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ESTIMATION OF THE LOAD CARRYING CAPACITY OF THE BELLOW COMPENSATOR FOR GAS PIPELINES IN THE MINING PRODUCTION AREAS

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Summary. *The paper deals with the estimation of the load carrying capacity of the bellow compensator DN100, made of stainless steel AISI 304, which is supposed to be used for providing the necessary level of deformability of main buried gas pipelines in the mining production areas. Experimental investigations of the compensator under cyclic loading by tension-compression with the simultaneous action of working internal pressure are carried out. According to the results of experimental research and numerical simulation, it is shown that such compensators can be used as structural elements of main buried gas pipelines in the mining production areas.*

Key words: *main pipeline, mining production, ground displacement, axial stresses, bellow compensator, finite element method.*

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Introduction. The problem of the buried pipeline failure as the result of geodynamic processes of the ground surface is very important. According to EGIG [1] 8 % of cases of loss-of-piping integrity in the main buried gas pipelines (MBGP) in Europe are caused by their failure as the result of geodynamic processes in the Earth crust. Furthermore, the activity of coal mines also results in the ground surface displacement.

The Coal mines influence on MBGP is an important problem on the territory of Ukraine as well since 22.1 km of MBGP [2] have been already located in the areas of their influence and this amount is constantly increasing due to the expansion of mining boundaries.

The area of the ground surface where the deformation processes occur as the result of mining production forms so called *"shift trough"* (see Fig. 1: H – mining depth; m – mining capacity; η_m – maximum ground subsidence).

As the result of mining development in the shift trough the compression areas and areas of the ground surface tension are formed (see Fig. 1) transmitting their effect on pipeline. Since the axial forces are the main load factor then the horizontal substitution component (vertical is usually neglected) has sufficient effect on the pipeline stressed state.

Analyzing the ground displacement kinetics during mining we determined [3] that for the worst case of lava mining (along MBGP) its most loaded areas are subjected to three consequent semicycles – tension – compression and again tension due to the relaxation processes in the ground. Depending on geological conditions, mutual location of the pipe with mining areas the MBGP section can reach the effect area of 15 minings and thus undergo 45 load semicycles.

To ensure reliable operation of buried pipelines during lava mining a number of measures aimed at stress state [4 – 6] reduction are used, such as:

1. Carrying capacity (on the design stage) is increased by:

- the use of pipes with larger diameter;
- pipeline enforcement by couplings.

2. The reduction of interaction forces between the pipeline and the ground is provided by means of:

- the excavation of pipeline sections and their air curing;
- the coating of pipeline sections by sand;
- the soil loosening in the pipeline section area.

3. The stress reduction is provided by means of complete excavation and cutting of the pipeline every 400 – 500 m.

4. The increase of the pipeline deformability is reached by means of compensators installing.

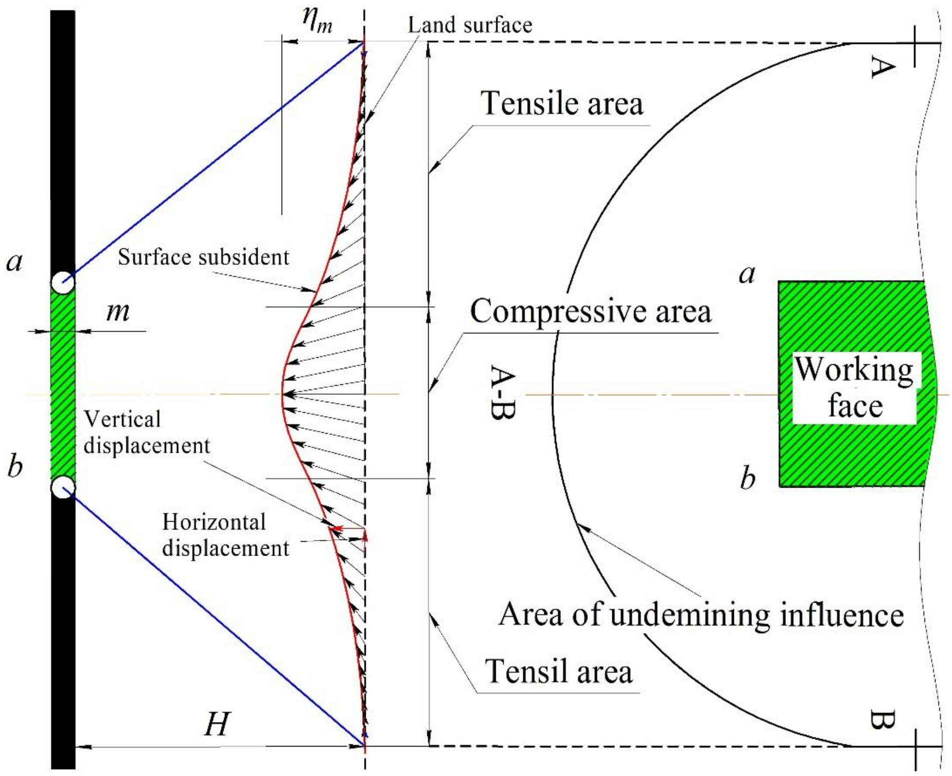


Figure 1. Scheme of the surface subsidence trough and distribution of forces in the area of undermining influence of mining production

The latter should be noted among the listed measures since its implementation makes it possible to ensure reliable pipeline operation over extended period of time. In general case the regulatory document [5] controls the use of P-, Z- and G-like compensators. A certain condition for the use of any compensators in the underground areas of the gas pipelines is installation of protective niches [5], providing compensator free movement but requiring additional ground removal and significant excavation and construction works [7] which in its turn sufficiently increases the cost and time of their installation. Along with П-, Z- and Г -like compensators, more compact rubber and lens ones [4, 8] are used. Their main disadvantage is small working pressure (up to 2.5 MPa) which makes it impossible to use them on MBGP where the internal pressure is 5.5 MPa

At the same time according to [9] it is possible for gaseous medium to use bellow compensators (BC) for internal pressure up to 6.3 MPa. In this case their installation (rubber as well as lens ones) does not require large amount of work i.e. technically and economically efficient in comparison with other considered alternatives.

Cases when MBGP sections get into mining areas which is not specified in the project are evident in modern practice. That is their design parameters (laying conditions, wall thickness, steel grade, etc.) were determined taking into account only standard operating conditions (internal pressure, temperature difference, etc.) Therefore mining production under such gas pipelines can result in carrying capacity loss as shown in Fig. 2.

a)

b)

Figure 2. Examples gas pipeline failure in the surface subsidence trough: a) – DN100; b) – DN300

In order to prevent accidents on MBGP before mining operations it is necessary to estimate the load in the pipeline from lava passing and develop and implement corrective actions ensuring the required level of gas pipeline carrying capacity by BC installing in its most stressed areas.

The first work of this kind in Ukraine is gas pipeline-offshoot DN100 near the gas distribution station in Dnipropetrovsk region where 900-meters pipe section appeared to be in the mining production area because of the mining boundaries expansion planned for the nearest 5 years. Therefore to ensure reliable gas pipeline operation the operation company (PJSC “UKRTRANSGAS”) considers the possibility of BC use which is require justification.

The objective of the given paper is to investigate the load carrying capacity of BC DN100 at loads corresponding to the real operating conditions in the most dangerous areas at maximum possible number of mining productions.

Materials and methods of research. At the request of the operating company LLP “NVO MARILAND” one BC DN100 was produced. Its technical drawing is shown in Fig. 3. The main element of BC is bellow itself (pos. 1) consisting of six layers with thickness 0.5 mm (see Section B) made of the stainless steel AISI 304 grade. The spool pieces (pos. 2 and 3) are made of the same steel as MBGP in order to avoid high-tech composite weld joints for BC welding with pipeline in field conditions. The guide tube (pos. 4) prevents the global bellow bending. In order to achieve maximum bellow fixation with spool pieces and providing the cylindrical part of the bellow with larger rigidity, the bellow ends are reinforced by stainless banding rings (pos. 5) which together with the bellow on the ends are welded to the spool pieces by composite weld (see Section A).

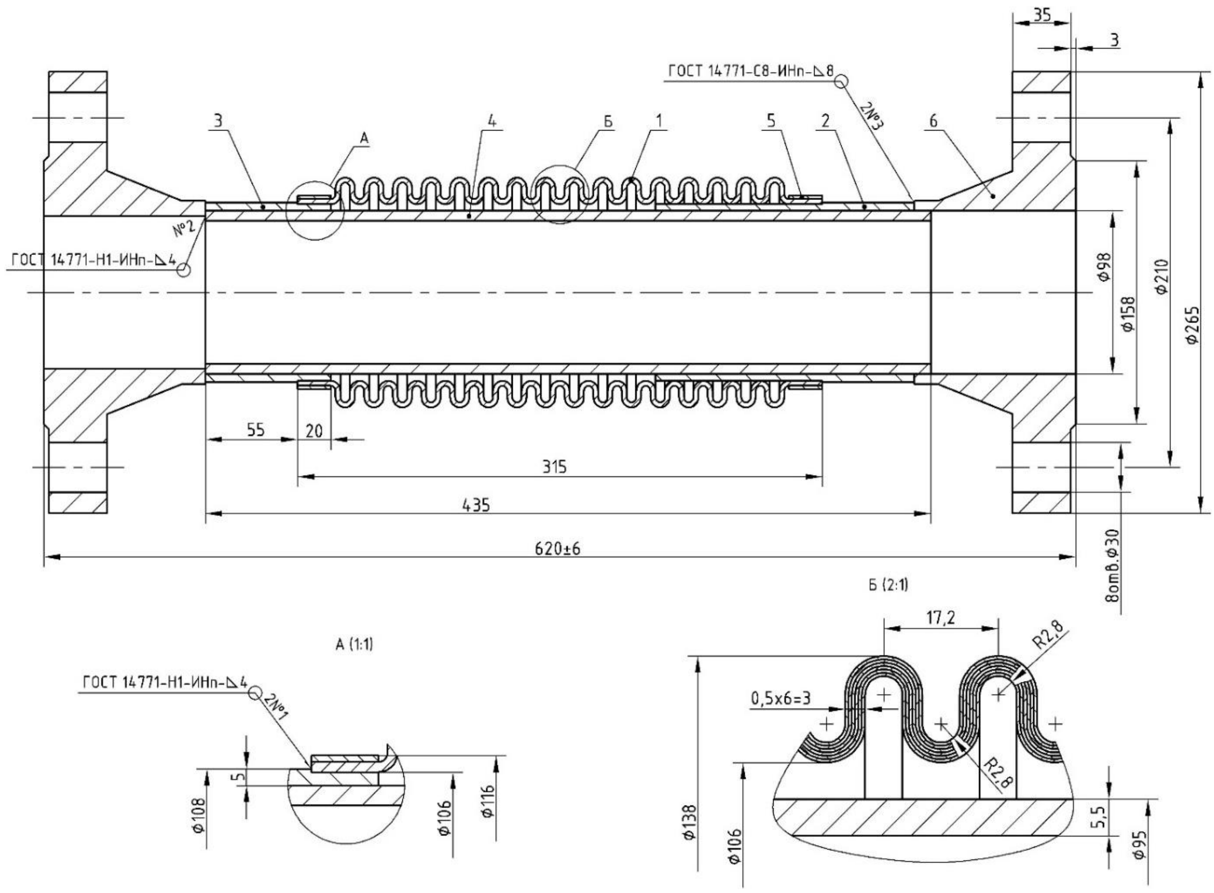


Figure 3. Drawings of the bellow compensator DN100 with flanges

In compensator technical specification the designer indicated the following main characteristics of the bellow:

– nominal diameter, mm	100;
– nominal pressure, kp/cm^2	60;
– hydrotest pressure, kp/cm^2	75;
– operating temperature,ºC	up to 100;
– axial working stroke, mm not more:	
- on compression	75;
- on tension	75;
– mean life at full stroke, cycles	26;
– axial stiffness, N/mm	904.

For complete reasoning of the possibility of BC use in gas pipeline-offshoot the operating company decided to carry out the examination of the characteristics declared by the manufacturer and get more complete information concerning bellow carrying and compensating capacity. For this purpose PJSC3 “UKRTRANSGAS” addressed G.S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine.

In order to comprehensive research of BC DN100 carrying capacity the series of experimental researches as well as numerical and analytical calculations have to be carried out.

Experimental researches

As it was manufactured only one BC the experimental research program was drawn up in such a way as to obtain as much information as possible and provided the following:

– hydrotest with axial displacements limitation;

– 26 tension-compression cycles with displacement amplitude ±75 mm with simultaneous action of nominal internal pressure i.e. checking of declared mean life at full stroke;
– investigations on compensating capacity evaluation at gradual increase of displacements amplitude at simultaneous nominal pressure action that is: 2 cycles for each of three displacement amplitudes [+85; -85], [+95; -85] and [+105; -85] mm (carried out in case of success (no failures) for the previous stage);
– test for determining the bellow compensating capacity at pressure 55 kp/cm^2 without axial displacements limitation.

The tests were carried out on the Pneumohydraulic Cryogenic Stand by G.S. Pisarenko Institute for Problems of Strength of the NAS of Ukraine under normal environmental conditions: temperature – 24°C, atmospheric pressure – 755 mm Hg, relative humidity – 40 %. For experimental tests the bellow compensator structure was supplied with flanges (pos. 6 in Fig. 30).

The testing scheme is shown in Fig. 4 where: 1 – gasholder filled with nitrogen; 2, 5 – stop valves; 3 – compressor installation KL 10/1000 for internal pressure loading; 4 – filter; 6 – branch sleeve; 7 – separating chamber; 8 – digital manometer MBS 3050 with accuracy of pressure measurement ±0,5%; 9 – SK; 10 – control indicating pressure gauge; 11 – volume (pressure) compensation vessel; 12 – installation VIST-15 designed for compensator axial stroke implementation and equipped with the load frame (four steel columns with diameter 100 mm) and hydraulic piston with maximum possible effort 15 tons. Water was used as compensator operating environment.

The flange cover-caps (see Fig. 5) are made of metal plates and have gripping ears through which the axial loads are act. The gaseous nitrogen from the gasholder was driven by compressor into one part of separating chamber which piston pressed the water which filled its second part and BC. Pressure compensation vessels (total volume 240l) performed the function of pressure stability maintenance in the compensator when loaded with axial displacements by VIST-15 installation.

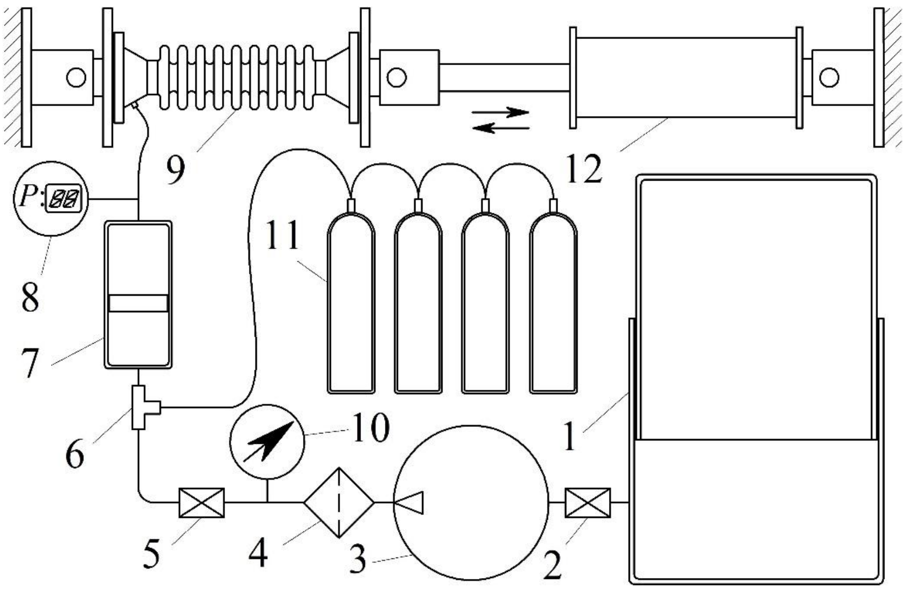


Figure 4. Test scheme

Hydrotest was carried out in order to estimate the quality of manufacturing and safety of further experimental researches in accordance with [10]. The load with internal pressure 75 kp/cm^2 with complete axial displacements limitation provided by pins with total stiffness approximately 20,000 times as much as the stiffness of BC. Under the nominal pressure the compensator was exposured for 2 minutes during which the visual inspection of both the compensator itself and loading system was carried out: flows, cracks, tears, sweating, fluid leakage through the joints and seals were not observed.

On the second stage of the experimental researches the declared by manufacturer bellow service life was at full stroke was verified – after 26 tension-compression cycles at loading speed 1 mm/s the flows, cracks, tears, sweating, fluid leakage through the joints and seals were not observed. It should be noted that during the tests the internal pressure in the system from the engineering point of view remained constant due to volume compensation vessels – its value measured by the digital transducer MBS 3050 ranged from 59,8 kp/cm^2 (bellow tension +75 mm, see Fig. 5a) to 60,2 kp/cm^2 (compression – 75 mm, see Fig. 5b).

a)

b)

Figure 5. The compensator during testing

Fig. 6 represents the axial force dependencies on the hydraulic piston rod of the installation VIST-15 from the compensator flanges displacement. We should point out that here the process of BC compression from tensile state is presented since the internal pressure 60 kp/cm^2 stretched the bellow to the size of restrictor fixed at the distance 75 mm from the initial state. The force measurement error was 2 %, the displacement was ±0,5 mm.

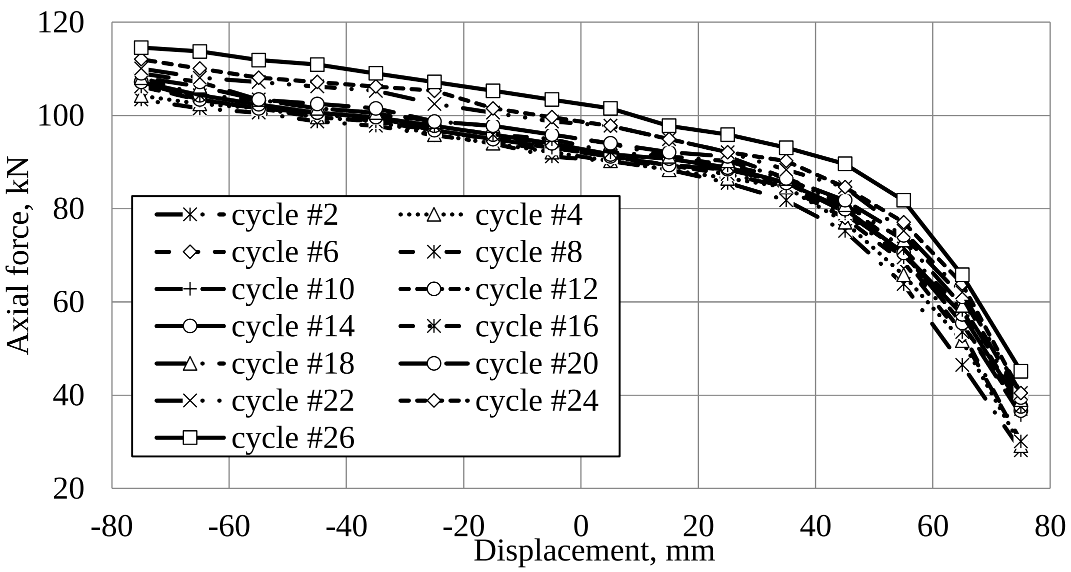


Figure 6. Dependence of displacements of the compensator on the applied force

According to the results of the third stage of research (2 load cycles for each three cases of displacement amplitude increase [+85; -85] mm, [+95; -85] mm and [+105;-85] mm at simultaneous action of internal nominal pressure) it is determined that BC has compensating ability store relatively to that one declared by manufacturer as flows, cracks, tears, sweating, are not observed by visual inspection. It should be noted that compressive deformation -85 mm by the reason of flange length limitation was selected in such a way as during loading the guide tube (pos. 4 in Fig. 1) did not collide with the flange cover-plug.

The last stage of the research was aimed at bellow simulation under the conditions of the long excavated gas pipeline section without displacements limitation. The loading produced by internal pressure of 55 kp/cm^2 resulted in 124 mm bellow deformation 106 mm of which was plastic component. Macrocracks occurred (see Fig. 7) on the bellow surface (especially in previously the most deformed slots – see Fig. 5b), however its tightness was not broken (the authors assumed that the similar situation was evident on the inner layer).

As the result of the series of carried out experiments it was determined that the investigated BC have the strength margin relatively to the operating internal pressure and compensating capacity margin both in terms of the cycles number and displacements amplitude.

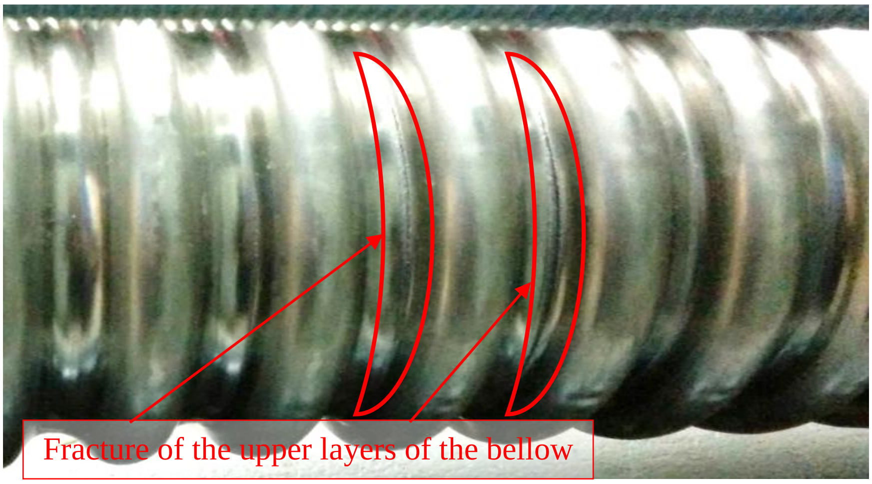


Figure 7. Cracks in the bellow under 55 kp/cm^2 pressure without limitation of axial displacements

Analysis of carrying capacity

The numerical bellow modeling was carried out by means of finite element method (FE) using ANSYS software package. Three defining tasks are solved:

– bellow axial stiffness within the linear elasticity limits;
– SSS of the bellow at its 75 mm tensile deformation;
– SSS of the bellow at its 75 mm compression.

To solve the given task the axisymmetric bellow FE model consisting of square eight-node element "*quad8*" (see Fig. 8a) is constructed. The model external layers are divided into 10 elements in thickness, and internal ones into 4. The quality of FE mesh according to "*orthogonal quality*" index is 0.91.

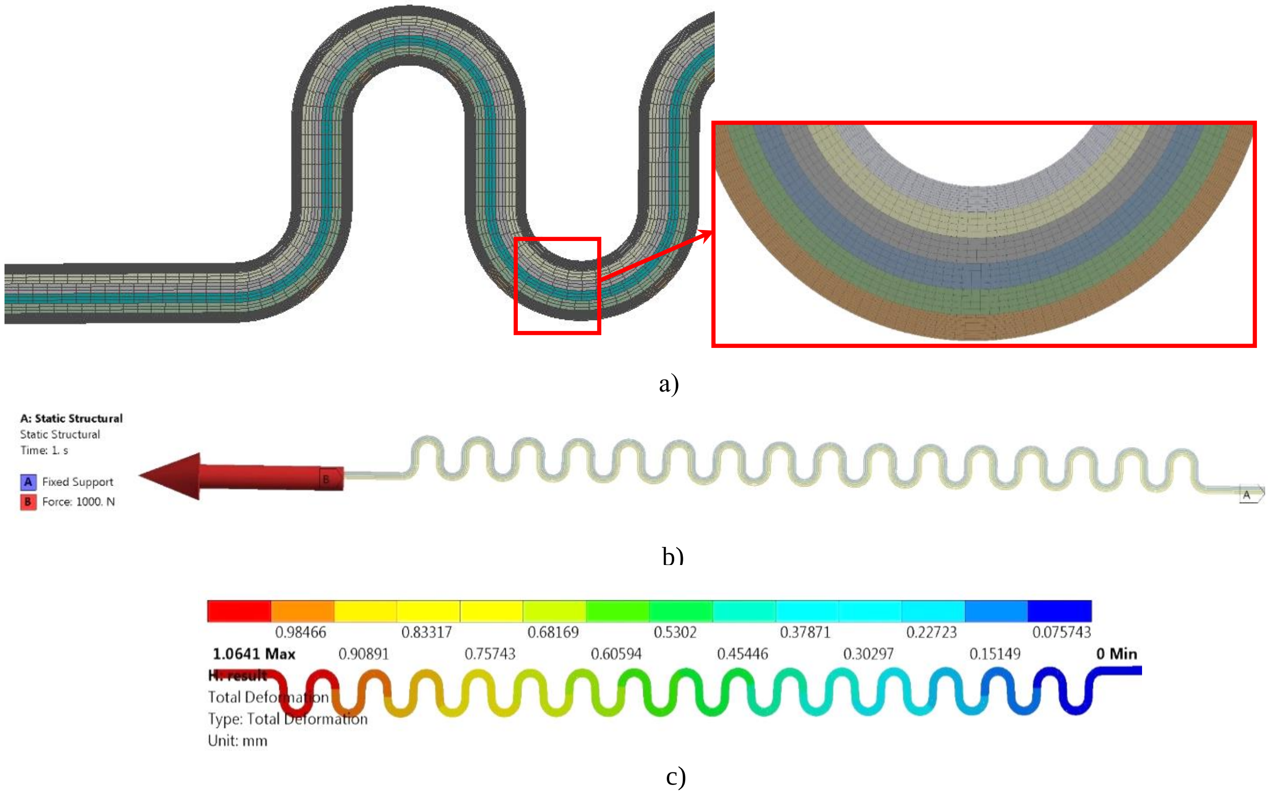
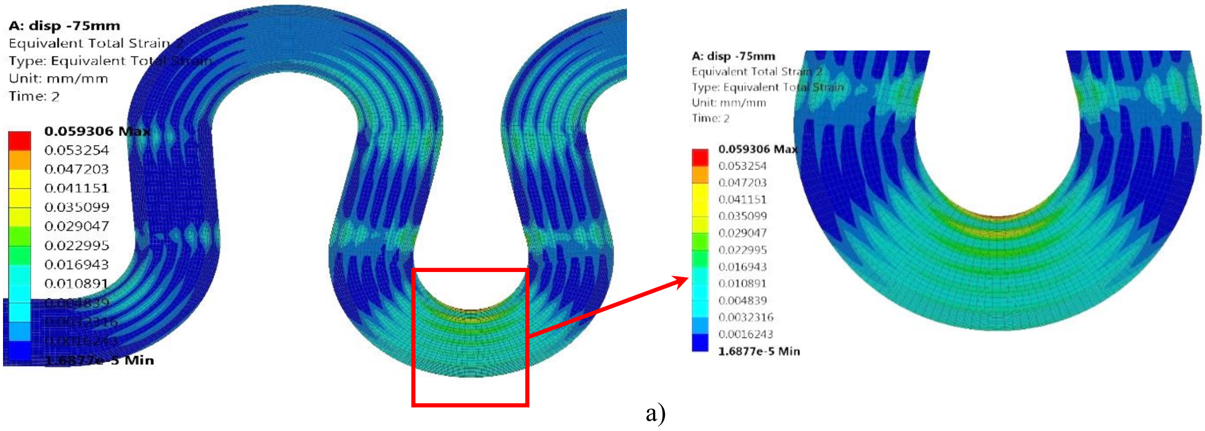


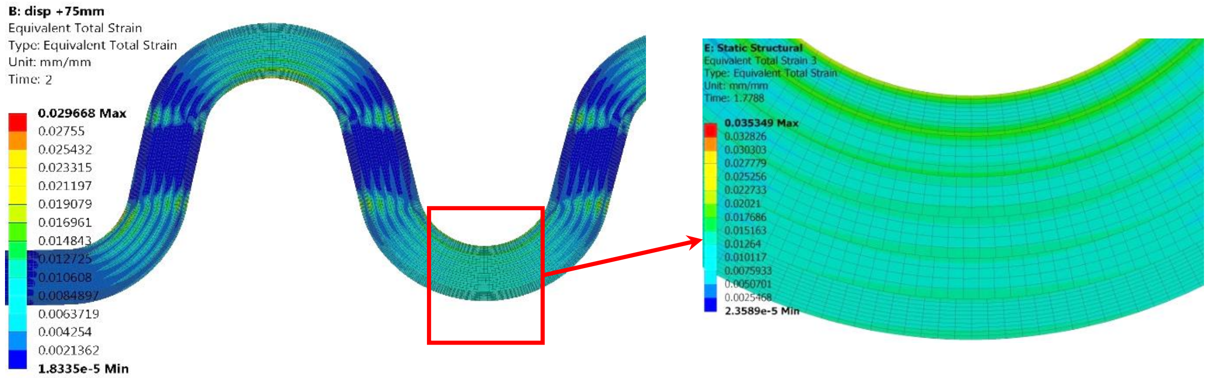
Figure 8. a) – model of the bellow; b) – boundary conditions for the problem of determining the stiffness of the bellow; c) – displacement for the same test

To determine the bellow stiffness the boundary conditions providing that one bellow end is fixed (Fig. 8b) and 1000 N force is applied to another end (Fig. 8b) are used. In order to determine the last condition such as the type of interaction between the bellow adjacent layers, several model problems are considered. As the result of their solution the linear type of contact interaction "*no separation*" providing mutual layers displacement at constant contact without friction. For this kind of interaction the stiffness of 940 N/mm is obtained. It correlates with the value of 974 N/mm obtained by the authors while processing the experimental results and correlates with the manufacturer data. Modeling of the bellow in deformed state is shown in Fig. 8c.

According to the results of experimental researches it is determined that the elastic component of the bellow displacement is less than plastic one. Therefore the bellow numerical modeling for tension and compression problems with the displacement of 75 mm should be implemented within the elastic-plastic behaviour of the metal. The stress-strain curve is built on the basis of mechanical characteristics of AISI 304 steel taken in [11] as for sheet material. Then in the tabular form it is imported into ANSYS. The results of the bellow deformed state at its tension and compression on 75 mm are shown in Fig. 9a and Fig. 9b respectively.



a)



b)

Figure 9. The results of the FE modeling of tension and compression of the bellows at value of 75 mm

It is evident from the presented results that under compression the bellow external layer is the most deformed. Under tension the uniformly distributed deformation along all compensator layers is observed.

The bellow deformation range in the maximum loaded layer (external layer, slots) is shown in fig. 10, where: ε_1 – is bellow tensile deformation; ε_2 – is compression (in directions: *x* – tangential deformation; *y* – axial; *z* – radial).

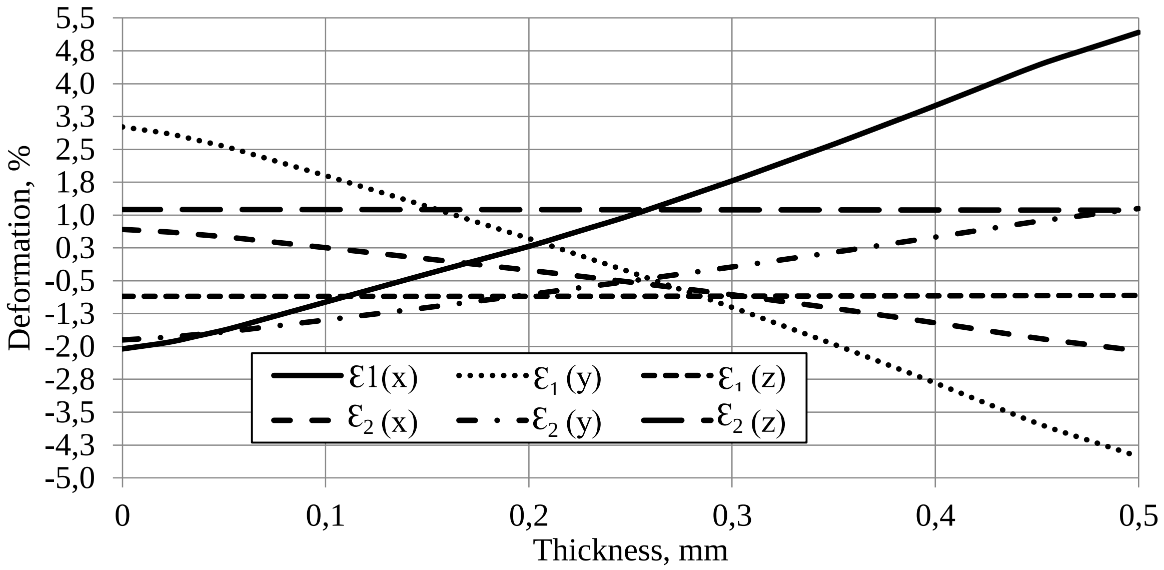


Figure 10. Deformation in the maximum loaded layer of the compensator

The von Mises deformation under tension is 2.15 %, under compression – 5.64 %. According to the amplitude of von Mises deformations and fatigue curve of the bellow material [12] (sheet steel AISI 304 under bending at room temperature) it is found that fatigue life is approximately 32 cycles.

However it should be noted that this value is approximate since during the numerical modeling the stress-strain curve and fatigue curve of the sheet material in the initial state is used. In this case, the bellow is manufactured by deep plastic deformation of tubular elements which in turn are made of the sheets bent into tubes by means of longitudinal welds. That is, the pre-hardering of the metal layers of the bellow which occurred during the process of its manufacturing is not taken into account in calculations estimations.

Conclusions. As the result of the experimental researches it is determined that investigated compensator has strength margin relatively to the operating internal pressure and compensating capacity margin both in terms of cycles number and displacements amplitude.

For bellow simulation under the conditions of long excavated section of the gas pipeline the compensating capacity from operating pressure which is 1.65 times greater than the working stroke guaranteed by the manufacturer is determined. The given estimation is approximate since it is obtained after experimental testing of the nominal cyclic durability. In this case, the macrocracks occurred in the bellow upper layer resulting in the compensator carrying capacity loss in tightness and static strength.

The deformation amplitudes in each layer are determined by means of the compensator finite element modeling. It is shown that the bellow external layer (as is proved by experiment) is the most loaded. It is defined according to the amplitude of von Mises deformations and fatigue curve of the bellow material that the bellow cyclic durability for tension-compression ±75 mm is up to 32 cycles.

The results of experimental and numerical-analytical investigations prove the possibility of bellow compensator DN100 use for compensation of axial displacements on the gas pipeline sections in mining areas for maximum 15 mine workings.

On the basis of obtained data the bellow compensators for gas pipeline-offshoot DN100 in mining areas will be implemented. Installation places and required number of compensators will be selected according to the results of predictable calculations of the pipeline stressed state using efficient methods [13] based on the bellow passport technical specification.

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ОЦІНЮВАННЯ НЕСІВНОЇ ЗДАТНОСТІ СИЛЬФОННОГО КОМПЕНСАТОРА ДЛЯ ГАЗОПРОВОДІВ У ЗОНАХ ШАХТНИХ ВИРОБІТОК

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Резюме. *Роботу присвячену оцінюванню несучої здатності сильфонного компенсатора Ду 100, виготовленого з нержавійної сталі AISI 304, який передбачається використовувати для забезпечення необхідного рівня деформаційної здатності підземних магістральних газопроводів у зонах дії шахтних виробіток. Виконано експериментальні дослідження компенсатора на циклічне навантаження розтягом-стиском з одночасною дією робочого внутрішнього тиску. За допомогою скінченно-елементного моделювання компенсатора визначено амплітуди деформацій у кожному шарі. Показано, що найбільш навантаженим є зовнішній шар сильфона (що підтвердилося експериментом). За амплітудою еквівалентних деформацій та кривою втоми матеріалу сильфона отримано, що циклічна довговічність сильфона для розтягу-стиску ±75 мм складає приблизно 32 цикли. У результаті виконаних досліджень показано, що компенсатор можна використовувати для забезпечення надійної експлуатації магістрального газопроводу-відводу Ду 100 у зоні відпрацювання шахтних лав (до 15 лав). Залежно від запланованої кількості шахтних лав та їх прогнозних інтенсивностей для конкретних ділянок газопроводу обирається кількість компенсаторів, необхідна для забезпечення безпечної експлуатації ділянки газопроводу. Місця для встановлення та необхідну кількість компенсаторів для ефективної компенсації осьових переміщень обирано за результатами прогнозних розрахунків напруженого стану газопроводів у зонах шахтних виробіток із використанням ефективних методик. На основі отриманих даних заплановано дослідження і введення в експлуатацію сильфонних компенсаторів як заходів забезпечення надійної експлуатації для магістральних газопроводів інших діаметрів.*

Ключові слова: *магістральний трубопровід, шахтна виробітка, зсув ґрунту, осьові напруження, сильфонний компенсатор, метод скінченних елементів.*

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