THERMAL MODEL TO AID THE CONCEPTUAL DESIGN OF HYDROGEN STORAGE VESSELS FOR AVIATION APPLICATIONS

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ABSTRACT

Hydrogen is deemed a viable contender to make the aviation industry more sustainable. However, while its mass-energy density of 120 MJ/kg with a density of 70 kg/m^3 is an improvement with respect to the energy density of 43 MJ/kg of conventional aviation fuels, it's volumetric energy density of only 8 MJ/m^3 is four times larger, which inevitably has a detrimental effect on the aircraft's aerodynamics. Accordingly, the fuel shall be stored under pressure and at low temperatures to achieve the assumed density values. The actual values for the storage pressure and temperature are topics of discussion. This research aims at studying the effects of storing liquid or gas hydrogen on the mission of an aircraft, by investigating the temperature and pressure profile during such a mission. During this study, multiple tank configurations and aircraft missions are investigated. Using a two-phase hydrogen approach an increase in the gravimetric efficiency by a factor of two can be achieved, compared to gas hydrogen. Moreover, trends have been found in the definition of the topology of hydrogen tanks for different aircraft missions. Increasing design freedom by allowing multiple tanks shows that the loss in gravimetric efficiency is limited to 10%.

1 INTRODUCTION

For the aviation industry to meet international sustainability goals, a lot of changes have to be made to reduce the emissions of aircraft. Different solutions are being investigated, ranging from fully electric aircraft to hybrid solutions with alternative fuels. One of the potential candidates as an alternative fuel is hydrogen. Hydrogen can be used in two manners, namely with direct combustion, or in combination with fuel cell technology. Independent of the type of propulsion system, hydrogen is to be stored onboard the aircraft.

The density of the fuel is to be maximised, to limit the aerodynamic penalty associated with the fuel. The increase in density can be achieved in two manners: increasing the pressure or decreasing the temperature. In literature, a lot of focus has been laid on the study of two-phase hydrogen tanks [1–6]. The benefit of this solution is that the fuel can be stored at near atmospheric pressure values, while the temperature is below 33K. Although the low-pressure value is beneficial for the design, the degradation of the material properties is not accounted for when computing the efficiency of the system. A less investigated option in the aviation industry, while commonly studied in the automotive industry, is the possibility to store gas hydrogen. Viable temperatures in this case lay around the 60K mark, while to achieve viable density values, a pressure around 300bar is required. The two solutions undoubtedly show a different behaviour, preventing a straightforward comparison. The pressurised storage is expected to require more mass, although the effect of the extreme low temperature on the durability of the tank material is unknown. Therefore, it is of interest to study the efficiency of gas hydrogen tanks, to investigate the potential of these solutions.

Furthermore, in literature tank configurations are studied, which are limited to a single mission of an aircraft. Therefore it would be of interest to understand what the influence of different tank dimensions is on the volumetric and gravimetric efficiencies, as well as what impact the use of multiple tanks has on the aforementioned efficiencies. This is achieved by analysing three concrete missions: a regional jet, a small to medium range aircraft, and a large passenger aircraft.

This research aims at providing insights in what the effects are of the fuel phase in a hydrogen fuel tank and how the design of the storage system affects the gravimetric and volumetric efficiencies. This is achieved by implementing a thermo-mechanical model that enables to define the thermal and pressure loading of the storage system, during the mission of the aircraft. With a general fuel flow the effect of the fuel phases and tank geometry are studied. Later with concrete missions, the effect of tank configurations are studied, which enables to achieve more freedom during the design of the aircraft, while taking into account the efficiency of the system.

With the results, key insights are provided to aircraft manufacturers regarding the layout of the hydrogen storage system, while the operational envelopes are defined, which can aid during the design of composite structures for hydrogen storage.

2 METHODOLOGY

2.1 Thermomechanical model

The thermo-mechanical model combines different aspects to quantify the volumetric and gravimetric efficiencies of a hydrogen storage vessel. To define the efficiencies, the mass and volume of the system are required. While the volume simply depends on the selected design of the tank, the mass depends upon the maximum operating pressure of the storage vessel. As such, the pressure envelope of the storage system is to be quantified, to determine the mass of the fuel tank. Quantifying the variation in pressure in the vessel is done by means of a dynamic model, which provides the variation in hydrogen properties as a function of the state of the tank, and the energy variation in the system. The energy variation in the system is originating from the heat flowing from the ambient into the storage vessel, and hydrogen being drawn from the tank. The state variations are concatenated with a linear multi-step method, which leads to the definition of the pressure and temperature envelopes of the storage vessel. The envelopes enable the computation of the efficiencies, and aid during the design of the pressure tank. The different building blocks of the model are reported with more detail below.

2.2 Tank Efficiencies

The key objective of the thermo-mechanical analysis is to define an efficient configuration for the hydrogen storage system. For this, gravimetric and volumetric efficiencies are used. The gravimetric efficiency denotes the ratio of the fuel mass with respect to the total weight of the system, as denoted in Equation 1. In the equation, η_{grav} is the gravimetric efficiency, m_{fuel} is the mass of the stored fuel, m_{struc} is the mass of the structure, and m_{ins} is the mass of the insulation.

$$\eta_{grav} = \frac{m_{fuel}}{m_{fuel} + m_{struc} + m_{ins}} \tag{1}$$

The volumetric efficiency, on the other hand, denotes the volume of the stored fuel (V_{fuel}) with respect to the volume of the total system (V_{sys}), as denoted in Equation 2.

$$\eta_{vol} = \frac{V_{fuel}}{V_{sys}} \tag{2}$$

Whereas in gravimetric efficiency the mass of the system is given by the sum of the components, in the definition of the volumetric efficiency the volume of the system is defined in a different manner. When analysing a single tank, the system's volume is simply the volume of the tank, the tank structure, and of the insulation. When multiple tanks are studied, it is assumed that they are organised in a hexagonal pattern, to achieve an efficient packing strategy. With this, the volumetric efficiency is obtained using the relation reported in Equation 3. In the equation, r_{tank} denotes the radius of the tank, l_{body} indicates the length of the cylindrical body, while r_{sys} is the radius of the system, which includes the radius of the tank, to which the thickness of tank itself and the thickness of the insulator are added.

$$\eta_{vol} = \frac{\pi r_{tank}^2 l_{body} + \frac{4}{3}\pi r_{tank}^3}{4 r_{sys}^3 \sqrt{3} + 2 r_{sys}^2 \sqrt{3} l_{tank}} \tag{3}$$

2.3 Dynamic Model

The dynamic model captures the variation in the properties of the stored hydrogen. [2,3,5,6] focus on the evolution of pressure in a hydrogen storage vessel for aviation applications, and use the dynamic model as suggested in [7]. However, in this study, it is chosen to use the model as suggested by [8]. This model provides more freedom in the analysis type, enabling the study of both single-phase tanks and two-phase tanks. Moreover, the model enables one to switch easily between the type of fuel being drained from the tank, as well as quantifying required venting and heat supply.

2.4 Tank Model

For the shape of the pressure vessel, a simple cylindrical tank is assumed, which is closed at the ends with spherical end caps. The load-bearing structure is assumed to be made of fibre-reinforced composites, leading to a type IV pressure vessel. The material properties are based on the Hexcel IM7/8552 material and are reported in Table 1. The material properties taken as given, and it has been decided not to include safety factors in the current study. In a final design, this would naturally need to be included, but in the current study, this does not create additional insights, as this would affect all designs in a similar manner. The fibre filaments are assumed to be wound at an angle of 55° with respect to the axial direction of the storage vessel [9]. Furthermore, in the cylindrical section of the pressure vessel additional hoop layers are added to cope with the hoop stress. With the provided material properties, the maximum operating pressure, and the geometry of the vessel, the mass of the pressure vessel can be determined using composite pressure vessel netting theory.

Variable	Value	Unit
Mass Density	1.58E-06	kg/mm^3
Failure Stress	2560	MPa

Table 1: Material properties of Hexcel IM7/8552.

The tank is assumed to be insulated with rohacell foam insulation, which has a density of $51.1 kg/m^3$. The insulation thickness is assumed to be constant at 40mm, to reduce the number of changing variables between the different studies. In later studies, the thickness of the insulation can be optimised for each tank variation. The thermal conductivity of the foam varies with temperature, where the temperature-dependent data is based on the values reported in [1]. Consequently, to obtain more accurate thermal conductivity values, through the thickness temperatures of the foam are required, which are computed with the method suggested in [3].

2.5 Hydrogen Properties

A key aspect of the model is the variation of the storage properties of the hydrogen during the mission of the aircraft. It is assumed that the fuel is either in the full gas state or in the two-phase state. In the case of the gas state, the properties of the fuel are dependent on a combination of pressure and temperature. In the case of two-phase hydrogen, the properties can be obtained knowing either the pressure or the temperature, as the fuel is assumed to follow the saturation line [10]. When the fuel is in the saturated state, the properties of para-hydrogen are to be taken, whereas, in the case of gas hydrogen, the properties of normal hydrogen are to be used [11]. The properties of hydrogen are obtained from the National Institute of Standards and Technology (NIST) database.

2.6 Thermodynamic Model

In [1–3, 10, 12] different thermodynamic models are presented to quantify the heat flux into the fuel tank. The thermodynamic model combines all the assumed heat transfer modes and couples these, so to determine the total heat flux into the system. Therefore all the heat transfer modes are to be determined, to quantify the required heat flux. On the inside of the tank natural convection of the hydrogen occurs, which may be split into two sections in the case of a two-phase tank. On the outside of the storage vessel convection of the ambient air occurs, along with radiation. Finally, through the wall of the tank and its insulation conduction occurs. The thermodynamic models defined in literature differ in the assumptions made regarding the type of convection occurring within, or on the outside of the tank. The biggest distinction is found in the type of convection on the outside of the tank, where in [10,12] it is assumed

Sample Number	ATR72-600 (REG)	A320neo (SMR)	A330-300 (LPA)	Units
Passengers	72	150	295	-
Cruise Mach Number	0.44	0.78	0.82	-
Cruise Altitude	5200	11278	11887	m
Harmonic Range	926	4560	7674	km
Loiter Time	30	30	30	min
Diversion Time	160	370	370	km
Fuselage Length	27.2	37.57	62.67	m
Fuselage Radius	2.87	4.14	5.64	m

Table 2: Mission and geometric properties of the reference aircraft [6].

that natural convection occurs, whereas in [2,3] a forced type of convection is defined, due to the airflow on the outside skin of the aircraft. The type of convection naturally depends on the manner of integration of the tank with the outer skin of the aircraft. In the current study, it is assumed that a forced type of convection occurs on the outer skin of the tank, leading to the outer model being that as suggested in [2,3]. For the inner convection, it is chosen to use the method as suggested in [2].

2.7 Aircraft Mission

The fuel flow is one of the key variables which lead to a variation in pressure in the storage vessel. In the different analysis types, various fuel flows are used. When analysing the dimensions of the fuel tank, and the phases of the fuel, a constant fuel flow is assumed to drain the tank, to simplify the analysis. The magnitude is based on the work of [3], which leads to a fuel mass flow of 0.08kg/s. This value is a representative value for the cruise phase of a regional aircraft.

In the multi-tank analysis, concrete missions are used, yielding more tangible case studies. The missions are based on [6], where a regional (REG), a small-medium range (SMR), and a large passenger aircraft (LPA) are studied. In Table 2 an overview of the properties of the aircraft and its mission parameters are reported, while in Table 3 an overview of the fuel flows for each mission section is reported.

Fuel Flow [kg/s]	ATR72-600 (REG)	A320neo (SMR)	A330-300 (LPA)
Take-off	0.113	0.998	3.518
Climb	0.097	0.415	1.465
Cruise	0.051	0.208	0.654
Descent	0.004	0.051	0.168
Alternate climb	0.110	0.599	2.112
Alternate cruise	0.072	0.379	1.266
Alternate descent	0.004	0.036	0.127
Loiter	0.029	0.186	0.586

Table 3: Fuel flows for the different mission sections of the reference aircraft [6].

2.8 Multistep Method

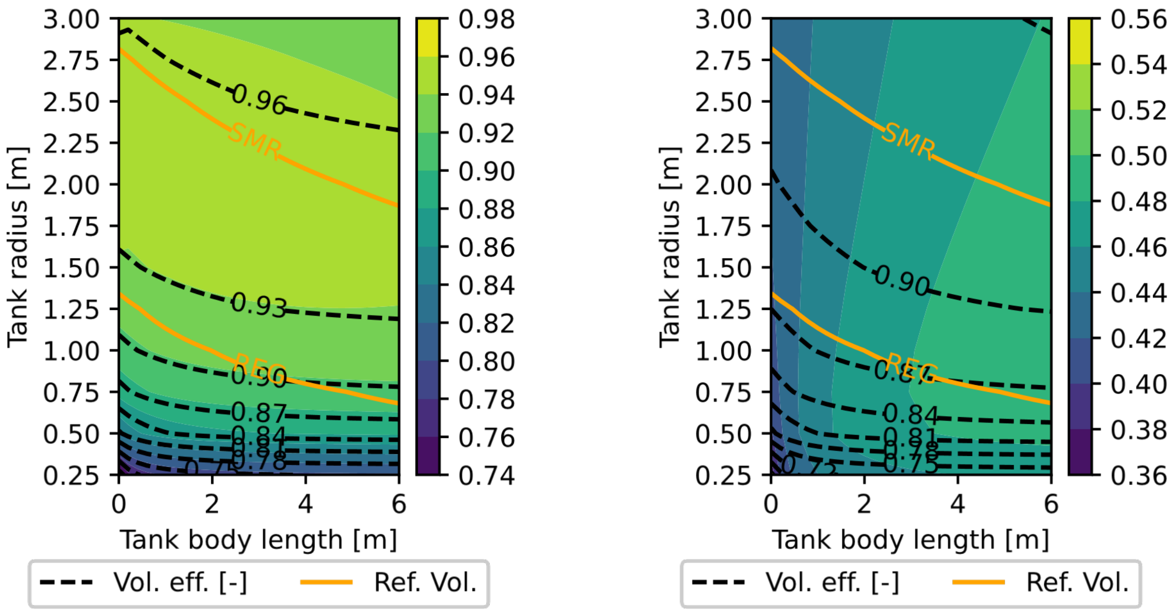
A time integration method is required, to link the different states in the fuel tank. As suggested in [8], the four-step Adam-Bashforth method is used. A timestep convergence study has been performed and it was found that a timestep of one minute was satisfactory.

3 RESULTS

Using the thermo-mechanical model different analyses have been performed. First general studies are performed on how the geometry of the fuel tank and the phase of the stored fuel influence both the gravimetric and volumetric efficiencies. Afterwards, concrete case studies are performed to understand how different missions and configurations perform for different types of aircraft.

3.1 Fuel Phase Analysis

First, it is studied how the geometry of the tank influences the gravimetric and volumetric efficiencies for a two-phase tank, where liquid hydrogen is drained for the propulsion system. The result of this is reported in Figure 1a. In the figure, it can clearly be seen that the geometry of the tank affects the efficiencies. This is expected for the gravimetric efficiency as the ratio between the surface area and volume of the tank dictates the amount of heat flux flowing into the system and the fuel mass it affects, which in turn influences the pressure rise in the tank. As such optimum radii can be found for each fuel tank length, where a desired balance can be found between the volume and surface area of the tank. Moreover, as the length of the body of the fuel tank increases, the range of radii yielding maximum gravimetric efficiency narrows. This means that when two-phase hydrogen is stored, and liquid hydrogen is drained, shorter tanks are desired, with larger radii.



(a) (b)

Figure 1: Gravimetric and volumetric efficiencies as a function of tank dimensions for: (a) two-phase hydrogen tank with liquid hydrogen draining, (b) gas hydrogen tank.

The volumetric efficiency follows a similar trend as the volume of the tank itself, which can be seen when comparing the black dashed line with the orange continuous line in Figure 1a. In general, the volumetric efficiency increases with increasing radius, where the amount of gain diminishes as the radius increases. Moreover, it is interesting to note that above a certain tank length, the volumetric efficiency is independent of tank length. This means that for a certain tank radius, there is a lot of design freedom for the dimensioning of the fuel tank. This can be beneficial for the creation of different size variations of similar aircraft, as the fuel tank can be sized by changing its length while keeping the tank radius constant.

In Figure 1a the energy requirement for a regional (REG) and small to medium-range (SMR) aircraft are also reported with the orange continuous line, as a reference for the required energy.

In a similar study, the initial pressure, which is linked to the temperature, has been found to influence gravimetric efficiency, as this changes the operational envelope of the pressure vessel. In fact, higher initial pressures lead to higher final pressures, yielding higher tank masses, while the gain in fuel mass is limited. As such low initial pressures are desired when storing a two-phase fuel. Therefore, for the studies of a two-phase tank an initial pressure of 150kPa is used.

While in literature the sole focus lies on two-phase hydrogen tanks, the authors deem that the effect the cold hydrogen has on the structure of the tank is underestimated. As such it is of interest to study the efficiencies of a gas hydrogen storage vessel, which operates at relatively higher temperatures. The results of this study are reported in Figure 1b. As expected, the gravimetric efficiency of the solution is much lower than those of the two-phase solution. When looking at Equation 1 it becomes clear what the origin of this difference is, namely the lower fuel mass and the increase in vessel mass. The decrease in fuel mass originates from the lower density of the gas fuel with respect to the liquid phase in the two-phase solution. Moreover, to achieve decent density values, the pressure in the tank is to be increased, leading to a higher tank mass.

Next to the geometric study, the effect of the initial storage properties has also been studied, where it was found that low initial pressure and temperature are desired to achieve high gravimetric efficiencies. The low temperature is desired to achieve higher fuel mass values, while the low-pressure values are desired to limit the mass of the fuel tank. In the above-mentioned study, the initial pressure and temperature are set to 30MPa and 70K, respectively.

Based on the aforementioned result it is studied how a two-phase tank behaves when gas hydrogen is drained from the tank to supply the propulsion system. Similar behaviour is obtained as found with the gas tank, where the pressure and temperature of the fuel drop as the fuel is drained from the tank. This is because as gas hydrogen is drained from the tank, liquid hydrogen needs to evaporate to restore the saturation equilibrium in the tank, which draws heat from the system, leading to its cooling. Therefore, also in this case the sole purpose of the insulation is to limit ice formation on the outer wall of the tank, as heat needs to be supplied to the system to limit the pressure drop in the storage vessel, to sustain a minimum feed pressure. Furthermore, also in this case the initial storage pressure drives the design of the pressure vessel, leading to the horizontal trend in Figure 2.

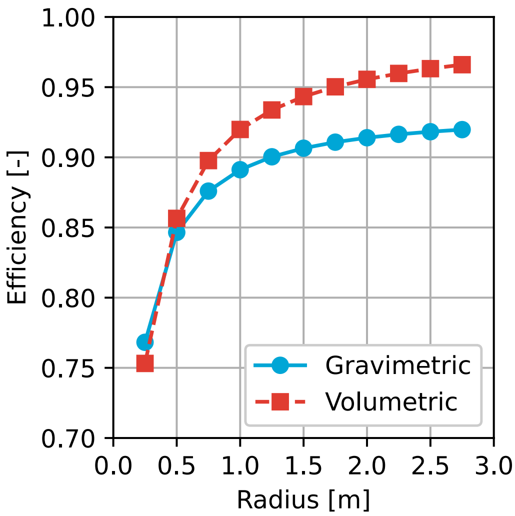


Figure 2: Volumetric and gravimetric efficiencies for a two-phase tank, switching between liquid and gas draining for the propulsion system.

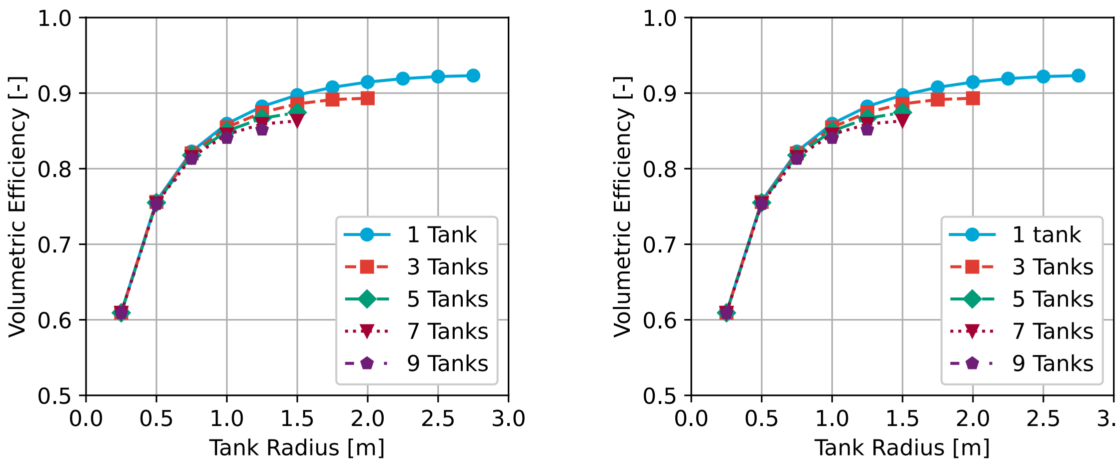
Thus, in a two-phase tank, when draining the liquid phase for the propulsion system the pressure increases in the tank, while when draining the gas part, the pressure decreases. By combining the two methods the pressure in the storage vessel can be regulated. With this, no additional heat is required, leading to a less energy-intensive solution, while the upper pressure of the storage vessel can be limited by draining gas hydrogen with intervals. As such this solution is coined the switch draining analysis, the results of which are reported in Figure 2. In the figure, it can be seen that as the radius of the fuel tank increases, the gravimetric efficiency shows a horizontal asymptotic behaviour, where previously the gravimetric efficiency would have peaked at a certain value and afterwards decreased again.

It must naturally be taken into account that the system would require a double feed system and that the propulsion system should be able to function with both hydrogen phases, thus a more system bases study is required to analyse the overall efficiency of the system. Nevertheless, the solution could provide a means to increase the efficiency of the fuel storage system, while gaining more design freedom for the size of the storage vessel.

3.1 Aircraft Mission Analysis

In the previous analysis, the effect of fuel phases and geometry have been studied with a general fuel flow. This section aims at studying concrete missions using reference data of regional, small to mediumrange, and large passenger aircraft, based on [6]. The study aims at understanding how the geometry of the tank and the use of multiple tanks influence gravimetric and volumetric efficiencies. The use of multiple tanks can be beneficial as this enables to stow the tanks in different locations, yielding more freedom during the design phase of the aircraft, which can be beneficial for aspects such as the centre of gravity and aerodynamic performance, which have been proven to be a challenge when designing hydrogen aircraft [4,6].

In Figure 3a it can be seen how the gravimetric efficiency varies for an SMR aircraft when the radius of the tank and the number of tanks is altered. It should be noted that by altering the radius and number of tanks, the length of the tank is also changed, as the total required energy for the mission of the aircraft is kept constant. Because of this, the radius of multiple tanks can be limited, as the total volume of the fuel system is to be constant.



(a) (b)

Figure 3: Fuel tank efficiencies for a small-medium range aircraft with changing number of tanks: (a) gravimetric and (b) volumetric.

From the figure, it can be seen that when small radii are used, the gravimetric efficiencies are similar for the different solutions which use an alternate number of tanks. Moreover, the reduction in gravimetric efficiency from the optimal radius with a single tank, to the optima of the tanks with multiple tanks is less than 10%. This means that more design freedom can be achieved, at a relatively low cost in efficiency. For example, when accounting for the fuselage radius of 4.4m, multiple tanks can be used with a limited loss in efficiency.

The use of multiple tanks is done to increase the packing freedom of the fuel tanks, such that these can be stowed in different locations. Using multiple tanks can lead to additional volume, as described in subsection 2.2. Therefore, in this study volumetric efficiency is crucial and is thus reported in Figure 3a. The figure shows that the efficiency does indeed decrease when using a multiple tanks with large radii, but the loss is marginal. When using multiple tanks with small radii, the efficiencies are almost indistinguishable.

When the range of the aircraft is increased, thus going from a small-to medium range aircraft to a large passenger aircraft, the right tails of the trend lines rises, thus bringing the efficiencies closer, as represented in Figure 4. This is as expected, as the size of the pressure vessels increases, thus these are less susceptible to the pressure rise, thus reducing the mass of the structure. When analysing large passenger aircraft this effect is more pronounced. A similar trend is observed for the volumetric efficiencies.

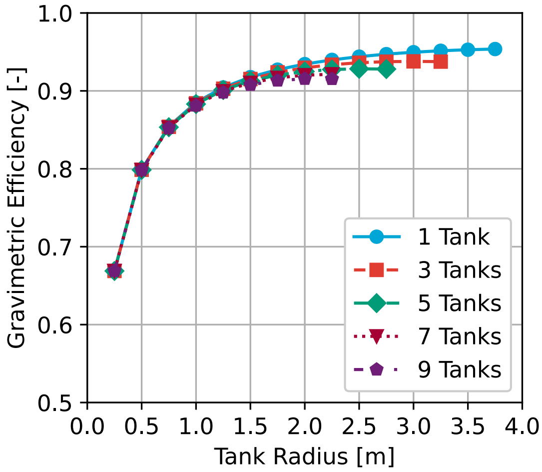


Figure 4: Gravimetric efficiencies for a multi-tank analysis for a large passenger aircraft.

4 CONCLUSIONS

In this paper, a thermodynamic model is implemented to quantify the thermomechanical loading of a composite hydrogen storage vessel. As the pressure vessels are to be used for aviation applications, the gravimetric and volumetric efficiencies are determined to analyse the tank's performance. The efficiencies have been determined by defining the operational window of the storage vessel, which enables quantifying the maximum operating pressure of the vessel, and thus estimating the weight and volume of the fuel storage system.

Hydrogen can be stored in multiple states. Using the aforementioned model it has been found that when storing two-phase hydrogen, the gravimetric efficiency doubles compared to gas hydrogen. This is because the densities of the fuel that can be achieved with gas hydrogen are lower than the densities obtained with saturated hydrogen, leading to lower amounts of fuel, and the system mass is larger due to the large difference in operational pressure, as expected from literature. It must be stated that the degradation in material properties are not accounted for in the saturated solution, which would be a valuable addition in future work.

The phase of the fuel being drained from the system for the propulsion system has a large influence on the pressure development during the mission of the aircraft. When draining liquid hydrogen from a two-phase tank, with fuel flows corresponding to cruise values of an aircraft, the pressure in the vessel increases. The pressure increase is dependent on the amount of heat entering the system, which can be limited with the use of insulation, and due to the gas hydrogen needing to condensate, for the tank to remain in equilibrium. Oppositely, when draining gas hydrogen, liquid hydrogen needs to evaporate for the equilibrium to be maintained, leading to decreasing temperature and pressure. Subsequently, heat needs to be supplied to the storage system to limit the temperature drop, and provide a minimum supply pressure for the gas hydrogen which may be required by the propulsion system.

Based on the aforementioned, when draining liquid hydrogen short tanks are desired with a large tank radius, as this is beneficial for the surface-to-volume ratio. When draining gas hydrogen, long tanks with smaller radii are desired when considering gravimetric efficiency. On the other hand, when considering volumetric efficiency, in both cases large radii are desired, but with increasing radius, the achieved gain stagnates. Furthermore, above a certain tank radius, the volumetric efficiency is insensitive to variations in tank length

The use of a single tank is found to be the optimal solution considering both the volumetric and gravimetric efficiencies. However, when using tanks with a small radius, the system's efficiency is insensitive to the number of tanks. Moreover, the larger the total energy requirement of the aircraft, the less sensitive the system becomes to the number of tanks.

Based on the findings in the current paper, it is confirmed that the use of liquid hydrogen leads to the most efficient solution, provided that the material of the pressure vessel can cope with the cryogenic environment. Furthermore, draining hydrogen gas leads to the biggest design freedom for the tank, due to the insensitivity of the efficiencies. However, as this is an energy-heavy solution, one could also opt to combine the liquid and gas draining, to regulate the pressure and temperature envelope of the storage vessel. This has been found to yield a lot of design freedom in the size of the tank while being a solution with low energy demand. To evaluate this solution further, a system study is to be performed.

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