THERMAL NONDESTRUCTIVE TESTING OF VESSELS UNDER INTERNAL PRESSURE

O.N.Budadin, D.Sc. in engineering; A.A. Filipenko, PhD in Technical Sciences; T.E. Troitsky-Markov, Vl. O. Kaledin

Currently, reservoirs made of polymeric composite materials (PCM) operating under elevated internal pressure are widely used in the gas, petrochemical, aerospace and other industries. The major requirement to ensure a trouble-free operation of potentially dangerous facilities involves an evaluation of the technical conditions of those facilities by using inspection and analysis techniques including ones used under the operating conditions of the facility.

Several attempts have been made to resolve this problem by means of various nondestructive testing methods which include ultrasonic testing, acoustic emission testing, acoustic contact leak detection, etc. However, in many cases desirable results was not achieved.

1. Conventional nondestructive testing (NTD) methods provide for macro defects detection (with a size over 60 … 100 microns), while depressurization, as a rule, is primarily caused by micro defects (microcracks, micropores, etc. with sizes within 60 … 100 microns).

2. The micro defects are basically formed in the course of pressure build-up inside an object being monitored, whereas the NTD methods are difficult to implement technically, as a rule, with the items under pressure. Besides, it is dangerous from the safety engineering point of view since a testing inspector should be near the item to conduct a nondestructive testing.

Thus, development of remote NTD methods for internally pressurized vessels operating under conditions of a high internal pressure (High-Pressure Vessels (HPV)), which enable to localize inner micro and macro defects with a high degree of reliability, is of great importance.

The drawbacks of conventional NTD methods for HPV can be sufficiently eliminated by using a thermal imaging diagnostics technique.

In practice the proposed method can be used to check the technical condition of reservoirs operating under excessive internal pressures: aerospace vehicle compartments, missile engines, pipelines, pressure vessels, pressure chambers, etc. The application of this method is especially effective for potentially dangerous objects testing, which are items with severe requirements for leak-tightness and control reliability, when the time for excessive pressure build-up is limited and it is necessary to detect not only open-end leaks but also inner micro defects, which may result in a breakdown afterwards.

The gist of the micro- and macro defects detection method is as follows.

When the test item is pressurized by fluid or gaseous mediums under pressure, this item expands revealing micro defects (cracks, pores, etc.). The medium having a temperature, which is different from the ambient temperature, penetrates through the micro defects (Fig. 1) to the surface of the test item or into the surface layer and creates areas with abnormal temperature values. In this way a sign of the area, which contains a micro defect affecting the leak tightness of the item, is formed.

Temperature profile abnormalities will occur also in case if the micro defects do not penetrate through to the surface of the item. The medium penetrates into the material, comes near the surface and causes the surface temperature abnormalities without reaching the surface. In this case the proposed method provides for detection of potentially dangerous areas of the item, which may lead to the depressurization due to operation modes change. The thermal diagnostics method affects the test item to a minimum degree because the internal pressurization process is stopped once the defects have been reliably identified (practically 15-20% of the maximum permissible pressure is sufficient for a positive defect detection).

The surface segments with an abnormal temperature are recorded by using a thermo imaging equipment during internal pressurization; then after a corresponding processing procedure they are represented as a thermograph. The processing procedure consists in detection of abnormalities against a noise and interference background, as required, identification of micro defects by the temperature abnormalities analysis, definition of coordinates and characterization of the micro defects.

When conducting the thermo imaging surveys, the thermal imager field of view shall exceed the size of potentially dangerous areas on the surface, and the temperature resolution capability of the infrared imager shall provide for detection of temperature abnormalities on the surface.

By results of the vessel temperature profile recording a defectogram is drawn, the defects are identified, their coordinates and characteristics are determined.

Before its supply to a vessel a medium must be heated up to a temperature exceeding the temperature of the vessel surface.

Due to a high cost of the experimental development of the proposed method, a mathematical simulation technique has been used instead. The following aspects were considered:

- a pronounced anisotropy and heterogeneity of the structure material containing layers with elasticity modulus differing from one another by several degrees, which leads to an essential dependence of the stressed state on the boundary conditions, hence making the simplified computed models unusable;

- influence of the material structure (reinforcement pattern and order of the layers' sequence in a composite material with various reinforcement directions) on the strength of a vessel shell (its resistance to delamination).

Besides, for the problems to be solved relating to the combined high-pressure vessels it is necessary to simultaneously consider various aspects of deformation considering a comparatively wide range of shapes and structures of test structure elements – from calculation of the entire stressed state of the vessel up to determination of stress concentration at layer interfaces, at flanges, crack-type defects, inclusions, etc.

The process of the problem solution in the theoretical investigations involves the following basic stages:

1. The derivation of the basic (resolving) equations of the reviewed physical field for a finite element.

2. The selection of rational types of Finite Elements (FE) and the approximation of the required variables inside the FEs by their values in the chosen node points by means of basic functions (shape functions).

3. The integration of the element equations into a uniform system for the whole computational domain.

4. The solution of the generalized system of equations, computation of the field parameters (shifts, stresses or strains) and behavior definition (change of characteristics) of micro defects in the pressure vessel structure when it is internally pressurized.

5. The solution of a nonlinear nonsteady problem of thermal conductivity in a 3D-field with subdomains for definition of the temperature profile on the object surface.

The known variational extreme approach was used for the derivation of the resolving equations according to the chosen FEM, which enables to avoid use of the simplifying hypotheses of the static or kinematic nature, and also provides for the most accurate consideration of the structural heterogeneities of the structures under research.

According to this approach, the displacement field is defined on the basis of the Lagrange variational principle from the requirement for a minimum potential energy of a structure:

$$\Phi = \frac{1}{2}\int_V e dV - \int_S \mathbf{P}_S^T \mathbf{u} dS - \int_V \mathbf{P}_V^T \mathbf{u} dV \to \min, \qquad (1)$$

Where Φ - potential strain energy;

V and S - volume and body boundary accordingly;

u - displacement vector;

$\mathbf{P}_s$ - vector of external surface load;

$\mathbf{P}_v$ - vector of volumetric loads;

$\boldsymbol{e}$ - potential strain energy density.

The potential strain energy density is defined from the following relation as a work performed by stresses in a body based on increments of strains:

$$e = \int_0^\varepsilon \boldsymbol{\sigma}^T d\boldsymbol{\varepsilon} = \boldsymbol{\sigma}_0^T \boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}_0^T \mathbf{D}\boldsymbol{\varepsilon} - \boldsymbol{\alpha}^T T \mathbf{D}\boldsymbol{\varepsilon} + \frac{1}{2}\boldsymbol{\varepsilon}^T \mathbf{D}\boldsymbol{\varepsilon}, \qquad (2)$$

This is derived with allowance for the correlations between stresses and strains of the following type:

$$\boldsymbol{\sigma} = \mathbf{D}(\boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}_0 - \boldsymbol{\alpha} T) + \boldsymbol{\sigma}_0 , \tag{3}$$

Where σ - stress vector;

D - elastic parameter matrix;

ε - strain vector;

ε- initial strain vector;

α - thermal strain coefficient vector;

T - temperature read from the initial state;

σ - initial stress vector.

The resolving system of the linear algebraic equations concerning the nodal displacement vector of the FE is derived from the requirement for a minimum of its potential energy (1) in the following form:

$$\mathbf{K}_k \mathbf{v}_k = \mathbf{P}_k \tag{4}$$

Where $\mathbf{K}_k = \int_{V_K} \mathbf{B}^T \mathbf{D} \mathbf{B} dV$ - element stiffness matrix;

$\mathbf{P}_k$ - resultant vector of nodal loads on an element.

The solution of system (4) results in finding of the FE nodal displacements, which are then used for finding of the displacement of **u**, strains ε and stresses σ in the selected points of the FE.

Let's consider a uniformly pressurized circular cylinder with a crack-type defect, which occurred due to the interaction of the internal yielding and external pressure layers (Fig. 1). The design model is given in Fig. 2.

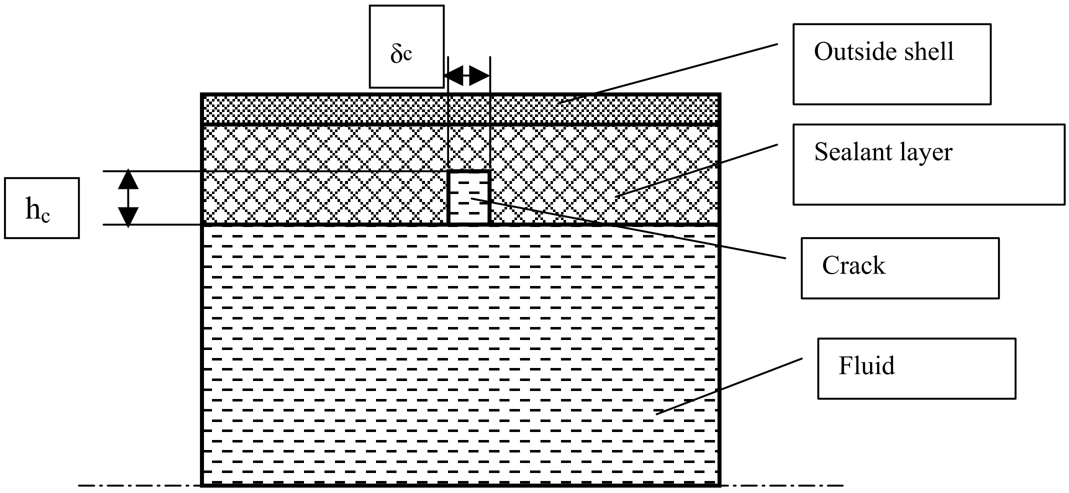

Fig. 1 Model area under analysis

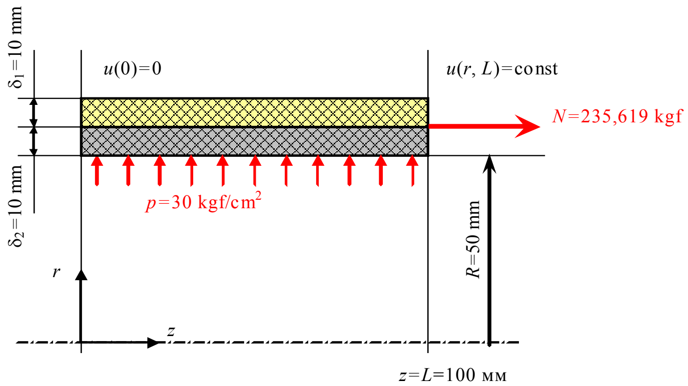

Fig. 2 Design model of cylindrical part of combined high-pressure vessel

Radially oriented cracks were analyzed when performing calculations. The presence of the crack was simulated by the absence of the force interaction between the adjacent elements, which are joining each other in the plane perpendicular to the spin axis.

Some representative results of calculations in the form of a graphic representation of the strain fields are given in Figures 3 and 4.

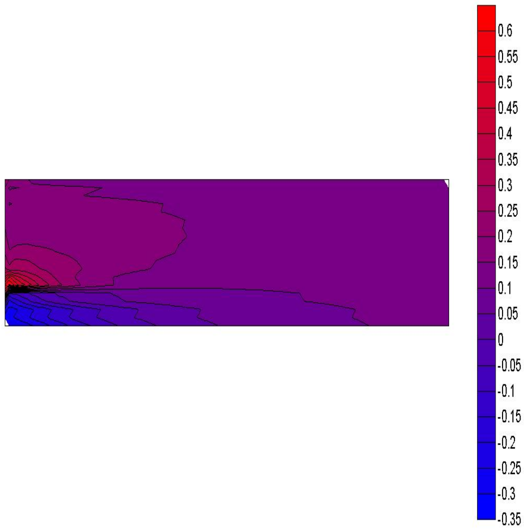

Fig.3. Distribution of longitudinal stresses σ_z (kgf/mm^2) in the sealant layer with a crack of 3mm deep with only annular reinforcement of the pressure shell (V=0)

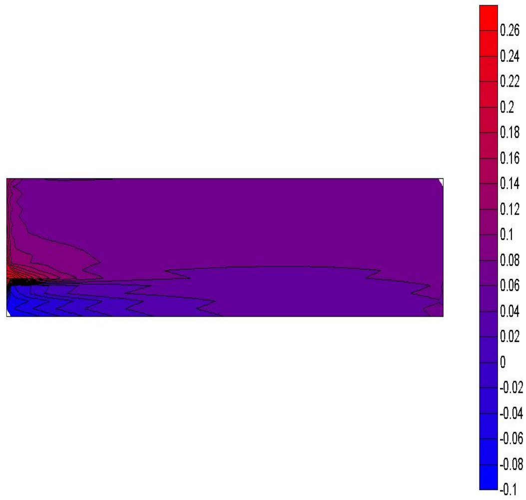

Fig.4. Distribution of annular stresses σ_z (kgf/mm^2) in sealant layer with a crack of 3mm deep with only annular reinforcement of the pressure shell (V=0)

To analyze the process of temperature profile formation on the outside surface of a high-pressure vessel due to the fluid penetration to the outside surface through the macro defects, a three-dimensional nonsteady problem of nonlinear thermal conductivity relating to the considered structure with subdomains (Fig. 4) featuring the corresponding boundary and starting conditions has been resolved:

$$\frac{\partial Q(\mathbf{r},t)}{\partial t} + \mathrm{div}\mathbf{J}(\mathbf{r},t) = 0\,, \qquad (5)$$

Where $Q(\mathbf{r},t)$ and $\mathbf{J}(\mathbf{r},t)$ - thermal energy volume density and thermal flow density respectively, defined as follows:

$$(10)\,Q(\mathbf{r},t) = \rho(\mathbf{r})\cdot C\rho(\mathbf{r})\ \cdot T(\mathbf{r},t) \qquad \mathbf{J}(\mathbf{r},t) = -\lambda(\mathbf{r})\frac{\partial T(\mathbf{r},t)}{\partial \mathbf{r}}\,, \qquad (6)$$

Where T($\mathbf{r}$,t) - temperature, ρ($\mathbf{r}$) – medium density, Cρ($\mathbf{r}$) - its specific heat, λ($\mathbf{r}$) - thermal conductivity.

Some calculation results are given in Fig. 5-8 as diagrams.

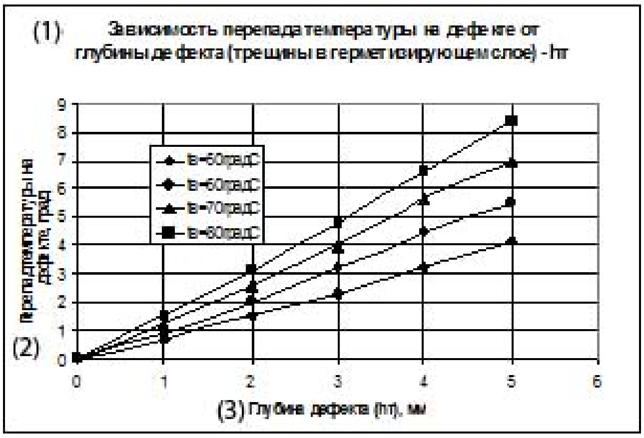

Fig. 5

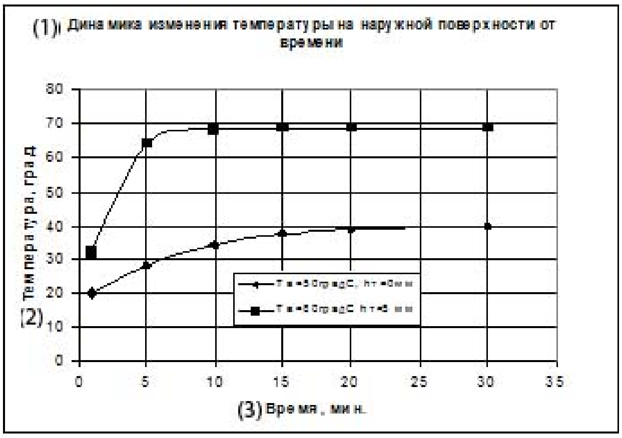

Fig. 6

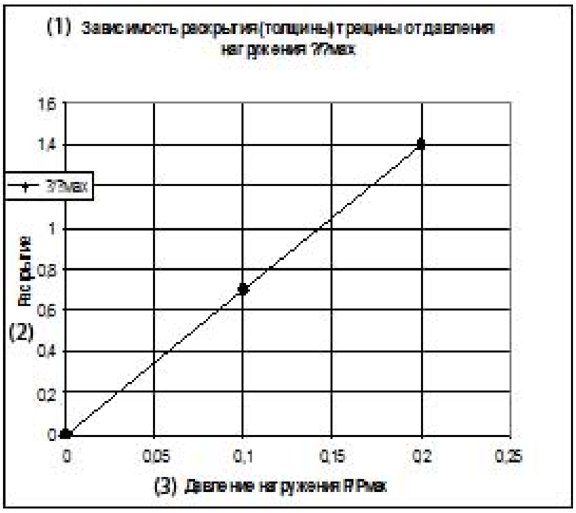

Fig. 7

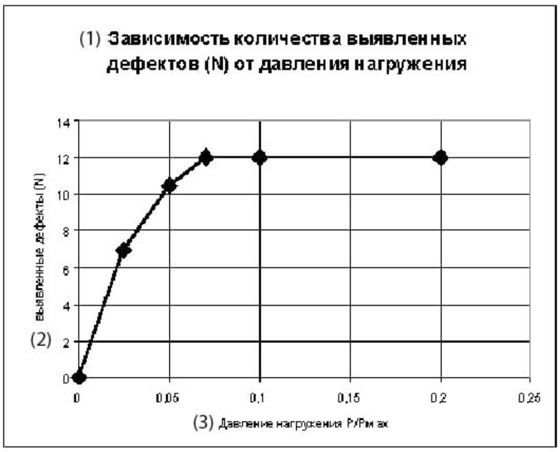

Fig. 8

Diagrams in Fig. 5-8 show that the temperature abnormalities, which are applicable for reliable defect identification, become apparent already at pressures over 5-10% of the corresponding vessel breakdown pressure.

The experimental research of the proposed method is focused on the solution of two problems:

- analysis of working efficiency of the proposed inspection method and its usefulness in real application conditions;

- analysis of inspection reliability versus its prototype and lowering of destruction probability of the test item;

The experimental research of the thermal NDT method for the pressure vessels has been conducted on a set-up, the functional chart of which is detailed in Fig. 9.

A double-layer vessel was used as an analyzed item: the external layer was made of fiberglass, the internal layer was a rubber-like sealant coating. 12 manufactured defects with various geometrical characteristics were made in the rubber-like sealant coating.

The set-up works, as follows.

The test item is filled with a fluid, temperature of which exceeds the ambient temperature.

By means of a special system the fluid internal pressure was increased.

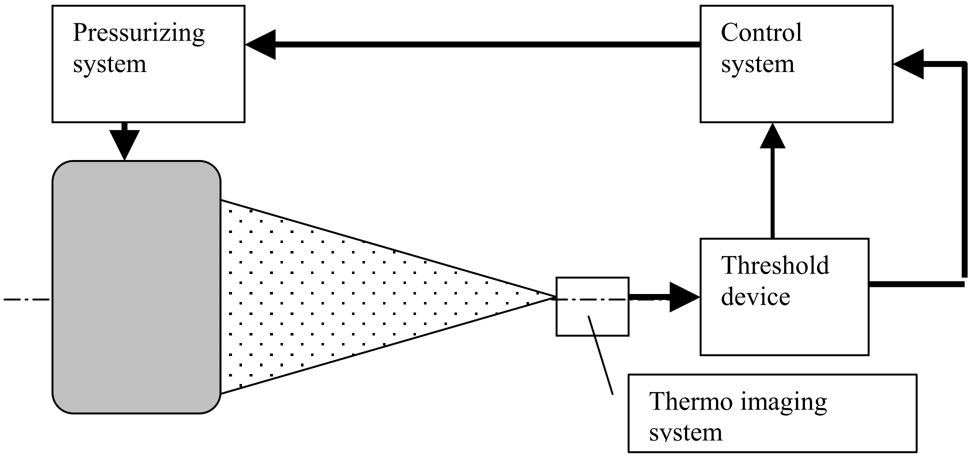

Fig. 9. Functional inspection diagram

While the vessel was pressurized, the temperature profile was recorded by the thermo imaging system. The temperature profile video image was transmitted to the information processing block where the data was processed in order to:

- detect abnormal segments among heterogeneities and noises,
- define characteristics of the defects.

Some surface thermographs of the analyzed items are given in Fig. 10 and 11 as examples.

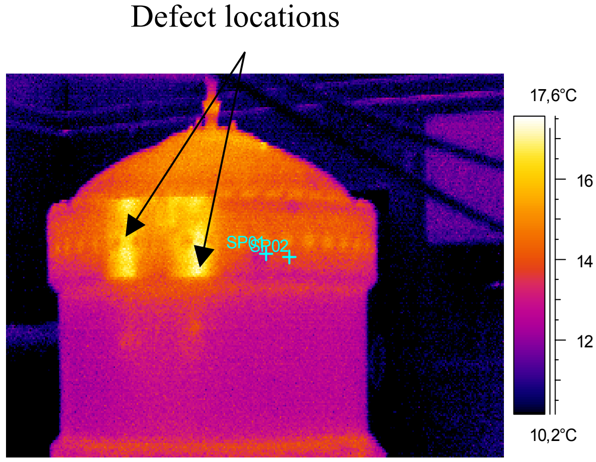

Fig.10

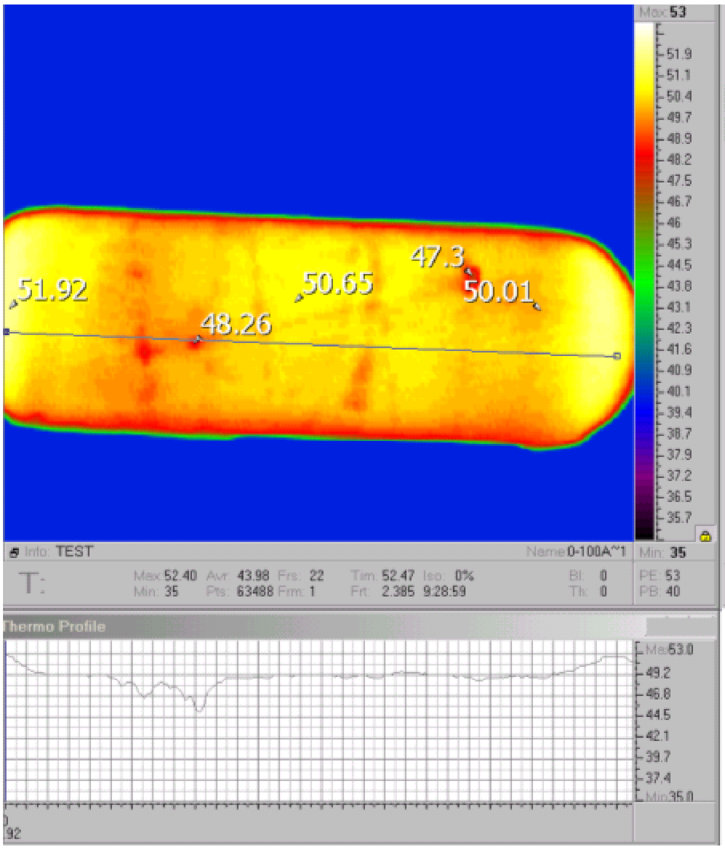

Fig. 11

An example of a high-pressure vessel filled with hot water at 60°C and 100atm is shown in Fig. 11. Temperature heterogeneity on the surface of the pressurized vessel (Δt ≈ 2.5ºC) can be seen in the chart (thermal profile), which denotes possible defective spots (delamination, swelling) in the wall of the item.

A curve based on the results of the experimental research is shown in Fig. 12.

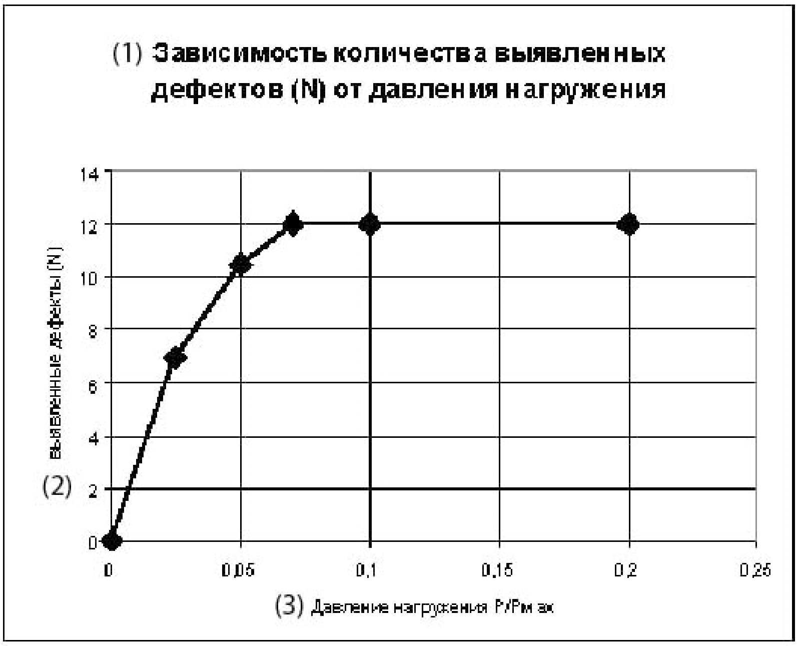

Fig.12

The experiments and theoretical studies have shown that starting from pressure of 5-10% of the maximum permissible pressure, the thermal NDT provides a reliable defect detection and identification with an error not exceeding 15%.

It ensures a low destruction probability of the item without prejudice to the reliability of the inspection, provides for a considerable economic benefit due to lowering of power and labor inputs when conducting tests. Besides, the low destruction probability provides for a low number of recurring defects.

The performed experimental research efforts have shown that this NDT method, along with the analysis of manufactured items leak-tightness condition according to the existing conventional procedure, enables a reliable detection of micro defects in the course of the NDT procedure. Later on this information was used for dedicated repair of manufactured items. This enabled the manufacturer to lower a defect ratio of components, essentially improve their quality and gain a considerable economic benefit.

List of references

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