15}$$

where: $\rho$– density of the liquid (colloidal gel); $v$ – characteristic flow rate; $D_h$– hydraulic diameter (inner diameter of the product line); $\eta$ – dynamic viscosity of the fluid (colloidal gel); $\nu$ – kinematic viscosity of the fluid (colloidal gel); $Q$ – flow rate (product pipeline capacity $Q$); $A$ – internal cross-sectional area of the pipe.

At the same time, the transition of the laminar flow mode to the turbulent one is guaranteed to lead to the destruction of the transported structured gel flow into a colloidal sol.

## RESULTS AND DISCUSSION

Admittedly, the main sign of the destruction of the coagulation-thixotropic gel system is the destruction of the spatial structure formed by the dispersed component (phase) of the colloidal solution. And the nature and moment of onset of such destruction are determined mainly by the internal diameter $2R$ (or $D_h$ and $A$) of the product pipeline, its productivity $Q$, flow rate $v$, characteristics of the coagulation-thixotropic gel system $\rho$, $\eta$, $\nu$, specific pressure $p$ in the product pipeline, tangential stresses $\tau$ and the velocity gradient $dv/_{dz}$.

The condition for stochastic transformation of the gel transported by the pipeline (coagulation-thixotropic structure) into sol is the destruction of its spatial structure, which is formed by the dispersed phase of the colloidal solution. Such a stochastic transformation of the coagulation-thixotropic structure can be observed both when reaching the mode that determines the turbulent motion of a viscous colloidal solution, and somewhat earlier – at the stages of the laminar flow regime of the solution. In this case, the average movement speed of the colloidal solution in the pipe according to the Poiseuil equation in accordance with (13) and (14) will be:

$$v_{avg} = \frac{Q}{\pi \cdot R^2} = \frac{1}{8} \cdot \frac{p}{\eta \cdot l} \cdot R^2 \tag{16}$$

Given that the values of the tangential stresses can be determined from the dependence (6) and for $r = R$, the following is obtained:

$$v_{avg} = \frac{1}{4} \cdot \frac{\tau}{\eta} \cdot R \tag{17}$$

If the maximum tangential stress that causes stochastic destruction of the spatial structure of the dispersed phase of a colloidal solution is $\tau_{max}$, then, consequently, (17), the following is obtained:

$$v_{cs}^{(1)} = \frac{1}{4} \cdot \frac{\tau_{max}}{\eta} \cdot R \tag{18}$$

where: $v_{cs}^{(1)}$ – critical velocity of the laminar mode of movement of a gel colloidal solution at which the spatial structure of its dispersed phase is destroyed in a pipeline with an internal pipe radius $R$.

The critical rate of transition of the laminar mode of motion of a gel colloidal solution to the turbulent mode of motion, which leads to the destruction of its spatial structure, according to the Reynolds criterion Re (15), will be:

$$v_{cs}^{(2)} = \frac{Re}{2} \cdot \frac{\eta}{\rho \cdot R} \tag{19}$$

where: $v_{cs}^{(2)}$ – critical rate of transition of the laminar mode of motion of the gel colloidal solution to the turbulent mode, at which the spatial structure of the dispersed phase of the solution is guaranteed to be destroyed in a pipeline with an internal pipe radius $R$.

Equation (18) shows that the critical velocity of the motion of gel colloidal solution at which the spatial structure of the dispersed phase is destroyed under laminar conditions in the pipeline increases with the internal pipeline diameter. On the other hand, as follows from equation (19), the rate at which the movement of the viscous gel in the pipeline acquires signs of turbulence, which is guaranteed to cause the destruction of the coagulation-thixotropic structure of the colloidal solution, is higher.

Upon equating (18) and (19), the following is obtained:

$$\frac{1}{4} \cdot \frac{\tau_{max}}{\eta} \cdot R = \frac{Re}{2} \cdot \frac{\eta}{\rho \cdot R} \tag{20}$$

Having defined the internal radius of the pipeline at which both critical velocities are equal to each other as the critical radius $R_{cs}$, the following is obtained:

$$R_{cs} = 2 \cdot \eta \cdot \sqrt{\frac{Re}{2 \cdot \rho \cdot \tau_{max}}} \tag{21}$$

A graphical interpretation of dependencies (18), (19), and (21) is shown in Figure 4.

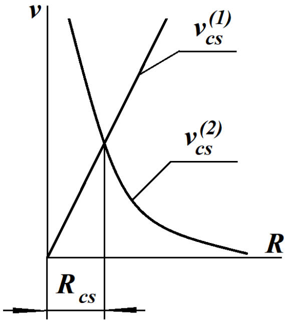

***Figure 4**. Critical flow rates of the coagulation-thixotropic structure of a colloidal solution in a product pipeline*

Following from the analysis of Figure 4, at $R<R_{cs}$, the coagulation-thixotropic structure of the colloidal solution in the pipeline is destroyed, it occurs before the

movement of the liquid flow reaches the turbulent regime. At the same time, at $R>R_{cs}$, the turbulent regime, the gel flow begins at a certain velocity value $v_{cs}$, which is still safe to prevent stochastic destruction of the coagulation-thixotropic structure of the gel.

To prevent the stochastic destruction of coagulation-thixotropic structures of gel flows in pipelines, it is necessary to distinguish several important characteristic values of tangential stresses $\tau$:

– the elastic limit $\tau_{el}$, which in this case coincides with the yield strength and at $\tau<\tau_{el}$, the flow of a colloidal solution with a coagulation-thixotropic structure is viscous, cannot be observed;

– conditional limit $\tau_{м}$ of the initial strength of the structure; up to this limit, the spatial coagulation-thixotropic structure is preserved without destruction;

– conditional yield strength $\tau_{fB}$ (according to Bingham); beyond this limit, uncontrolled avalanche-like stochastic destruction of the coagulation-thixotropic structure begins (Fig. 5);

– the limit $\tau_B$ of structural viscosity, upon reaching which there is a gradual transition to a viscous flow of "Newtonian fluid";

– the conditional limit $\tau_{cm}$ of ultimate destruction of a coagulation-thixotropic structure (ultimate structural strength); at $\tau>\tau_{cm}$, a dispersed system (solution), as a rule, can only be in the form of sol and reveals only the properties of a rheological Newton body (viscous fluid flow).

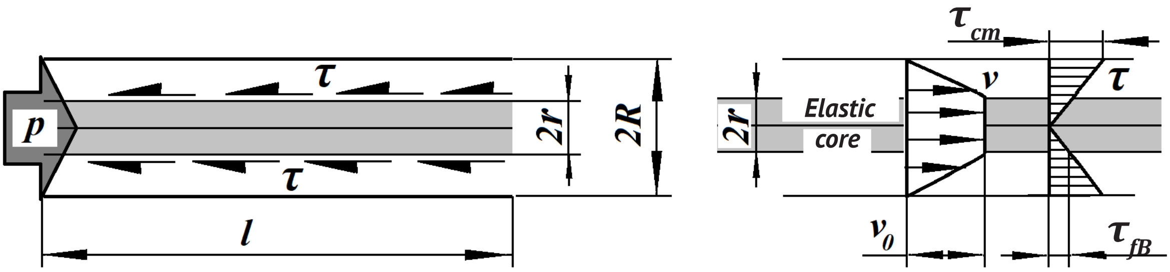

***Figure 5**. Movement of the Bingham rheological body in the cylindrical tube of the product pipeline*

Consequently, the nature of deformation of the structure of a gel-like coagulation-thixotropic colloidal solution during transportation in the pipe of the product pipeline continuously changes. The "rheological models" (rheological characteristics) and corresponding mechanical properties of such structures change.

Next, the study considers the possibility of practical application of the obtained analytical results at the design stage of technological (production) pipelines for transportation of SAE-10 and SAE-40 engine oils. The main physical characteristics of these lubricants are as follows: dynamic viscosity – $\eta = 0.065$ $(Pa \cdot c)$ for the SAE-10 brand and $\eta = 0.319$ $(Pa \cdot c)$ for the SAE-40 brand; density – $\rho = 800$ $\left(kg/m^3\right)$ for both brands; destruction limit of the coagulation-thixotropic structure of the oil – $\tau_{cs} = 0.02$ $(Pa)$ – pressure-free gravity flow and $\tau_{cm} = 20$ $(Pa)$ flow movement created in the pipe by pumps SP1, SP2 and GP3; Reynolds criterion – $Re = 2500$.

The results of design calculations of technological (production) pipelines for transportation of SAE-10 and SAE-40 engine oils are presented in Table 1.

***Table 1**. Results of design calculations of optimal pipeline diameters for the transportation of SAE-10 and SAE-40 engine oils*

| **Property indicator** | **SAE-10 engine oil** | | **SAE-40 engine oil** | |
|---|---|---|---|---|
| | **flow motion generated by pumps SP1, SP2 and GP3** | **gravity-fed flow motion** | **flow motion generated by pumps SP1, SP2 and GP3** | **gravity-fed flow motion** |
| Dynamic viscosity $(Pa \cdot c)$ | 0.065 | 0.065 | 0.319 | 0.319 |
| Density, $kg/m^3$ | 800 | 800 | 800 | 800 |
| Structure destruction limit, $Pa$ | 0.2 | 20 | 0.2 | 20 |
| Reynolds criterion | 2500 | 2500 | 2500 | 2500 |
| Flow radius, $m$ | 0.5 | 0.05 | 1.2 | 0.13 |
| Optimal product pipeline diameters, mm:<br>– minimum<br>– maximum | 100<br>not limited | | 250<br>not limited | |

The above example of design calculation shows the possibility of further development and creation of a universal regulatory framework that would be clearly focused on the needs of designers of pipeline transport systems for main product pipelines and for purely technological “interoperable” production pipelines. At the same time, such technological pipelines under certain production conditions would not only maintain the quality indicators of the transported materials, but under certain transportation modes they could perform specific production functions, such as certain technological operations aimed at obtaining finished products.

## CONCLUSIONS

The proposed analytical method of engineering optimisation of the design diameter of the transport pipeline, based on the strength criterion of bound-dispersed coagulation-thixotropic gel structures, allows establishing optimal technical characteristics of the pipeline at the design stage, in particular, the conditional internal diameter of the pipe, steel (cast iron) product pipelines. The basis for such optimisation was the basic physical properties of the transported material (density, kinematic and dynamic viscosity, tangential shear stresses), as well as the structural and technological parameters of the pipeline (productivity or technological flow rates, speed of the transported gel, specific pressure in the product pipeline). Optimised structural and technological parameters of “interoperable” production pipelines provide not only transport functions through technological transitions, but can also be included in production processes as direct technological operations.

Further studies of dispersed flows of gels and soles in pipelines should be aimed at improving universal (generalised) methods of engineering calculations of design parameters of systems and individual technical objects of pipeline transport and the development of appropriate regulatory documentation. Such measures would ensure the automation of design work at the stage of preparation of projects for the construction of both main product pipelines and technological "interoperable" production pipelines.

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# АНАЛІТИЧНИЙ КРИТЕРІЙ МІЦНОСТІ ЗВ'ЯЗАНО-ДИСПЕРСНИХ ГЕЛЕЙ ПРИ ТРАНСПОРТУВАННІ ЇХ У ТРУБОПРОВОДАХ

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**Анотація**. Сучасні трубопровідні системи, як магістральні, так і промислові, дозволяють транспортувати широку номенклатуру не лише рідких і газоподібних речовин, але й різноманітні тверді сипкі матеріали, корисні копалини, будівельні матеріали та суміші тощо. Однак, розвиток трубопровідних транспортних систем в сучасних умовах стримується недостатністю теоретичних напрацювань за реалізації практичних інженерних проектів створення як магістральних, так і промислових продуктопроводів різного призначення. Отже, подальший розвиток теорії потоків різноманітних речовин у трубопроводах і створення на підставі цієї теорії універсальних методів інженерних розрахунків проектних параметрів трубопровідних систем є пріоритетними завданнями для подальшого розвитку продуктопровідного транспорту. Дослідження виконувались відповідно до умови стохастичного перетворення коагуляційно-тиксотропної структури гелевого потоку в золь. Таке стохастичне перетворення коагуляційно-тиксотропної структури може спостерігатись як за досягнення режиму, що визначає турбулентний рух в'язкого колоїдного розчину, так і дещо раніше – на стадіях ламінарного режиму течії розчину. На підставі формально-феноменологічного аналізу визначено, що під час переходу ламінарного режиму руху потоку рідини Ньютона у циліндричній трубі в турбулентний режим гарантовано відбувається руйнування транспортованого структурованого гелевого потоку в колоїдний золь. На підставі прикладу типового проектного розрахунку технологічного (виробничого) трубопроводу для транспортування моторних олив марок SAE-10 та SAE-40 визначено оптимальні умовні внутрішні діаметри труб продуктопроводу, встановлено відповідність проектних конструкційних параметрів трубопроводів відповідним фізико-механічним властивостям транспортуємих рідин. Пропоновані методи інженерних розрахунків проектних параметрів технічних об'єктів трубопровідного транспорту мають розширити та доповнити типову нормативну документацію підготовки проектів будівництва як магістральних продуктопроводів, так і технологічних «міжопераційних» виробничих трубопроводів

**Ключові слова**: трубопровід, потік, гель, ламінарний режим, турбулентний режим, проектні параметри трубопроводу