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RESIDUAL EXPANSION OF CYLINDERS. INTERMEDIATE TEST RESULTS

ОСТАТОЧНОЕ РАСШИРЕНИЕ БАЛЛОНОВ. ПРОМЕЖУТОЧНЫЕ РЕЗУЛЬТАТЫ ИСПЫТАНИЙ

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Abstract: The paper presents some results of testing of cylinders by inner hydraulic pressure to fracture with determination of volume characteristics, performed at E. O. Paton Institute. A stable connection between burst ratio and ratio of permanent volume expansion to total expansion is shown. The idea of assigning the limit admissible coefficient of permanent expansion, depending on the required burst ratio is proposed. Validity of assessment of cylinder technical condition using the degree of change of their residual volume is shown. Investigations are performed within the EU 7th Framework Program “INNOPIPES”. 15 References, 8 Figures, 1 Table.

Keywords: cylinders, testing, strength margin, permanent expansion, water jacket, deformation, internal pressure, volume change, cylinder testing.

1. Introduction

Cylinder burst ratio (n_b) is defined as the ratio of cylinder burst pressure (P_b) to working pressure (P_w), and it should be not lower than that specified by the respective normative documents [1-5]. Burst pressure determining the cylinder limit state, can differ from cylinder to cylinder, even within one batch, in view of deviation of geometrical parameters and scattering of mechanical properties, as well as presence of possible defects formed during manufacture or in service. Actual burst pressure can be determined only at cylinder hydraulic testing to limit state. In service the burst ratio of a specific cylinder can slightly decreases. Degree of lowering depends on many factors, related to service conditions, service duration, etc.

Cylinders after their manufacture, as well as during their periodical examination, are subjected to hydraulic testing by internal test pressure (P_h), which is 1.25 - 3 times higher than working pressure, depending on cylinder material and design. At such loading we can unambiguously state that burst ratio of examined cylinder is not lower than excess of test pressure over working pressure, whereas it is impossible to say what this coefficient actually will be. It is also impossible to assess the extent of residual deformations, is these occurred. Slight deformations cannot be detected visually. And as is well known, the higher the residual deformations, the closer is the limit state (see Fig. 1). Therefore, values of total expansion of cylinder volume at test pressure (ΔV_t) and its permanent expansion (ΔV_p) after test pressure release to zero began to be used over the recent years for residual deformation monitoring at steel verifying testing.

Total expansion is associated with geometrical characteristics of a specific cylinder, permanent expansion - with the magnitude of plastic deformations, if they occurred in the cylinder wall at test pressure. In view of a certain scatter of geometrical characteristics of cylinders in one batch, their ΔW_t value will be different, to say nothing of cylinders from different batches or, in general, manufactured in different types of productions and by different technologies. Therefore, to ensure uniformity, the ratio of cylinder permanent expansion to total expansion is taken, which is called coefficient of permanent expansion (K_{pe}). This coefficient characterizes the extent of plastic deformations in the cylinder, and is an integral criterion of technical condition that is often expressed in percent. In all probability, the greater the cylinder deviation from an ideal shape and the lower the material yield point, the greater will be the coefficient of total expansion at test pressure. In view of thickness difference within one cylinder and localizing of possible defects, residual deformation can also be non-uniform. At subsequent loading of the cylinder by test pressure, for instance, at subsequent testing, provided no changes occurred with it, the coefficient of total expansion should be equal to zero.

In normative documents, specifying testing performance with determination of coefficient of permanent expansion, its limit permissible values are specified, which are equal to 5 and 10% [2, 6, 7]. For some types of cylinders this coefficient should be specified by developer proper [2]. Here, it is not indicated what principles he should follow.

Information on the methods of determination of the coefficient of permanent expansion, equipment used for realization of these methods, and differentiated approach to assigning the terms of subsequent cylinder testing can be found in the brief review of normative documents given in the paper “Permanent Expansion of Cylinders (Brief Review)” [8]. This paper also indicates the types of cylinders, for which the method of permanent expansion is already used. This method is not yet widely applied to welded cylinders. During performance of testing for permanent expansion the loading rate should be below the maximum permissible one and soaking time at test pressure should be longer than the minimum admissible one. All that is specified in the respective in Regulatory Compliance (RC).

Fig. 1 gives a typical dependence between volume change and cylinder internal pressure, experimental data are given in Fig. 6.

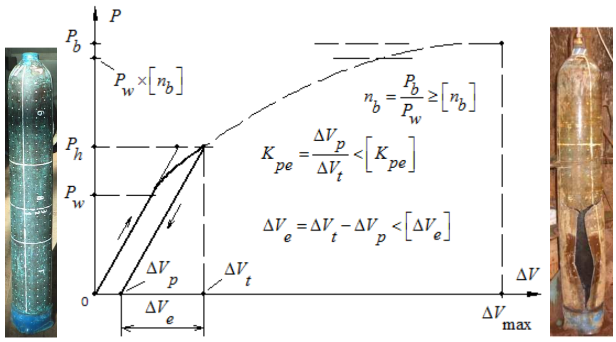

Fig. 1. To determination of cylinder volume expansion and coefficient of cylinder permanent expansion

P_w, P_h, P_b is the inner working, test and calculated burst pressure of the cylinder; ДV$_t$ is the total expansion of cylinder under test pressure; ДV$_p$ is the permanent expansion of cylinder volume after release of test pressure to zero; ДV$_e$ is the elastic expansion of cylinder volume at its loading by test pressure; ДV$_{max}$ is the maximum change of cylinder volume at possible taking it to fracture. All the above characteristics of volume change are measured in milliliters.

We could not find in published sources any information related to ideology of specifying limit permissible coefficient of permanent expansion [K_{pe}], given in the normative documents. RC proper do not differentiate between limit permissible coefficient of permanent expansion for the case of manufacture and for the case of periodical testing of cylinders in service. The process of permanent expansion accumulation from one periodical testing to another one is not specified, either. It is obvious that K_{pe} of a specific cylinder determined after its manufacture, should be related to its geometrical parameters and mechanical properties, and the one, determined during periodic examinations performed after a certain time interval, should be associated with the influence of service.

In view of the fact that cylinders are made by different technologies, and from different materials, they will have different tolerances for deviations of geometrical shapes and mechanical property scatter. As regards thickness difference, even within one cylinder, this parameter in many cases is not specified at all. Moreover, considering that K_{pe} is used for assessment of further serviceability also of different composite cylinders, having steel, aluminium and even nonmetallic case, and, in general, covers a range of cylinders with different normative burst ratios, the same for all maximum permissible coefficient of permanent expansion may not meet reliability criteria.

Considering the fact that some cylinders have been in service for quite a long time, it is necessary to ensure the maximum safe further service of these cylinders and timely removal from service of cylinders, not meeting the objective criteria. Application of assessment of the change of volume characteristics might help in solving these problems.

2. *Results and discussion*

The E. O. Paton Electric Institute of the NAS of Ukraine performed research to establish correlations between K_{pe} and other cylinder parameters, characterizing its performance and reliability, as well as to objectively assign limit permissible coefficient of permanent expansion of the cylinders at their loading by test internal hydraulic pressure.

With this purpose "water jacket" test unit was designed and built, which allows testing to be performed with determination of cylinder permanent expansion, for experimental confirmation of theoretical prerequisites and establishing the actual dependence between the coefficient of cylinder permanent expansion and burst ratio. The unit further allows determination of the coefficient of pressing up of the medium used for hydraulic testing. Layout and manufacturing of "water jacket' unit are not complicated in principle. And if this method for determination of the coefficient of permanent expansion is used for precisely concrete tasks, unit schematic can be simplified. The tested cylinder is placed into a hermetically closed water-filled tank (water jacket), the water from which at cylinder loading by internal pressure, as a result of its expansion, is driven into a calibrated burette, by which total expansion is determined. At pressure release in the cylinder, part of the water from the burette may not come back to the water jacket – permanent expansion.

There exist several schematics by which the coefficient of cylinder permanent expansion can be determined. The schematic realized using the water jacket has the highest accuracy. It is used predominantly for small capacity cylinders. The presented investigations were performed with application of exactly this technique. Now, at application of other schematics it is necessary to take into account the effect of water pressing-up [9 - 13].

Fig. 2 gives the block-diagram and photo of "water jacket" unit implemented at the E. O. Paton Institute for testing cylinders for permanent expansion. The Figure also shows as an example, 40 liter oxygen cylinder being tested, which was made to GOST 949-73.

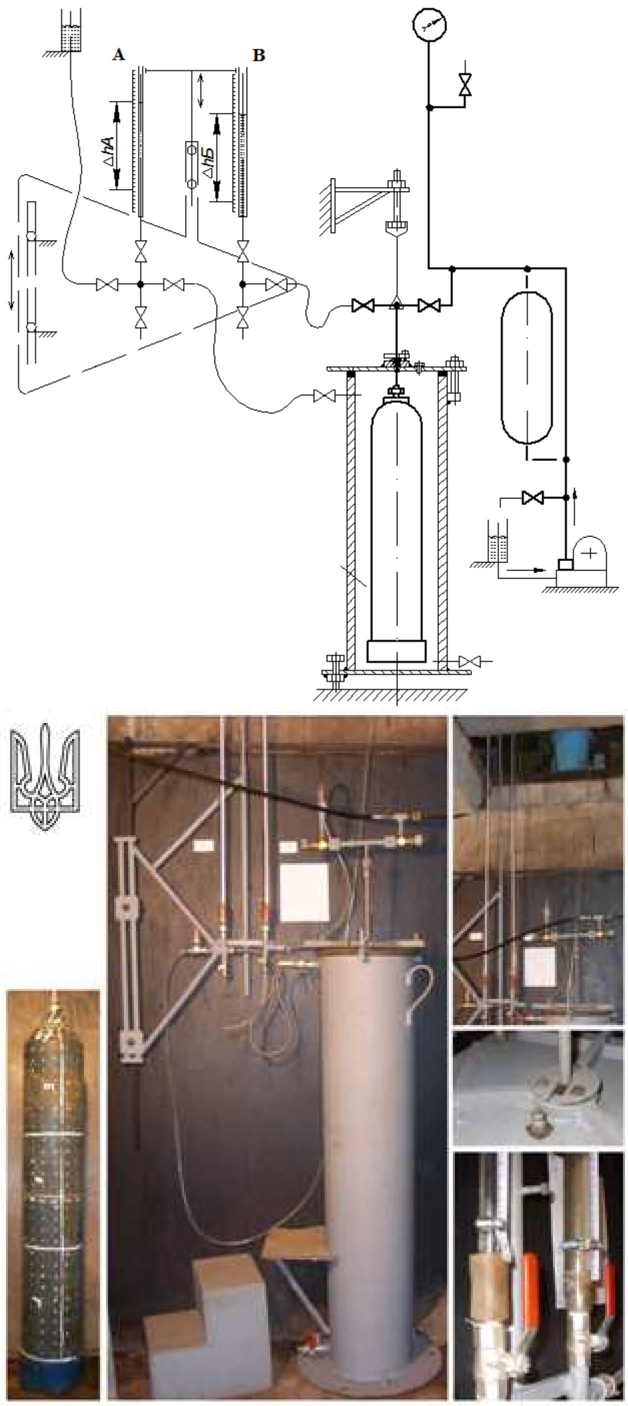

Fig. 2. Block-diagram and photo of "water jacket" unit implemented at the E. O. Paton Institute for cylinder testing for permanent expansion. (A B are burettes).

Investigations are performed on 40 liter oxygen cylinders made to GOST 949-73. (P_w=14.7 MPa, P_h=1.5P_w=20.05 МПа, [n_b]=2.6). Wall thickness was measured for more than 30 cylinders, about 400 measurement points for each. Nine cylinders were tested by internal pressure to fracture. Two cylinders passed tests in water jacket. Mariupol metallurgical works presented data on mechanical properties of cylinders after their manufacture. Examined cylinders have large difference of wall thickness, reaching 30%, as cylinders were made from hot deformed pipes, and considerable scatter of steel mechanical properties [4]. Cylinders, on the one hand, have much higher burst ratio than the normative requirements (2, 6), and, on the other hand, higher burst ratio of examined 40 liter cylinders is achieved due to increase of minimum wall thickness that in combination with nonuniform thickness of the wall in the cross-section leads to significant increase of cylinder weight and lowering of its technological properties.

Experimental dependencies are given for cylinder № I made in 1963. For cylinder № II manufactured in 1956, the dependencies are similar.

Table 1 Data on oxygen cylinders I and II

		I	II
Year of manufacture		1963	1956
Operation life, years		46	57
Average wall thickness, mm	s_o	8.43	8.191
Mean root square deviation of wall thickness, mm	σ	0.266	0.308
Outer diameter, mm	D	219.84	220.78
Initial volume, l	V_{in}	39.255	41.04
Change of cylinder volume at 22 MPa, cm^3	ΔV	99.2	109
Water injected by the pump at 22 MPa, $см^3$	ΔV_{pump}	498.2	531
Pressure of permanent expansion fixing, MPa	P_{kpe}	25.7	26.6
Total yield stress, MPa	P_Y	35.8	36.3
Burst pressure, MPa	P_b	57.5	59.61
Burst ratio	n_b	3.91	4.06

Fig. 3 gives dependencies of volume expansion of cylinder № I and quantity of water pumped into it on internal pressure. In the elastic work domain linear dependencies are observed, and test results coincide with the results of calculations for an ideally cylindrical pipe with covers of volume equal to that of the cylinder, and wall thickness equal to the average one for the cylinder. Quantity of water injected by the pump into the cylinder is also readily calculated, allowing for its pressing up. Experimentally found isothermal coefficient of volumetric compression of water coincides with values given in published sources, and depends on pressure and temperature.

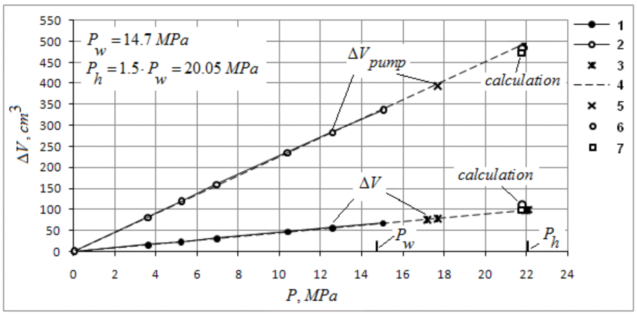

Fig. 3. Results of elastic testing of cylinder I.

Change of cylinder outer volume at loading up to working pressure - 1, up to test pressure - 3,volume of water injected by the pump into the cylinder at loading up to working pressure - 2, up to test pressureo - 5, linear approximations of the change of outer volume and volume of water injected into the cylinder by the pump - 4 (P=22 MPa, ΔV=99.2 cm^3, $ΔV_{pump}$=498.2 cm^3), calculated values allowing for axial deformation and without allowing for it - 6, 7.

Cylinders I and II were loaded by internal pressure in stages, pressure was increased from stage to stage, and after each stage pressure was lowered to zero. In the elastic domain and at the beginning of plastic deformations, testing was performed in water jacket and at stages close to failure – outside the jacket. All the cylinders were ultimately tested to failure. According to requirements to rupture shape and boundaries indicated in ISO [6], cylinders tested by us by hydraulic pressure to failure, broke in the brittle mode, which is also true to testing Charpy samples cut out of the cylinders. According to plasticity theory [15], plastic deformation process will loose its stability, when pressure in the cylinder stops rising. From Fig. 4 it is seen that in plastic deformation domain with increase of cylinder internal pressure the rate of its rise decreases and approaches zero. Rate of water feeding by the pump into the cylinder is close to a constant one. Loading diagram (pressure-time dependence) in deep plastic interval is readily approximated by quadric equation with the peak close to break point. Rate of pressure change here decreases by a linear law and is equal to zero, where the vertex of approximating parabola is observed.

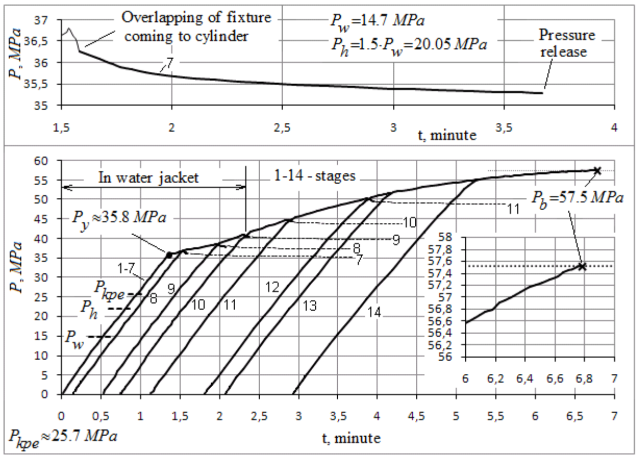

Fig. 4. Diagram of stage by stage loading of cylinder I by internal pressure right up to its failure.

Fig. 4. gives the diagram of stage-by-stage loading of examined cylinder to failure, which shows working and test pressure at calibration testing, pressure at which K_{pe} became different from zero and total yield stress of the cylinder. Loading was first applied in the water jacket and then outside it for safety reasons. When the cylinder was in the water jacket, K_{pe} was determined for each stage, and was recalculated as if loading were applied only once, see Fig. 5.

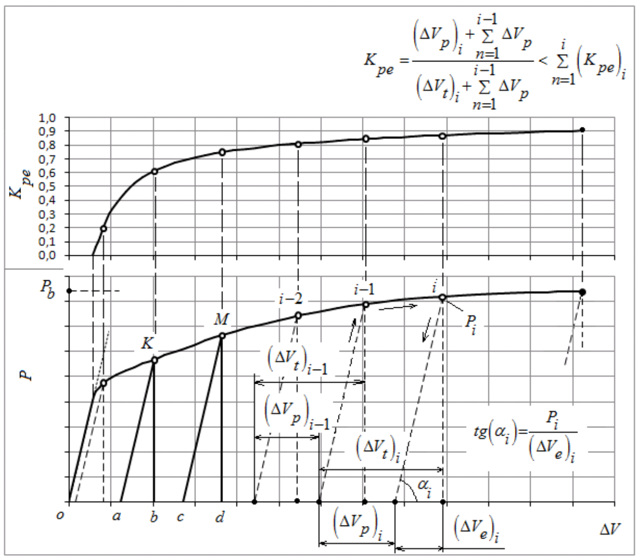

Fig. 5. Block diagram of K_{pe} recalculation at the intermediate stage

It is also interesting to note that after stopping the pump the cylinder continued expanding for some time that resulted in pressure drop. Pressure dependence on expansion is linear that is logical, provided there are no leaks. Such an effect was observed after K_{pe} became different from zero – plastic deformation domain. Maximum pressure of the stage was used for calculations and plotting diagrams

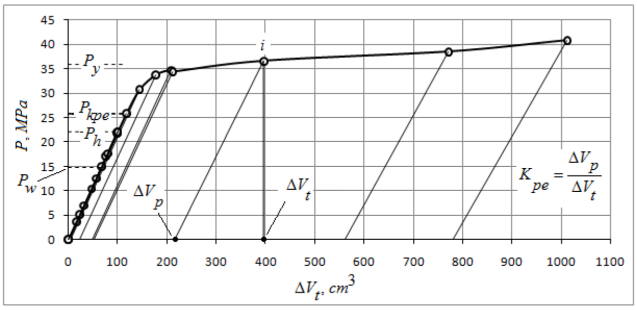

Fig. 6. Experimental dependence of pressure and actual permanent expansion of cylinder I, derived in water jacket

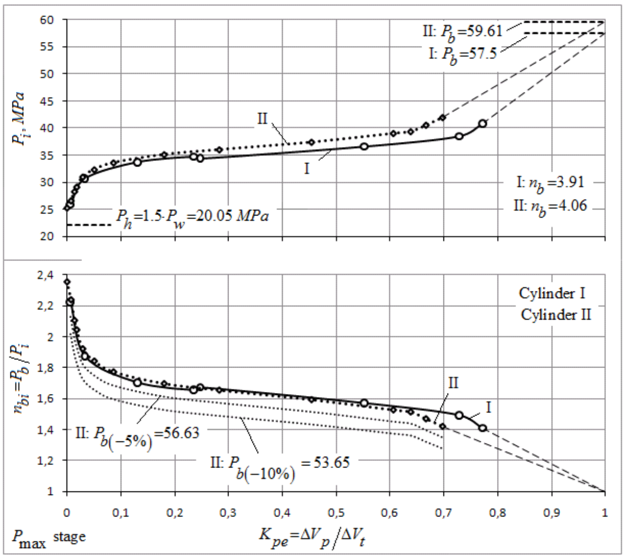

Fig. 7. Experimental data on cylinders I and II.

In Fig. 7 K_{pe} is the pressure and one can see that K_{pe} became different from zero at pressure a little higher than the test pressure, but lower than that of cylinder total yield stress - this is an indication of the influence, primarily, of difference in thickness.

As proposed by E. F. Garf (E. O. Paton Institute), burst ratio for each loading stage was determined as cylinder burst pressure referred to pressure reached at this stage. And such a burst ratio was correlated with the coefficient of cylinder permanent expansion at this stage. In the extreme case, this dependence ultimately tends to a unity.

It is seen that at elastic loading of the cylinder K_{pe} is equal to zero, and it is the most sensitive at initial stages of plastic deformation, and then it reacts only slightly to further deformation that is understandable from the definition of this coefficient.

Fig. 7 also gives the results of testing cylinder № II. Even though its burst pressure turned out to be higher, nonetheless, dependence of burst ratio on the coefficient of permanent expansion practically coincided with similar dependence for cylinder № I. Fig. 7 gives the cases, if burst pressure of cylinder II were by 5 or 10% lower. Cylinders were selected randomly, and failed from internal pressure as a result of exhaustion of metal load-carrying capacity - pressure rise rate in the prelimit state was close to zero. At multiplication of ordinates of burst ratio dependence on K_{pe} by 1.5, we obtain a diagram for the case of cylinder testing by 1.5 pressure. That is, the higher the permanent expansion demonstrated by the cylinder at its re-examination, the lower burst ratio it will have. In all probability, the determinant characteristics of this diagram will change slightly from cylinder to cylinder, provided they all have the same mechanism of reaching the limit state. And this is valid, if cylinders have no delaminations or folds, and have passed visual inspection.

To allow for the features of manufacturing technology, used materials, service conditions and schedule of re-examination of high pressure cylinders for commercial gases, a procedure of pressure testing is being developed, which allows guaranteeing the specified by normative requirements burst ratio at cylinder examination after their manufacture, as well as at their periodical reexamination. To increase the reliability of new cylinders and, particularly, cylinders after long-term service, it is necessary to guarantee the normative burst ratio for each specific cylinder without breaking it. Dependence of burst ratio on permanent expansion of cylinders of one type should, in all probability, be established experimentally on several specially selected cylinders, for instance, those with maximum ratio of internal volume to weight, which are then brought to fracture by a special technology.

After failure of cylinder № I by internal pressure, samples were cut out in the circumferential direction from the zone not exposed to plastic deformation - in the point of shoe putting on, and they were subjected to tensile testing. Having tensile stress-strain diagram, $\bar{\sigma}, \bar{e}$, it can be re-plotted into the actual stress-strain curve by the following dependencies: $\varepsilon_i = \ln(1+\bar{e}), \sigma_i = \bar{\sigma}(1+\bar{e})$, see Fig. 8. Internal pressure (P), intensity of stresses (σ_i) and strains (ε_i) can be correlated by the following equation: $P = \frac{2s\sigma_i}{\sqrt{3}r} = \frac{2s_0}{\sqrt{3}r_0} \cdot \frac{\sigma_i}{e^{\sqrt{3}\varepsilon_i}}$, where s_o is the average value of wall thickness in the initial state, r_o is the middle surface radius before plastic deformations. Fig. 8 gives the calculated dependencies and results, derived by measurement of cylinder perimeters between the stages.

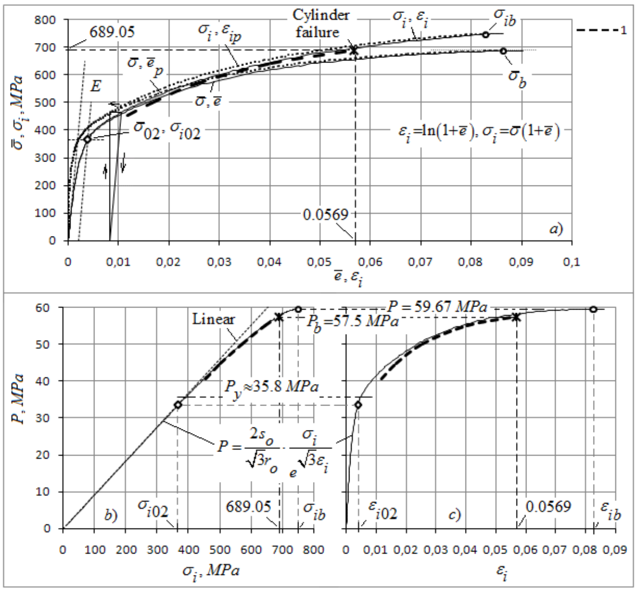

Fig. 8. Dependence of internal pressure in cylinder I on intensities of stresses and strains, plotted by the actual stress-strain curve (circumferential direction), and by results of measurement of perimeter change - 1.

Comparison of elastic volumetric expansion of pipe element with covers, before mounting a band on it along the entire length, and after mounting, allows determination of the degree of deformation lowering in the pipe wall and effective thickness of the band recalculated for pipe material.

When searching for interrelations between the coefficient of cylinder permanent expansion and other parameters, characterizing its performance and reliability, the following problems were solved:

- analytical plotting of diagrams of bending moments, tensile and shearing forces and finding stresses in the case of elastic loading by internal pressure of a pipe of elliptical cross-section with covers;
- ratio of pressures of yield start of an elliptical pipe with covers, and an ideal pipe, depending on ovality percentage;
- theoretical plotting of the diagram of dependence of burst ratio on permanent expansion coefficient of an ideal pipe with covers from material tensile stress - strain diagram, and its experimental confirmation;
- experimental determination of isothermal coefficient of volumetric compression of liquid, and its comparison with published data,
- analytical and experimental workup of uniform elastic, plastic and residual deformations of an ideal cylinder at its loading by slowly rising internal pressure right up to its fracture.
- establishing an analytical interrelation between the coefficient of permanent expansion and uniform deformations of an ideal pipe with covers, its experimental confirmation, etc.

3. Conclusions

1. Pressure testing of cylinders does not provide sufficiently full idea of their operating reliability. Such testing allows only stating that burst ratio of cylinders which passed testing is not less than excess of test pressure over working pressure. This, however, is insufficient to guarantee operating safety.
2. Theoretical investigations showed that cylinder permanent expansion can be an integral characteristic of its reliability. To allow for the features of manufacturing technology, used material and service conditions, dependence of burst ratio on cylinder permanent expansion should be established experimentally.
3. An experimental unit was developed, which allows cylinders to be tested by internal pressure with determination of permanent expansion coefficient, characterizing the extent of plastic deformations in cylinder wall.
4. Experimental studies were performed in the unit and an interrelation between the extent of plastic deformation in cylinder wall and burst ratio was established.
5. A procedure is being developed which allows by the results of pressure testing and measurement of the coefficient of cylinder permanent expansion establishing its actual burst ratio and performing cylinder rejection by their reliability level.
6. Theoretical substantiation is provided of the validity of evaluation of cylinder technical condition through an integral criterion - coefficient of cylinder permanent expansion.

On the whole, CPE method provides an integral characterization of the cylinder as a structure, and provides a real possibility of assessment of cylinder technical condition, both at their manufacturing stage, and at the stage of their periodical examination.

Acknowledgements

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