High-pressure cylinders of gas-fuel system made of composite materials

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Abstract. Use of gas fuel systems will allow to carry out the ecological tasks facing the Russian automotive industry, it is essential to cut down expenses of consumers on fuel and to increase an engine lifetime. As a basis of such modernization it is necessary to consider development, calculation, a design binding and technological security of production of cylinders of pressure as capacities for the compressed or liquefied natural gas. For the purpose of weight reduction of cylinders the preference is given to the polymeric composite materials using methods of winding of the rein

1. Introduction
Russian automotive industry is being developed in several directions: assembly of well-known brands of foreign vehicles and production of new Russian vehicles, for example Lada series (Lada Kalina, Lada Priora, Lada Granta, Lada Vesta, Lada Largus). One of the ways of increasing competition of Russian vehicles is the improvement of ecological characteristics and decrease fuel expenses. This direction can be developed without high expenses on purchasing new technologies and equipment, increase of sales volume can be reached by transition to new consumer appeals and fulfillment of discharge consent of dangerous gaseous products. Directions of improvement that were mentioned above are possible due to the usage of compressed gas vehicles equipment with pressure balloons made of composite materials.

2. Advantages of gas fuel
Gas fuel burns fully than petrol, so the concentration of carbonic oxide and other gases in car emission is much lower than in petrolic cars (figure 1).

Figure 1. Comparison of CO, HC, NO₂ and CO₂ emission when using petrol (1) and gas (2)

Compressed natural gas is several times safer in operation than petrol and explosive liquefied gas (propane-butane). It is lighter than air and in case of a leak it vanishes; besides maximum allowable concentration in the air for fulminating is from 5 to 18 per cent. The same number for petrol is 70 per cent that proves the fact that an explosion of huge gas masses in case of a leak inside a vehicle is impossible.
On the background of highly developing usage of hybrid and electro mobiles we should consider that compressed and liquefied natural gas is a fuel of the future. Nowadays comfortable conditions for spreading this type of fuel are created everywhere. This tendency exists in Europe which is worried about two main problems: how ecological and cost efficient the fuel is. There are several good conditions for development of natural gas motor fuel market in Russia: gas-transport system, low cost of natural gas and finally high reserves of gas.

We can claim that nowadays The Russian Federation has vehicle production which engines work using alternative fuels (Lada Vesta CNG и Lada Largus CNG). Among such fuels the most interesting one is natural gas (methane), which has low prime cost and its cost is more attractive in comparison with traditional fuels. Moreover its energetic efficiency in comparison with petrol AI 95 is equal to numbers of AI 140 (for example one liter of petrol with octane number AI 92 is equal to approximately 0,8 m³ of compressed gas with octane number AI 140). So, using of natural compressed gas as a fuel will solve several tasks: it will increase ecological characteristics of Russian vehicles, from 3 to 10 times decrease the consumers’ expenses on fuel and increase engine lifetime in 1,5-1,8 times.

3. Requirements to technology of production of high-pressure cylinders

Balloons for natural compressed gas which is used as a fuel for vehicles must be extremely light and fulfill all safety requirements for vessels which work under pressure. For efficient work of high-pressure cylinders construction it is necessary to choose right material and technology and its production. When choosing it is necessary to follow the rules of optimality and take into consideration not only existing materials but also the possibility of its modernization and possibility of producing new materials which will be designed for certain working conditions.

For producing of high-pressure cylinders it is necessary to solve several tasks:
- researching of strain-stress state of cylinders;
- selection of joining and reinforcing filler for composite shell of high-pressure cylinder;
- optimization of cylinder construction in shape and mass with changes in production technology;
- selection of technology of components modification in order to improve the qualities of adhesive contact;
- selection of technological parameters of production of adapter for spooling pressure shell of a cylinder;
- selection of technological parameters of spooling process, dipping and polymerization of composite layer of high-pressure cylinder;
- analysis of main technological and economical markers of production of high-pressure cylinder and also its prime cost;
- analysis of ecological safety of technological process of cylinders’ production [1].

On the basis of working conditions there are several requirements to the construction of pressure cylinders made of composite materials:
- safe operation management;
- contentment of strength characteristics;
- providing optimality at which performance function is mass minimization of pressure cylinder;
- processability of construction which involves interrelation and interdependence of a product, technology of production, storage and usage requirements.

It is well-known that polymeric composites are nonhermetic, that is why constructions made of them, depending on the level of basis of design requirements, include additional pressure-sealed layers, shells etc. Pressure-sealed shell (liner) is usually used as an adapter for spooling layers of a pressure shell [4].

Original constructive and technological decisions which are the basis of creation of hermetic polymeric shell (liner), strengthened by glass fiber (or carbon fiber), let us to lower the mass of cylinders in 5 times in comparison with metal ones, to increase corrosion resistance, increase resistance to aggressive environment, fire and explosive prevention, guarantee destruction without shatters. Fatigue crack life is more than 15000 stress cycles, assurance coefficient after performing cyclic tests not less than 2,6; temperature operation range from 40 degrees below zero to 80 degrees above zero; service life not less than 10 years.

4. Design engineering of gas cylinder

Projecting design of gas cylinder comes down to definition of design parameters of the construction, which allow the fulfillment of the following conditions:
- minimal mass of a designed construction;
- preserving required strength and ruggedness during design load;
- technologic realizability;
- supporting minimal cost of a cylinder.
Main parameters of a cylinder which are defined during engineering process are:
- contour of a shell bottom;
- spreading of reinforcing angles with fiber;
- number of layers of reinforcement material which form the shell.
Main loads which appear in the cylinder under internal pressure are pictured in figure 2, and dependence of contour shape of the cylinder under different parameter $\lambda$ values, defining the shape of the meridian of optimized shell is in figure 3.

**Figure 2.** Spreading the loads in a pressure shell depending on coordinates: $P$ - internal pressure; $R_1$, $R_2$ – principal radii of a shell curvature; $Q$ – axial force; $R$-radius of a cylindrical part of the cylinder

**Figure 3.** Diagram of dependence of contour shape of the cylinder under different parameters of $\lambda$ for laying of fiber angles on the centerline $\varphi = 7^\circ 49'$; $\bar{\gamma}$ and $\bar{\xi}$ - nondimensional coordinates referred to radius value of centerline $R$

Enumerated dependencies are used in the starting stage of the engineering at defining geometrical characteristics of optimal cylinder, which let to set up strength and ruggedness characteristics in size of maximum operating pressure $P$, which is 2.4 MPa, on the next stage.

Producing composite cylinder of high-pressure was done by method of “wet” winding of reinforcement fiber: glass (fiberglass roving PBMH 19-1480-80), carbon (gasket “Tornel T700”), basaltic (roving RVMN-19-1200-KB42), combined with epoxide joining EDU to metal or plastic liner. Spooling machine WM2.800 was used for winding (figure 4). Hardening of the products was done by standard method using an automated system of heating process control [7].

**Figure 4.** Technological process of spiral winding of pressure cylinder
On figure 5 there are images of metal composite cylinder BK-7 before testing and after destruction due to triple overpressure (80 MPa).

![Figure 5. Metal composite high-pressure cylinder before destruction tests (a) and after the tests (b) under pressure of 80 MPa](image)

Simultaneousness of creation material and construction from polymeric composites defines a necessity of fundamental material research, usage of the most modern methods of modification of materials on the level of components, and also structuring research which is directed to optimization of features of material in construction.

In table 1 there is data about composite high-pressure cylinders in which metal and plastic liners were used, and strength shells were made of fiberglass, carbon fiber composite and basalt fiber reinforced polymer. The cylinders are designed for working pressure which is 29 MPa.

| № п.п. | Liner      | Strength shell                  | Fracture pressure, MPa |
|--------|------------|---------------------------------|------------------------|
| 1      | Steel      | Carbon fiber composite          | 81,0                   |
| 2      | Steel      | Fiberglass                      | 78,0                   |
| 3      | Steel      | Basalt fiber reinforced polymer | 80,0                   |
| 4      | Polypropylene | Fiberglass                | 65,0                   |

5. Conclusion
The weight of composite cylinders with metal liner is not more than 3 kg. When using carbon fiber composite as strength shell the weight goes down to 1.8 kg under the same working pressure 29 MPa.

Metal composite cylinder of high pressure have almost triple safety factor which allows increasing its lifecycle to 10 years or more with obligatory control and service.

Fracture behavior of the cylinders at reaching critical pressure is with no shatters.

Economic efficiency of using composite cylinders for gas-fuel automobile systems is defined with two main criteria: sales volume of vehicles and fuel costs. Transition to bifuel system has several suppositions for gas-engine market:
- huge natural gas (metane) reserves in Russia;
- unstable situation at the world oil market;
- natural gas is less volatile in comparison with liquefied gas;
- usage of natural gas decreases rate of wear of an engine;
- serious decrease of cylinder weight and increase of its working pressure.

Therefore polymeric composite materials are becoming more and more popular in modern automotive industry, they tend to decrease specific amount of metal and specific amount of material in products and con-
structions. It can be considered that these materials are the materials of the XXI century, following the fifth level of technological wave.

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