DESIGN & THERMAL PROPERTIES OF A STORAGE TANK FOR HYDROGEN FUELLED COMMERCIAL AIRCRAFT WITH STRUTTED WINGS

Introduction

In this short report, a comparison is made between existing storage tank design configurations and the most appropriate design is chosen for the strutted wing configuration. Furthermore, the gap in research is identified for the chosen configuration of the storage tank and addressed. In this case, the gap was identified in the form of thermal analysis for the chosen storage tank configuration.

Comparison between existing storage tank designs

The main references were derived from the SPECTRAL series of projects that aims to design a hydrogen fuelled aircraft with an unconventional geometry. The storage tank design for the strutted wing configuration was made after through considerations between the existing storage tank designs. It is important to keep in mind that [1] uses A321LR as a reference aircraft where as [2] and [3] use A318 as a reference aircraft. The comparison with the main storage tank properties is as shown in Appendix A.

After careful consideration, the storage tank design parameters in [2] were chosen to be the most suitable for the strutted wing configuration as it shows a good congruence to our objective of designing a storage tank for a hydrogen fuelled aircraft with a strutted wing. No radical changes to storage tank design are expected by the addition of the strutted wing. However, reinforcement may be needed in certain areas of the fuselage and the performance characteristics will also alter the sizing criteria of the storage tank.

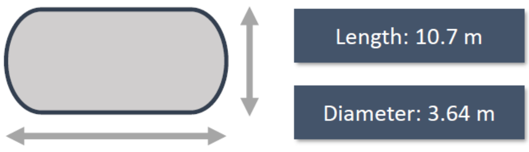

Figure 1 Dimensions of storage tank [2]

Considering that the reference aircraft for the strutted wing configuration is the A318, the basis for comparison remains consistent. An integral tank design with the tank located in the rear of the fuselage and made of Al2219 is chosen. The tank shape is cylindrical with hemispherical ends for optimized volumetric efficiency. The dimensions of the tank are 10.7m x 3.64m x 3.2mm with a volume of 136.59 m^3. The empty tank mass is 2277kg (3720 kg with support structures).

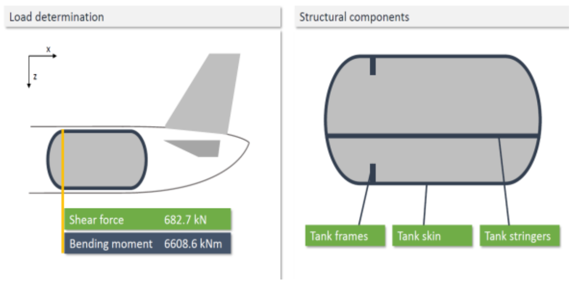

Figure 2 Location and structural support members of storage tank [2]

The weight of insulation is determined to be 756 kg and a multi-layer insulation with closed cell foam, MAAMF, Open cell foam and composite is chosen. The total tank mass is 11760kg with a volumetric efficiency of 0.837 and weight fraction of 0.252. A 36-point truss system was also developed and analysed as a support structure for the tank.

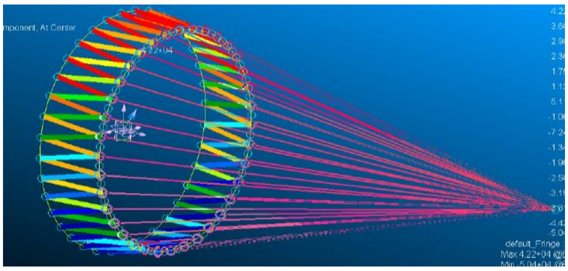

Figure 3 36-point support truss structure of storage tank [2]

However, in this design no thermal analysis was performed on the storage tank design which is a pivotal aspect of hydrogen storage tank design. Therefore, the thermal properties of this storage tank design configuration are unknown. The supporting truss structures analysed using NASTRAN show the effects of bending and shear on the support structure. In the compression loading case, the support structure fails. From the original design of the tank as adopted from [1] there is an overall increase in empty tank mass by 65%.

In the storage tank design offered in [1] and [2], thermal analysis was performed to analyze the thermal properties of the storage tank. Using this and [4] as basis, thermal analysis was performed on the chosen storage tank design as shown in the subsequent section.

Thermal analysis for the chosen storage tank design configuration

Heat transfer is an important aspect of thermal analysis which is broadly divided into external heat transfer and internal heat transfer. External heat transfer is further divided into convective heat transfer between outer atmosphere and integral tank insulation, radiation heat transfer between outer atmosphere to integral tank insulation and conductive heat transfer from insulation to tank inner diameter while internal heat transfer is divided into convective heat transfer between LH_2 and tank inner diameter and convective heat transfer between gaseous H_2 and tank inner diameter.

In this report, none of the formulas used for thermal analysis computations are made as they are readily available in both [2] and [4]. The same equations have also been developed as a python code in order to facilitate ease of access as well as integration of storage tank design eventually into FAST-OAD.

Appendix B provides the results as well as all the constants/ assumptions made while performing the calculations for the external heat transfer while Appendix C provides the results for the conductive heat transfer in the insulation. Appendix D provides the results for the internal heat transfer.

As seen in Appendix B, we observe a large difference in the convective thermal properties of the storage tank design when compared to [1]. This is due to variety of reasons. The reference aircraft in [1] is A321 which has a different wingspan than the A318. The main difference is in the length of the tank. There is a difference of almost 8 m between the length of the two tanks which explains the massive difference in the external heat transfer properties. The radiation heat transfer is a function of the temperature of the fuselage and the temperature outside the aircraft. This is the same and therefore the radiation heat transfer coefficient remains the same. The total external heat transfer is a function of the length of the tank as well as the radius of the fuselage. We observe after performing analytical calculations that the selected design offers more resistance to the transfer of heat than the design in [1] owing to the difference in tank dimensions primarily.

As observed in Appendix C, the difference in the convective heat transfer in insulation is again primarily due to the change in the length of the tank.

The internal heat transfer is primarily a function of the properties of hydrogen and not a function of the storage tank design considerations. A lot of assumptions are made while calculating the internal heat transfer (such as the height of hydrogen in the tank, Boil-off) The internal heat transfer will not change as it is a function of the properties of hydrogen and not the physical tank itself. The internal heat transfer is considered for both the gaseous phase as well as the liquid phase. The results are summarized in Appendix D.

The total thermal resistance is calculated as the sum of the external, insulation and internal heat transfer. The total thermal resistance is calculated to be 0.020624 W/K. There is an increase in total thermal resistance by a factor of 65% owing to the difference in tank dimensions.

Limitations and intended future work

The calculation of the internal heat transfer is heavily reliant on assumptions. Using an integral tank design poses major certification issues which are extremely hard to resolve. The addition of struts to the wing and fuselage should not have a very large consequence to the physical design of the tank as such. Reinforcements may be needed in certain areas of the fuselage.

The immediate task planned is to **begin the integration of the storage tank design into FAST-OAD**. In terms of the storage tank design as such, a composite structural design can be explored.

References:

[1] Oak M, et al. (2021) Internship Report TAS Aero

[2] Biermann, J & Bui, A-Q. (2022). Structural design of a liquid hydrogen tank for a medium range airliner

[3] Oak, M., Fabre, A., Delavenne, M., Van, E.N., Benard, E. and Defoort, S., 2022, February. Spectral project-application of FAST-OAD code to the conceptual design of a hydrogen fuelled commercial aircraft. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1226, No. 1, p. 012027). IOP Publishing.

[4] [1] D. Verstraete. Long range transport aircraft using hydrogen fuel. International Journal of Hydrogen Energy, 2013.

Appendix A: Storage tank design comparison

Parameter	TAS-2021 [1]	SWP 8: 2021 [2]	EASN 2021 [3]
Reference a/c	A321	A318	A318
Tank Shape	Cylindrical with hemispherical ends	Cylindrical with hemispherical ends	Cylindrical with hemispherical ends
Tank type	Integral	Integral	Integral
Number of tanks	2	1	1
Tank Length	18.2 m	10.7 m	9.79 m
Tank Height	3.65 m	3.64 m	3.7 m
Tank Thickness	1.61 mm	3.2 mm	3.3 mm
Tank Volume	219.63 m^3	136.59 m^3	95 m^3
Tank Material	Aluminum (4.4 % Cu) 2014-T6	Al2219	Aluminum (4.4 % Cu) 2014-T6
Parameter	TAS-2021	SWP 8: 2021	EASN 2021
Empty Tank Mass	2243.36 kg	2277 kg (3720 kg with frames, stringer, and support)	1425 kg
Tank Insulation	Multi-Layer insulation with Closed cell foam, MAAMF, Open Cell Foam and Composite	Multi-Layer insulation with Closed cell foam, MAAMF, Open Cell Foam and Composite	Multi-Layer insulation with Closed cell foam, MAAMF, Open Cell Foam and Composite
Insulation Weight	1094.85 kg	756 kg	428 kg
Tank Volumetric Efficiency	-	0.837	-
Tank Weight Fraction	0.598	0.252	0.291
Total Tank Mass (With Fuel)	15583 kg	11760 kg	8421 kg
Support Structure for tank	No Analysis Performed	36-point truss system	No Analysis Performed
Thermal Analysis	Performed	Not Performed	Performed

Appendix B: External heat transfer calculations

Parameter	SWP 8 2021[2]	TAS 2021 [1]	
Reynolds Number	69795850.48	122824690.5	
Prandtl Number	0.563805104	0.563805104	
Nusselt Number	53377.36	83892.2853	
External heat transfer coefficient	56.498 W/m^{2}K	116.90 W/m^{2}K	(-51% in comparison to [1])
Aircraft Surface Temperature	260 K	260 K	
Temperature outside aircraft	222.64 K	222.64 K	
Emittance for white painted aircraft	0.95	0.95	
Stefan-Boltzmann Constant	5.67E-08	5.67E-08	
Equivalent convective coefficient	3.046 W/m^{2}K	3.046 W/m^{2}K	
Total external heat transfer coefficient	59.544 W/m^{2}K	119.95 W/m^{2}K	(-50% in comparison to [1])
Thermal Resistance for the external heat transfer	12.6E-05 K/W	3.62E-05 K/W	(+248% in comparison to [1])

Appendix C: Insulation heat transfer calculations

Parameter	SWP 8 2021[2]	TAS 2021 [1]	
Thermal conductivity of closed cell foam	0.026 W/mK	0.026 W/mK	
Density	35 kg/m^3	35 kg/m^3	
Insulation outer diameter	3.88 m	3.88 m	
Insulation inner diameter	3.65 m	3.65 m	
Maximum insulation thickness	0.1149 m	0.1149 m	
Internal Surface Area	254.90 m^2	254.90 m^2	
Thermal conductivity of open cell foam	0.035 W/mK	0.035 W/mK	
Density	8 kg/m^3	8 kg/m^3	
Thermal resistance of closed cell foam	0.01802 K/W	0.01101 K/W	(+6% % in comparison to [1])
Thermal resistance of open cell foam	0.00222 K/W	0.00115 K/W	(+93% % in comparison to [1])
Total thermal resistance to insulation	0.02024 K/W	0.01216 K/W	(+66% in comparison to [1])

Appendix D: Internal Heat transfer Calculations [1]

Description	Parameter	Value	Unit
Internal convection thermal resistance (Gas + Liquid)			
Volume percentage for boil-off H2 gas		0.03	
volume occupied by gas in tank (3% of total Volume)	VGH2	6.5889	m^3
Height of GH2 starting from LH2 (iterative calculation between calculated & assumed GH2 volume)	h	0.255	m
Radius of tank	R	1.825	m
cross-sectional area of GH2	A	0.321053263	m^2
volume occupied by gas in tank -calculated	VGH2	5.957734451	m^3
	d	1.57	m
Width of GH2 volume	w	1.860886885	m
Wetted area of GH2 (projected approximation)	SwGh2	34.53218	m^2
volume occupied by liquid in tank (97% of total Volume)	VLH2	213.0411	m^3
Wetted area of LH2 (approximation)	SwLh2	178.25565	m^2
Tank internal wall temperature	Tw	50.00000	K
Cryogenic temperature of liquid H2	TLH2	20	K
	β (1/TLH2)	0.05	
Density of LH2	⍰	71	kg/m^3
Heat capacity	Cp	9410	J/kg.K
Gas diffusivity	α	1.54166E-07	m^2/s
viscosity	⍰	0.00001392	Pa-s
Acceleration due to gravity	g	9.81	m/s^2
Thermal conductivity of LH2	KLH2	0.103	W/mK
Height of LH2 from bottom of tank	hliquid	3.395	m
Rayleigh number	Ra	2.68319E+14	
Prandtl number	Pr	90.29214757	
Nusselt number of liquid Hydrogen	Nu liquid; NuLH2	3902.16605	
HT coefficient from LH2 to tank internal surface	hLH2	118.3867756	$W/(m^2.K)$
Nusselt number of gaseous Hydrogen	Nu Gas	17	
Thermal conductivity of GH2	KGH2	0.0167	W/mK
HT coefficient from GH2 to tank internal surface	hGH2	1.113333333	$W/(m^2.K)$
Total thermal resistance in convective HT	**Rint**	0.000258017	K/W