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Results of Complex Studies on Methods of Reinforcement of Main Steel Gas Pipelines in The Context of Extended Failure

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Abstract: At present gas, like oil, is the main source of energy for many consumers in the world. In recent decades, the role and importance of natural gas in the energy balance of the world economy has steadily increased due to its high efficiency as an energy resource and raw material for industry. It is clear that the intensive construction and reconstruction of steel gas pipelines will continue, and great attention will be paid to maintaining them in working and technically viable condition. Therefore, the aim of this study is to develop methods for strengthening existing gas transmission pipelines. Theoretical studies were carried out in the ANSYS software complex with comparison of obtained values with the results of experimental studies. As a result, it was found that different temperature loads (-400C, -100C, +200C and +500C) the proposed methods reduce the propagation of crack in longitudinal stress from 2 to 5 times depending on the geometric parameters and temperature effects, a transverse house 1.9 times. The results of this study will benefit production in operation of gas transmission pipelines in the investigation of extended failure prevention.

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1 INTRODUCTION

At present gas, like oil, is the main source of energy for many consumers in the world. Over the past decades, the role and importance of natural gas in the energy balance of the world economy has been steadily increasing, due to its high efficiency as an energy resource and raw material for industry, as well as its ecology. From 1980 to 2020, the rate of increase in natural gas consumption was 168%, with the rate of increase in oil consumption over the same period being 44% and coal -102%. On average, gas consumption is growing at 7% per year. The world's proven natural gas reserves are now 138 trillion. m^3[1]. According to proven reserves of natural gas, the Republic of Kazakhstan ranks 14th with 2.7 trillion m^3 [2]. It is clear that the intensive construction and reconstruction of steel gas pipelines will continue, and great attention will be paid to maintaining them in working and technically viable condition. It is also evident that significant funds will be allocated to the restoration of the carrying capacity of existing steel gas transmission pipelines.

Because the construction and operation of steel gas transmission pipelines are associated with high material costs, fire- and explosive hazard, risk of environmental pollution, danger to human life, they are assigned to especially responsible structures. The design and construction of such structures should be based on well-founded scientific regulations and technically feasible, fundamentally new designs, as well as optimal and cost-effective design solutions. Analysis of domestic and foreign sources shows [3-7] that various accidents of different natures occur in the gas transmission pipelines for various reasons. At the same time, the fact that in Kazakhstan more than 70% of gas pipelines are worn out and it is a particularly important problem on a national scale [8].

The problem of avalanche failure of gas transmission pipelines in recent decades is quite widely discussed. Let's consider the most complete and interesting in terms of problems of studying the characteristics of extended failure of gas transmission pipelines. The experience of construction and operation of gas transmission pipelines shows that their failure does not occur as a result of insufficient structural strength of pipes, but due to the development of existing or acquired in the process of construction and operation defects and damages.

The literature review of the problem of pipeline collapse shows that since the middle of the 20th century an intensive study of the issue of the destruction of gas transmission pipelines for oil and gas has been conducted, which led to the development of adopted design standards [9-19].

The first studies on crack formation in pipelines and methods of stopping them date back to 1970 [20]. Field studies on pipe fracture of large diameters have being already conducted in the 80s of the last century, where the main focus was given to methods of tube manufacture and their mechanical characteristics [21,22]. Since the 90's, the theory of mechanics of failure has been developed and with its involvement the problem of movement of main crack, which is initiated by the movement of gas [23,24]. Advanced method of finite elements is used in the works [25,26], which is applied to the simulation of stress state near the crack, which has demonstrated its accuracy and reliability in evaluation.

Since the beginning of 2000, numerical methods using software packages are intensively used to model pipeline failures. Thus, a number of studies on the application of the finite element method to model extended pipeline failures were conducted by the authors of the article [27]. The methods to stop the development of a crack are discussed in the article [28]. The use of prestress steel wire winding and composite threads to isolate and stop the crack failure movement was discussed. The numerical procedure for modelling the gas dynamics observed when gas is discharged from a pipe is described in the article [29]. The results of experimental and numerical studies of gas pipeline section with bending and operating under internal pressure are shown in the works [30,31].

In the last ten years, research on the formation, distribution and localization of cracks in gas transmission pipelines of large diameter has been dominated by work on the mathematical description of processes in the propagation of crack failure, modeling of various problems of crack propagation dynamics and use of computational complexes and programs in them. Thus, computational approach to calculate the movement of main crack in the shell is proposed in the paper [32]. Several existing analytical methods for calculation of pipeline failure are discussed in the article [33]. The experience of the European Research Group on Gas Pipeline Strength is presented in the article [34]. Existing approaches to assess resistance to plastic rupture of pipelines are described. The results of finite-element calculation of crack development in the pipeline are considered and compared with the results of experimental studies of shell models and their failure due to rapid crack development in the article [35]. It is shown that the crack propagation rate also depends on the decompression rate of gas in the pipeline.

Thus, based on review it can be concluded that the task of modelling extended avalanche failure in large diameter gas pipelines taking into account the factors causing rapid (avalanche) crack propagation is relevant. At present, the issue of the distribution of cracks along pipeline sections under various operating conditions (internal pressure in the pipeline, temperature of the medium, structural features, nature of the soil) is poorly studied and requires further comprehensive studies.

The analysis of these works also leads to the conclusion that, as dampers for gas transmission pipelines, it is necessary to apply dampers with a simple structural scheme with minimal costs and which does not require additional special equipment, control devices and equipment. One of promising way to localize and stop the rapidly growing crack break in pipelines is the method of prestress. The prestress of the structures is carried out by the welding of a high-strength profile (wires, tapes or rings) in one or more layers on the surface of the shell, a traditional design solution [36-47].

2 METHODS AND MATERIALS

The design feature of such a solution is that the high-strength winding makes it possible to redistribute the forces in the pipe wall and bring its performance to the level of the sphere by equalizing the longitudinal and annular stresses in the wall, that increases the strength and reliability of the pipeline. The local change in the stress state of pipe material is made by changing the thickness of pipe by coil winding. The winding may be carried out at an angle to the direction of maximum tensile stresses in the form of intersecting strips or several strips with different angles of inclination [40], Figure 1.

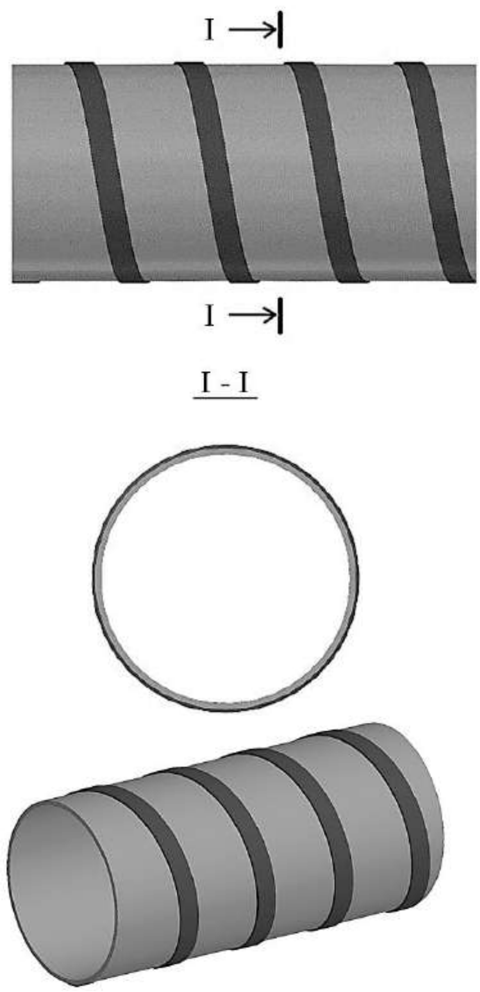


Figure 1: Method of increasing resistance to extended crack propagation by locally changing the pipeline wall thickness.

At the first stage, numerical studies of the dynamic stress-deformed state and failure of a section of steel pipe, considering the influence of temperature, were conducted using the ANSYS software complex [52,53]. The numerical research on the effect of temperature on the extended avalanche-type failure of gas transmission pipelines was carried out on the section between the supports of the “Beyneu-Bozoy-Shymkent” gas transmission pipeline. The pipeline section scheme is provided in accordance with the works [52,53]. A straight section of the pipe with length L = 10 m, internal diameter of the pipe D =1.047 m; wall thickness of the pipe H = 15.9 mm was studied. The mechanical properties of the pipe material are adopted by the similar mechanical properties of the pipe material of the problem [52,53].

The section of the pipe with crack is subjected to non-stationary internal pressure. The pressure change over time is defined in tabular form based on experimental data obtained in the study. The process of changing the internal pressure in the pipe, from the working pressure to the critical pressure, followed by a pressure drop due to gas leakage through crack, is modeled. The calculated values of internal pressure over time are presented in Table 1.

Table 1: Values of non-stationary internal pressure in the pipeline over time [52,53].

t, mc	0	1	2	3	4	5	6	7	8	22	30
P(t), MPa	7.5	9.8	9.8	9.1	7.5	5.0	3.5	3.2	2.5	2.5	1.5

The material of the pipe is steel X70. The density of steel was taken as ρ = 7810 kg/m³, and the Poisson's ratio μ = 0.3. The mechanical properties of steel, such as Young's modulus E, tensile strength σ_U, and yield strength σ_y, depend on the temperature. The studies were conducted within a temperature range from -40°C to +500C [52,53].

Table 2: Mechanical properties of steel in the temperature range from -40°C to +500C.

Temperature, T, 0C	–40	–10	+20	+50
Breaking strength, σ_U, MPa	574	572	570	568
Liquid limit, σ_y, MPa	525	515	505	495
Elastic module, E, GPa	211	209	206	203.5

In the second phase, experimental studies of reduced models of gas transmission pipeline for avalanche failure were carried out. The method of conducting experimental studies is based on a set of rules, which consists in reproducing operational, technological, geometric and constructive parameters with maximum reproduction of real conditions, with appropriate test equipment, measuring instruments and apparatus, as well as corresponding modern processing software packages. The study object chosen is a model of steel gas transmission pipeline, which was manufactured on the basis of the similarity criteria of the model and natural reservoir. The main geometrical dimensions of steel pipeline model are shown in table 3. Main mechanical properties are presented in the work [54].

Table 3: Geometric dimensions of the reduced model of steel gas transmission pipeline.

Testing option	Length model, mm	Diameter model, mm	Wall thickness model, mm	Winding diameter,mm	Winding type *
I-1	2000	250	0.8	1	A
I-2					B
I-3					C
II-1					A
II-2					B
II-3					C
III-1		350			A
III-2					B
III-3					C
IV-1					A
IV-2					B
IV-3					C

*A-without winding; B-Steel ring; C-Wire winding

The following design options were modelled to achieve the objectives of the experimental study on the basis of gas transmission pipeline model: 1-traditional construction of gas transmission pipeline (without prestress); 2- gas transmission pipeline with prestress steel ring on the crack tops; 3- gas transmission pipeline with prestress wire winding with 0.25m thread pitch and angle-900.General gas pipe models prepared for testing and their design diagram, are presented in Figure 2.

Figure 2: General view of reduced models of gas transmission pipeline.

3 RESULTS AND DISCUSSION

3.1 Results of the analysis of the stress-deformed state of straight section of the pipeline with crack at various temperatures in ANSYS

The stress state and the failure process of the pipeline section with crack are investigated at temperatures of -40°C, -10^{0}C, +20^{0}C, and +50^{0}C. The displacements in the pipe at the following time moments: the onset of critical pressure *t* = 1mc are shown in Figure 3 (t = 1 mc), the maximum crack opening *t* = 10 mc and the crack arrest *t* = 20 mc under the temperature effect of -10^{0}C.The crack with local change in pipe thickness.

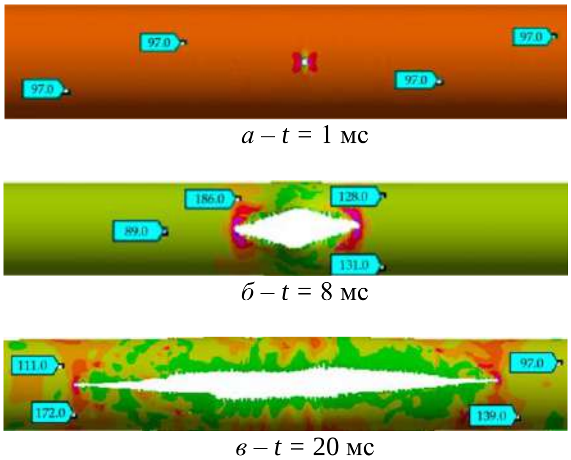


Figure 3: Equivalent stresses (MPa) in the pipe wall at different points in time at a medium temperature of -10^{0}C [52.53].

A similar analysis was also carried out taking into account the remaining temperature impacts (-40^{0}C,-10^{0}C, +20^{0}C and +50^{0}C. Summarized analysis are presented in tables 4-7.

Table 4: Values of the coordinate z for the left and right crack tips at a medium temperature of -40°C.

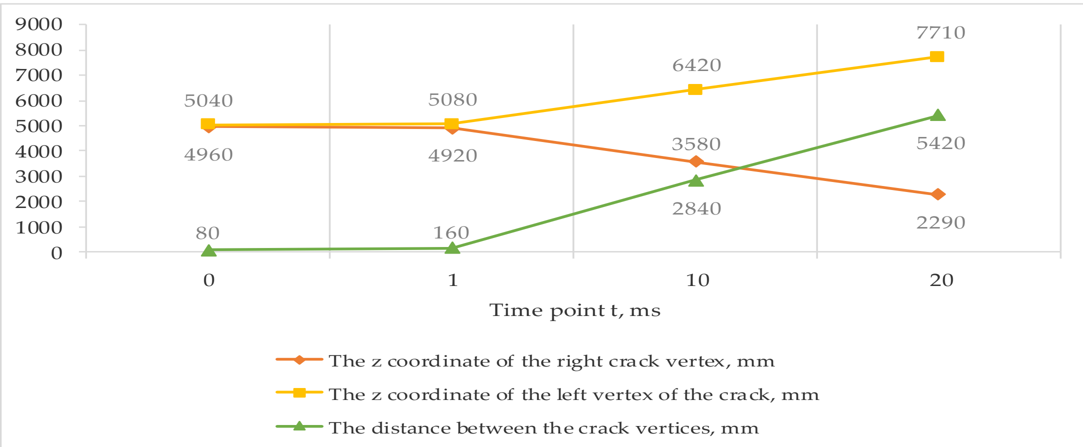


Table 5: Values of the coordinate z for the left and right crack tips at a medium temperature of -10^{0}C.

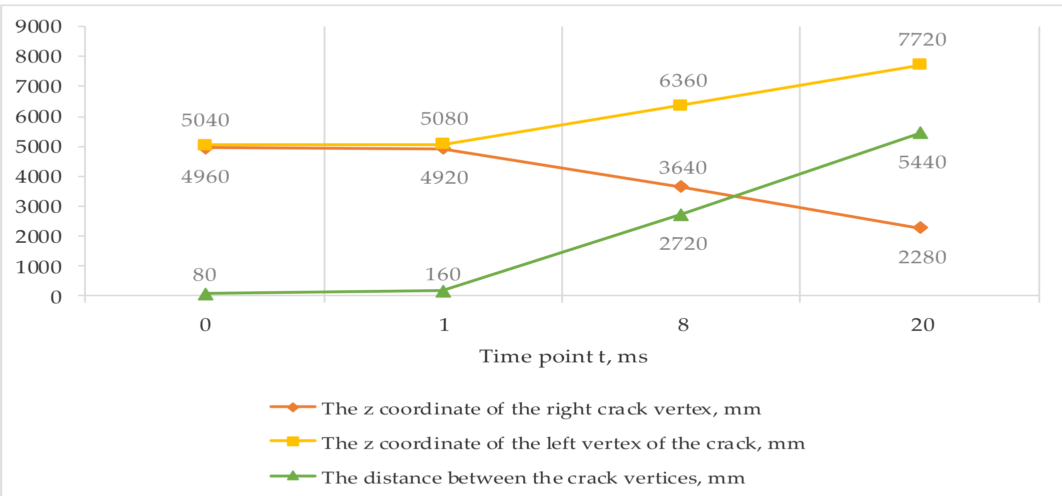


Table 6: Values of the coordinate z for the left and right crack tips at a medium temperature of +200°C.

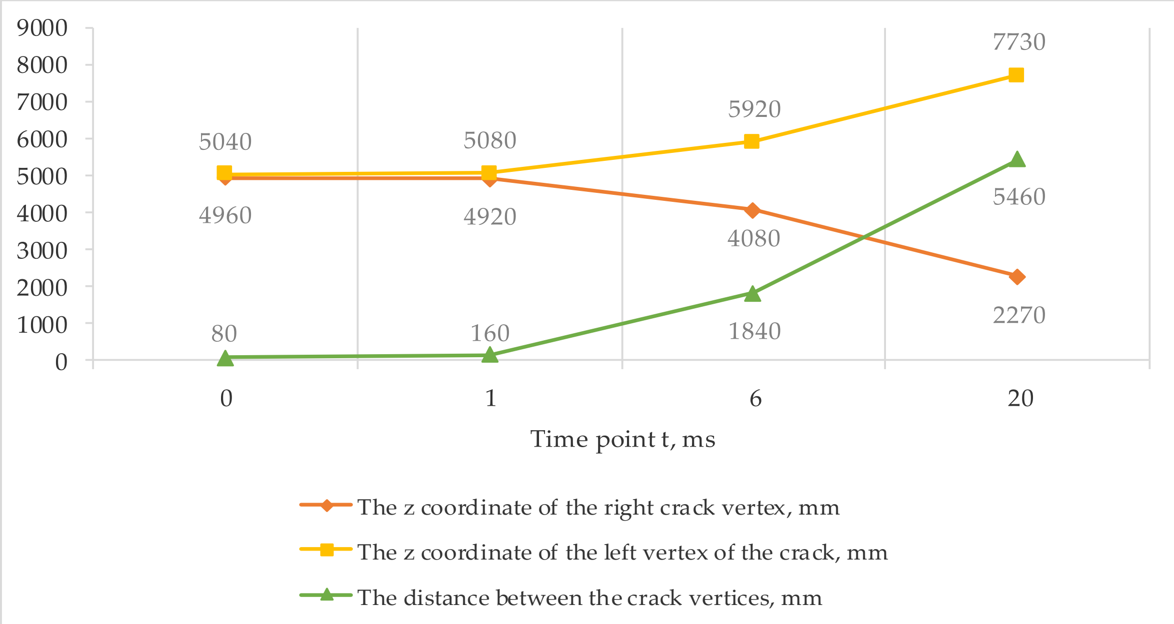
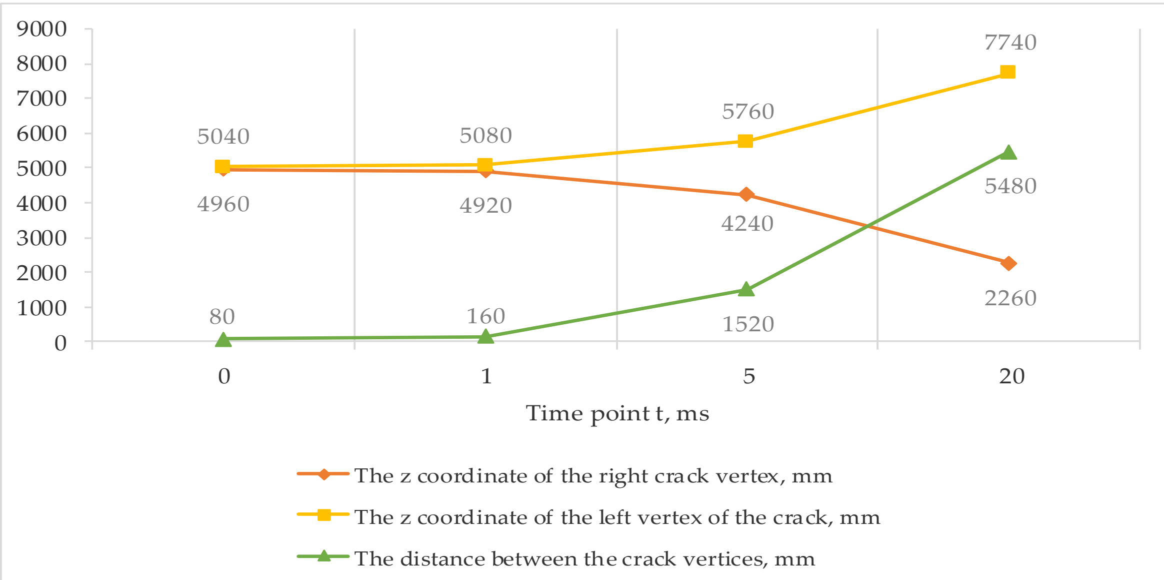


Table 7: Values of the coordinate z for the left and right crack tips at a medium temperature of +500C.



The computational studies on the influence of environmental temperature on the process of extended avalanche failure of gas transmission pipelines were conducted. A mathematical and finite element model of the dynamic stress-deformed state and failure of the section of transmission pipelines, considering the effect of temperature (-40^{0}C, -10^{0}C, +20^{0}C and +50^{0}C), was developed using ANSYS software complex. It was shown that during the first millisecond, when the pressure is increased from the operating value of 7.5 MPa to the critical value of 9.8 MPa, the length of the failure crack is increased by a factor of two (from 80 mm to 160 mm). This is characteristic for the entire temperature range.

The stressed condition of pipe wall outside the crack area is uniform, and the deformations are elastic. Crack growth to its maximum width is done differently for each temperature. Thus, at a temperature of -40^0C the crack is maximized only by the time point of 10 mc. At the same time, the crack length in the longitudinal direction is increased. For example, at time 10 mc the crack length is already 2.84 m, which is 35.5 times more than its initial length. From time 8 mc to time 22 mc, the internal pressure reaches 2.5 MPa, which is 25.5% of the critical pressure. The crack growth is stopped by the time of 20 mc. Overall, at a temperature of -10^0C the crack is 68 times longer and reaches 5.44m in size, at a temperature of $+20^0$C the crack is 68.25x longer and reaches 5.46m in size, and at a temperature of $+50^0$C the crack is 68.5x longer and reaches 5.48m in size

3.2 Results of experimental studies on reduced models of gas transmission pipelines for extended failures

12 series of tests were conducted on models of gas transmission pipeline in the experiment [55]. The experimental studies were carried out in three stages:

Stage 1 – Tests of the pipeline model without winding.

Stage 2 – Tests of the model with prestress steel rings.

Stage 3 – Tests of the model with prestress wire wrapping.

The test results on the traditional and prestress gas pipeline models are presented in the Table 3, in Figures 4-6 [55].

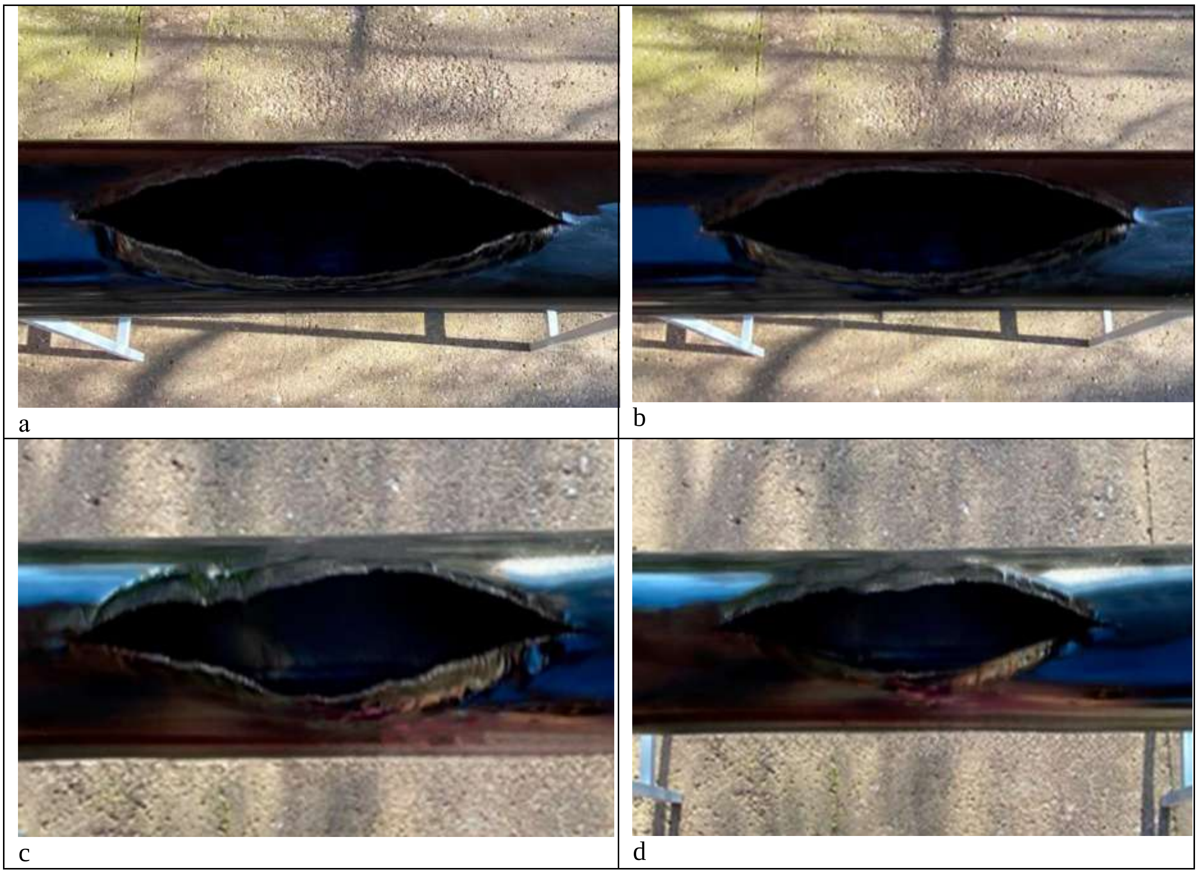
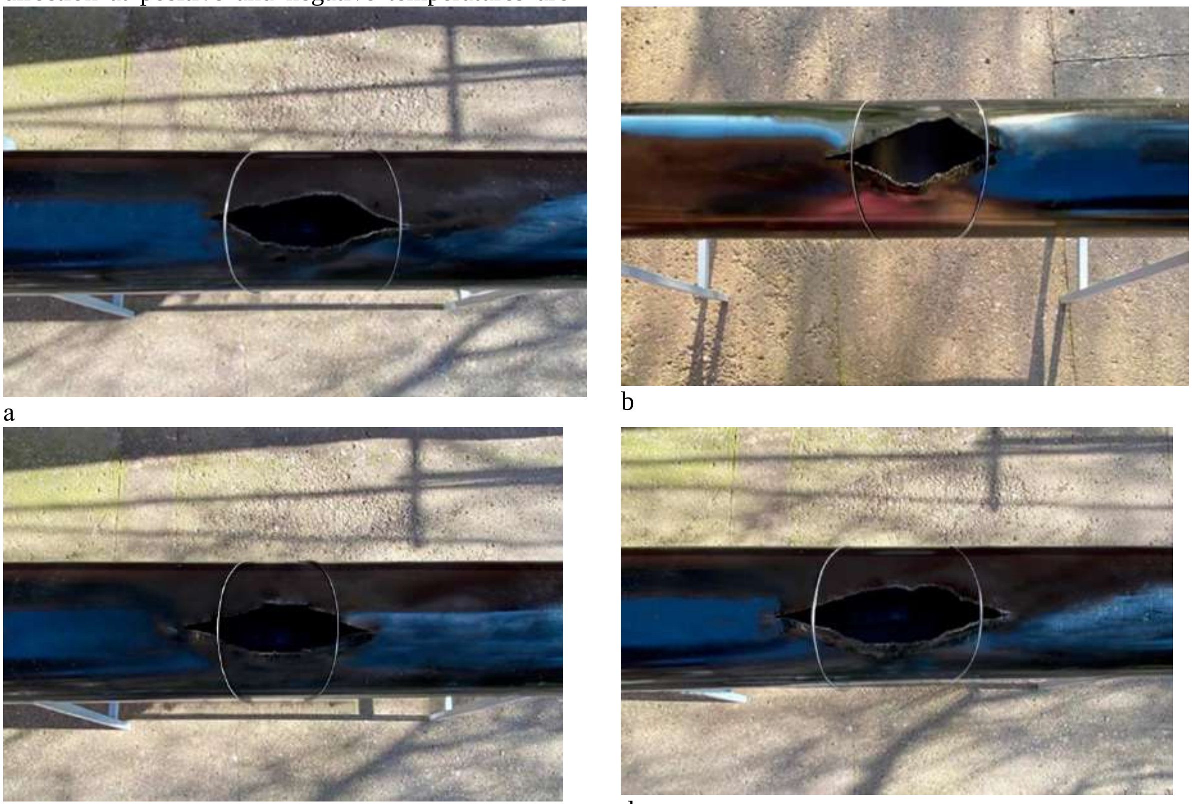


Figure 4: Photo of the gas pipeline model tests by series: a) I-1, b) II-1, c) III-1, d) IV-1 [55].

The experimental study results of traditional gas pipeline model under external temperature conditions +20°C showed that the 250 mm diameter (series I-1) model with internal critical pressure of 1.519 MPa is deformed in the circumferential direction as crack expansion to 183.3 mm, the deformation occurs as a lengthening of the crack to 375.6mm in the longitudinal direction. The stress state near the crack is shown in Table 3.7, where it can be seen that the maximum stress in the circular direction comes from the centre of the crack. In this case, the tension in the longitudinal direction is minimal. The same situation was also found at a negative temperature of -10°C (II-1), where the deformation in the annular direction as an expansion crack is 165.2mm and in the longitudinal direction is 354.8mm. Similar situation was observed in the 350 mm diameter model test according to series III-1 and IV-1, where the deformation of crack in the annular direction at positive and negative temperatures are 235.4mm and 226.6mm, the crack is deformed as elongation to 416.4mm and 398.7mm respectively when in the longitudinal direction at similar temperatures.

In the second stage, tests were conducted on models of steel gas transmission pipeline strengthened with single steel rings on both sides of crack, according to series I-2, II-2, III-2, IV-2, are presented in Figure 6.



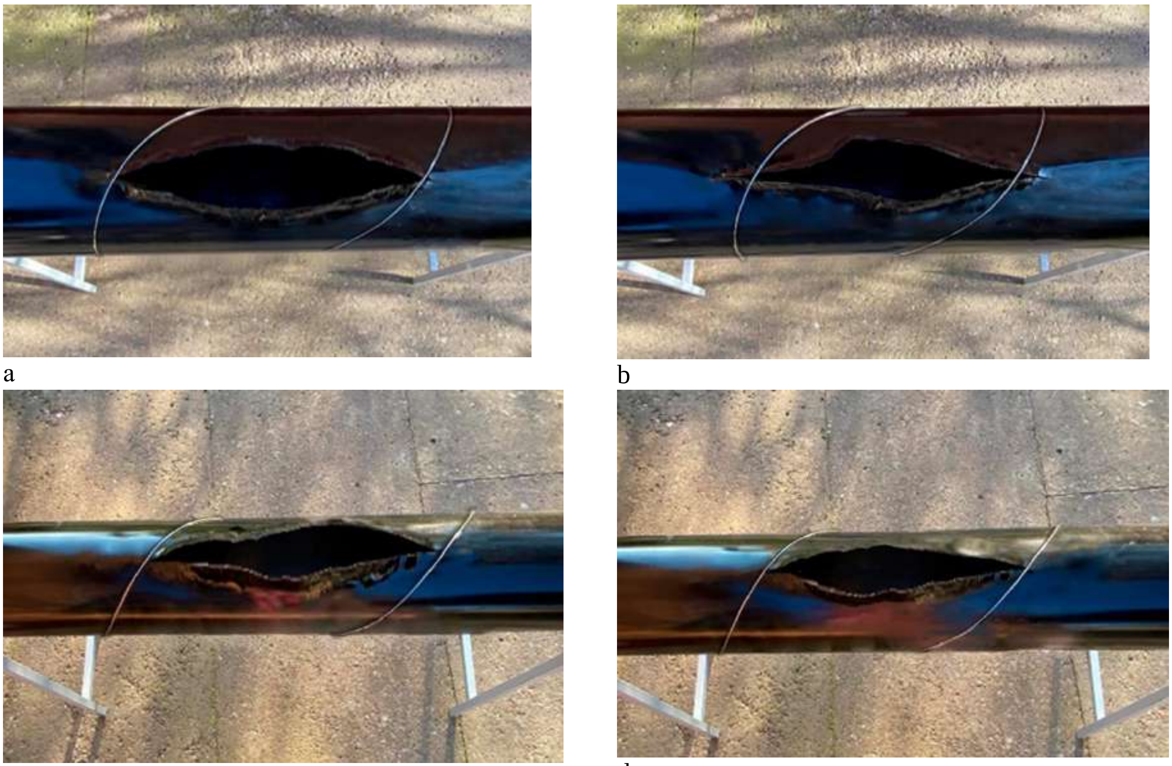
a b c d

Figure 5: Photo of the gas pipeline model tests by series: a) I-2, b) II-2, c) III-2, d) IV-2 [55].

The analysis of Figure 5 shows that the deformation in the form of crack propagation in circular and longitudinal direction under conditions of positive temperature for I-2 series with a diameter of 250mm model is 112.5mm and 172.2mm respectively, and the deformation is equal in the circular direction to 108.8mm, in the longitudinal 144.5mm for II-series tests2 at a negative temperature of -10°C with a similar diameter. Similar situation regarding deformation in the form of crack propagation was established for series III-2 and IV-2, where it was found that for series III-2 crack propagates at a positive temperature in the annular direction up to 151.2mm, and in the longitudinal direction up to 215.4mm. The crack is spread in the circular and longitudinal directions to 141.1mm and 203.5mm respectively in the IV-2 series.

In the third stage, tests were conducted on models of steel gas transmission pipeline strengthened with wire winding, with a winding pitch of 0.25 m, according to test series I-3, II-3, III-3, and IV-3. The results of these tests are presented in Figure 6.

(Note: in Figure 6 there is a visual representation of the described results from tests, as it cannot be generated or displayed images.)



a b c d

Figure 6: Test photos of gas pipeline model by series: a) I-3, b) II-3, c) III-3, d) IV-3 [55].

The analysis of Figure 6 showed that at a positive temperature and diameter of 250 mm according to the I-3 test series, the crack is deformed in the circular direction as an expansion up to 120.5 mm and lengthwise up to 264.1 mm. The deformation rate in the annular direction as a crack expansion is 129.2mm at negative temperature, and in the longitudinal up to 250.2mm (series II-3). The model's 350mm diameter test results also showed a similar deformation, so at a positive temperature the crack widened to 164.5mm and lengthened to 296.1mm (III-3 series). In the negative case, this values were154.4mm and 275.5mm (series IV-3).

4 CONCLUSION

Computational and experimental studies were conducted on the influence of the surrounding temperature on the process of extended failure gas transmission pipelines. Finite element models of dynamic stress-strain state and destruction of pipeline sections were developed, taking into account the temperature effects (--100C, +200C and+500C), using the ANSYS software complex. Based on classical mechanical similarity theory and affine modeling, the natural gas pipeline structures were modeled, and the similarity criteria were defined.

It was found that at a temperature of -40°C, the length of crack failure is increased by 67.75 times from initial length, reaching a value of 5.42 m. At temperatures of -100C, +200C and +500C, the crack is opened maximally at 8 mc, 6 mc, and 5 mc, respectively. The pattern of maximum crack opening remains the same for these temperatures. For all considered cases, the crack growth is ceased at 20 mc. The crack is extended by 68 times, reaching length of 5.44 m at a temperature of -100C, the crack is extended by 68.25 times, reaching 5.46 m, at a temperature of +200C, and the crack is extended by 68.5 times, reaching 5.48 m at a temperature of +500°C.

It should be noted that the proposed methods promote to reduce crack propagation by up to 5 times, depending on geometric parameters and temperature influences, which is an important result for improving the safety and operation of gas transmission pipelines.

Results of experimental tests of reduced models of prestress single-ring pipeline models under positive (+20°C) and negative (-10°C) conditions temperatures showed that the crack opening width in the annular direction is decreased to 1.63 times and 1.9 times respectively. The crack length (longitudinal direction) is decreased to 2.18 times and 2.45 times respectively. It is stated that this can be considered a positive point in the solution of the problem of localization and stop the crack destruction in gas transmission pipelines. The crack opening width in the circular direction is decreased to 1.5 times and 1.46 times respectively. The crack length (longitudinal direction) is decreased to 1.4 times and 1.44 times respectively. This can be considered as a positive point in the solution of the problem of localization and stop the breakdown crack in gas transmission pipelines.

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