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Conceptual study of non-cylindrical tank for gaseous fuels

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1. Motivation

There is increased pressure from regulatory organs to move to greener and lower emission propulsion systems in aviation. That is possible thanks to recent development of electric propulsion systems. The biggest problem of such system is the energy source, most common type are lithium batteries, which are difficult to manufacture and the process is not ecological. The biggest problem of batteries however is their low gravimetric energy density compared to the standard aviation gas. In the figure [1] below (see Fig. 1), a graph of gravimetric energy densities compared to the volumetric energy densities is seen. From this graph the best gravimetric energy density is achieved by hydrogen compressed to either 30 or 70 MPa. Lithium Ion batteries have the worst energy densities of all listed substances. After hydrogen goes through the fuel cell, the only emission is water vapor and excess heat, making it the most ecologic of the listed energy sources.

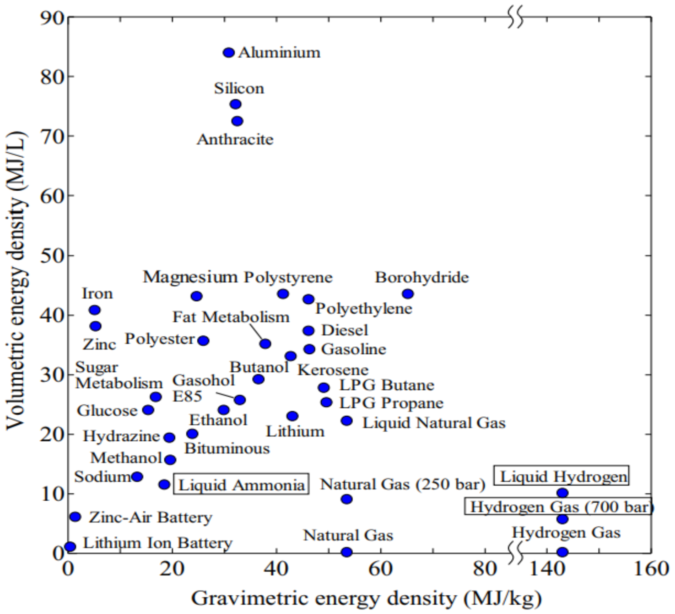

Fig. 1. Graph of energy densities [1]

The biggest problem of hydrogen is its low volumetric energy density, meaning it occupies larger volume to contain the same amount of energy as other sources with higher volumetric energy densities. In aircraft applications nowadays, the hydrogen tanks are attached outside of the airplane. This is hindering flight performance, because of increased drag. To mitigate this problem, tanks mounted inside the airframe can be used. However typical cylindrical tanks do not fit inside with sufficient volume. Thus, noncylindrical tanks, that can efficiently use internal free space, are proposed. In addition, to save weight, tanks can be designed to bear external loads such as torsion for example.

2. Mass of tanks and amount of fuel determination

Calculation is based on principle of "constant" amount of energy stored in gas. It is calculated for small motor glider developed by the Department of Aerospace Engineering. For reference a similar aircraft of the same category was selected. Amount of gas in tanks: $V_f = 2 * 50\,\text{l} = 100\,\text{l}$, [3]. Gas: Avgas – volumetric energy density $\rho_{Evf} = 30.81\ \text{MJ/l}$, [1]. The equation

$$E_G = V_f * \rho_{Evf} = 100 * 30.81 = 3081\ \text{MJ} \qquad (1)$$

determines amount of energy of the gas carried by similar aircraft. Next energy "on the shaft" is defined by equation

$$E_{G\,shaft} = E_G * \eta_{combustion} = 3081 * 0.35 = 1078.35\ \text{MJ}. \qquad (2)$$

The efficiency of hydrogen fuel cell based propulsion is calculated by equation

$$\eta_H = \eta_{fc} * \eta_{mc} * \eta_{em} = 0.85 * 0.99 * 0.9 = 0.757\ \ [1], \qquad (3)$$

where η_H is the overall efficiency of the system, η_{fc} is the efficiency of fuel cell [4], η_{mc} is the efficiency of motor controller and η_{em} is the efficiency of electric motor of similar power as a corresponding combustion engine used in similar category aircraft. Equation

$$E_\text{H} = E_{G\,shaft}/\eta_H = 1078.35/0.757 = 1424.5\ \text{MJ} \qquad (4)$$

determines the amount of energy needed to be stored in the compressed hydrogen. E_H is the energy stored in hydrogen, $E_{G\,shaft}$ is energy "on the shaft" defined by equation (2) and η_H is the efficiency of hydrogen fuel cell based propulsion system defined by (3). V_H is the volume of compressed hydrogen at 70 MPa to contain the energy as calculated in (4):

$$V_H = \frac{E_H}{\rho_{EvH}} = \frac{1424.5}{5} = 284.5\ l, \qquad (5)$$

where ρ_{EvH} is the volumetric energy density of compressed hydrogen [MJ/l], was found in [2].

Based on the density of hydrogen compressed at 70 MPa as seen in Fig. 2, it is possible to determine the mass of needed hydrogen.

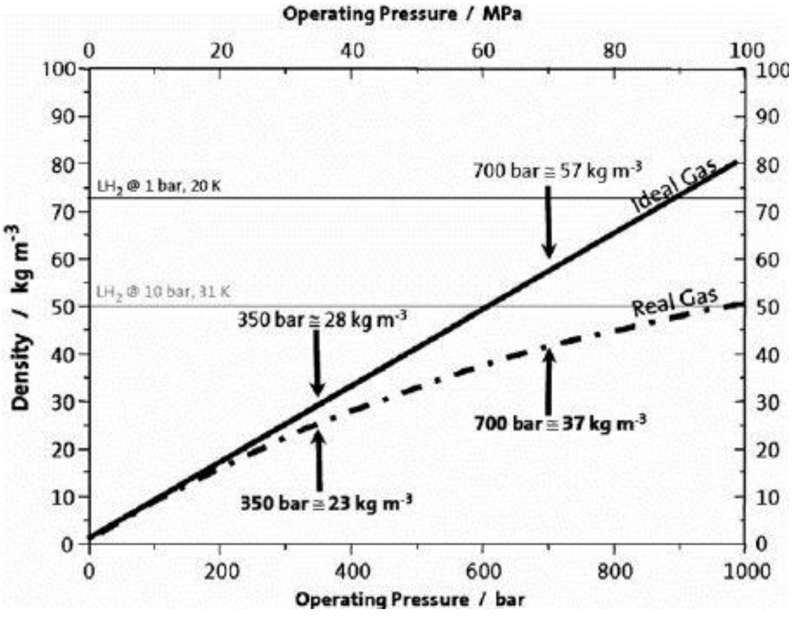

Fig. 2. Graph of hydrogen density based on pressure [1]

The mass of hydrogen needed

$$m_H = V_H * \rho_{H70} = 0.2845 * 37 = 10.53 \text{ kg}, \tag{6}$$

where V_H is the volume of hydrogen (converted to m^3) and ρ_{H70} is the density of hydrogen compressed at 70 MPa.

$$m_f = V_f * \rho_f = 0.1 * 690 = 69 \text{ kg} \tag{7}$$

defines the mass of petrol fuel m_f, V_f is the volume of fuel (converted to m3) carried by the aircraft and ρ_f is the density of petrol. Next, the mass of the whole propulsion system using petrol is defined as

$$m_{ps} = m_{ft} + m_f + m_e = 4 + 69 + 80 = 153 \text{ kg}, \tag{8}$$

where m_{ft} is the mass of fuel tanks, m_f is the mass of petrol fuel defined by (7) and m_e is the mass of a combustion engine. Rotax 912 UL is considered. Based on weight of the whole propulsion, it is possible to determine the maximal weight of the compressed hydrogen tank. The goal is to keep the aircraft's maximal take-off weight the same as with a combustion engine propulsion system, to keep the aircraft in the same regulatory category. Maximal available mass of tank m_{tH} is determined as

$$m_{tH} = m_{ps} - m_H - m_{fc} - m_{mc} - m_{em} = 153 - 10.53 - 41 - 4.2 - 15.3 = 81.97 \text{ kg}, \tag{9}$$

where m_{ps} is the mass of petrol propulsion system as calculated (8), m_H is the mass of compressed hydrogen as calculated (6), m_{fc} is the mass of fuel cell, m_{mc} is the mass of motor controller and m_{em} is the mass of electric engine.

Based on knowledge of the mass of combustion engine propulsion system and the amount of petrol carried by the aircraft, maximal available mass of hydrogen tanks has been determined. The mass of the propeller or reduction gear, if used, is assumed the same as for a combustion engine and thus has not been calculated with. Furthermore, the mass of piping and hoses for routing gas or hydrogen has been neglected, as their length is yet to be determined. According to a 3D model of the proposed aircraft it is possible to store up to 400 l of hydrogen inside the structure of the wings, however the mass of the tanks would probably exceed the maximal allowable mass in its regulatory category.

3. Conceptual designs

So far, four conceptual designs of a tank for compressed hydrogen have been designed (see Fig. 3) and analysed. All of these are integrated into the wing structure, meaning they need to fit inside the airfoil envelope. The goal is to select the best concept for further more detailed design and analysis. The main criterion is minimal mass compared to the volume of gas it can store. Technology is also considered. All concepts have been analysed by membrane stress theory

$$t_n = \frac{p * k * R_n}{\sigma_{max}} \tag{10}$$

for given radiuses R_n, the wall thickness t_n has been calculated, maximum strength has been empirically selected to $\sigma_{max} = 1000$ MPa. Working pressure p has been multiplied by a safety factor $k = 2.3$. This value is given by regulations for composite pressure vessels. The wall thickness is different for each concept variant and each radius. Radius values have been obtained from CAD. For mass evaluation, the length of curve of each part in each concept variant has been obtained from CAD as well. These are used to calculate the section area of composite by a simple multiplication of curve lengths and wall thicknesses. In the Table 1 are wall thicknesses of each concept as well as their relative volume, i.e. volume per unit of mass. Concept number 1 does not have the wall thickness of vertical walls between cells displayed in the table. These were calculated analogically. FEM analysis shows good overall compliance with analytical examination, however FEM shows stress spikes on the edges of the membranes see Fig. 4. These regions would have to be reinforced.

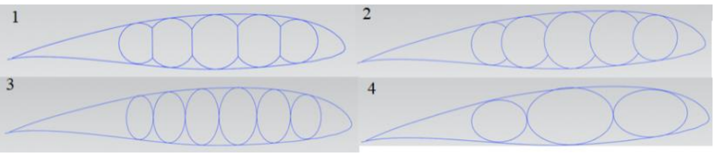

Fig. 3. Overview of evaluated concepts, fitted inside airfoil envelope

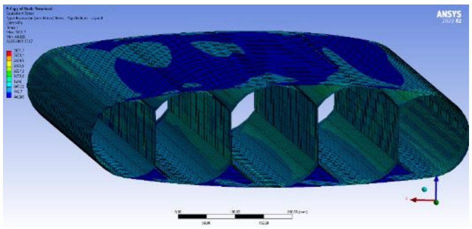

Fig. 4. FEM simulation of concept 1

Table 1. Wall thicknesses and relative volume of each concept

Concept Nr.	t_1 [mm]	t_2 [mm]	t_3 [mm]	t_4 [mm]	t_5 [mm]	t_6 [mm]	Relative volume [l/kg]
1	10.787	13.041	14.49	13.846	11.592	-	1.370357
2	10.787	13.041	14.49	13.846	11.592	-	1.348574
3	11.109	12.88	14.168	14.49	13.524	11.27	0.802497
4	14.49	22.54	19.32	-	-	-	0.797562

4. Conclusion

Due to increased demand for carbon neutral propulsion systems in aviation, hydrogen is highly considered. To use compressed hydrogen efficiently it is needed to design tanks that can conform to airframe structure and use internal volume. First, the necessary amount of hydrogen compressed to 70 MPa is calculated based on the energy stored and transferred to the propeller. Thanks to the knowledge of conventional propulsion system using combustion engine, the mass of both systems was compared and maximum allowable mass of the hydrogen tank has been calculated. Next, 4 concepts of conformal hydrogen tank fitted inside the airfoil envelope have been designed and analytically evaluated, FEM analysis was further performed to confirm the results. Both analyses show good agreement, however FEM shows stress spikes in places where membrane stresses connect. Concept 1 has the best relative volume and is the most promising for further optimization and development.

Acknowledgement

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References

[1] Felderhoff, M., Weidenthaler, C., Helmolt, R., Eberle, U., Hydrogen storage: The remaining scientific and technological challenges, Physical chemistry chemical physics 9 (2007) 2643-2653.
[2] Prewitz, M., Bardenhagen, A., Beck, R., Hydrogen as the fuel of the future in aircrafts – Challenges and opportunities, International Journal of Hydrogen Energy 45 (2020).
[3] UFM 13/15 Lambáda, available from: https://www.distar.cz/ufm-13-15-lambada/ (online)
[4] Types of Fuel Cells, U.S Department of energy, Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html, https://web.archive.org/web/20100609041046/http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html (online)