

Article

Pressurised Fuel Vessel Mass Estimation for High-Altitude PEM Unmanned Aircraft Systems

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Abstract: The power to weight ratio of power plants is an important consideration, especially in the design of Unmanned Aircraft System (UAS). In this paper, a UAS with an MTOW of 35.3 kg, equipped with a fuel cell as a prime power supply to provide electrical power to the propulsion system, is considered. A pressure vessel design that can estimate and determine the total size and weight of the combined power plant of a fuel cell stack with hydrogen and air/oxygen vessels and the propulsion system of the UAS for high-altitude operation is proposed. Two scenarios are adopted to determine the size and weight of the pressure vessels required to supply oxygen to the fuel cell stack. Different types of stainless-steel materials are used in the design of the pressure vessel in order to find an appropriate material that provides low size and weight advantages. Also, the design of a hydrogen pressure vessel and mass estimation are also considered. The estimated sizes and weights of the hydrogen and oxygen vessels of the power plant and propulsion system in this research offer a maximum of four hours of flying time for the UAS mission; this is based on a Horizon (H-1000) Proton Exchange Membrane (PEM) stack.

Keywords: PEM fuel cell; high altitude; pressure vessel design; mass estimation; UAS



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1. Introduction

Due to many civilian applications that have been identified recently, unprecedented growth has occurred in the unmanned aviation sector. Many platform types that address a specific application area have been proposed, with most platforms depending on operational requirements and payload capacities being powered either by electric motors, internal combustion engines or by gas turbine engines. The power to weight ratio of the power plant is one of the limiting design factors. One of the applications of Unmanned Aircraft Systems (UAS) is in high-altitude long-endurance (HALE) aircraft; such systems can be used as communication relay systems, and or for weather monitoring. Since the fuel cell uses hydrogen and oxygen, due to the lack of oxygen at high altitudes, oxygen storage alongside hydrogen storage is needed [1,2].

Materials that have properties such as high strength, high stiffness, high fracture toughness, low density, and low permeability to hydrogen molecules are recommended for the design and construction of hydrogen storing tanks [1]. Lowering the weight of the fuel tank would reduce the lift force and power consumption, hence increasing the endurance of the flight and the payload of the UAS [3]. In pressure vessel fabrication, composite materials are widely used due to their higher strength to weight ratios [3]. A high storage density for hydrogen or oxygen could be achieved by creating a composite of

ultra-light vessel materials such as polymer liners [4]. However, aluminium is the most suitable material, among the metals that fulfil the recommendations of NASA for tank fabrication, for flight applications [5].

Romeo et al. [6] reported that hydrogen and oxygen in a pressurised form could be stored in pressure vessels mounted inside the wing of a plane. The weight and size of the storage tanks need to be optimised to reduce the power required by the flight. Verstraete et al. [1] proposed a preliminary design model of 1.2 bar cryogenic liquid hydrogen tanks developed for a small regional and large long-range subsonic aircraft. Two different insulation techniques, namely multi-layer insulation and low-density foam materials, were used in order to balance the weight and the dimensions of the designed tanks, and consequently the dimensions and total weight of the fuselage.

Adam and Leachman [3] developed and fabricated a light-weight storage tank for liquid hydrogen for a Proton Exchange Membrane (PEM) fuel cell power system integrated and designed for a small UAS (<25 kg). The fuel tank consisted of a cylindrical-shaped cryogenic vessel placed inside an outer vessel, while an insulating blanket made from multi-layer insulation was used to wrap the inner vessel to reduce radiation heat loss. Aluminium (6061-T6) material was used to construct the inner and outer vessels; the total mass of the two vessels was 6.3 kg, excluding the insulation materials.

Radmanesh et al. [7] reported that storing hydrogen in the form of highly pressurised gas is the cheapest method, due to developments in composite materials that offer a storing pressure up to 800 bar. However, pressurised hydrogen gas is usually stored in steel tanks with a pressure ranging between 200 and 300 bar.

Furrutter and Meyer [8] employed a light aluminium vessel weighing 0.255 kg and filled with 30 bar of pressurised hydrogen, enough hydrogen to supply a continuous nine-minute flying time, using a 100 W Horizon PEM fuel cell power plant system placed in a small-scale fixed wing UAS; this was in order to provide enough power to maintain a steady and stable flying level with a 13 m/s maximum flight velocity, for a total mass of 5.3 kg.

Romeo et al. [6] proposed a parametric analysis to determine the impact of internal pressure and in-flight loads on the size of the hydrogen pressure vessel, in order to reduce the weight of the vessel and to examine the safety margins between the applied pressure and the burst pressure, so as to fulfil the safety regulation requirements for a composite material pressure vessel filled with 100 bar of pressurised hydrogen mounted inside the wing of a UAS for a high-altitude long-endurance mission.

Bradley et al. [9] proposed using a 310 bar compressed hydrogen tank providing a storage volume capacity of 0.192 m³ (i.e., before compression) for a 500 W, 32-cell self-humidified PEM fuel cell as the main and only source of power for an unmanned powered aircraft. To overcome the problem of a very low power to weight ratio, the entire proposed fuel-cell-powered aircraft was designed to be operated at a low speed and stable-altitude flight level with slow manoeuvring, with a maximum flying altitude up to 30 m, for less than three minutes of total flying time. However, the proposed integrated power fuel cell aircraft system was designed without consideration of the payload or endurance requirements. The total mass of the combined power plant and propulsion system was about 9.4 kg, which accounted for about 57% of the 16.4 kg total mass of the UAS.

Barbir et al. [4] reported that oxygen storage is the only option for space applications. However, most of the research focuses on the design of hydrogen vessels for low-altitude and low-speed UAS applications, and for supplying air extracted directly from the surroundings; hence, no oxygen pressure vessel has been used in this application. At a high altitude of 11 km (~36,000 ft.), the atmospheric temperature and pressure are approximately −56 °C and 0.227 bar, and the air density is around 0.365 kg/m³; these are severe condi-

tions for a fuel cell to operate in. Also, the experimental data published for such operating conditions are very limited [10]. Therefore, air or oxygen pressure vessels are crucial for providing sufficient oxygen to the fuel cell power system. Moreover, using pure oxygen instead of air to feed the fuel cell stack leads to an increase in the cell output voltage; this is because the pressure and diffusion rates of pure oxygen in the cathodes are higher than the partial pressure and diffusion rates of oxygen in the mixture of nitrogen–oxygen in air. However, using pure oxygen elicits its own issues regarding maintenance and safety. Operating a fuel cell stack with air requires a pumping device such as a blower or a compressor, resulting in further parasitic losses. Thus, the use of pure oxygen or air must be decided based on the application [4].

The operation of the fuel cell at very high altitudes poses many technical challenges. Most research has focused on the design of hydrogen vessels for low-altitude and low-speed UAS applications; however, at low altitudes, oxygen is freely available, negating the use and design of oxygen storage. In this paper, the design of hydrogen and oxygen pressure vessels is considered in order to predict the operational power plant mass and its associated components for UAS operation at high altitudes.

2. Pressure Vessel Governing Equations

A cylindrical shell with hemispherical ends is frequently used in the design of pressure vessels. A hemispherical-ended shell is more efficient than a flat-ended shell in enduring equivalent pressure [3]. The stresses in a cylindrical shell with two closed ends under internal uniform pressure P can be determined under the conditions of static equilibrium, as given in Equations (1)–(3), respectively [11].

$$\sigma_L = \frac{P \cdot r}{2t} \quad (1)$$

$$\sigma_t = \frac{p \cdot r}{t} \quad (2)$$

where σ_L is stress in the longitudinal direction (i.e., the stress in the direction of closed ends), σ_t is tangential stress, which represents the stress applied to the curved surface of the cylinder, t is the thickness of the shell, and r is the radius of the cylinder, as shown in Figure 1. Tangential stress can be expressed in terms of the internal radius r_i of the cylinder, as presented in Equation (3).

$$\sigma_t = \frac{p}{t}(r_i + 0.5t) \quad (3)$$

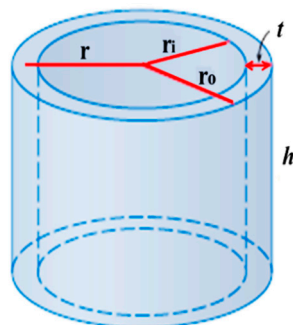


Figure 1. The cylindrical shell of the pressure vessel.

The minimum shell thickness (inch) is determined by using Equations (4) and (5) [11,12].

$$t = \frac{P \cdot r_i}{(\sigma_t - 0.5P)} \quad (4)$$

$$t = \frac{P \cdot r_i}{(S \cdot E) - 0.6P} \quad (5)$$

where E represents the weld joint efficiency coefficient, S is the maximum allowable stress of the metal (psi), r_i is the internal radius (inch), and P is the internal pressure (psi). Equation (5) is only valid for a thin shell with a thickness (t) less than ($\frac{1}{2} r_i$) or a pressure less than ($0.385 S \cdot E$). According to the weld joint efficiency coefficient code, E has a value of 1.0 for fully radiographed (100% joint efficiency), 0.85 for spot-radiographed, and 0.7 for not radiographed [12]. For a cylindrical shell vessel under uniform external pressure, the thin wall of the vessel collapses at a stress much lower than the yield strength due to the instability of the shell. The instability of the shell is governed by many factors, such as the properties of the materials used in manufacturing the vessel, the operating temperature, the shell thickness, the unsupported length, and the outside diameter. The behaviour of a thin-walled shell under the impact of external pressure will differ according to the cylinder length. The pressure at which the shell collapses is defined as the collapse or critical pressure (P_c) [11]. A short cylindrical shell would collapse due to the impact of the plastic yielding stress alone at high stresses close to the yield strength of the metal. Hence, the ordinary tangential shell stress given above in Equation (2) can be used to determine the critical pressure, as given in Equation (6) [11]:

$$P_c = \frac{S_y \cdot t}{r_o} \quad (6)$$

where S_y represents the yield stress of the metal (psi), t is the shell thickness (inch), and r_o is the outside radius of the shell (inch) and ($r_o = r_i + t$). However, long and intermediate cylinder lengths are not going to be considered in this research, as these types of cylinders are out of the scope of this research application. A yield stress point is defined as the point up to which deformations occurring in the material are fully recovered upon the removal of the applied load (i.e., the material returns to its original status before being loaded); this region is called the elastic region. Most ductile materials, such as steel, experience plastic deformation, especially when the applied load exceeds the yield stress point; hence, the material will not completely return to its original condition after the applied load is removed.

The volume of a cylindrical shell with an inner radius r_i , outer radius r_o , and height h can be determined by subtracting the volume of the inner cylinder from the volume of the outer cylinder, as given in Equation (7).

$$V_{cyl} = \pi \cdot r_o^2 \cdot h - \pi \cdot r_i^2 \cdot h = \pi \cdot h \cdot (r_o^2 - r_i^2) \quad (7)$$

The difference between the outer radius and inner radius represents the thickness of the shell ($r_o - r_i = t$). Similarly, the volume of the two hemispherical ends of the shell can be calculated as follows:

$$V_{sph} = \frac{4}{3} \pi \cdot (r_o^3 - r_i^3) \quad (8)$$

Hence, the volume (V_{shell}) and the mass (M_{shell}) of the shell of a pressure vessel with a cylindrical shape and hemispherical ends can be determined by Equations (9) and (10).

$$V_{shell} = \pi \cdot h \cdot (r_o^2 - r_i^2) + \frac{4}{3} \pi \cdot (r_o^3 - r_i^3) \quad (9)$$

$$M_{shell} = V_{shell} \cdot \rho_m \quad (10)$$

where ρ_m is the density of the material (g/cm^3) used in manufacturing the shell. The total height of the shell (h_{shell}) can be determined by Equation (11):

$$h_{shell} = h + 2 r_o \quad (11)$$

The volume of the gas inside the cylindrical shell with hemispherical ends can be determined by Equation (12):

$$V_{gas} = \pi \cdot r_i^2 \cdot \left(h + \frac{4}{3} r_i \right) \quad (12)$$

The ideal gas law equation is given below [13]:

$$P \cdot V = N \cdot R \cdot T = \frac{m}{M} \cdot R \cdot T \quad (13)$$

where P is the pressure (kPa), V is the volume of gas (m^3), T is the absolute temperature in kelvin (K), R is the universal gas constant ($R = 8.31441 \text{ kPa} \cdot \text{m}^3 / \text{kmol} \cdot \text{K}$), and N is the number of moles, which is the ratio of mass m in (kg) to the molar mass of gas M in (kg/kmol). The term (R/M) represents the specific gas constant R_s in ($\text{kPa} \cdot \text{m}^3 / \text{kg} \cdot \text{K}$).

$$P = \frac{m}{V} \cdot R_s \cdot T = \rho \cdot R_s \cdot T \quad (14)$$

where the term (m/V) is the density of gas ρ in (kg/m^3). For two volumes of gas, the pressures of the gas are defined as follows:

$$P_1 = \frac{m_1}{V_1} \cdot R_s \cdot T_1$$

$$P_2 = \frac{m_2}{V_2} \cdot R_s \cdot T_2$$

Under a constant temperature and a fixed mass of gas, ($T_1 = T_2$ and $m_1 = m_2$) yields the following:

$$P_1 \cdot V_1 = P_2 \cdot V_2 \quad (15)$$

The above equations for the design of a pressure vessel offer a generic weight estimation approach that enables the designer to estimate the size and weight of storage vessels by taking into consideration the power capacity of the fuel cell stack and the flight endurance, and hence determining the total weight of the UAS, which is a key requirement in the preliminary aircraft design phase. The mass flow rates of reacted oxygen and hydrogen inside the fuel cell stack are determined by Equation (16) and Equation (17), respectively [14].

$$W_{O_2, rct} = M_{O_2} \cdot \frac{n \cdot I_{st}}{4F} \quad (16)$$

$$W_{H_2, rct} = M_{H_2} \cdot \frac{n \cdot I_{st}}{2F} \quad (17)$$

where $W_{O_2, rct}$ and M_{O_2} represent the mass flow rate of reacted oxygen (g/s) and the molar mass of oxygen ($32 \text{ g}/\text{mol}$), $W_{H_2, rct}$ and M_{H_2} represent the mass flow rate of reacted hydrogen (g/s) and the molar mass of hydrogen ($2.02 \text{ g}/\text{mol}$), n is the number of fuel cells in the stack, I_{st} is the current drawn from the stack (A), and F is the Faraday constant ($96,485 \text{ C}/\text{mol}$).

A PEM fuel cell is commonly supplied with hydrogen and oxygen at a level higher than the reaction rate in order to prevent starvation. The ratio of the mass flow rate of

supplied gas to the mass flow rate of reacted gas, defined as the utilisation factor μ , is given in Equation (18) below [15]:

$$\mu = \frac{\text{Mass flow rate of supplied gas}}{\text{Mass flow rate of reacted gas}} \quad (18)$$

3. Hydrogen and Air–Oxygen Consumption

Based on the flow rates of hydrogen and air for the Horizon (H-1000) fuel cell stack, as presented in the previous published research work [16], at a current of 20 A and a power of 990 W, the flow rate of supplied air is 1.766 m³/min (105.96 m³/hour), and the flow rate of supplied hydrogen is 11.85 L/min (0.711 m³/hour or 0.064 kg/hour). Based on the developed model of the PEM fuel cell stack comprising 72 cells, as presented in [14,17], at a current of 20 A and a power of 877 W, the flow rate of supplied air is 97.9162 m³/hour, and the flow rate of supplied hydrogen is 0.6368 m³/hour. Here, at the standard temperature and pressure, the density of dry air is 1.225 kg/m³, the density of oxygen is 1.429 kg/m³, the ratio of oxygen to air is 21%, and the density of hydrogen is 0.0899 kg/m³. Equations (16)–(18) can be used to determine the mass flow rates and the utilisation factor of the oxygen and hydrogen supplied to the stack of 72 fuel cells, as given below.

$$\text{Mass Flow of Supplied O}_2 = 97.9162 * 0.21 = 20.5624 \text{ m}^3/\text{hour} = 29.384 \text{ kg/hour}$$

$$W_{O_2, rct} = M_{O_2} \cdot \frac{n \cdot I_{st}}{4F} = \frac{32 * 72 * 20}{4 * 96485} = 0.1194 \text{ g/s} = 0.43 \text{ kg/hour} = 0.3 \text{ m}^3/\text{hour}$$

$$W_{H_2, rct} = M_{H_2} \cdot \frac{n \cdot I_{st}}{2F} = \frac{2.02 * 72 * 20}{2 * 96485} = 0.015 \text{ g/s} = 0.054 \text{ kg/hour} = 0.6 \text{ m}^3/\text{hour}$$

$$\mu_{O_2} = \frac{\text{Mass flow of supplied Oxygen}}{\text{Mass flow of reacted Oxygen}} = \frac{20.5624}{0.3} = 68.5 \approx 68$$

$$\mu_{H_2} = \frac{\text{Mass flow of supplied Hydrogen}}{\text{Mass flow of reacted Hydrogen}} = \frac{0.6368}{0.6} = 1.06$$

It is clear that the amount of oxygen/air supplied at sea level is 68 times higher than the reacted amount required to produce 20 A of current. The excess air/oxygen is a design feature of the Horizon Stack in order to maintain a low stack temperature and enable the purging of the stack. It has been reported in the literature that in order to ensure a faster and better response against sudden changes in the load demand, a high hydrogen utilisation factor needs to be applied to prevent starvation, due to a high amount of current being drawn from the fuel cell. However, this will lead to extra hydrogen and air not being used in the reaction, which leads to more losses. Therefore, a compromise between the utilisation factor and the size of the gas storage must be considered [15,18].

Shih et al. [19] reported that there is an increase of up to 32% in the maximum power of a fuel cell stack fed by pure oxygen, in comparison with a stack fed by atmospheric air. Bégot et al. [20] recommended setting the stoichiometry rate to 1.5 for the hydrogen supplied to the PEM fuel cell stack, with a 90% relative humidity for a fuel cell stack operating under sub-zero ambient-temperature conditions. Meanwhile, the air compressor is controlled to keep the air supplied to the stack at a 2.5 stoichiometric ratio [21].

In this research, two scenarios are considered to determine the size and weight of the pressure vessels required to supply oxygen to a fuel cell stack for high-altitude operations (11 km). Moreover, three different types of stainless-steel metals are adopted in the design of the pressure vessels in order to find an appropriate metal that provides low size and weight advantages. The stainless-steel materials are chosen based on their specifications, offering a high yield strength, high stress resistance and high corrosion resistance, and their

availability in a decent range of thicknesses. They are also chosen for their suitability in storing highly pressurised gases for aerospace and industrial applications. However, all calculations related to the design of pressure vessels and power plant mass estimations in the following sections of this research will be determined based on the developed model of the PEM fuel cell stack in [14,17], and Equations (3), (5), (6), (9)–(12) and (15) proposed above.

AK 2205 Duplex stainless steel has high corrosion resistance, high strength and high stress resistance, and low thermal expansion. These specifications make this type of steel highly suitable for applications like heat exchangers, pressure vessels, tanks and pipes, and oil field equipment. AK 2205 Duplex is manufactured and supplied with a standard thickness (0.25–2.29 mm), a 0.2% yield strength equal to 621 MPa (90,069.5 psi) at room temperature, and a material density of about 7.85 g/cm³ [22]. For pressure vessel design calculations using AK Steel 2205 Duplex, it is assumed that the weld joint efficiency coefficient is $E = 0.85$ and the maximum allowable stress of the metal is $S = 90,069.5$ psi.

AK 15-5 PH stainless steel provides high strength, good corrosion resistance, and good stress resistance in transverse and longitudinal directions; this type of steel is widely used in petrochemical, chemical and aerospace applications. AK15-5 PH is manufactured and supplied in its original class-A condition, which is prepared for immediate use by consumers. AK 15-5 PH class-A has a standard thickness (0.38–3.18 mm), a maximum 0.2% yield strength equal to 1103 MPa (159,979 psi), which is acceptable for material specification, and a material density of about 7.78 g/cm³ [23]. For pressure vessel design calculations using AK Steel 15-5 PH, it is assumed that the weld joint efficiency coefficient is $E = 0.85$ and the maximum allowable stress of the metal is $S = 159,979$ psi.

AK 440A stainless steel in hardened and stress-relieved conditions provides high strength and corrosion resistance; this type of steel is widely used in dental and surgical instruments, and in the manufacturing of crushing machines. AK 440A is manufactured and supplied with a standard thickness (0.25–3.68 mm), a maximum 0.2% yield strength mechanical properties equal to 1655 MPa (240,040.4 psi), and has a material density of about 7.74 g/cm³ [24]. For pressure vessel design calculations using AK Steel 440A, it is assumed that the weld joint efficiency coefficient is $E = 0.85$ and the maximum allowable stress of the metal is $S = 240,040.4$ psi.

3.1. Pressure Vessel for Compressed Oxygen

It is clear that using compressed air for high-altitude operations needs approximately five times the storage capacity of oxygen (i.e., the ratio of oxygen to air is 21%); therefore, the design of air vessels will be excluded in this research. At sea level, based on the developed model of a PEM fuel cell stack in [14,17], for one hour of operation at a maximum current of 20 A and a power of 877 W, the required supply of pure oxygen is 20.5624 m³/hour under 1 atm ambient pressure. Using Equation (15) above to determine the volume of oxygen under compression, assuming $P_1 = 1$ atm = 1.01317 bar = 14.504 psi and $V_1 = 20.5624$ m³, and assuming that oxygen is going to be pressurised up to 230 bar (3335.92 psi), the new volume of oxygen V_2 is equal to 0.09 m³.

BOC Industrial Gases UK [25] provides different sizes of cylindrical oxygen vessels with maximum filling pressures that vary between 137 and 230 bar at an ambient temperature of 15 °C. A type W cylinder can store 11.09 m³ (15.85 kg) of oxygen, with vessel dimensions ($D \times H$) of (23 cm $\times$ 146 cm) and a gross weight of 80 kg. Equations (3), (5), (6), (9)–(12) and (15) can be used to determine the dimensions and masses of the air and oxygen cylindrical pressure vessels with two hemispherical ends for the operation of a PEM fuel cell stack for one hour, at a maximum power output of 877 W at 20 A, and for different stainless steel materials, whilst the oxygen is compressed up to 230 bar and 300 bar, as

presented Table 1. It is found that the impact of increasing the compression pressure of oxygen up to 300 bar would reduce the diameter of the vessel due to the increase in height, with no significant impact on the whole mass of the vessel. Although AK 440A stainless steel provides a pressure vessel with the lowest size and weight in comparison with AK 2205 Duplex and AK 15-5 PH. But, AK 2205 Duplex stainless steel has high corrosion resistance, high strength and high stress resistance, and low thermal expansion. These specifications make this type of steel highly suitable for application in pressure vessels and heat exchange [22]; therefore, this type of steel will be considered for further investigation in this research.

Table 1. Dimensions and masses of oxygen cylindrical pressure vessels with two hemispherical ends for the operation of a PEM fuel cell stack for one hour, at a maximum power output of 877 W at 20 A.

Types and Thickness of the Stainless Steel	O ₂ Compressed up to 230 Bar to Supply Flow Rate of 20.5624 m ³ /hour				O ₂ Compressed up to 300 Bar to Supply Flow Rate of 20.5624 m ³ /hour			
	Dimensions of Vessel		Mass of Vessel (kg)		Dimensions of Vessel		Mass of Vessel (kg)	
	Height (m)	Diameter (cm)	Empty Vessel	Filled Vessel	Height (m)	Diameter (cm)	Empty Vessel	Filled Vessel
AK 2205 Duplex, (2.29 mm)	11.014	10.676	64.854	94.24	14.486	8.23	65.309	94.693
AK 15-5 PH, (3.18 mm)	1.8478	26.18	37.06	66.5	2.368	20.14	36.412	65.796
AK 440A, (3.68 mm)	0.7331	45.313	29.345	58.73	0.8727	34.81	26.783	56.166

3.2. Pressure Vessel for Limited Volume of Compressed Oxygen

The amount of air supplied at sea level is 68 times higher than the reacted amount required to produce the maximum power output. The excess air/oxygen is a design feature of the Horizon Stack that enables the maintenance of a low stack temperature and the purging of the stack [14]. Pukrushpan et al. [26,27] proposed that an instantaneous limit on the oxygen excess ratio, which represents the ratio of supplied to reacted oxygen equal to ($\mu_{O_2} = 2$), is the optimum rate needed to maintain the desired value of net power for the fuel cell stack. However, in order to manage the temperature of the stack and purging process, any viable techniques, such as a high-speed air pump or water flow heat exchanger, can be used to maintain the temperature of the stack within the desired operational conditions. In this research, a fuel cell stack is assumed to be supplied by pure oxygen with enough flow rate to observe a full reaction. It has been determined that 0.3 m³/hour of oxygen needs to be fully reacted in order to produce the maximum power at 20 A. In order to ensure that the cathodes of the stack are fully occupied with pure oxygen over the whole operational time of the stack, the flow rate of supplied oxygen is assumed to be equal to 0.6 m³/hour; hence, the utilisation factor is ($\mu_{O_2} = 2$). Therefore, for the operation of the stack consisting of 72 cells for one hour, at the maximum power output at 20 A, the necessary proposed flow rate of supplied oxygen is assumed to be equal to 0.6 m³/hour under 1 atm ambient pressure. Using Equation (15) above to determine the volume of oxygen under compression, assuming $P_1 = 1 \text{ atm} = 1.01317 \text{ bar} = 14.504 \text{ psi}$, $V_1 = 0.6 \text{ m}^3$, and that oxygen is going to be pressurised up to 230 bar (3335.92 psi), the new volume of oxygen V_2 is equal to 2609 cm³.

Equations (3), (5), (6), (9)–(12) and (15) can be used to determine the dimensions and masses of an oxygen cylindrical pressure vessel with two hemispherical ends when using AK 2205 Duplex stainless steel with a 2.29 mm metal thickness, several hours of operation, a maximum power output of 877 W at a current of 20 A, and a limited volume of compressed oxygen up to 230 bar at an ambient temperature of 15 °C, as presented Table 2.

Table 2. Dimensions and masses of oxygen cylindrical pressure vessel with two hemispherical ends, using AK 2205 Duplex stainless steel with a 2.29 mm metal thickness, several hours of operation, a maximum power of 877 W at a current of 20 A, and, and a limited volume of compressed oxygen up to 230 bar at 15 °C.

Hours of Operations	Before Compression at Atmospheric Pressure		After Compression up to 230 Bar	Dimensions and Masses of Pressure Vessel			
	Volume (m ³)	Mass (kg)		Height (m)	Diameter (cm)	Mass of Empty Vessel (kg)	Mass of Filled Vessel (kg)
1	0.60	0.8574	2609	0.357	10.68	2.09	2.95
2	1.20	1.715	5217	0.677	10.68	3.98	5.7
3	1.80	2.5722	7826	0.997	10.68	5.86	8.44
4	2.40	3.43	10,435	1.316	10.68	7.74	11.17
5	3.0	4.287	13,043	1.634	10.68	9.62	13.91

3.3. Pressure Vessel for Compressed Hydrogen

At sea level, based on the developed model of a PEM fuel cell stack in [14,17], for one hour of stack operation at a maximum power of 877 W at a current of 20 A, the required supply of hydrogen is 0.637 m³/hour, with a hydrogen supply pressure of 0.55 bar. Using Equation (15) above to determine the volume of hydrogen under compression, assuming $P_1 = 0.55 \text{ bar} = 7.98 \text{ psi}$, and $V_1 = 0.637 \text{ m}^3$, and assuming that hydrogen is going to be pressurised up to 175 bar (2538.2 psi), the new volume of hydrogen V_2 is equal to 2002 cm³.

BOC Industrial Gases UK [28] provides different sizes of cylindrical hydrogen vessels with a maximum filling pressure up to 175 bar at an ambient temperature of 15 °C. Using AK 2205 Duplex stainless steel with a 2.29 mm metal thickness, Equations (3), (5), (6), (9)–(12) and (15) can be used to determine the dimensions and masses of the hydrogen cylindrical pressure vessel with two hemispherical ends, for several hours of operation, at a maximum power of 877 W at a current of 20 A, and for a limited volume of compressed hydrogen up to 175 bar at an ambient temperature of 15 °C; these are presented in Table 3.

Table 3. Dimensions and masses of hydrogen cylindrical pressure vessel with two hemispherical ends, using AK 2205 Duplex stainless steel with a 2.29 mm metal thickness, several hours of operation, a maximum power of 877 W at a current of 20 A, and a limited volume of compressed hydrogen up to 175 bar at 15 °C.

Hours of Operations	Before Compression at Pressure of 0.55 bar		After Compression up to 175 Bar	Dimensions and Masses of Pressure Vessel			
	Volume (m ³)	Mass (kg)		Height (m)	Diameter (cm)	Mass of Empty Vessel (kg)	Mass of Filled Vessel (kg)
1	0.637	0.05725	2002	0.1892	13.98	1.45	1.5073
2	1.274	0.1145	4004	0.3287	13.98	2.53	2.6445
3	1.911	0.1718	6006	0.4682	13.98	3.6105	3.7823
4	2.548	0.2291	8008	0.6078	13.98	4.692	4.9211
5	3.185	0.2864	10,010.0	0.7473	13.98	5.773	6.0593

It is clear from the results obtained for the pressure vessel design presented above, that it is not possible to use high flow rates of oxygen (20.5624 m³/hour), as presented in the first scenario to supply the fuel cell stack, particularly for high-altitude UAS applications; this is because it requires a vessel with a great size and heavy mass to carry the compressed air or oxygen. Alternatively, using limited volumes and flow rates of hydrogen (0.637 m³/hour) and oxygen (0.6 m³/hour) in order to supply the fuel cell stack, as presented in the second scenario, can offer an optimum pressure vessel design in terms of lowering the size and weight of the vessel, hence saving more power and extending the endurance of the mission, and allowing further payload to be added for the same mission duration.

Figures 2 and 3 present the accumulative volumetric flow rates (m^3/hour) of the supply of hydrogen and oxygen for five hours of continuous operation based on the developed model of a PEM fuel cell stack, using limited volumes and flow rates of hydrogen ($0.637 \text{ m}^3/\text{hour}$) and oxygen of ($0.6 \text{ m}^3/\text{hour}$) under various current load demands and up to five hours of operation.

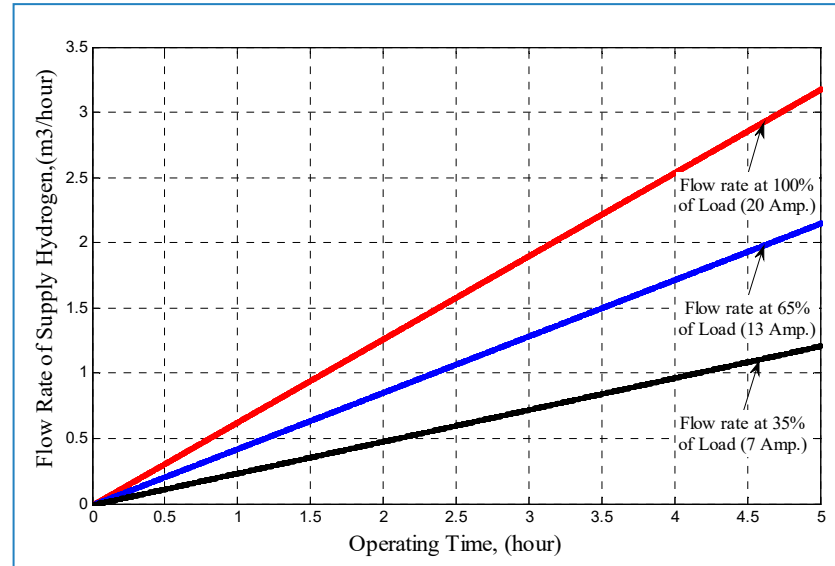


Figure 2. Volumetric flow rates of hydrogen supply based on the developed model of a PEM fuel cell stack, using a limited flow rate of hydrogen ($0.637 \text{ m}^3/\text{hour}$) under various current load demands and up to five hours of operation.

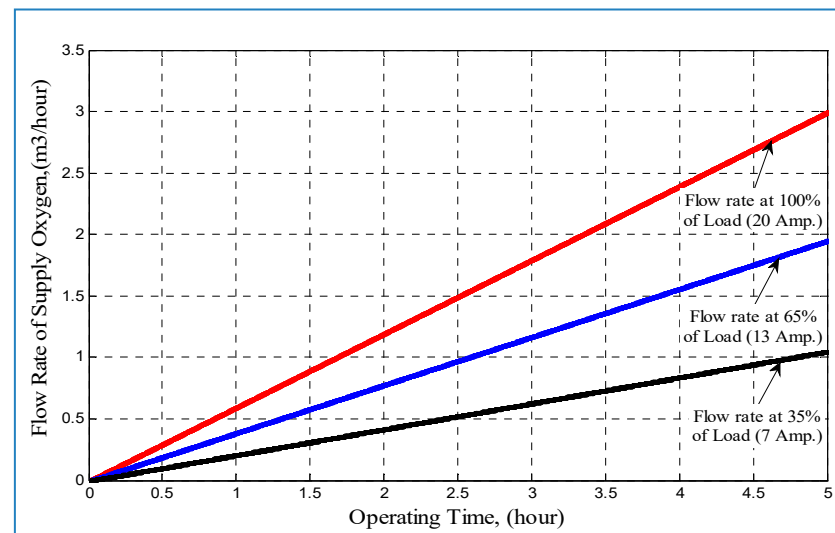


Figure 3. Volumetric flow rates of oxygen supply based on the developed model of a PEM fuel cell stack, using a limited flow rate of oxygen ($0.6 \text{ m}^3/\text{hour}$) under various current load demands and up to five hours of operation.

4. Power Plant Mass Estimation for a PEM Fuel-Cell-Based UAS

A power supply system of a UAS can be divided into a fuel cell power plant and a fuel cell subsystem. A fuel cell power plant consists of the fuel cell stack, and air and hydrogen supply, regulation systems, and a cooling system. A fuel cell subsystem consists of an electrical distribution bus and power management system. The power supply system provides power to the propulsion system through the DC bus. The propulsion system

consists of an electric motor, motor speed controller, and the propeller [9,29]. The power generated from the PEM fuel cell power system is determined according to the size of the fuel cell stack, while the energy capacity is determined according to the storage capacity of the hydrogen and oxygen vessels [4]. However, if the size of the hydrogen tank is fixed, the endurance of the aircraft is limited by the efficiency of the propulsion system and the power plant system [9].

In UAS missions, the highest power consumption occurs during take-off and climb to the designated cruise altitude, while the lowest power consumption occurs during descent. The largest time and energy consumptions are during the cruise stage at constant altitude, where the weight of the aircraft is equal to the lift, and the thrust is equal to the drag [30,31].

Kim et al. [31] reported that during take-off and flight manoeuvrings, power will be supplied from both the fuel cell and batteries, while the fuel cell stack will supply steady power during the cruise mode.

Seo et al. [32] reported a cruising speed of 59.8 km/hour for a small UAS (<7.5 kg) that used a 200 W PEM fuel cell stack to achieve a flying mission that achieved an altitude up to 200 m during the 57-min continuous flying test. Meanwhile, Furrutter and Meyer [8] reported that at a steady and stable flying altitude, the maximum flight velocity was 46.8 km/hour for a small-scale fixed wing UAS using a 100 W Horizon PEM fuel cell power plant system, and that the total mass of the UAS was 5.3 kg.

Adam and Leachman [3] reported that a flow rate of 0.825 m³/hour of hydrogen is sufficient to produce a 979 W power output from the Horizon (H-1000) fuel cell stack during the take-off and climb phase for a small UAS (<25 kg), while a flow rate of 0.4165 m³/hour of hydrogen is sufficient to produce a power of 498 W for the cruise phase. In this research, it is assumed that the UAS will need one hour to climb to the cruising altitude of 36,000 ft. (i.e., climbing speed is ~3 m/s), with a maximum power of 877 W at a current of 20 A (100% load current) drawn from the power supply system represented by the fuel cell stack. During the cruising mode, the current drawn from the fuel cell stack will be assumed to be equal to 13 A (i.e., 65% of max. load). Also, the UAS is assumed to spend 45 min descending and landing from the cruising altitude, with the current drawn from the fuel cell stack being 7 A (i.e., 35% of max. load). Based on the developed model of the PEM fuel cell stack in [14,17] and the calculations made for the pressure vessel design, the volumes of oxygen and hydrogen supplied according to the load demand and flying mode are presented in Table 4. Meanwhile, the volumes and masses of the oxygen and hydrogen supplied to the fuel cell stack for the flying hours of 2.25 to 7.75 h are presented in Table 5.

Table 4. Volumes of oxygen and hydrogen supplied to the fuel cell stack according to the load demand and flying mode, based on the developed model of a PEM fuel cell stack and the pressure vessel design.

Flying Mode	Operating Time (Minutes)	Fuel Cell Stack Current (A)	Current Load %	Fuel Cell Stack Output Power (W)	Volume of Supply Oxygen (m ³)	Volume of Supply Hydrogen (m ³)
Climb	60	20.0	100	877.0	0.60	0.637
Cruise	60	13.0	65	609.0	0.391	0.4316
Descent	45	7.0	35	352.0	0.158	0.1825
Total Volumes of Supplied Gases					1.149	1.2511

Table 5. Volumes and masses of the oxygen and hydrogen supplied to the fuel cell stack according to the total flying hours, based on the developed model of a PEM fuel cell stack and the calculations of the pressure vessel design.

Total Flying Time (Minute)	Total Flying Time (Hour)	Cruising Time (Hour)	Volume of Supply Oxygen (m ³)	Mass of Supply Oxygen (kg)	Volume of Supply Hydrogen (m ³)	Mass of Supply Hydrogen (kg)
135	2.25	0.5	0.9535	1.3626	1.0353	0.0931
165	2.75	1	1.149	1.6419	1.2511	0.1125
195	3.25	1.5	1.3445	1.9213	1.4669	0.1319
225	3.75	2	1.54	2.2007	1.6827	0.1513
255	4.25	2.5	1.7355	2.48	1.8985	0.1707
285	4.75	3	1.931	2.7594	2.1143	0.1901
315	5.25	3.5	2.1265	3.0388	2.3301	0.2095
345	5.75	4	2.322	3.3181	2.5459	0.2289
375	6.25	4.5	2.5175	3.5975	2.7617	0.2483
405	6.75	5	2.713	3.8769	2.9775	0.2677
435	7.25	5.5	2.9085	4.1562	3.1933	0.2871
465	7.75	6	3.104	4.4356	3.4091	0.3065

Using the data given in Table 5, it is possible to determine the desired flying hours of the mission of the UAS, and using the results obtained from Tables 2 and 3, the total mass and sizes of the oxygen and hydrogen pressure vessels can be determined for a cylindrical pressure vessel with two hemispherical ends that uses AK 2205 Duplex stainless steel with a 2.29 mm metal thickness, a limited volume of compressed oxygen up to 230 bar, and a limited volume of compressed hydrogen up to 175 bar, at 15 °C. Table 6 and Figure 4 present the design specifications for the oxygen and hydrogen pressure vessels according to the desired flying hours, based on the model of the PEM fuel cell stack developed in [14,17] and the evaluation of the pressure vessel design. Meanwhile, the masses of the items and components used in the design of the power plant system and the propulsion system, which are associated with the estimated mass of the UAS frame structure and the carried payload for UAS applications, are presented in Table 7 [16].

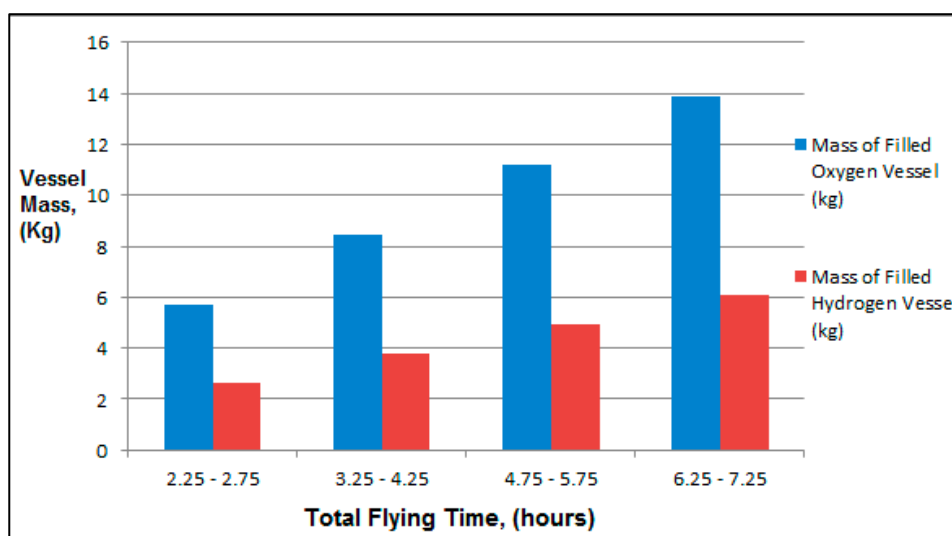


Figure 4. Total masses of the oxygen and hydrogen pressure vessels vs. flying hours, based on the developed model of the PEM fuel cell stack and the Simulink tools used for pressure vessel design.

Table 6. Design specifications for the oxygen and hydrogen pressure vessels according to the desired flying hours, based on the developed model of a PEM fuel cell stack and the calculation of the pressure vessel design for a cylindrical pressure vessel with two hemispherical ends, using AK 2205 Duplex Stainless Steel with a 2.29 mm metal thickness, a limited volume of compressed oxygen up to 230 bar, and a limited volume of compressed hydrogen up to 175 bar, at 15 °C.

Total Flying Time (Minute)	Total Flying Time (Hour)	Cruising Time (Hour)	Oxygen Pressure Vessel Design with Diameter (10.68 cm)		Hydrogen Pressure Vessel Design with Diameter (13.98 cm)		Levels of H ₂ /O ₂	Total Mass of Filled H ₂ /O ₂ Vessels (kg)
			Height (m)	Mass of Filled Vessel (kg)	Height (m)	Mass of Filled Vessel (kg)		
135 165	2.25 2.75	0.5 1	0.677	5.7	0.3287	2.65	EFTA FOL	8.35
195 225 255	3.25 3.75 4.25	1.5 2 2.5	0.997	8.44	0.4682	3.7823	EFTA EFTA FOL	12.23
285 315 345	4.75 5.25 5.75	3 3.5 4	1.316	11.17	0.6078	4.9211	EFTA EFTA FOL	16.1
375 405 435	6.25 6.75 7.25	4.5 5 5.5	1.634	13.91	0.7473	6.0593	EFTA EFTA FOL	20.0

EFTA: Extra Flying Time Available. FOL: Fuel on Limit (for both hydrogen and oxygen).

Table 7. Masses of the items and components used in the design of the power plant system and propulsion system with the estimated mass of the UAS frame structure and the carried payload for UAS applications [16].

Item Description	Mass (kg)
Horizon (H-1000) PEM Stack with Controller	4.5
BLDC motor KMS Quantum 4130/07	0.4
Propeller (15" × 8")	0.3
DC-DC Converter (Mean Well SD-1000L-24)	1.5
Estimated mass of batteries, electronics and connections	0.5
Estimated mass of high-speed air pump	0.5
Estimated mass of UAS frame structure	10
Estimated mass of payload	1.5
Total	19.2

For a four-hour cruising mission (345 min total flying time), as given in Table 6, and from the total calculated mass in Table 7, the total mass of the whole UAS is estimated to be equal to $(16.1 + 19.2 = 35.3 \text{ kg})$. It has been reported by M Saleh [16] that the maximum permitted mass of UAS is 32.55 kg for a 0.2 static thrust to weight ratio, especially for the developed model of a PEM fuel cell at (11 km) high-altitude operation. The estimated sizes and weights of the hydrogen and oxygen vessels of the power plant and propulsion system in this research can offer a maximum of four hours of flying time for the UAS mission; this is based on a Horizon (H-1000) PEM stack. A generic weight estimation mechanism could easily be inferred from this work. Furthermore, reducing the mass of the frame structure and the payload, and choosing light equipment to be carried on board, would reduce the

total mass of the UAS; in addition, a reduction in aerodynamic drag would extend the flying mission, as the power requirement would be reduced. The design of the power plant system and UAS frame structure may vary according to the type of mission in terms of the cruising altitude, required flying hours, and the size and weight of the payload. Therefore, the designer must consider all these parameters during the design of the entire UAS.

5. Conclusions

In this research, a pressure vessel design that can estimate and determine the total size and weight of a fuel cell stack power plant combined with hydrogen and air/oxygen vessels and the propulsion system of a UAS for high-altitude operation was proposed. The design of hydrogen and oxygen pressure vessels was investigated in order to determine the weight and size of the vessel based on the mass flow rates of gases and the power demand per operational hour for high-altitude UAS operation. Two scenarios were adopted to determine the size and weight of the pressure vessels required to supply oxygen to the fuel cell stack. Different types of stainless-steel materials were used in the design of the pressure vessel in order to find an appropriate material that provides the advantages of a low size and weight. Hydrogen pressure vessel design and mass estimation were also considered.

It is clear from the results obtained for the pressure vessel design presented above that it is not possible to use a high flow rate of oxygen ($20.5624 \text{ m}^3/\text{hour}$), as presented in the first scenario, to supply the fuel cell stack, particularly for UAS applications, as this requires a vessel with a large size and heavy mass to carry the compressed oxygen. Alternatively, using limited volumes and flow rates of oxygen ($0.6 \text{ m}^3/\text{hour}$) and hydrogen ($0.637 \text{ m}^3/\text{hour}$), as presented in the second scenario, can offer the optimum pressure vessel design in terms of lowering the size and weight of the vessel; this would reduce power consumption, extend the endurance of the mission, and allow further payload to be added for the same mission duration. The estimated sizes and weights of the hydrogen and oxygen vessels in the power plant and propulsion system in this research offer a maximum of four hours of flying time for the UAS mission; this is based on a Horizon (H-1000) PEM stack. A generic weight estimation mechanism could easily be inferred from the work. Furthermore, by reducing the mass of the frame structure and the payload and choosing light equipment to be carried on board, it would be possible to reduce the total mass of the UAS. A reduction in aerodynamic drag would also extend the flying mission, as the power requirement would be reduced. The design of the power plant system and UAS frame structure may vary according to the type of mission, in terms of the cruising altitude, required flying hours, and the size and weight of the payload. Therefore, the designer must consider all these parameters during the design of the entire UAS.

To improve this research further, real-world experiments or simulations could be conducted to validate the theoretical models. This could involve testing prototype pressure vessels under various conditions to confirm the accuracy of the results. Hence, a comparison between the proposed designs and the pressure vessel designs currently used in similar UAS applications could be performed in order to provide a benchmark for performance. Moreover, research could consider the effect of the environmental conditions at high altitudes, such as the extremely low atmospheric temperatures and pressures and potential radiation exposure, on the performance, material durability, and fuel cell efficiency of the power plant system.

Author Contributions: I.M.A. has developed the model and investigated the available models in the literature, developed the methodologies and carried out the results analysis. A.M.A.-B. was involved in revising the paper and introducing technical suggestions, whilst R.A. was involved in providing technical guidance, developing the methodologies and investigating the developed model with I.M.A. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

E	Weld joint efficiency coefficient
F	Faraday constant (C/mol)
H	Height of the cylinder (inch)
H_{shell}	Total height of the shell (inch)
I_{st}	Current drawn from the stack (Ampere, A)
m	Mass (kg)
M	Molar mass of gas (g/mol)
M_{shell}	Mass of the shell (kg)
N	Number of fuel cells
P	Gas pressure (psi, kPa, bar)
P_c	Critical pressure (psi, kPa, bar)
r	Radius of the cylinder (inch)
R_i	Internal radius of the shell (inch)
R_o	Outside radius of the shell (inch)
R	Universal gas constant (kPa.m ³ /kmol.K)
R_s	Specific gas constant (kPa.m ³ /kg.K)
S	Maximum allowable stress of the metal (psi)
S_y	Yield stress of the metal (psi)
t	Thickness of the shell (inch)
T	Absolute temperature (kelvin, K)
V	Volumes of the gas (m ³)
V_{cyl}	Inner volume of the cylinder (m ³)
V_{gas}	Volume of the gas inside the cylindrical shell (m ³)
V_{shell}	Volume of the shell (m ³)
V_{sph}	Volume of two hemispherical ends of the cylinder (m ³)
$W_{H_2, rct}$	Mass flow rate of reacted hydrogen (g/s, m ³ /s)
$W_{O_2, rct}$	Mass flow rate of reacted oxygen (g/s, m ³ /s)
ρ_m	Density of the material (kg/m ³)
σ_L	Longitudinal stress in the direction (psi)
σ_t	Tangential stress (psi)
μ	utilisation factor

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