CASE-STUDY

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“Comparitive Study for the use of basalt fibers vs. glass and carbon fibers in pressure vessel applications

Content:

- Dimensioning of two different pressure vessels using basalt fibers:
  - Example 1, CNG Tank, 190 l Volume, 200 bar service pressure
  - Example 2: LPG Tank, 20l volume, 20 bar service pressure
- Comparison of results with equivalent design (in carbon fiber for CNG tank, in glass fiber for LPG tank)
- Estimation of material consumption (fiber, resin)
- Estimation of production time
- Comparison of material consumption, material costs, production time and production costs
- Future perspectives

Example 1: CNG Tank, 190 l Volume, 200 bar service pressure, Type IV (plastic liner, fully wrapped)

Current product: The case study does base on a pressure vessel currently produced by a well known supplier located in Europe. The vessel is products by use of a plastic liner, fully wrapped with carbon fiber and epoxy resin. Service pressure of this vessel is 200 bar, burst pressure at least 470 bar. Safety factor is 2.35.

Laminate construction carbon:
Several layers with different fiber orientation, +/-12°, +/-30°, +/-54°, +/-70°, 90°
Fiber: Standard Carbon Fiber, 8 Rovings a 1600 tex, 25€/kg (confirmed by fiber supplier)
Resin: Epoxy, amine hardener, very tough, high elongation at break, 10€/kg (confirmed by resin supplier), wastage 10%
Safety factor calculated: 2.55
Safety factor required: 2.35

Laminate construction Basaltex:
Same laminate construction as carbon vessel
Fiber: Basaltex, 16 Rovings a 2400 tex, 3.5 €/kg
Resin: Epoxy, amine hardener, very tough, high elongation at break, 10€/kg (confirmed by resin supplier), wastage 10%
Safety factor calculated: 3.65
Safety factor requested: 3.65
Comment: Due to international standards vessels made of fiber glass are to be designed with a higher safety factor than carbon fiber vessels (3.65 instead of 2.35)! For Basalt fibers the safety factor is not fixed jet. Therefore the factor for glass fiber was chosen.

Machine:
2-Spinel, European Brand
Continuous curing oven
Handling system
Invest: app. 1 Mio €, depreciation 5 years

Worker: 1/shift, 35,000€/anno

Production: 2 shifts/day, 220 days/year

Productivity: 6.5h / shift

Space: 300 m², 8€/m²/month

Energy: 65kW, 0.13€/kWh

Dimensioning:

For the dimensioning work the commercial software tool CompositeStar was used. The work was done by the following steps:

- Recalculation of the existing laminate design to confirm the required safety factor.
- Calculation of the same laminate design by use of Basaltex to estimate the remaining safety factor at burst pressure considering fiber strength.
- Extrapolation of the wall thickness, laminate weight etc. considering the required safety factor.
- Calculation of material costs.
  Comment: The price for the resin was given by HEXION, Germany. Pressure vessel require a very tough and flexible resin system, therefore the choice is limited.
- Calculation of production costs, Machine costs are estimated.

The following table compares material consumption, weight, production time and costs of the above mentioned pressure vessel.

Vessel 190 l, CNG, 200bar service pressure				
Price Basalt Fiber	3.50	€/kg		
Resin price	10	€/kg		
Weight [kg]	Carbon	Basalt	Difference	% Basalt/Carbon
Fiber	24.40	87.54	63.14	358.8%
Resin	11.43	27.34	15.91	239.2%
Laminate	35.83	114.88	79.05	320.6%
Vessel	54	133.05	79.05	246.4%
Production Time [s]	Carbon	Basalt	Difference	%
	3874	4539	665	117.2%
Costs	Carbon	Basalt	Difference	%
Fiber	609.98 €	306.39 €	-303.59 €	50.2%
Resin	114.31 €	273.43 €	159.11 €	239.2%
	724.29 €	579.82 €	-144.48 €	80.1%
Production	60.76 €	71.19 €	10.43 €	117.2%
Total	785.05 €	651.00 €	-134.05 €	82.9%

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Vessel 190 l, CNG, 200bar service pressure				
Price Basalt Fiber	3.25	€/kg		
Resin price	10	€/kg		
Weight [kg]	Carbon	Basalt	Difference	% Basalt/Carbon
Fiber	24.40	87.54	63.14	358.8%
Resin	11.43	27.34	15.91	239.2%
Laminate	35.83	114.88	79.05	320.6%
Vessel	54	133.05	79.05	246.4%
Production Time [s]	Carbon	Basalt	Difference	%
	3874	4539	665	117.2%
Costs	Carbon	Basalt	Difference	%
Fiber	609.98 €	284.50 €	-325.48 €	46.6%
Resin	114.31 €	273.43 €	159.11 €	239.2%
	724.29 €	557.93 €	-166.36 €	77.0%
Production	60.76 €	71.19 €	10.43 €	117.2%
Total	785.05 €	629.12 €	-155.93 €	80.1%

The Table indicates the drastic increase of weight when changing from carbon fiber to Basaltex (246%). Due to the much higher volume of fiber also the resin consumption does increase.
To avoid an increase of production time the amount of rovings handled at the same time got doubled (16 instead of 8)
Costs: The much lower price of basalt fibers causes just a little lowering of the total costs. The amount of fibers is much higher, therefore the resin consumption doe increase. Compared to the fibers the resin is rather expensive. The production costs are a little higher when exchanging carbon fiber by basalt fiber. So in total the costs for a pressure vessel gets reduced by app. 20%.

Comparison with E-glass:

Vessel 190 l, CNG, 200bar service pressure				
Price E-Glass	1.80	€/kg		
Resin price	10	€/kg		
Weight [kg]	Carbon	E-Glass	Difference	% Basalt/Carbon
Fiber	24.40	101.74	77.34	417.0%
Resin	11.43	31.78	20.35	278.0%
Laminate	35.83	133.52	97.69	372.6%
Vessel	54	151.69	97.69	280.9%
Production Time [s]	Carbon	E-Glass	Difference	%
	3874	5197	1323	134.2%
Costs	Carbon	E-Glass	Difference	%
Fiber	609.98 €	183.13 €	-426.85 €	30.0%
Resin	114.31 €	317.78 €	203.47 €	278.0%
	724.29 €	500.92 €	-223.38 €	69.2%
Production	60.76 €	81.51 €	20.76 €	134.2%
Total	785.05 €	582.43 €	-202.62 €	74.2%

Example 2: LPG-Tank, 20 l Volume, 20bar service pressure, Type IV (plastic liner, fully wrapped), required burst pressure 60 bar

Dimension: Diameter 250mm, elliptical dome shape , cylindrical length 295mm, total length 460mm

Laminate construction E-glass:

Several layers with different fiber orientation, +/-14°, 90°, total laminate thickness 2mm

Fiber: E-Glass, 6 Rovings a 1200 tex, 1,80 €/kg

Resin: Vinylester-Resin, very tough, high elongation at break, 3 €/kg, wastage 10%

Laminate construction Basaltex:

Same laminate construction as E-glass vessel

Fiber: Basaltex, 6 Rovings a 1200 tex, 3.5 €/kg

Resin: Vinylester-Resin, very tough, high elongation at break, 3 €/kg, wastage 10%

Machine:

5-Spinel, European Brand

Continuous curing oven

Handling system

Invest:	app. 1 Mio €, depreciation 5 years
Worker:	1/shift, 35,000 €/year
Production:	2 shifts/day, 220 days/year
Productivity:	6.5h / shift
Space:	250 m², 8€/m²/month
Energy:	35 kW, 0.13€/kWh

Dimensioning:

For the dimensioning work the commercial software tool CompositeStar was used. The work was done by the following steps:

- Recalculation of the existing laminate design to confirm the required safety factor.
- Calculation of the same laminate design by use of BASALTEX to estimate the remaining safety factor at burst pressure considering fiber strength.
- Extrapolation of the wall thickness, laminate weight etc. considering the required safety factor.
- Calculation of material costs.
- Calculation of production costs, Machine costs are estimated.

The following tables compare material consumption, weight, production time and costs of the above mentioned pressure vessel for three different prices for the glass fiber.

Vessel 20 l, LPG, 60 bar burst pressure				
Basalt fiber price	3.50	€/kg		
Resin price	3	€/kg		
Weight [kg]	E-Glass	Basaltex	Difference	% Basalt/E-Glass
Fiber	1.17	0.91	-0.27	77.3%
Resin	0.39	0.28	-0.11	72.7%
Laminate	1.56	1.19	-0.37	76.2%
Vessel	3.6	3.23	-0.37	89.7%
Laminate Thickness [mm]	2	1.5	-0.55	72.7%
Production Time [s]	E-Glass	Basaltex	Difference	%
	572	497	-75	86.8%
Costs	E-Glass	Basaltex	Difference	%
Fiber	2.11 €	3.17 €	1.06 €	150.3%
Resin	1.29 €	0.93 €	-0.35 €	72.7%
	3.40 €	4.11 €	0.71 €	121.0%
Production	3.41 €	2.96 €	-0.45 €	86.8%
Total	6.81 €	7.07 €	0.26 €	103.9%

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Vessel 20 l, LPG, 20 bar service pressure				
Basalt fiber price	3.25	€/kg		
Resin price	3	€/kg		
Weight [kg]	E-Glass	Basaltex	Difference	% Basalt/E-Glass
Fiber	1.17	0.91	-0.27	77.3%
Resin	0.39	0.28	-0.11	72.7%
Laminate	1.56	1.19	-0.37	76.2%
Vessel	3.6	3.23	-0.37	89.7%
Laminate Thickness [mm]	2	1.5	-0.55	72.7%
Production Time [s]	E-Glass	Basaltex	Difference	%
	572	497	-75	86.8%
Costs	E-Glass	Basaltex	Difference	%
Fiber	2.11 €	2.95 €	0.84 €	139.6%
Resin	1.29 €	0.93 €	-0.35 €	72.7%
	3.40 €	3.88 €	0.49 €	114.3%
Production	3.41 €	2.96 €	-0.45 €	86.8%
Total	6.81 €	6.84 €	0.04 €	100.5%

The higher strength of Basaltex allows reducing the laminate thickness, the resin consumption and the laminate weight. Also production time gets less which reduces these costs.

The higher price of Basaltex does compensate the gain of production costs and resin costs totally. There is no economic benefit by use of basalt fibers.

Additional aspects and future perspectives

The two different pressure vessels considered in this study are commercial products manufactures in series today. Main reason for their use is less weight in both cases.

- The CNG-Tanks should be light not to increase the weight of a vehicle to much. Many of these vessels are used in busses, whereby they are installed on the roof. This does explain the need for lowering the weight.

  Compared with a steel vessel the weight of a carbon vessel is just one quarter, the weight of a basalt fiber vessel would be 60% of it. The cost reduction between carbon and basalt fiber vessels are app. 20%.

  One should not forget, that there are pressure vessels of Type II. These ones are made from a steel liner hoop wrapped with carbon fiber. The next table compares the weight of different vessels again:

	Steel Type I	Steel/Carbon TypeII	Carbon Type IV	Basaltex Type IV
Weight [kg]	215	130	54	133

  Additionally the low stiffness of the laminate raise the question if the calculated weight might be realized, or if the additional effort by use of alternative resin systems will be effective (see below).

- The dimensioning of pressure vessels is a stress analysis by recalculating the tension in fiber direction. Just fiber strength is important for this calculation. A safety factor (2.35 for carbon fiber, 3.65 for glass fiber) indicates the ratio between service pressure and burst pressure.

  The different safety factors for carbon and glass fiber have something to do with the different stiffness of the fibers. At service pressure there is of course an elongation, also transverse to the fiber direction. This deformation might exceed critical values and causes so called Inter Fiber Fractions (IFF).

The following table dispays the safety factor against Fiber Fraction (FF) and Inter Fiber Fraction (IFF) for the two different pressure vessels.

	190 l CNG Tank Carbon	190 l CNG Tank Basaltex	20l-LPG Tank Glass	20l LPG Tank Basaltex
Safety against FF	2.557	3.65	4.47	4.47
Safety against IFF	1.336	0.87	0.83	0.9

This comparison shows, that both vessels would get some failure due to Inter Fiber Fraction. This does not mean that they will burst at a lower pressure. But they might fail at a lower amount of pressure cycles by fatigue.

There are two options to handle this conflict, in general the use of resin systems with much higher elongations, as Polyurethane and Thermoplastics.

Polyurethane can be handled as common epoxy resin, with the same equipment and the same process.

Thermoplastic matrices can not be handled as liquid resin systems. It is necessary to produce a commingled roving (like Twintex) or a pre-impregnated roving. In both cases these rovings are to be melted in the moment of placing them on the mandrel. But consolidating is difficult, additional heat might impact the liner. Void content normally is much higher compared to common wound structures, which causes an increase of material consumption due to less good laminate properties.