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Prototype Product Based on the Functional Test of ANG Fuel Vessel Applied to Composite Carbon Fiber

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탄소섬유 복합재료를 적용한 ANG 연료용기의 시제작 및 성능평가

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ABSTRACT

Recently, an automobile market used to natural gas has emerged as fast-growing as the several countries, who holds abundant natural fuel resources, has promoted to supply the national agency for an automobile car. LNG fuel vessel is more efficient in another way as the energy density is high, but it requires a high technology and investment to maintain extreme low temperature. CNG fuel vessel are relatively low-cost alternative to LNG, but poorly economical in terms of energy density as well as showing safety issues associated with compressed pressure. The development of adsorbed natural gas (ANG) has emerged as one of potential solutions. Therefore, it is desirable to reduce the weight of vessel by applying light-weighed a composite carbon fiber in order to response to the regulation of CO_2 emission.

Herein, this study make the prototype ANG vessel not only based on the optimal design and analysis of material characteristic but also based on the shape design, and it suggest a new type for the composite carbon fiber vessel which verified functional test. Moreover, the detail shape design is analyzed by a finite element analysis, and its verifies the ANG vessel.

Key Words: Fuel Vessel(연료용기), Composite Carbon Fiber Material(탄소섬유 복합재료), Prototype Fuel Vessel(연료용기 시제작), Optimum Design(최적설계), Functional Test(성능시험)

1. Introduction

Korea's natural gas automobile market has increased in a similar to that of the global market. However, it has decreased recently and the number of registered natural gas vehicles by the end of 2016 was about 39,000. Nonetheless, the number of compressed natural gas (CNG) buses is still increasing steadily due to the policy of reducing air pollution control[1-2].

The core of the natural gas vehicle is a natural gas

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fuel tank, which includes liquefied natural gas (LNG) fuel tanks that have liquefied natural gas at cryogenic temperatures and CNG fuel tanks that compress natural gases at high pressure. Natural gas fuel tanks require technology to store LNG or CNG safely against external environmental conditions. An LNG fuel tank is efficient due to its high energy density but requires high-cost investment and technology to maintain cryogenic temperatures. Meanwhile, a CNG fuel tank is relatively inexpensive but uneconomical due to the low energy density and safety problems due to the high pressure[3-4]. Therefore, the development of adsorbents that can store natural gas efficiently at a relatively low pressure and adsorbed natural gas (ANG) fuel tanks that can store such adsorbent have actively been developed in recent years to solve these problems.

The composite carbon fiber's typical characteristics in this study are lightness, high specific strength, and specific stiffness. In addition, the composite carbon fiber is a state-of-the-art material with excellent vibration damping properties, heat resistance, corrosion resistance, chemical resistance, electrical conductivity, thermal conductivity, thermal dimensional stability, abrasion resistance, X-ray permeability, electromagnetic wave shielding, bio-compatibility, and high fatigue strength[5-7].

In this study, an ANG tank was a prototyped production using a carbon composite material based on design and analysis of the ANG fuel tank where a carbon fiber composite material was applied, and a new configuration of ANG fuel tank was proposed that could utilize the carbon composite fibers through a functional test with the prototyped product.

2. Optimal design of ANG fuel tank using a composite carbon fiber material

A liner was manufactured according to the verified fuel tank's design through finite element analysis(FEM) and an ANG fuel tank made of a composite carbon fiber material was manufactured through carbon fiber filament winding. The liner plays an important role in maintaining air-tightness for the natural gas. Thus, a liner was manufactured using jointless aluminum to prevent cracks.

The jointless aluminum liner had a dome shape by applying the isotensoid dome theory as shown in Fig. 1. The dome's curvature changes continuously from the cylinder to the boss. Thus, the composite carbon fiber's angle also changed continuously. Accordingly, an isotensoid dome shape was applied to prevent composite carbon fiber sliding in the filament winding procedure. In addition, the liner's wall thickness was calculated by considering the fatigue characteristics due to repeated pressure, and the port in the boss was designed in consideration of the shear stress according to the thread type.

Fig. 2 shows the design drawing of the aluminum liner as verified through functional tests in this study. The inner diameter, thickness, and total length including the boss of the liner are 160.9 mm, 2.1 mm, and 524.6 mm. In the dome and boss of the liner, the thickness was increased in consideration of applying the 0.875-14 UNF 2B thread. Fig. 3 shows the boss' design drawing that includes the thread.

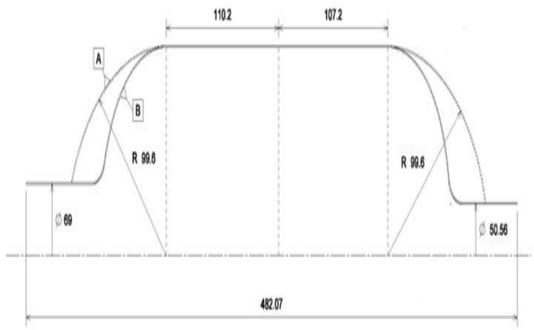

Fig. 1 Isotensoid dome contour

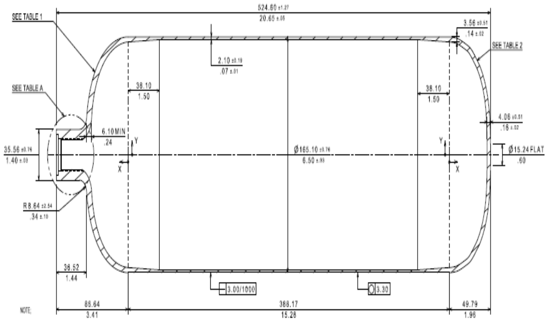

Fig. 2 Design of aluminum liner for ANG fuel tank

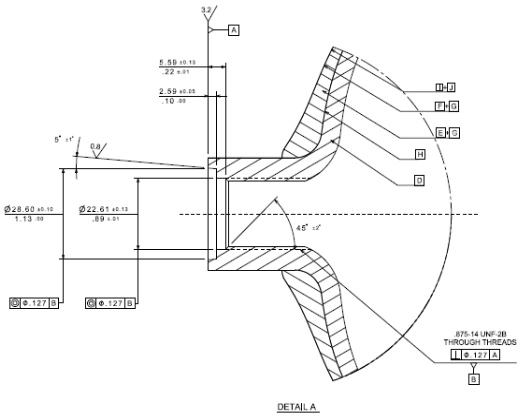

Fig. 3 Design of screw boss

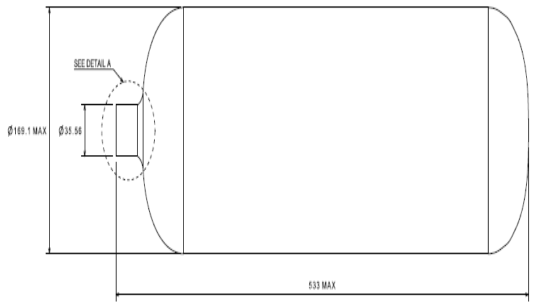

Fig. 4 Design of carbon fiber composite ANG fuel tank

Fig. 4 shows the finished product design of the ANG fuel tank in which a composite carbon carbon fibers are filament-wound. The total length of the ANG fuel tank including the boss after autofrettage was 533 mm, and the cylinder's outer diameter was 169.1 mm. The manufactured ANG fuel tank required a fuel tank that could consider the characteristics and shape of the absorbent since filling and exchanging the absorbent were difficult due to the narrow open shape. Moreover, it ensured the heat exchange capability could control temperature changes in the fuel tank during the charging and emission processes of natural gases in relation to heat management, which was the core purpose of the ANG fuel tank.

3. Production process of an ANG fuel tank

The process of manufacturing the ANG fuel tank using a composite carbon material consisted of the following pre-processes: the composite deep drawing and ironing process, spinning process, heat-treatment process, tapping process, and prototype production. This involved the following prototype processes: primer treatment, filament winding treatment, curing treatment, and autofrettage processes.

3.1 Deep drawing and composite ironing process

3.1.1 Deep drawing process

This is a molding process that turns aluminum plate into a cup shape as shown in Fig. 5. The liner's shape is manufactured through this continuous process. Through the trimming process, the irregular part of the opening in the semi-finished product after drawing was complete and the upper side of the cup was trimmed. The semi-product in the liner after the completion of trimming was removed and stress that was applied to the aluminum material in the drawing process was removed through annealing work. The thickness of the opening inlet in the liner where the annealing work was complete was increased by performing the ironing process to manufacture thread processing possible. Then, the final product's dimension for the liner was determined through the ironing process.

3.1.2 Spinning process

In the spinning process, the liner with complete cup shape was fixed in the fixture, rotated, and heated to a suitable temperature for spinning, and the tank inlet shape was manufactured through the spinning head. Here, the boss’s thickness was determined for the thread production process.

3.1.3 Heat treatment process

The aluminum liner after completing the spinning was made to the T0 state and then heat-treated with T6 condition to satisfy the aluminum liner’s physical property values. Table 1 presents the heat treatment conditions of the aluminum liner used in the ANG fuel tank. Once the heat treatment was complete, a specimen of the aluminum liner was sampled to conduct a tensile test and two samples per lot were collected to perform tensile tests, thereby determining the physical property values after checking them.

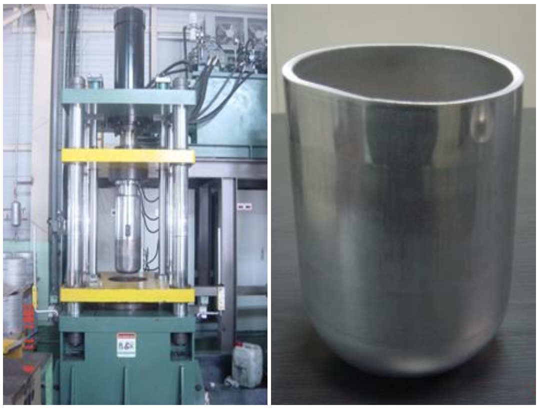

Fig. 5 Deep drawing process

Table 1 T6 heat treatment of aluminum liner

	Solution	Quenching	Aging
Temperature(℃)	543±20	50±15	179±5
Time(hr)	2.83	0.0083	7

3.1.4 Tapping process

After the completion of heat treatment and lot test, the liner was passed through the tapping process where threads were processed in the molded boss by spinning. Then, 0.875-14 UNF 2B thread was applied to the ANG fuel tank to manufacture a boss shape.

3.2 Production of the fuel tank made of composite carbon fiber material

The cylinder portion in the fuel tank where applied the composite carbon fiber material was a balanced laminate shape in which plus and minus fiber orientation angles were layered alternately. However, hoop winding was conducted in the outermost angle to support the load due to the internal pressure in the circumferential direction. The dome portion’s curvature changes continuously from the cylinder to the boss so that the angle of the fiber with respect to the meridian and thickness change continuously. Since the surface shape was continuously changed as winding progressed, the angle of a composite carbon fiber also changed in the thickness direction. Accordingly, the isotensoid dome shape was applied to prevent a composite carbon fiber sliding.

3.2.1 Primer treatment

Primer treatment was conducted in the aluminum liner prior to the filament winding process. This process aimed to prevent galvanic corrosion, which occurred when aluminum material was contacted with carbon fiber. In this process, epoxy primer resin, which was mixed at a constant ratio, was coated on the liner surface, and then cured for more than 30 min at 125℃ after putting it to a curing oven. Then, a knob was attached for filament winding at the opposite side of the liner boss.

3.2.2 Filament winding treatment

Filament winding was the wet winding of filament around the liner after the carbon fiber was impregnated with an epoxy resin. The epoxy resin for winding was from Sejin ENC co. and the base and curing agents were mixed at a constant ratio prior to their use, and the bubbles inside were removed through desaturation process.

After the desaturation process, the resin was completely impregnated with carbon fiber as shown in Fig. 6, and helical winding and hoop winding were conducted. Three-spindle and four-axis machine tool were used for the winding equipment, which was a model that could implement precise patterns. In the filament winding process, the fiber's tension, winding speed, band width, winding angle, surrounding temperature, and resin viscosity should be controlled. The same pattern used in Table 1 in the finite element analysis was applied for the winding pattern.

3.2.3 Hardening and autofrettage treatment

The first hardening was conducted at 85℃ for one hour and the second hardening was conducted at 125℃ for 100 min. In autofrettage, water pressure that exceeds the pressure in the internal pressure test was applied to the fuel tank made of the carbon fiber composite material after hardening was complete and then the pressure was removed to generate a compressive residual stress in a liner to have the aluminum liner induce plastic deformation as shown in Fig. 7. Here, the autofrettage pressure was set to 125 bar.

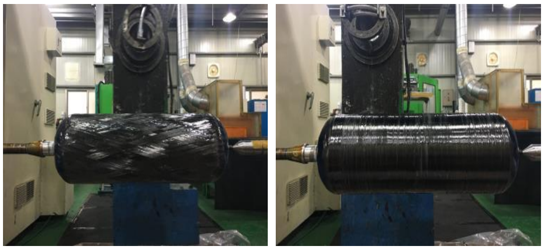

Fig. 6 Helical and hoop winding of carbon fiber/epoxy composite

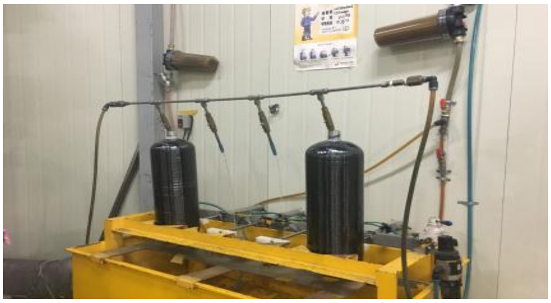

Fig. 7 Autofrettage process for ANG fuel tank

4. Functional test of the ANG fuel tank manufactured of composite carbon fiber material

Functional tests were conducted with the ANG fuel tank after autofrettage was complete and the design validity for the ANG fuel tank manufactured of a composite carbon fiber material was verified. If the criteria were not satisfied after the functional test, the design was complemented and fuel tank was re-manufactured to conduct the test again.

4.1 Internal pressure test

As shown in Fig. 8, abnormal expansion or leakage in the fuel tank was checked through an internal pressure test. The tests complied with the calibration test standards and precision specified in the CGA Pamphlet C-1. The internal pressure test results of the manufactured ANG fuel tank showed that the fuel tank had no abnormal expansion or leakage. The volume expansion rate was less than 5%, which satisfied the goal given in Table 1.

4.2 Iterative pressure test

The iterative pressure test showed that no leakage or bursts in the fuel tank should be found even if at least 11,250 times the iterative pressure were applied at the working pressure of 60 bar after filling the ANG fuel tank with water. The manufactured ANG fuel tank satisfied the iterative pressure test.

4.3 Disruptive test after iterative pressure application

The minimum disruptive pressure in the burst test should be more than 2.25 times the working pressure according to KGS AC412. In addition, for the pressure application rate in the disruptive test, the set limit value in the test was 1.4 MPa/s in a pressure that exceeded 80% of the design disruptive pressure. This study utilized a fuel tank that satisfied the 11,250x repeated pressure test for the disruptive test, and for the minimum disruptive pressure, the goal value was set as 180 bar (i.e. three times the working pressure) as presented in Table 1. The ANG fuel tank manufactured of the composite carbon fiber material had a fracture at 296 bar, which was slightly higher than the design disruptive pressure at 270 bar. Fig. 9 shows the ANG fuel tank before and after the disruptive.

5. Conclusions

The ANG fuel tank manufactured in this study was 9.2, and 60 bar pressure tank manufactured of a composite carbon fiber material that had a jointless aluminum liner in the inside and Toray T700S carbon fiber impregnated with epoxy resin filament-wound around the outside.

Fig. 8 Internal pressure test of ANG fuel tank

Fig. 9 ANG fuel tank before and after burst test

(1) The internal pressure test, iterative pressure application test, and disruptive test after iterative pressure application were conducted according to KGS AC412, and the result showed that the fuel tank satisfied all required standards. The ANG fuel tank was approximately 2.5 kg, which was 24% of the stainless-steel pressure tank with the same disruptive pressure.

(2) Since the difference between actual disruptive pressure and the design disruptive pressure was approximately 25 bar, the ANG fuel tank in this study was appropriate. However, the actual disruptive pressure was 297 bar, which was slightly over-designed compared to 180 bar, which was the minimum disruptive pressure. Nonetheless, the safety factor was set high to satisfy 11,250 cycles, which was the number of repeated pressure applications required by KGS AC412. This design meant that the fuel tank could satisfy the goals in all required test items.

(3) The total volume required considering driving distance and fuel efficiency was calculated to apply the ANG fuel tank to natural gas vehicles, and an appropriate fuel shape was determined for to the vehicle space. If a conformable vessel is manufactured for space utilization, liner's injection molding or welding method should be investigated to evaluate any potential damage and the results should be taken into consideration.

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