DOI: 10.17122/ntj-oil-2020-2-80-90
УДК 622.692.43.004

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EVALUATION OF ABOVE-GROUND PIPELINE STRESS-STRAIN STATE AT DIFFERENT FRICTION COEFFICIENTS

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ОЦЕНКА НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ НАДЗЕМНЫХ ТРУБОПРОВОДОВ ПРИ РАЗЛИЧНЫХ КОЭФФИЦИЕНТАХ ТРЕНИЯ

Background

The shifting of the key work scope of main pipeline construction to the regions with permafrost and difficult climate conditions because of the dislocation of oil and gas extraction centers to the new regions is the characteristic of pipeline transportation development in Russia in recent years. According to analysts, the reclamation of hydrocarbon fields in the areas with the permafrost soils in arctic and subarctic regions is going to carry forward in the coming years; in such areas the above-ground pipelines on supports are the optimal structural design [1]. However, as of today, the real conditions of working of linearly extended above-ground pipelines at permafrost are not sufficiently studied [2]. This article is concerned with one of the valid scientific objectives of this field – the study of the stress-strain state of above-ground pipelines at different friction coefficients at supports.

Введение

Характерной особенностью развития трубопроводного транспорта России за последние годы является смещение основного объема работ по строительству магистральных трубопроводов в районы со сложными мерзлотно-грунтовыми и климатическими условиями в результате смещения центров добычи нефти и газа в новые регионы страны. По прогнозам аналитиков, в ближайшей перспективе продолжится активное освоение месторождений углеводородов в районах распространения многолетнемерзлых грунтов (ММГ) на арктических и приарктических широтах, где оптимальной является надземная конструктивная схема прокладки трубопроводов на опорах. Однако на сегодняшний день действительные условия работы линейно-протяженных надземных трубопроводов на ММГ изучены недостаточно. Данная работа посвящена одной из актуальных научных задач в этой области: оценке напряженно-деформированного состояния (НДС) надземных магистралей с учетом сил трения на опорах.

Aims and Objectives

The main purposes of the article are the study of the friction force's influence at supports on the stress-strain state of linearly extended above-ground pipelines with trapezium-shaped compensation parts and the definition of the most optimal structural design that could minimize stress-strain state under construction at permafrost.

Methods

In compliance with the object and purpose, the following methods were used: analysis, comparison, generalization, and mathematical simulation (finite element analysis).

Results

The dependencies of pipeline's peak transversal displacements (in horizontal plane) and stresses appearing in the deformation's self-compensation process (in working state) on system's design factors at different friction coefficients at supports (for various sliding friction pairs) were obtained as a result of the study of stress-strain state of an above-ground pipeline with trapezium-shaped compensator with the application of mathematical simulation.

Цели и задачи

Основными целями исследования являются оценка влияния сил трения на опорах на напряженно-деформированное состояние линейно-протяженных надземных трубопроводов с компенсационными участками трапециевидной формы и определение наиболее оптимальных конструктивных решений из условия минимизации НДС при их строительстве на ММГ.

Методы

Для достижения поставленной цели были использованы следующие методы исследования: анализ, сравнение, обобщение и математическое моделирование (конечно-элементный анализ).

Результаты

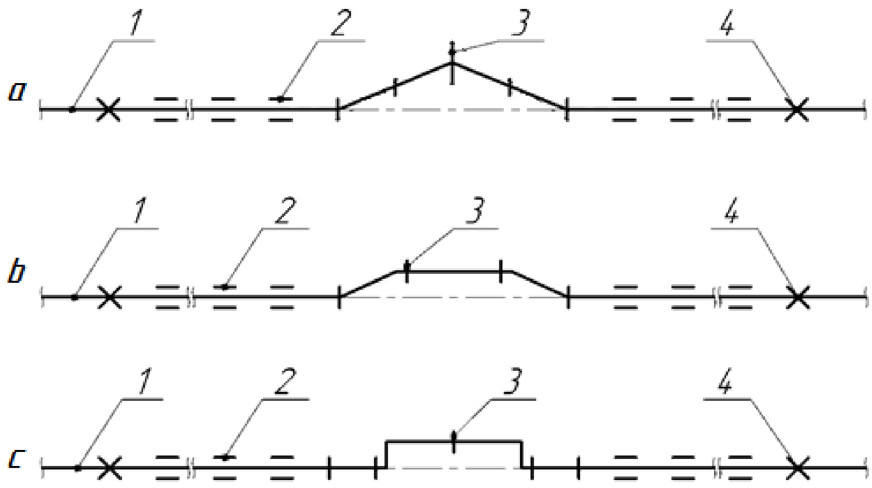
В результате исследования напряжённо-деформированного состояния участка надземного трубопровода с компенсатором трапециевидной формы посредством математического моделирования получены зависимости максимальных поперечных перемещений трубопровода (в горизонтальной плоскости) и напряжений, возникающих в процессе самокомпенсации деформаций (в рабочем состоянии), от конструктивных параметров системы при различных коэффициентах трения на опорах (для различных скользящих пар трения).

Key words: above-ground pipeline; stress-strain state; friction coefficient; sliding supports; trapezium-shaped compensator; mathematical simulation; finite element analysis

Ключевые слова: надземные трубопроводы; напряженно-деформированное состояние; коэффициент трения; подвижные опоры; трапециевидный компенсатор; математическое моделирование; конечно-элементный анализ

The compensation of longitudinal deformation requires special attention in the process of the extensive above-ground pipeline construction in permafrost areas characterized by considerable temperature difference [1, 2]. This compensation should be provided by using the special compensator parts (Figure 1) and the supports of various designs [3–5].

The supports of the above-ground pipeline are divided into fixed (FS) and sliding (SS) by the way of working. Sliding supports come in two types: linear-sliding (LSS) and free-sliding (FSS). Linear-sliding supports are used at the straight sections of the above-ground pipelines (except for the supports of the compensating section), and they ensure the pipeline axis translation. It is better to use free-sliding supports at the compensatory section where they should ensure the free pipeline transition in the horizontal plane under the deformations coming from seasonal and daily temperature differences, and internal product pressure in the pipeline [6, 7].



1 – pipeline; 2 – suspension linear-sliding support;
3 – suspension free-sliding support; 4 – fixed support

Figure 1. Scheme of straight-line laying of pipelines with curved compensation sections: triangular compensator (a); trapezium-shaped compensator (b); U-shaped compensator (c)

Friction force appears at the sliding supports in the process of above-ground pipeline exploitation and prevents transversal displacements of the pipeline. The friction force of sliding equals the reaction of the support (gravity force) multiplied by friction coefficient that depends on the material and physical condition of friction surfaces. The sliding friction pair of the sliding supports of the above-ground pipeline is made from antifriction, wear-resistant and corrosion-resistant materials. Table 1 presents the main considered variants of friction surfaces for sliding supports and corresponding approximate values of friction coefficient [8].

According to the study of stress-strain behavior (deformability) of above-ground pipeline, the friction forces at the supports influence significantly the stress-strain state of the pipeline; the study was conducted by specialists of laboratory of pipelines constructed in special environment (VNIIST) with the use of experimental model of straight section with slightly curved triangular compensator [9–12]. This influence was additionally proved by the field tests on the real gas pipeline in permafrost [13, 14].

Adding to that, in the scope of this research, it was defined that, considering all the pros and cons of triangular, trapezium-shaped, and U-shaped compensators, the trapezium-shaped compensator is optimal for linearly extended above-ground pipelines [15, 16]. The analysis of the largest pipeline projects at permafrost in the latest years has also proven this fact (ex. the Zapolyarye – Purpe, the Vankor Field – Purpe, Eastern Siberia – Pacific Ocean) [5, 6].

This research has studied the influence of the force of friction at supports on the stress-strain state of above-ground pipelines with trapezium-shaped compensator sectors.

Mathematical simulation of the «real» above-ground pipeline in ANSYS (R 17.1) was used to evaluate the stress-strain state of the mentioned systems with consideration to friction coefficient [12].

The authors have preliminary calculated the main design factors of the above-ground pipeline and have defined the actual load to create the correct mathematical simulation according to the current technical guidance document (Table 2) [17, 18].

Table 1. Approximate values of the friction coefficient

Sliding friction pair	Friction coefficient, *Kfr*
Carbon steel to carbon steel (no corrosion)	0.3
Teflon to carbon steel (no corrosion)	0.2
Teflon to Teflon, or polished stainless steel	0.1
Roller bearing or ball bearing	0.05

Table 2. The basic input for modeling

The basic input for calculations:	According to the current technical guidance document:
outside diameter pipeline – 1020 mm	wall thickness pipeline – 28 mm
tensile/yield strength – 640/555 MPa	the estimated weight of the pipeline, taking into account the existing loads – 16.02 kN/m
operating pressure – 10 MPa	
section category – II	the span between supports (*l*), taking into account the possible subsidence of the intermediate supports at permafrost – 20 m
product – oil	
location of construction – Urengoy	

Following, the authors have performed the series of calculations to evaluate the stress-strain state of the above-ground pipeline section under the different friction coefficients at sliding supports (Table 1) subject to the following design parameters of the system: (1) distance between fixed supports (*L*); (2) the length of compensator (*Lc*); (3) and the angle of inclination of the branch of the compensation section (*α*). The optimal system design factors, taking into account the variable parameters and friction forces at supports, were defined as the result of the FE analysis made in ANSYS.

It is important to note, that the friction coefficient at supports influences the deformability and stress-defined state of above-ground pipeline despite the system's load conditions; at that, the relationship is non-linear (Figure 2).

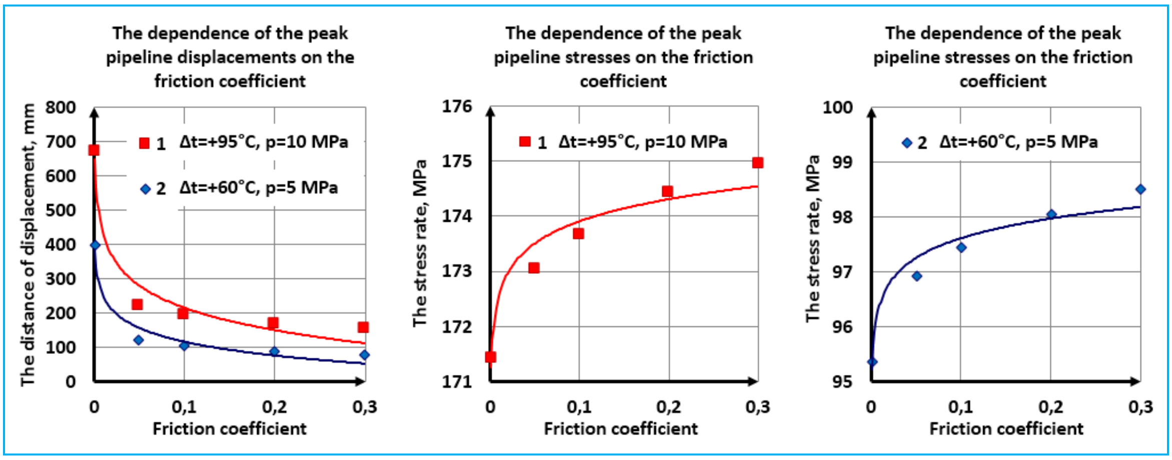


Figure 2. The dependence of the transverse displacements of the pipeline and stresses on the change of friction coefficient at the supports

The dependence of the stress-strain state of an above-ground pipeline on the distance between fixed supports (L) under different friction coefficients at the supports (Kfr)

Figure 3 shows the scheme of the above-ground pipeline section being modeled with the trapezium-shaped compensator. The constant design factors of the system are *l* = 20 m, *Lc* = 78 m, *α* = 45°. Factor *L* varies from 238 to 478 m in increments of 4*l* (80 m) under various support conditions (*Kfr* = 0.05-0.30). The graphic presentation of the results of the calculations (Figure 3) shows that the dependences of pipeline transverse displacements and peak stresses on the distance between the fixed supports (*L*) in the case of straight-line construction with trapezium-shaped compensators are known to have linear character despite the friction coefficient at supports (*Kfr* = 0.05-0.30).

However, it is important to note, other things being equal, the numerical value of peak displacement at *Kfr* = 0.3 is approximately twice as little than at *Kfr* = 0.05, and the value of peak stress at *Kfr* = 0.30 is marginally bigger than at *Kfr* = 0.05.

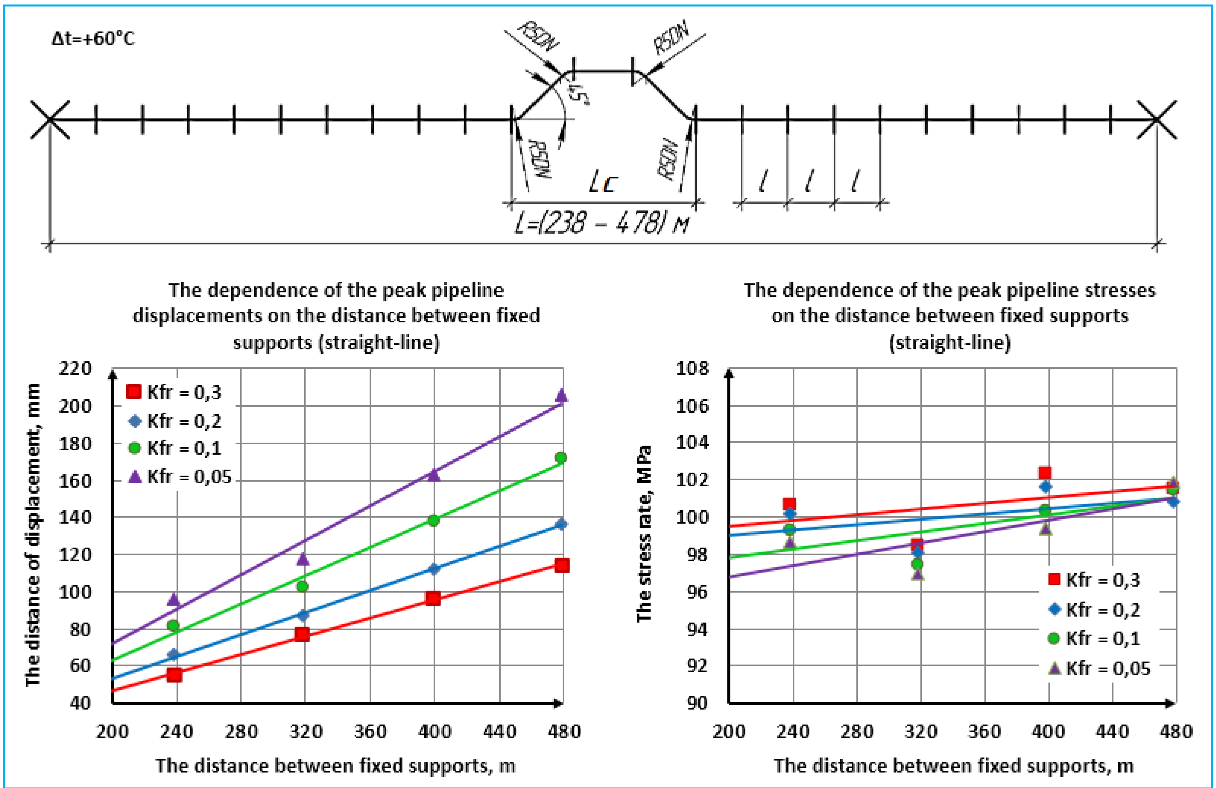


Figure 3. The dependence of the transverse displacements of the pipeline and stresses on the change in the value of *L* at various friction coefficients at the supports

Dependence of the stress-strain state of the above-ground pipeline on the length of the compensation section (Lc) at various friction coefficients at the supports (Kfr)

Let's take into consideration the straight-line section of the above-ground pipeline with trapezium-shaped compensator which length varies according to a number of spans at the top (54 m, 78 m, 126 m which means 2, 3, and 5 spans corresponding) under different support conditions (*Kfr* = 0.05–0.30). Figure 4 shows the scheme and the results of the FE analysis for the section mentioned.

Having analyzed the results of the calculations, we can see that at *Kfr* = 0.3 and *Kfr* = 0.2 the transversal displacements of the system are minimal at *Lc* = 78 m (3 spans). The displacements rise significantly at *Lc* = 54 m (2 spans) and *Lc* = 126 m (5 spans). At *Kfr* = 0.10 and *Kfr* = 0.05 the transversal displacements of the system are minimal at *Lc* = 126 m (5 spans). The values of peak stresses, occurring at the branches, adjoining the straight-line section, are approximately equal at *Lc* = 54 m and *Lc* = 126 m, but at *Lc* = 78 m these values are minimal at all the friction coefficients at the supports given.

Consequently, under the condition of minimization of stress-strain state of the pipeline, at *Kfr* = 0.3 and *Kfr* = 0.2, the rational system is a system with compensator's length of *Lc* = 78 m (3 spans). At *Kfr* = 0.1 and *Kfr* = 0.05, it is a system with compensator's length of *Lc* = 126 m (5 spans). At this length of the compensator section, the length of supports' grillages would be minimal thus boosting the system's cost-effectiveness. At *Kfr* = 0.3 and *Kfr* = 0.2, the system with the value of *Lc* = 126 m (5 spans) falls short of the one with *Lc* = 78 m (3 spans) as by the value of peak displacements, as by the value of the peak stresses. For the same reason, we can not name the construction with *Lc* = 54 m (2 spans) rational, too.

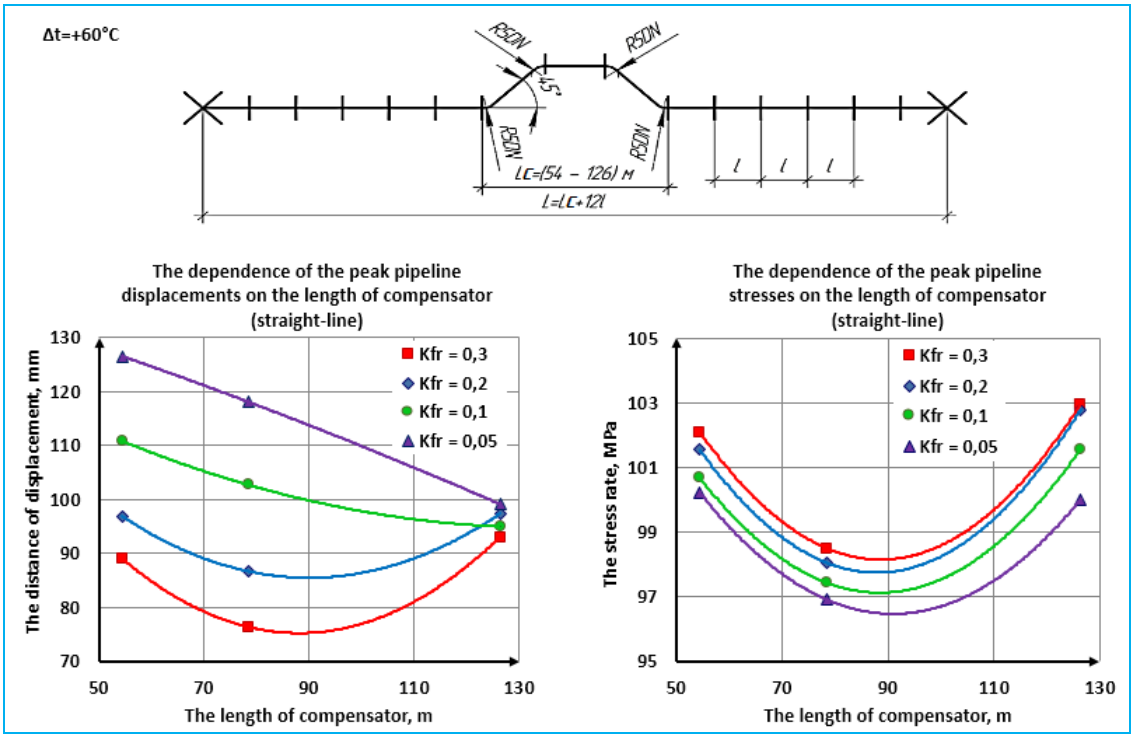


Figure 4. The dependence of the transverse displacements of the pipeline and stresses on the change in the value of *Lc* at various friction coefficients at the supports

Dependence of the stress-strain state of the above-ground pipeline on the angle at the compensation section (α) at various friction coefficients at the supports (Kfr)

In the study of the dependence of the stress-strain state of above-ground pipeline section on the angle at the compensation section under different support conditions, the value of variable factor α was chosen according to industrialization of bent branch production (α = 6°, 12°, 18°, 24°, 30° и 45°).

The constant design factors of the system are l = 20 m, $L = Lc + 12l$, Lc = 78 m.

Figure 5 shows the dependence diagrams that describe the results of calculations for trapezium-shaped compensator under different values of friction coefficient at supports.

It should be noted, that bigger values of transversal displacements and peak stresses (in the compensator branch, adjoining the straight-line section) are common for narrow angles α at all values of *Kfr,* but at that, the general pipes expense is lower.

The calculations have proven the stated conclusions at other accepted values of L and Lc.

As the angle α rises, the numerical values of peak displacement and the peak stress decline (other conditions being equal).

The value's deviation also declines at the change of the value of *Kfr* from 0.05 to 0.30 (Figure 5).

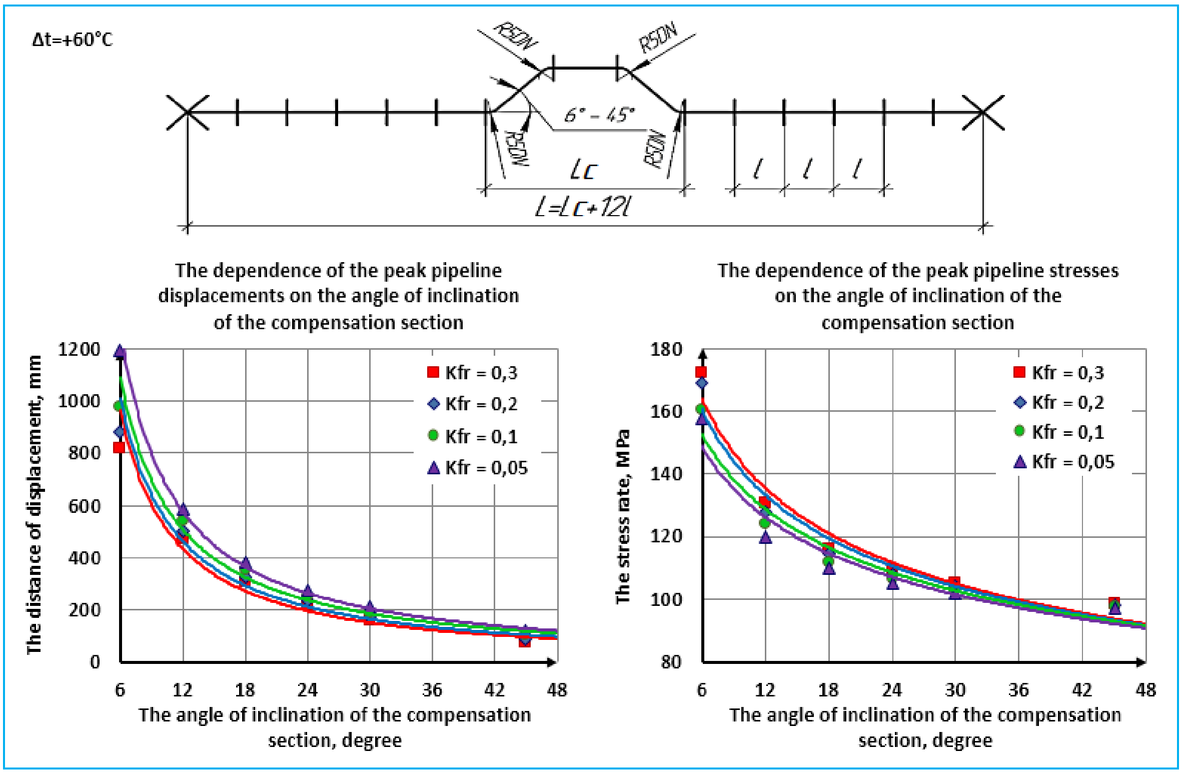


Figure 5. The dependence of the transverse displacements of the pipeline and stresses on the change in the value of α at various friction coefficients at the supports

Conclusions

As the results of the study of friction forces at supports at stress-strain linearly extended above-ground pipelines with the trapezium-shaped compensators, the authors can make the following conclusions (for given input data).

1. Deformability of above-ground pipeline at straight-line construction with trapezium-shaped compensator sections (just as for triangular compensators [15]) substantially depends on the value of friction coefficient at supports. On change of the value of *Kfr* from 0.05 to 0.30, the value of peak transversal displacements of the pipeline is decreasing by 45–55 % depending on the loading conditions considered.

2. By contrast with above-ground pipelines with the triangular shape of compensators sections, the stressed-defined state of extended pipeline systems with trapezium-shaped compensators far less depends on the friction coefficient at supports. In the case of an optimal combination of design factors, the deviation (the rise) of peak stresses under change of *Kfr* from 0.05 to 0.30 for trapezium-shaped equals about 1 %, while for triangular shape – 12 % [15].

3. Detached from the friction coefficient at supports (*Kfr* = 0.05–0.30) and from the value of *Lc,* the dependence of the stress-strain state of above-ground pipelines at the change of the distance between fixed supports (*L)* is of linear character. Herewith, the value of *Kfr* influences the stress-strain state of the system insignificantly. The value of compensating length at extended pipelines construction should be taken as a maximum allowed value by strength calculation and taking into consideration the terrain relief and pipeline's turning angles.

4. Under the terms of minimization of stress-strain state of above-ground pipeline, the optimal value of compensating sections equals: for *Kfr* = 0.3 and *Kfr* = 0.2 *Lc* = 78 m (3 spans), and for *Kfr* = 0.1 and *Kfr* = 0.05, *Lc* = 126 m (5 spans).

5. Under the terms of providing high compensatory capacity and acceptable values of factors studied (the peak displacements and stresses), the optimal value of angle α for a system with a trapezium-shaped compensator equals 45 ° detached from support condition (*Kfr* = 0.05–0.30).

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