Study of formation peculiarities of containment and pressure shells of combined containers of high pressure

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Abstract
The researches results of joint formation peculiarities of containment and pressure shells of combined containers of high pressure are presented in the article. Conditions of tension unavailability between shells of combined containers in case of adherence to technology of their production are determined. Possibility of formation of ring cracks when composite strengthening and sections with microdamages of its internal layer under the pressure lower than operating is shown. The necessity of further researches of change of the stress-strain state of a metal liner considering the obtained results is justified.
Keywords: COMBINED CONTAINERS OF HIGH PRESSURE, COMPOSITE STRENGTHENING, METAL LINER, TENSION.

Introduction

Containers of high pressure have widespread application in oil and gas industry and modern automotive industry, aerospace engineering and other industries. The engineering level of such constructions is evaluated by their mass perfection. The use of the composite material (CM) in combined containers of high pressure with the containment metal shell allows significant improving of this index. The basic reason constraining growth of this index in such constructions is the discrepancy of elastic limit deformations of metals and composites. Nature of development of the modern materials science shows that it is impossible to provide the optimum conformation of deformation characteristics of the metals and composites used as materials for production of combined containers of high pressure in practice. Currently, the growth rates of elastic deformations even in new metal alloys lag considerably behind this index in composites.

2. Analysis of literary data and problem statement

In the majority of works about "the combined shells", the researchers consider the problem of solution and optimization of task of joint deformation of metal and composite shells. The importance of this problem is determined by not only significant distinction of physical and mechanical properties of metals and CM, but also distinction of types of their deformation: elastic-plastic in metal and elastic (or elastic with variable parameters of elasticity) in composites.

Mostly, solutions of this problem are proposed on the basis of reduction of structural stiffness of the containment shell.

The technological methods of increase of the general elastic deformation of metal shells are known; they are based on use of regions of compressive elastic deformations. To provide redistribution of residual tension between shells is main objective of these methods. Thus, compression stress is characteristic for a metal shell if there is no internal pressure.

Regardless of variety of suggestions of application of both constructive and technological methods, increase of elastic deformations range is limited in industrial constructions due to the difficulties with their technical implementation. Therefore, traditional doubly-shell scheme is the main constructive scheme for the combined containers implementation, and power method, which is implemented by a pretension of the reinforcing fibers, is used for regulation of residual technological deformations region. At the same time, the combined containers of a high pressure including big volume metal-composite cylinders are high-risk objects, which destruction under operating conditions can cause unpredictable consequences. In order to prevent the destructions, the technical conditions of metal of composite cylinders are controlled. The selection of control methods is one of the main objectives of their safe operation.

According to "Rules for the Construction and Safe Operation of Containers Operating under Pressure" (MSDS 10-115-96) [1], metal-composite cylinders are subject to obligatory technical inspection every three years. In particular, engineering certification includes external and internal examination of cylinder and hydraulic (pneumatic) tests. The objective of external and internal examination of cylinder is detection of visible defects: cracks, dents, imperfections (out-of-roundness, deflections, etc.), laminations and ruptures of composite pressure shell. The hydraulic pressure tests of cylinder are carried out in case of satisfactory results of examination in order to check the strength of a composite shell and hermiticity of metal liner.

However, equipment examination, which is performed once every three years according to the specified rules, does not provide failure prediction of a cylinder during the period between examination and repair. Moreover, technical expert examination is rather difficult procedure for the organizations operating the metal-composite cylinders of big size. The examination must be carried out only in the specialized organizations, where the customer should deliver cylinders, and moreover, requires their preliminary preparation.

The long period between each equipment examination, the considerable costs for its performance, the high danger of operation of big size cylinders and high working pressure cause the necessity for monitoring of cylinders working efficiency during their operation for failure prediction.

3. Objectives and research tasks

Researches of peculiarities of joint deformation of containment and pressure shells of combined containers of high pressure in the course of their operation were conducted in order to select the appropriate control methods of technical condition.

4. Description of task solution

Currently, the metal-composite of cylinders is based on criterion of construction strength uniformity [2]. According to this criterion, the strength factor of cylinder body is accepted as equal (no less than 2.6 in relation to working pressure value) for both cylindrical and bottom part of cylinder; it stipulates their almost simultaneous breakdown [3]. At that, the researches have shown that breakdown of cylindrical part generally takes place along its generatrix. Its bottom parts are subject to splinters formation.

At the same time, as results of external examination of CNG-2 cylinders show, the ring cracks are characteristic for a composite shells. Such cracks do not affect the composite strength, but allow moisture to penetrate the steel shell. As a result its unprotected surface undergoes corrosion damage. On a steel shell surface, the quite wide, in comparison with their sizes, sections with surface corrosion are formed near cracks [4]. The condition of an internal surface of high-pressure cylinder composite shell, which was broken after long period of its testing for fatigue life, is indicative of it.

If we go back to peculiarities of combined containers design, it is necessary to remember that preliminary tension is created between the liner and composite strengthening. Dark fringes on composite strengthening testifies to possibility of moisture ingress to these zones, and therefore, this poses the question of existence of initial tension between shells while containers operating.

In the paper [5], initial stresses σ_0^c in composite strengthening created by a preliminary tension of a roving in the direction of material fibers axis are determined by formula

$$\sigma_0^c = k \cdot \sigma_{ten}, \qquad (1)$$

where σ_{ten} – tension in a technological tape during winding;

$k = \dfrac{1}{\sqrt{1 + E_1 \cdot h_c / E \cdot h_m}}$ – coefficient of tension slackening in a technological tape after its putting in the metal case, where E_1, E – composite modulus of elasticity along fibers and metal of liner respectively; h_c, h_m – thickness of composite strengthening and metal liner.

In turn, tension in a technological tape σ_{ten} is determined as follows

$$\sigma_{ten} = \frac{T_0 \cdot \gamma \cdot H_0 \cdot 10^3}{M}, \quad (2)$$

where T_0 – tension force when winding of two bobbins; γ – volumetric density of glass; H_0 – volume criterion of composition; M - the linear density of roving.

Initial circular stress in metal liner created by a preliminary tension of roving when winding is due to the previous stress σ_0^c in composite strengthening by dependence

$$\sigma_{\beta 0}^m = -\sigma_0^c \cdot \frac{h_c}{h_m}. \quad (3)$$

in case of absence of internal pressure.

Under such initial conditions, the absolute diametrical deformation of metal liner and composite strengthening will be respectively determined as follows

$$\Delta d_m = \frac{\sigma_{\beta 0}^m \cdot d_m^{av}}{E}; \quad \Delta d_c = \frac{\sigma_0^c \cdot d_c^{av}}{E_1}, \quad (4)$$

where $d_m^{av} = D + h_m$, $d_c^{av} = D + 2 \cdot h_m + h_c$

D– the internal diameter of metal liner.

Thus, after formation of composite strengthening, cylindrical part of combined type cylinder can be considered as connection with a tension which value is equal to

$$\delta = \Delta d_c - \Delta d_m. \quad (5)$$

At that, it is accepted that deformation of a metal liner does not influences significantly the change of its average diameter. At the same time, the external diameter of a metal liner before application of composite strengthening is determined as $d_m^{ex} = D + 2 \cdot h_m$, and if there are no initial stresses caused by its contact with the liner, the internal diameter of composite strengthening is $d_c^{in} = d_{cm} - \Delta d_c$, where $d_{cm} = d_m^{ex} - \Delta d_m$ – diameter of contact surface of a metal liner and composite strengthening at temperature corresponding to winding conditions.

As it was noted in paper [6], operation of the containers intended for transportation of compressed natural gas provides change of their material temperature as a result of both change of environment temperature and change of gas temperature when its loading and unloading. Although, according to the paper [4], ring cracks are formed due to temperature fluctuations even if there are no loadings by internal pressure. It is reasonable to establish the value of temperature change of container material, which can cause the lack of tension between metal liner and composite strengthening.

Considering the Hooke's law, having added the temperature deformations to the deformations caused by tension, generally for cylindrical shell we obtain

$$\varepsilon_\beta = \frac{\sigma_\beta}{E} + \alpha \cdot \Delta T, \quad (6)$$

where E – circle tension; E – elastic modulus; ΔT– coefficient of linear thermal expansion; ΔT – temperature change.

In turn, the relative deformation

$$\varepsilon_\beta = \frac{\Delta d}{d}, \quad (7)$$

where d – diametrical deformation of cylindrical shell of diameter d.

In case of temperature change of cylindrical part of container of combined type, the tension between metal liner and composite strengthening if there is no internal pressure (5), (6), (7) will be determined as follows

$$\delta = \frac{\sigma_0^c \cdot d_c^{av}}{E_1} - \alpha_c \cdot \Delta T \cdot d_c^{in} - \frac{\sigma_{\beta 0}^m \cdot d_m^a}{E} + \alpha_m \cdot \Delta T \cdot d_m^{ex}, \quad (8)$$

where $\delta = 0$ – coefficient of the linear thermal expansion of composite along fibers and metal of liner.

For this case, a condition of absence of a tension between parts of capacity is interesting; this state is implemented even under conditions when $\delta = 0$. For this purpose, change of temperature should be

$$\Delta T = \frac{\dfrac{\sigma_0^c \cdot d_c^{av}}{E_1} - \dfrac{\sigma_{\beta 0}^m \cdot d_m^{av}}{E}}{\alpha_c \cdot d_c^{in} - \alpha_m \cdot d_m^{ex}}. \quad (9)$$

In the given expression, the coefficient of linear thermal expansion of composite strengthening (α_c) is the parameter, which value can change in rather wide range and depend on several factors. It can vary in the range from $5 \cdot 10^{-6}$ K^{-1} to $10 \cdot 10^{-6}$ K^{-1}. Some sources indicate that it can reach minimum value of $2 \cdot 10^{-6}$ K^{-1} [7]. Regardless of it, for the container of combined type with the parameters specified in [5] ($D = 0{,}205\, m$, $h_m = 3{,}15\ mm$, $h_c = 2{,}8\ mm$), having accepted that the coefficient of linear thermal expansion of metal liner is $\alpha_m = 12 \cdot 10^{-6} K^{-1}$ [8], it was determined the value of temperature change that leads to tension loss for the specified value range of coefficient of linear thermal expansion of composite strengthening (Fig. 1).

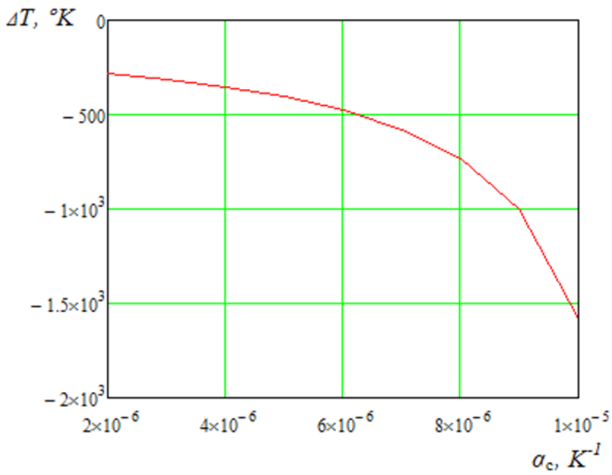

Figure 1. Change of temperature that causes tension loss between elements of container of combined type

Regardless of the fact that during researches, the impact of pressure on the stress-strain state of container of combined type is not considered, it can be claimed that a tension between construction elements should take place in the whole operating temperature range in case of adherence to production technique. The internal pressure of gas is conducive to its increase.

Analyzing the above mentioned results and features of stress-strain state of containers of the combined type, it should be noted that its local destruction is the potential reason of formation of both ring cracks and dark fringes on internal surface of composite strengthening. Destruction takes place under the conditions of destructive tension emergence in composite strengthening, namely in the direction perpendicular the reinforcing fibers. In order to confirm or dispose our reasoning, let us use the metal-composite cylinder calculation method suggested by authors [9]. At that, the corrections caused by design features of CNG-2 cylinder are introduced.

From the balance equations of element of double-layer cylindrical shell under the conditions of internal pressure, we obtain

$$N_\alpha = \frac{pR}{2}; \quad N_\beta = pR. \qquad (10)$$

Total axial (N_{ax}) and circular (N_β) forces may be presented in the following form:

$$N_\alpha = N_\alpha^m + N_\alpha^c; \quad N_\beta = N_\beta^m + N_\beta^c, \qquad (11)$$

where N_α^m, N_β^m and N_α^c, N_β^c – forces in metal liner and composite shell.

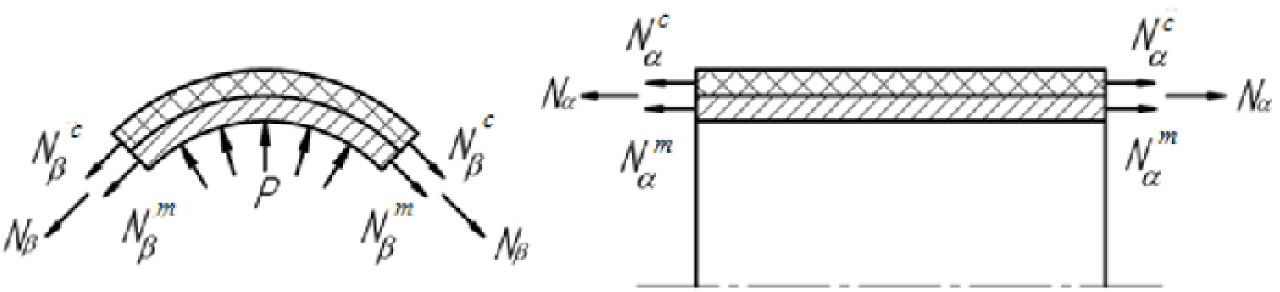

Figure 2. The design diagram of determination of axial and circular forces in an element of double-layer cylindrical shell

For metal liner

$$N_\alpha^m = \sigma_\alpha \cdot h_m; \; N_\beta^m = \sigma_\beta \cdot h_m. \qquad (12)$$

Considering the Hooke's law for isotropic body,

$$\varepsilon_\alpha = \frac{1}{E}\cdot(\sigma_\alpha - \nu\cdot\sigma_\beta); \; \varepsilon_\beta = \frac{1}{E}\cdot(\sigma_\beta - \nu\cdot\sigma_\alpha), \qquad (13)$$

which in reciprocal form is of the following form:

$$\sigma_\alpha = \overline{E}\cdot(\varepsilon_\alpha + \nu\cdot\varepsilon_\beta); \; \sigma_\beta = \overline{E}\cdot(\varepsilon_\beta + \nu\cdot\varepsilon_\alpha), \qquad (14)$$

where $\overline{E} = \frac{E}{1-\nu^2}$, forces in metal liner are determined as follows:

$$N_\alpha^m = \overline{E}\cdot h_m\cdot(\varepsilon_\alpha + \nu\cdot\varepsilon_\beta); \; N_\beta^m = \overline{E}\cdot h_m\cdot(\varepsilon_\beta + \nu\cdot\varepsilon_\alpha), \qquad (15)$$

where ν – Poisson ratio.

For a composite shell, considering assumptions (12) and (14), connection of forces $N_\alpha^{\tilde{n}}$ and $N_\beta^{\tilde{n}}$ with axial (ε_α) and circular (ε_β) deformations on the basis of the generalized Hooke's law is of the form [10]:

$$N_\alpha^c = B_{11}^c\cdot\varepsilon_\alpha + B_{12}^c\cdot\varepsilon_\beta; \; N_\beta^c = B_{12}^c\cdot\varepsilon_\alpha + B_{22}^c\cdot\varepsilon_\beta, \qquad (16)$$

where stiffness ratio in the case of the unidirectional composite will be of the form:

$$B_{11}^c = h_c\cdot\overline{E}_2; \; B_{12}^c = h_c\cdot\overline{E}_1\cdot\nu_{12}; \; B_{22}^c = h_c\cdot\overline{E}_1. \qquad (17)$$

$$\overline{E}_1 = \frac{E_1}{1-\nu_{12}\cdot\nu_{21}}, \; \overline{E}_2 = \frac{E_2}{1-\nu_{12}\cdot\nu_{21}},$$

$E_1\cdot\nu_{12} = E_2\cdot\nu_{21}$, where E_2 - the modulus of composite elasticity in the cross direction.

In case of substitution of formulas (15) and (16) in the equation (11), we obtain:

$$N_\alpha = B_{11}^e\cdot\varepsilon_\alpha + B_{12}^e\cdot\varepsilon_\beta; \; N_\beta = B_{12}^e\cdot\varepsilon_\alpha + B_{22}^e\cdot\varepsilon_\beta, \qquad (18)$$

where stiffness ratio is

$$B_{11}^e = \overline{E} \cdot h_m + B_{11}^c;\ B_{12}^e = \nu \cdot \overline{E} \cdot h_m + B_{12}^c;$$
$$B_{22}^e = \overline{E} \cdot h_m + h_c \cdot \overline{E}_1, \quad (19)$$

or considering (17):

$$B_{11}^e = \overline{E} \cdot h_m + B_{11}^c;\ B_{12}^e = \nu \cdot \overline{E} \cdot h_m + B_{12}^c;$$
$$B_{22}^e = \overline{E} \cdot h_m + B_{22}^c, \quad (20)$$

Solving the equations (18) simultaneously, we determine the deformations on the contact surface of composite shell and metal liner:

$$\varepsilon_\alpha^e = \frac{1}{B_e} \cdot (B_{22}^e \cdot N_\alpha - B_{12}^e \cdot N_\beta);$$
$$\varepsilon_\beta^e = \frac{1}{B_e} \cdot (B_{11}^e \cdot N_\beta - B_{12}^e \cdot N_\alpha), \quad (21)$$

where $B_e = B_{11}^e \cdot B_{22}^e - (B_{12}^e)^2$.

As it was already mentioned, at this stage, we are interested in destruction of composite strengthening in the direction perpendicular to the reinforcing fibers; axial tension will be determined as follows:

$$\sigma_\alpha^c = \frac{N_\alpha^c}{h_c} = \frac{1}{h_c}\left(B_{11}^c \cdot \varepsilon_\alpha^e + B_{12}^c \cdot \varepsilon_\beta^e\right) =$$
$$= \overline{E}_2 \cdot \left(\frac{1}{B_e} \cdot (B_{22}^e \cdot N_\alpha - B_{12}^e \cdot N_\beta)\right) + \overline{E}_1 \cdot \nu_{12} \cdot \left(\frac{1}{B_e} \cdot (B_{11}^e \cdot N_\beta - B_{12}^e \cdot N_\alpha)\right). \quad (22)$$

Having used the expression (22) for container with above-mentioned geometrical parameters and properties of material of liner and composite strengthening according to [5, 7], the dependence of axial tension in composite strengthening on the internal pressure was obtained (Fig. 3).

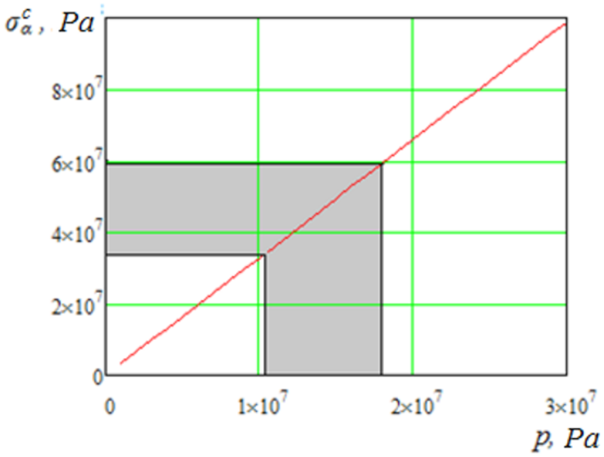

Figure 3. Dependence of axial tension in composite strengthening on the internal pressure

As strength of unidirectional CM with glass fibers on the basis of epoxy matrixes in both directions along and across fibers depends on many factors and varies in the certain range, the interval, which corresponds to CM strength in the direction across fibers (35-60 MPa), is marked in dependence presented in Fig. 3. As it is seen, destruction, and consequently, formation of ring cracks is possible at pressure in cylinder equal to 11 MPa. Further growth of pressure causes the increase in relative deformation ε_α^e on contact surfaces of composite shell and metal liner. Considering that after formation of ring cracks, the composite strengthening and liner are ideally bounded with each other; the further breakage of composite internal layer in the sections, where relative deformation ε_α^e will reach destructive values, is obvious.

Although, all the cylinders after production are subject to test by sesqui-fold operating pressure (not less than 30 MPa) [11], at a stage of putting into operation of each of them, there are sections, for which microdamages of composite internal layer are characteristic. Such damage probably leads to change of initial ring tension in metal liner. As a result, in CNG-2 cylinder, there are conditions of existence of sections with various initial tensions. Under the conditions of repeated cylinder loadings by internal pressure, such sections change the stress-strain state of a metal liner. The level of these changes may be evaluated by comparison of a profile of external surface of metal liner at internal pressure or its absence. Considering the design features of CNG-2 cylinders, in order to control a profile, it is reasonable to use the special automated system on the basis of the high-frequency inductive sensor of metal losses in each control point [12]. Possibility and reasonability of use of such systems for reproduction of an external surface profile of a metal liner are confirmed with the results given in papers [13, 14].

Conclusions

According to the results of the conducted theoretical researches, it was established that during filling of the combined containers of high pressure, the formation of ring cracks is possible even at a pressure equal to 11 MPa. The increase in internal pressure to the test one leads to formation of sections with microdamages of composite internal layer that under the conditions of repeated loadings of containers by internal pressure stipulates changes of the stress-strain state of a metal liner. In order to evaluate the level of these changes, the special automated system on the basis of the high-frequency inductive sensor should be used.

So that to prevent the accidental damages of the combined containers of high pressure in the course of their operation, the formation of stress-strain state of metal liner needs further investigation considering possibility of its corrosion damage on sections close to ring cracks in composite strengthening.

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