TECHNOLOGICAL IMPLEMENTATION OF A TOROIDAL COMPOSITE PRESSURE VESSEL FOR HYDROGEN STORAGE

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ABSTRACT

Previous pressure vessels made of fibre reinforced plastic with high gravimetric and volumetric energy density essentially address classical designs consisting of a cylindrical core and elliptically shaped bottom geometries. Current efforts to solve the storage problem of hydrogen require new designs and shapes for pressure vessels due to extensive changes in the entire powertrain and the resulting changes in installation space in electric vehicles and related applications such as mobile power generators. Efforts to develop new concepts have so far focused exclusively on convex and concave envelopes but have not deviated from the standardized longitudinal design. With the ring-shaped pressure vessel, preferably made of carbon fibre reinforced plastic and a new filament winding technology, the authors are taking an alternative approach. This design offers great potentials to mass saving along with resource saving and above all cost-reduced production, due to the fact that up to 70% of the total costs are generated by the carbon fibre material for current composite pressure vessels. Combining various processes, such as injection moulding, laser welding of the thermoplastic liner and a new approach of winding technology, an entirely new product is to be created, that will meet the maximum mass requirement of 6.5% of the storage medium's dead weight.

1 INTRODUCTION

In the course of the mobility turnaround, fuel cells as an emission-free and ecologically balanced drive concept for solving the range question for electrically powered vehicles have been intensively discussed at international level for several years now. Possible storage solutions for compressed hydrogen (CGH_2) are an essential part of the discussions. These range from cryogenic storage applications through pressure vessels with a storage pressure of 700 bar to higher pressures above 1000 bar at stationary facilities such as hydrogen filling stations and central hydrogen storage facilities. However, developments of type IV vessels up to 700 bar designed with carbon fibre reinforced polymer (CFRP) and a thermoplastic liner (e.g. Polyamide 6) have demonstrated very positive results regarding cycling resistance, burst pressure, H_2 tightness, gravimetric and volumetric storage capacities [1-3]. These vessels are designed in the classical geometry consisting of a cylindrical core and elliptically shaped bottom geometries [4].

Contrary efforts demand new designs and shapes for pressure vessels due to extensive changes in the entire drive train and the resulting changes in installation space in electric vehicles. With the toroidal composite pressure vessel (TCPV) and its new manufacturing technology, the authors are taking an alternative path with a large mass saving potential (up to 30%) and the associated resource-saving and cost-reduced production.

This advantages of a lightweight TCPV have high potential for the use in other markets such as mobile power generation with hydrogen. Figure 1 shows a fuel cell operated mobile power generator of FAE Elektrotechnik GmbH & Co. KG with 1 kW constant electrical output. For the storage of hydrogen, a heavy steel bottle or an innovative hybrid bottle, called GENIE® by Linde AG, can be used. For refilling empty vessels, a customer has to contact a rental or refilling company. Another option for customers is to refill the vessels by themselves at a hydrogen filling station. In both cases weight and design of the steel vessel are not suitable for transportation by one person. The GENIE® with its optimised handling and 32.7 kg weight is much lighter, but the filling volume is limited. Together with an increased 700 bar filling pressure a TCPV can store 5 times the hydrogen mass with an equal weight (cf. chapter 3.2).

Figure 1: left: Fuel cell operated mobile power generator of FAE Elektrotechnik GmbH & Co. KG with 1 kW constant electrical output and a standard steel bottle (filling volume 8.9 m³, filling pressure 200 bar, weight 80 kg), right: GENIE® bottle (filling volume 5 m³, filling pressure 300 bar, weight 32.7 kg) of Linde AG (www.linde-gas.com/genie)

This paper presents the development of a TCPV with 700 bar filling pressure for a fuel cell operated mobile power generator with 5 kW constant electrical output within the funded project "HZwo:FRAME - Tank". All partners and research tasks are shown in Table 1. The project was established within the network HZwo (ww.hzwo.eu) and is funded from 10/2018 until 09/2021 by SAB Sächsische Aufbaubank within the Free State of Saxony. The goal of the network HZwo is the establishment of an innovation cluster around fuel cells and green hydrogen as well as the establishment of a comprehensive value chain network in Saxony.

Partners	**Research tasks**
Chemnitz University of Technology, Department of Lightweight Structures and Polymer Technology	• Material development and characterisation • Development and design of the ring winding machine in cooperation with Cetex Institut gGmbH, Chemnitz
Chemnitz University of Technology, Department of Advanced Powertrains	• Flow simulation for H_2 refuelling • H_2 permeation tests

Partners	Research tasks
Albert Polenz GmbH, Großweitzschen	• Development of an injection moulding tool for top and bottom part of the polymer liner • Integration of a metallic filling insert in the injection moulding tool
LSE GmbH, Chemnitz	• Design, analytical and numerical simulation of TCPV • Joining of the top and bottom part of the polymer liner by laser welding in cooperation with Fraunhofer Institute for Material and Beam Technology, Dresden • Analyses and optimisation of the ring winding technology in cooperation with Cetex Institut gGmbH, Chemnitz • Manufacturing and testing of TCPVs
FAE Elektrotechnik GmbH & Co. KG, Heidenau	• Definition of all technical requirements and part specifications • Adaptation, design and manufacturing of fuel cell operated mobile power generator (5 kW) with TCPVs

Table 1: Partners and their tasks within the funded project "HZwo:FRAME - Tank"

2 MATERIALS AND JOINING TECHNOLOGY

2.1 Materials

The following main parts of a TCPV are comparable to typical state-of-the-art type IV composite vessels: Polymer liner with low hydrogen permeation, filament winded CFRP to support the high internal pressure and metallic insert for filling and extraction of hydrogen.

The hydrogen permeation behaviour of polymers depends on pressure and temperature [5]. Table 2 shows some selected properties of different analysed materials. Rosen measured the hydrogen permeation according to DIN 53380-2 for room temperature [6-7].

Polymer	Density in g/cm^3	H_2 permeability in $cm^3/m^2*d*bar$	Price
PE	0.96	25-55	low
PP	0.9-1.0	65	low
PA6	1.14	7	medium
PVC	1.2-1.4	10	low
PVDF	1.78	3	very high

Table 2: Properties of analysed polymers for the liner material [6, 8]

Liner production is carried out by injection moulding with a half-shell tool. Requirements for the polymer are to fulfil the permeation properties for the storage of hydrogen (< 1 H_2 $Ncm^3/h/L$ according to EIHP II [5]) as well as processability for injection moulding. For further investigations PE as a low cost and light polymer together with PVDF as a high-end material for hydrogen storage are analysed in detail. Despite its good balanced properties as a liner material, PA6 is not further considered due to its hygroscopic material behaviour.

Filament winded carbon fibres are state-of-the-art for the reinforcement of composite pressure vessels with a filling pressure of 350 bar to 700 bar [1-3, 9]. Typically, the fibres are pre-impregnated or will be subsequently impregnated with epoxy resin for example by resin transfer moulding. One advantage of the TCPV design is the closed ring geometry, which allows to orient all fibres only to support the internal pressure load case and no axial load case. Table 3 presents characteristic properties of available carbon fibres, whereof the tensile strength is the most important criterion for a load-related design. The depicted scale from low to very high for the price of carbon fibres is defined as a range from approx. 10 to 50 EUR/kg.

Type of carbon fibre	Density in g/cm³	Tensile strength in MPa	Young's modulus in GPa	Price
Zoltek PX35 50K	1.81	4137	242	low
Toray T700 24K	1.80	4900	240	medium
Tenax-E UTS50 24K	1.78	5100	245	medium
Tenax-E IMS65 24K	1.78	6000	290	very high

Table 3: Properties of analysed carbon fibres (source: material data sheet)

Toray T700 is a well-known fibre with a good compromise between tensile strength and material costs. Consequently, many pressure vessels are made of this fibre (e.g. in [1]). Regarding strength and costs, the Tenax UTS50 is a comparable carbon fibre with ultra-high tenacity which is optimised for filament winding. With the very high tensile strength of a Tenax IMS65 the wall thickness and weight of a TCPV could be additionally minimised. However, the reduction in fibre volume does not compensate the increase in manufacturing costs due to higher fibre prices. Currently, Zoltek PX35 is one of the cheapest carbon fibres on the market and could be used for a TCPV with lower requirements.

For applications at temperatures from -40 °C to +85 °C, a standard epoxy resin and hardener with 250 mPas mixing viscosity and 210 min pot life are used. Using the technology of filament winding, a fibre volume content of approx. 50-60% is reached whereas the tensile strength of the composite is assumed to be reduced by fibre fractures during the winding process. Therefore, it is essential to analyse the tensile strength at application temperatures on filament winded tube specimens manufactured with the named resin and fibres (Table 3). Figure 2 shows the corresponding explosion-proof test rig for hydraulic pressure tests with tube specimens.

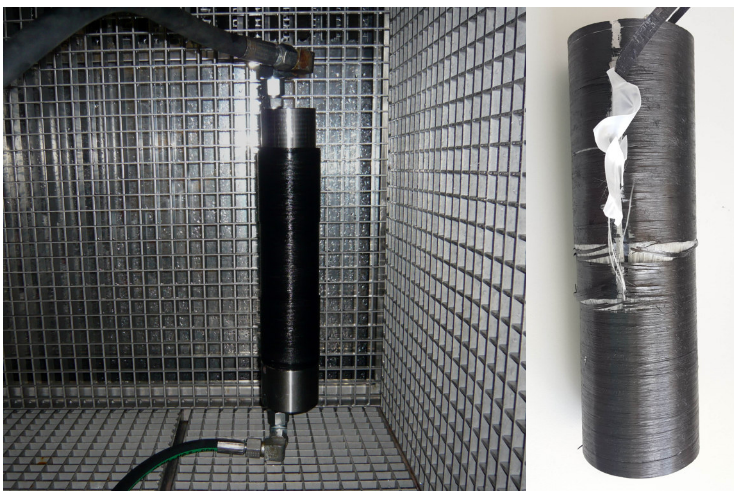

Figure 2: CFRP tube specimen mounted in the inner pressure test rig of Maximator GmbH at Chemnitz University of Technology and tested specimen with fibre failure

2.2 Joining technology

Liner production is realised by injection moulding using two half-shell tools and laser joining of half-shells. The laser-absorbing bottom part (e.g. by adding 1% graphite to natural polymer) of the liner is manufactured in the first mould and the laser-transmitting top part of the liner with the metallic insert in the second mould (cf. Figure 3). Both parts are designed with a conical joint geometry to achieve an optimised positioning during the laser joining process and to allow putting an axial force on the joining surface. The laser welding with a welding factor up to 0.99 can guarantee the good permeation properties of the polymer against hydrogen also in the joining zone.

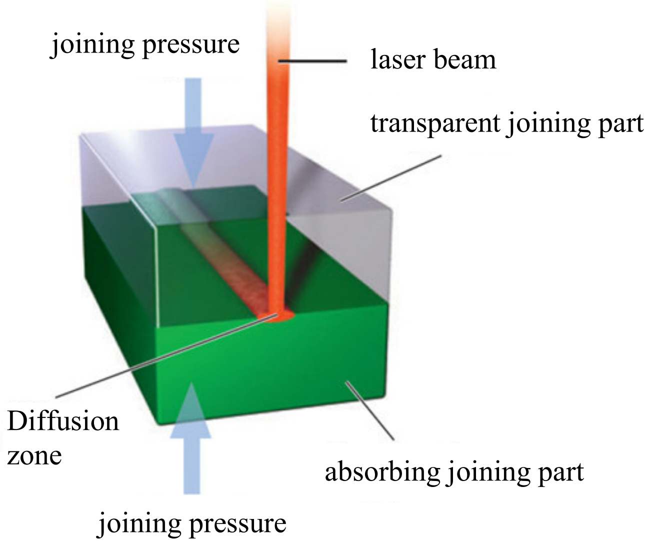

Figure 3: Sequence of the laser welding process

The process characteristics, the welding factor and the permeation properties of welded samples of the selected polymers named in Table 2 are analysed with the support of Fraunhofer Institute for Material and Beam Technology IWS in Dresden. For PE a Clean Laser 50 with a wave length of 1060 nm, a welding speed of 800 mm/s and laser power between 40-80% were investigated. Figure 4 shows the welded samples with an overlapping of 13x25 mm for tensile tests according to DIN EN 1465 [10] and it results with 7 MPa tensile strength of laser-transmitting (white) and laser-absorbing (black) specimen compared to 2.1-2.2 MPa tensile shear strength of welded samples with a laser power between 40-80%. Under respect of the microscopy analysis the best results can be achieved with a laser power of 60%. In the ongoing investigations further materials and joining geometries are investigated.

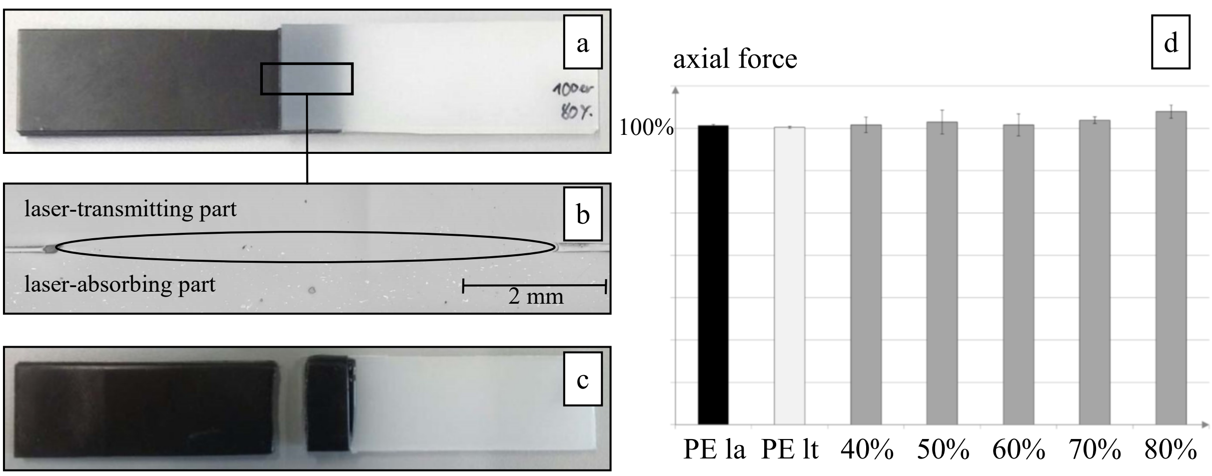

Figure 4: a) Laser welded PE sample with an overlapping of 13x25 mm, b) Microscopy picture of the welding area, c) Laser welded PE sample after tensile test, d) Results of tensile tests

3 ANALYTICAL APPROACH AND DESIGN

3.1 Analytical Approach

Based on [11-12], the project will be supported by its own analytical and numerical design. The preliminary design and geometric optimization of the TCPV is carried out under the assumption of a thin-walled structure (validity of the membrane theory). With only the internal pressure load assumed, radial loadings in thickness direction r can be neglected as well as intralaminar shear loads due to rotational symmetry of the geometry ($n^{\varphi\vartheta} = n^{\varphi r} = n^{\vartheta r} = n^{rr} = 0$). Thus, for the constant internal forces in the circumferential direction $n^{\vartheta\vartheta}$, an amount of:

$$n^{\vartheta\vartheta} = \frac{p\,r}{2} = n^{\mathrm{II}} \tag{1a}$$

and a position-dependent (parameterized by angle φ) cutting force flux in meridian direction $n^{\varphi\varphi}$:

$$n^{\varphi\varphi} = \frac{p\,r}{2}\,\frac{2\,R + r\sin(\varphi)}{R + r\sin(\varphi)} = n^{\vartheta\vartheta}\,\frac{2\,R + r\sin(\varphi)}{R + r\sin(\varphi)} = n^{\mathrm{I}}\,, \tag{1b}$$

remain as main force flux in the vessel membrane (cf. [13] and Figure 5).

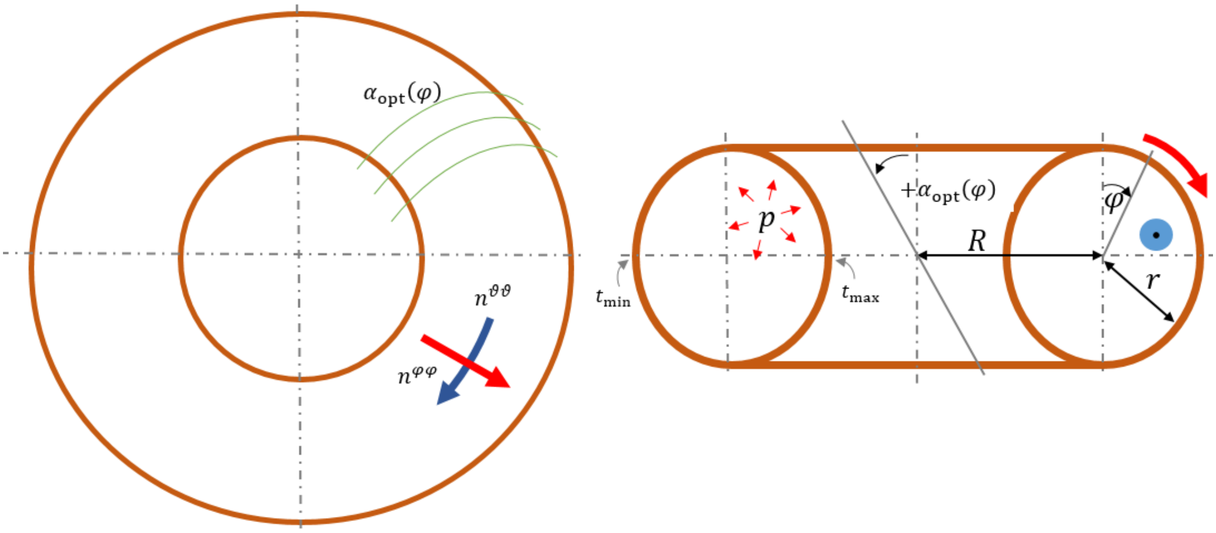

Figure 5: Geometric characteristics and parameters for the preliminary design of TCPVs

From this local stress ratio, caused by the internal pressure load, an optimal meridian angle-dependent fibre orientation for a two-layer composite can be determined for a given geometry, cf. (2).

$$\begin{aligned}\alpha_{\mathrm{opt}}(\varphi) &= \pm\tan^{-1}\left(\sqrt{\frac{n^{\mathrm{II}}}{n^{\mathrm{I}}}}\right) = \pm\tan^{-1}\left(\sqrt{\frac{n^{\vartheta\vartheta}}{n^{\varphi\varphi}}}\right);\ .\frac{n^{\vartheta\vartheta}}{n^{\varphi\varphi}} \geq 0 \\ &= \pm\tan^{-1}\left(\sqrt{\frac{2\,R + r\sin(\varphi)}{R + r\sin(\varphi)}}\right)\end{aligned} \tag{2}$$

Optimal in this context means that the individual layers must be oriented such that only stresses in the longitudinal direction of fibres occur. This design strategy is known as the net theory (cf. [14]).

Having the optimum orientations determined according to (2), the required angle-dependent minimum wall thickness of the vessel can also be obtained using net theory:

$$t_{\min}(\varphi) = \frac{p\,r}{2\,X^{t}}\,\frac{3R + 2r\sin(\varphi)}{R + r\sin(\varphi)}. \tag{3}$$

This minimum total wall thicknesses $t_{\min}(\varphi)$ with optimal local orientations and a fiber tensile strength X^{t} is composed of equal parts of the two layers with positive and negative orientations, $\pm\alpha_{\mathrm{opt}}(\varphi)$.

Due to the ring winding process and the toroidal geometry, the resulting wall thickness depends on the production restriction (inner diameter < outer diameter). Assuming a constant fibre volume, the resulting thickness distribution is:

$$t_{\mathrm{res}}(\varphi) = \frac{R + r}{R + r\sin(\varphi)}\,t_{\min}\,, \tag{4}$$

wherein the minimum wall thickness according to (3) on the outside ($t_{\min}(90°) \equiv t_{\min}$) of the TCPV defines the starting point of the ring winding process, which leads to following maximum wall thickness on the inside $t_{\mathrm{res}}(-90°) \equiv t_{\max}$:

$$t_{\max} = \frac{R + r}{R - r}\,t_{\min}\,. \tag{4a}$$

In addition to mechanical effects resulting from thick wall thickness, the applied design strategy also neglects orientation deviations of the winding structure resulting from production and geometry restrictions (mechanically optimal winding angles ≠ geodetic courses, ring winding process ≠ geodetic courses). Numerical simulations of the thick-walled structure with a deviation of < 10% from the result according to net theory has justified the strategy so far. However, manufacturing tests on demonstrators are required to model a realistic representation of the final orientations. Furthermore, the valuation was carried out in the undisturbed zone only. Additional tests and numerical simulations will be performed in the area of local thickening of the metallic filling insert.

3.2 Design

Based on the results of the experimental tests in Chapter 2 and the presented analytical approach a TCPV project demonstrator was designed to fit the following requirements: the minimum winded inner diameter is limited to 400 mm by the size of the carbon fibre bobbin, which rotates around and within the TCPV, and the outer diameter of the polymer liner is limited to a maximum 760 mm by the budget for the injection moulding tools. The final CAD design is presented in the left picture of Figure 6. The right picture shows a first demonstrator for filament winding analysis in the same size, which is manufactured in two half-shells by reaction injection moulding of Polyurethane (PU), being additionally glued together. With this demonstrator the analytically calculated and true fibre angle of each layer (cf. α_1 and α_2 in Figure 6) can be validated. The labelling of the components in Figure 6 reads: 1) CFRP (epoxy resin + Toray T700, fibre volume content approx. 50%), 2) metallic filling insert, 3) top part of PE liner (laser-transmitting, t = 4 mm), 4) storage volume of H_2, 5) bottom part of PE liner (laser-absorbing, t = 4 mm), 6) glued PU liner of winding demonstrator, α_1) winding angle of approx. 90°, α_2) winding angle of approx. ±75°.

The TCPV project demonstrator is named "LSE 1.4" due to the storage capacity of 1.4 kg of hydrogen at filling pressure of 700 bar. Further notable properties of this TCPV are: design space 780x410x185 mm, filling volume 33.4 l, weight including metallic insert approx. 23.2 kg, averaged CFRP wall thickness t = 13.5 mm and a calculated burst pressure 1575 bar according to ISO 15869.3.

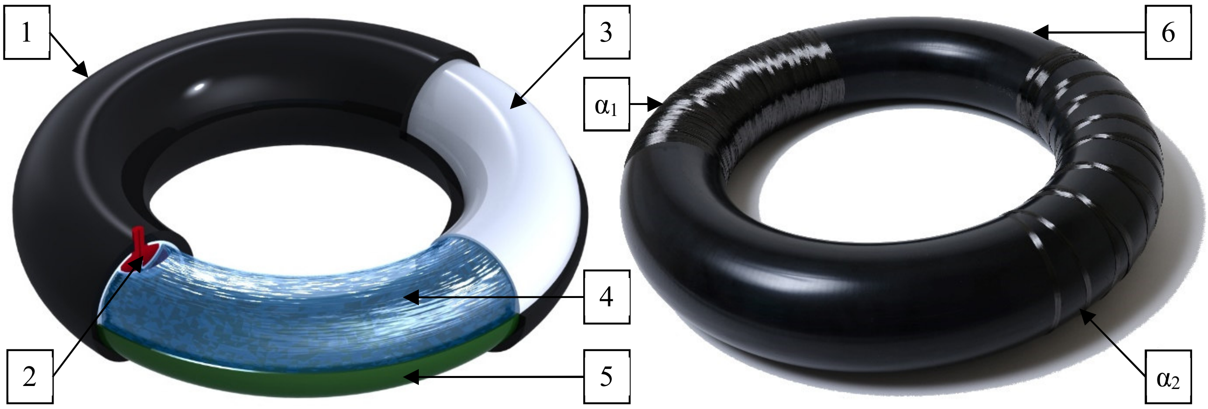

Figure 6: CAD design of TCPV type LSE 1.4 (left) and winding demonstrator with PU liner (right)

To compare composite pressure vessels for hydrogen storage system, weight and maximum design space for an equal filling or burst pressure are the significant characteristics. Additionally, national and international technical or political recommendations and targets can be consulted. For the on-board hydrogen storage for light-duty fuel cell vehicles the target explanation document, revised by the U.S. DRIVE Partnership in May 2017, which is a partnership between the U.S. Department of Energy (DOE), the U.S. Council for Automotive Research (USCAR), energy companies, utility companies and organizations is respected [15]. One main property within this document is the system gravimetric capacity, which measures the specific energy of net useful energy per total on-board storage system mass, not the storage medium mass only. The unit is net useful energy in kg H_2 per maximum system mass in kg in percent. The "maximum system mass" includes everything necessary for the storage system plus the maximum charge of hydrogen. The targets within the upcoming years for the system gravimetric capacity are 4.5% for 2020, 5.5% for 2025 and 6.5% for a so called "Ultimate Full Fleet" target. Figure 7 shows the net useful energy in kg H_2 per maximum system mass in kg for the TCPV LSE 1.4 (see light green bar) compared with the above-mentioned targets.

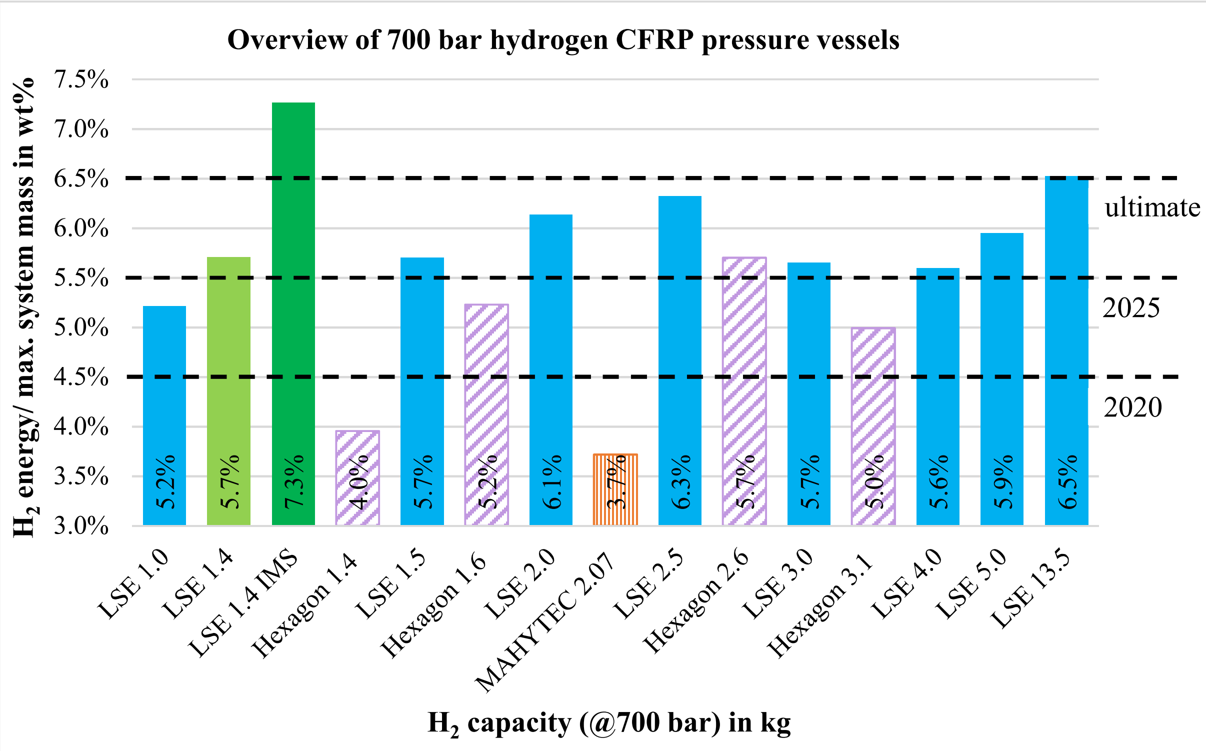

Figure 7: Overview of 700 bar hydrogen CFRP pressure vessels

Additionally, the capacity of the TCPV LSE 1.4 is compared to own calculated TCPVs with H_2 capacities from 1.0 to 13.5 kg for 700 bar filling pressure and cylindrical CFRP vessels for 700 bar available on the market, offered by the companies Hexagon and MAHYTEC. The highest ranked type LSE 1.4 IMS (see dark green bar) has the same liner size as the project demonstrator but is reinforced with Tenax-E IMS65 fibres. For the storage of an energy quantity equal to 50 l petrol, the TCPV LSE 13.5 with 13.5 kg of hydrogen storage is the adequate design.

4 MANUFACTURING TECHNOLOGY

There are no ring winding machines for TCPVs available on the market, but some research approaches with prototyping machines [16-18] and an US patent for the manufacturing of the rim of bicycle wheels [19] are known. Within the project a prototype ring winding machine designed for the TCPV type LSE 1.4 has been developed by Cetex Institut gGmbH (see Figure 8), to analyse and optimize the limits of the manufacturing process with regard to manufacturability, productivity and process stability. The system consists of two modules. On the one hand a ring winding module, which applies the carbon fibre layer to the pressure vessel and on the other hand a drive module, which enables rotation of the pressure vessel. The ring winding machine has a footprint of 1450x1650 mm and a maximum height of 1600 mm. The rotor disc with two bobbins is driven radially by a cam belt. The roving of each bobbin is guided to the pressure vessel by guiding elements. An opening of the part removal, on the rotor disc allows the pressure vessel to be inserted or removed manually.

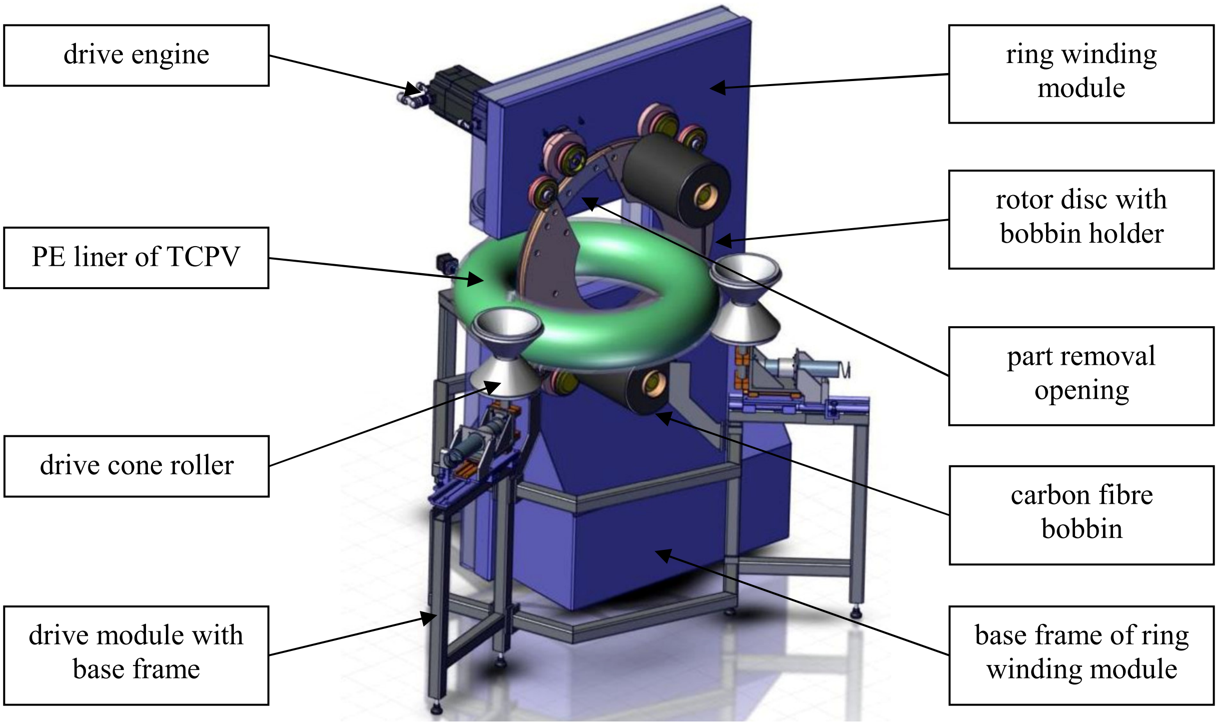

Figure 8: Prototype ring winding unit by Cetex Institut gGmbH

The pressure vessel is rotated by the active drive module. The position and fixation of the pressure vessel is created by three cone rollers evenly distributed on the outer ring. Manually adjustable bracket elements allow the pressure vessel to be positioned and removed from the ring winding machine easily. In addition, the drive module compensates deviations of the pressure vessel's position caused by the winding process. The rotation speed ratio between drive and ring winding module is optimized for a precision winding. In order to produce an entirely closed wrapping, the fibre material including the bobbin is guided through the inner diameter of the ring. Reaching a maximum speed of 44 rpm by the ring winding module, both the rotation speed of the drive module and the ring winding module can be adjusted to attain the required winding angle.

5 CONCLUSIONS

This paper presented the current development of a toroidal composite pressure vessel for mobile hydrogen storage with 700 bar filling pressure for a fuel cell operated mobile power generator with a constant electrical output of 5 kW within the funded project "HZwo:FRAME - Tank". For the injection moulded polymer liner half-shells and the laser joining of those, a polyethylene with a tolerable hydrogen permeation coefficient was investigated. The metallic filling insert will be integrated in one part by injection moulding. For the burst pressure of 1575 bar according to ISO 15869.3 the reinforcement structure is designed using the inhouse developed analytical and numerical method with a Toray T 700 carbon fibre and an epoxy resin with a fibre volume content of approx. 50% for filament winding. Compared to cylindrical hydrogen composite vessels available on the market, regarding the H_2 gravimetric capacity regarding the system weight of the developed toroidal composite pressure vessel is lower and already reaches the target for year 2025 for on-board hydrogen storages for light-duty fuel cell vehicles of the U.S. Department of Energy.

For each application and under respect of technical requirements, e.g. lightweight targets or available design space, an optimal design can be achieved applying the mentioned method. The toroidal composite pressure vessel will be manufactured automated with the developed ring winding machine. This prototype machine has been developed within the project and is currently under construction. First filament winding tests are planned for the end of 2019. The authors are looking forward to continuing the research tasks and to finish the funded project successfully until September 2021.

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