Defence Science Journal, Vol. 72, No. 1, January 2022, pp. 3-9, DOI : 10.14429/dsj.72.17239

Common Bulkhead Tank Design for Cryogenic Stage of an Indian Launch Vehicle

Yogesh Pratap Singh[*], Harjit Singh[@], Prahlad Kumar Sahu[#], and R. Muthukumar[@]

[*]Department of Mechanical Engineering, Indian Institute of Science, Bengaluru - 560 012, India
[@]Liquid Propulsion System Center, Indian Space Research Organisation, Trivandrum - 695 547, India
[#]Department of Mechanical Engineering, National Institute of Technology, Raipur - 492 001, India
[*]E-mail: yogeshsingh@iisc.ac.in

ABSTRACT

Indian Space Research Organisation (ISRO) has been advancing in space technology with its cost-effective techniques. Currently, ISRO, in its cryogenic stages, uses truss type intertank structure, which induces large concentrated loads at the truss interfaces. As a remedial measure, works on closed intertank are being carried out by them, but this configuration will considerably increase the launch vehicle mass compared to truss type. Therefore, after a thorough literature survey, a Common bulkhead (CBH) tank seemed to be the best solution to the aforementioned problem. Detailed research on sandwich-type CBH has been carried out in this paper with the motivation of saving mass and height in launch vehicles. Suitable core and facesheet material were selected. A novel foam-filled honeycomb core is suggested in this work. Several comparisons in various CBH dome designs were carried out to reach for the best possible configuration and composition that can be used. MATLAB®, SolidWorks®, and ANSYS® were used in parallel for all computations dealing with design and analysis. A mass saving of approximately upto 490 kgs and a height reduction of upto 1.755 m was obtained with the final selected configuration with respect to the current GSLV configuration. These savings can add extra payload capacity to ISRO launch vehicles in their future missions.

Keywords: Common bulkhead; Intertank; Inner wetted thermal insulation; Sandwich common bulkhead; Cryogenic

1. INTRODUCTION

In spacecraft hardware development, mass optimisation has always been a prime concern because the cost of delivering hardware into space is enormous. In recent years, ISRO has been in the limelight for its cost-effective missions. With the same objective of mass savings, this paper introduces the concept of a common bulkhead (CBH) tank to Indian launch vehicles in their cryogenic stages. A cryogenic propulsion system provides approximately 80% higher specific impulse than a solid propulsion system[1]. India has made significant progress from tiny Rohini sounding rocket in the 1960s to the current GSLV MkIII with cryogenic stages[1,2].

ISRO uses Liquid Hydrogen (LH2) as fuel and Liquid Oxygen (LOX) as the oxidizer in their cryogenic stages[2]. These are stored in propellant tanks which are arranged in tandem with the intertank structure in the middle. These intertanks can have several construction techniques like truss/framed, monocoque, closely stiffened, etc.[3]. Presently ISRO intertank structures are made of truss rods, as shown in Fig. 1. These truss rods are meant to allow radial contraction through spherical joints at both ends since the intertank is at ambient temperature, contrary to the low temperature of cryogenic tanks. However, this configuration introduces large, concentrated loads at the truss interfaces, which in turn results in local buckling[4]. Additionally, in this configuration, components on the dome are left open to the aerodynamic flow and acoustic loads. ISRO is thus working on developing a closely stiffened intertank structure (see Fig. 2) that will allow a uniform distribution of stresses at the joint[4]. However, this configuration will lead to an increase in mass and thus is a non-economical solution. It was found that the closely stiffened intertank contributed

Figure 1. Truss rod type intertank structure.

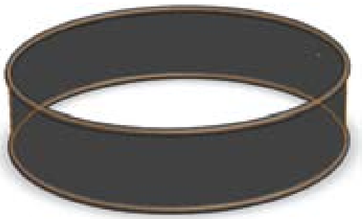

Figure 2. Closely stiffened intertank structure.

Received : 13 July 2021, Revised : 27 September 2021
Accepted : 04 October 2021, Online published : 05 January 2022

to approximately an extra 100 Kg of mass. Therefore, the concept of a common bulkhead seems a plausible approach to minimise mass and overcome the above-mentioned problems of concentrated stresses.

A CBH tank comprises two independently pressurised compartments for fuel and oxidizer. Common bulkhead is a separation used to separate liquid hydrogen (at 20 K) from the liquid oxygen (at 77 K) compartment (see Fig. 3). Since the temperature levels at which these liquids are stored differ by approximately 57 K, so CBH must be designed to provide excellent thermal insulation capabilities and mechanical performances at a minimum weight, thus eliminating entire intertank structures that ISRO has been using for their launch vehicles. CBH tanks in our current Indian launch vehicles are limited to earth storable liquid stages where the thermal gradient factor is not present. However, CBH had shown a good response in foreign launch vehicles like Ariane 5, Saturn S-II, etc.[5-7]. This paper presents an optimised extension of this concept to an Indian launch vehicle.

Another approach to minimise mass with respect to the current vehicle's configuration apart from the CBH tank can be a " Nested tank[8] " (see Fig. 4). This can be used as a last option when the perceived risk of a CBH tank is unacceptable, but severe height and space limitations remain a requirement. Nested tanks consist of two separate and distinct tanks nested in close proximity to each other. The two tanks do not share a common wall like the CBH tanks. Instead, the adjacent heads of the two tanks share a common contour. But compared to CBH tank, it will have a significantly higher mass due to an extra head, and hence, we move forward with the concept of a CBH tank.

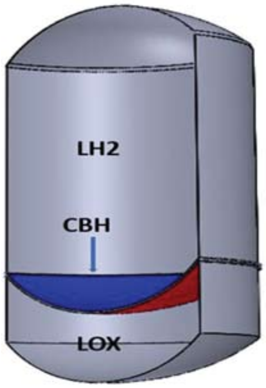

Figure 3. Common bulkhead tank.

Figure 4. Nested tank.

CBH tanks offer the following advantages as compared to current configurations:

(a) CBH tanks offer mass savings. CBH tank was used to reduced 8000 pounds [9] in Saturn V.
(b) Stage, as well as rocket height, would be reduced, offering flight as well as aerodynamic advantage.
(c) The problem of concentrated load as in truss rod type is eliminated.
(d) The number of domes will also be reduced from four (currently) to three.
(e) Better payload performance comparable to separated tanks.

Height reduction in the vehicle can be justified by Fig. 5, where it can be observed that the entire intertank is eliminated from the previous launch vehicle configuration. Height reduction is slightly less than the height of the intertank removed. It is because some additional height and hence additional volume is required in the CBH tank to incorporate the same amount of cryogenics as present in previous structures.

After literature review, the two most feasible approaches to CBH designs are "Inner wetted thermal insulation (IWTI)" and "sandwich common bulkhead". Inner wetted thermal insulation is a material capable of providing thermal insulation when it is in direct contact with the cryogenic medium (liquid LH2). Airbus Safran Launchers[10] developed insulation that applies to liquid hydrogen tanks and external surfaces of both compartments. The major part of their IWTI concept is polyurethane (PU) insulation. Keeping in mind permeation of LH2(He) molecules into the foam, metallic and polymeric liner variants were considered. On the other hand, sandwich common bulkhead[5-7] consists of specific core material sandwiched between two thin Aluminium sheets. MT aerospace[7], under ESA guided technology development program, used a reactor foam, i.e., AIREX R82.xx, as a CBH core material. In terms of mass, solutions favored combined mechanical and thermal function in a sandwich core.

In terms of recent advancements in this field, MT Aerospace had worked relentlessly to optimise the upper stage in Ariane 5. They had developed mass and cost-effective upper stage concepts to bring down about 1.9 tonnes of dry mass for their purpose. MT Aerospace has continuously improved this technology under ESA R&D funding. They developed a computer-based model to predict global system properties

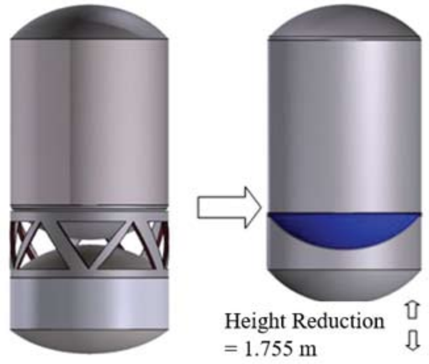

Figure 5. Height reduction in the CBH tank as compared to a truss type.

like pressure, temperature stratification, and mass fluxes with little resources. To investigate individual physical phenomena and the accuracy of these theoretical modelling and CFD simulations, a demonstrator (CHRONUS) was developed. CHRONUS features two compartments with a Sandwich common bulkhead in between them[9]. They have extensively carried out works on production and manufacturing, e.g., peen-formed gore panels, ring rolling, foam thermoforming, resin injection, etc.[7].

Cerquettini[5] described the use of sandwich type phenolic honeycomb core in the common bulkhead of Saturn S-II by NASA for their cryogenic stage. Along the same lines, Aggarwal[6], *et al.* presented the same concept of sandwich type honeycomb core used by NASA in Ares I.

CBH Tanks are mostly used for short-duration flights and are infeasible for long spacecraft missions[8]. It needs to have resistance against reverse pressure, minimised mass, and optimum heat leak in the dome structure as well as in the interfaces. Loads on it will emerge not only due to different pressure levels but also from inertia loads prevailing during the launch. After some brief design and analysis of IWTI in terms of mass savings and keeping in mind the typicality of liner material, we concluded that sandwich common bulkhead is a better approach to the CBH design. A novel concept of a foam-filled honeycomb core is adopted to extract the advantages of honeycomb and foam.

2. SANDWICH CBH DESIGN

For the design of the CBH dome, we need to focus on buckling due to reverse pressure, heat leak that corresponds to 57 K temperature gradient between the two compartments, and the rules of thin pressure vessel design. The shape of CBH can be hemispherical or ellipsoidal, independent of the shape of the tank[8].

The classical buckling theory overestimates buckling load, and factors leading to this overestimation are (a) material parameters, (b) geometrical parameters, (c) pre-buckling deformations, (d) boundary conditions, and (e) geometric imperfections[11]. Quantifying geometrical imperfections is difficult as they are introduced during construction. To incorporate experimental factors, a load factor of 1.25 is taken for analysis in each case. The classical theory is based on a complete spherical shell. To design spherical caps under reverse pressure, we stick to NASA's formulation for curved shells under uniform external pressure [12].

$$P_{cl} = \frac{2}{\sqrt{\left[3\left(1-\mu^2\right)\right]}} E\left(\frac{t}{R}\right)^2 \tag{1}$$

$$\lambda = \left[12\left(1-\mu^2\right)\right]^{\frac{1}{4}} \sqrt{\frac{R}{t}}\, 2\sin\frac{\phi}{2} \tag{2}$$

$$\frac{P_{cr}}{P_{cl}} = 0.14 + \frac{3.2}{\lambda^2}, (\lambda > 2) \tag{3}$$

where,

P_{cr} is the critical buckling load in the form of radial pressure.

P_{cl} is classical buckling pressure for a complete spherical cap.

ϕ is half the angle included for a spherical cap (Fig. 6).

E is the Young's modulus.

μ is the Poisson's ratio.

t is the thickness of the shell.

R is the radius of the shell.

For thermal analysis, aluminium will remain thermally transparent, and the temperature in it will be evenly distributed. The gradient will only appear across the core due to its low conductivity. Since the core (foam-filled honeycomb) is made of foam material and phenolic honeycomb material, we have these two materials in parallel. The subscript *hc* stands for honeycomb, and *c* stands for foam material. Hence for thermal analysis of the core:

For foam, thermal resistance = $R_c = \dfrac{t_{\circ}}{A_c k_c}$

For honeycomb, $R_{hc} = \dfrac{t_{\circ}}{A_{hc} k_{hc}}$

here, $t_{\circ}$ is the thickness of the sandwich part or the core, A and k are the areas and conductivity of respective component and total Area, $A_{total} = A_c + A_{hc}$.

Effective thermal Resistance, $R_{eff} = \dfrac{R_c R_{hc}}{R_c + R_{hc}}$

$$R_{eff} = \frac{\dfrac{t_{\circ}}{A_c k_c} \cdot \dfrac{t_{\circ}}{A_{hc} k_{hc}}}{\dfrac{t_{\circ}}{A_c k_c} + \dfrac{t_{\circ}}{A_{hc} k_{hc}}} = \frac{t_{\circ}}{A_c k_c + A_{hc} k_{hc}}$$

So, the heat flux per unit area is given by

$$q = \frac{\Delta T\left(A_c k_c + A_{hc} k_{hc}\right)}{\left(A_c + A_{hc}\right) t_{\circ}} \tag{4}$$

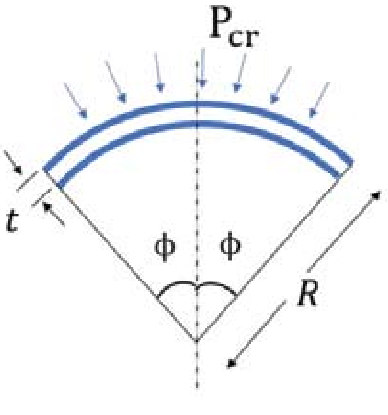

Figure 6. Spherical cap.

3. MATERIAL USED AND TEST CONDITIONS

For our analysis and calculation purpose, AIREX R82.80 was selected as a foam material[7]. Its thermal and strength properties at cryogenic and room temperature are taken from previously available test data[7]. Phenolic honeycomb properties are taken from the HexWeb® HRH-10 manual. We took a 3.2 mm cell size series designated as HRH-10-3.2-xx, where xx is the corresponding density. With an increase in density, the strength and modulus of these materials increases. Aluminium-2219 was used as a face sheet on both sides of the sandwich material. The sandwich structure comprises both foam and honeycomb core in parallel. So, the effective modulus is given by

$$E_p = \frac{E_c A_c + E_{hc} A_{hc}}{A_c + A_{hc}} \tag{5}$$

where $A_{total} = A_c + A_{hc}$. From this formula, the effective modulus of each series member of HRH-10-3.2-xx combined with foam material was calculated and used for further calculations and analysis in ANSYS®. Our analysis assumes that the given foam and honeycomb material forms an ideal foam-filled honeycomb core.

The values of reverse pressure, maximum permissible heat leak, the pressure of each tank, the height of tanks is taken as per ISRO specifications and flight test data. Maximum permissible heat leak is the amount of heat leak allowed to go through the barrier without causing LH2 boiloff or increase in its specific volume.

4. CALCULATIONS

ANSYS®, SOLIDWORKS®, and MATLAB® have been used for all computational and simulation works. MATLAB® is used to arrive at an initial guess for configurations using the theoretical models. SOLIDWORKS® is used for modelling purposes, whereas ANSYS® is used for simulations.

4.1 Hemispherical CBH Dome

Initial calculations were carried out for hemispherical CBH dome since well-defined and widely accepted theories are available for this (Eqns 1 and 4). It was found that the thickness of the core obtained by these equations is governed by buckling values, not by the thermal criteria (Eqn 4), and hence, we got a thermal safety factor of about 2 for the case of minimum mass design. The design of the sandwich part thus obtained was also checked against thin pressure vessel criteria *(pd/4t)* to ensure its safety. Near exact values were obtained in ANSYS simulation results. With this motivation, we moved to a truncated shell to choose a proper configuration for the CBH dome.

4.2 Truncated CBH Dome

Design of truncated CBH dome by buckling load is governed by Eqns (1), (2), and (3). The thickness here also is determined by the buckling criteria, while the thermal criteria remain satisfied automatically. The design of the sandwich part thus obtained is checked against thin pressure vessel criteria *(pd/4t)* to ensure its safety. The design of the Aluminium face plate is based on thin pressure vessel criteria.

Following three comparisons were carried out for selecting a design with minimum mass (keeping all other parameters constant):

i. For different densities (material type) corresponding to a 3.2 mm cell size available in HRH-10 manual.
ii. For different radii of CBH with respect to the fixed radius of the tank.
iii. For different densities and radii together to obtain a 3D graph.

The objective of these comparisons is to obtain a minimum mass point among some standard material compositions and configurations. The comparison points used are thus discrete, keeping in mind feasibility, availability and other constraints of design and material used. Height reduction is calculated after we obtain this point of minimum mass. The method used for these comparisons involves taking out mass values independently for each such possible design variation in terms of geometries, material properties etc.

(i) Comparison among various material type

As already discussed, in HRH-10-3.2-xx, different honeycombs are available, given by their density values. With the increase in density, their modulus increases. An increase in density should imply an increase in mass but, it is not so due to the conflicting nature of thickness with respect to modulus. With an increase in modulus, the thickness would reduce as per the buckling criteria (Eqs. 1, 2, and 3), which would, in turn, reduce mass. Hence the lowest density value honeycomb material will have the maximum thickness and vice versa. Comparisons were carried out for mass against this conflict and are shown in the graph (see Fig. 7). The point to be noted here is that mass used for comparisons is taken out only at available material properties in the manual and the point of minimum mass was selected among the mass values thus obtained. This is now shown only for one radius value, i.e., 2.5 m. however, we later extended it for all other chosen radii to obtain a general 3D plot (see Fig. 10). This is just one of the possible comparisons to set a base for better visualisation of the 3D plot. This case of R=2.5 m is shown separately as later it turns out to be the point of minimum mass (See Fig. 10).

We used tank radius, a=2 m (used in GSLV MkIII), CBH dome radius R=2.5 m for this case. From the graph, we found that the minimum core mass corresponds to HRH-10-3.2-96 material with a corresponding core thickness of 44.7 mm. Each thickness value in Fig. 7 corresponds to some available density of the honeycomb.

(ii) Comparison among different radii of CBH

Since the cryogenic tank radius is fixed to 2 m, CBH can have any radius equal to 2 m or above this, as shown in Fig. 8. The thickness of the Aluminium skin will change as per thin pressure vessel criteria for each of the radii. Table 1 shows

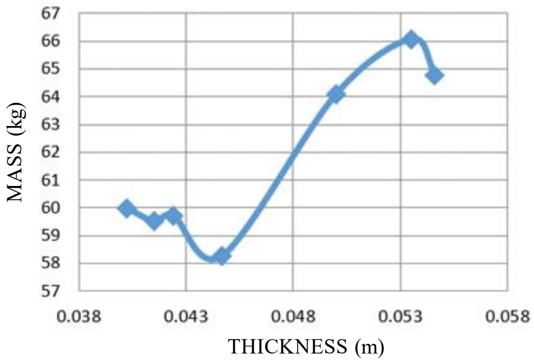

Figure 7. Sandwich core mass comparisons for different thickness values (corresponding to available densities of the honeycomb).

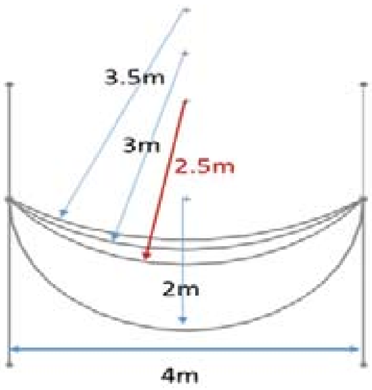

Figure 8. Different CBH dome radii.

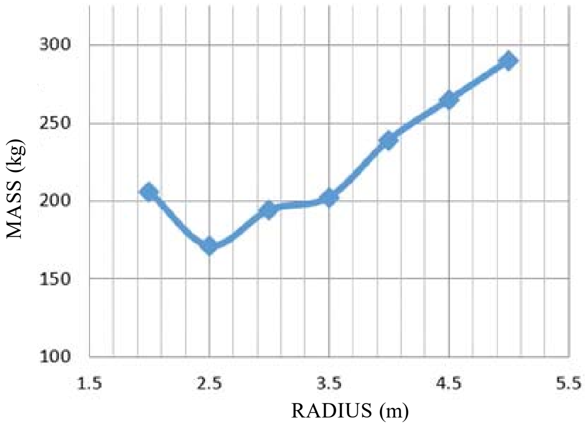

Figure 9. CBH mass comparison for different CBH dome radii.

details of the masses of each face sheet and sandwich core. Minimum total mass corresponds to a CBH radius of 2.5 m (see Fig. 9). This comparison is now taken at one specific material value, i.e., HRH-10-3.2-96, which will be extended to other available materials in Fig. 10. This case of HRH-10-3.2-96 is shown separately as later it will turn out to be the point of minimum mass. (Refer to Fig. 10). We used tank radius, *a*=2 m (used in GSLV MkIII), HRH-10-3.2-96 material for this case.

(iii) General comparison

Case I was a specific comparison of different densities at a particular CBH radius value, while case II comparison was at a particular material property for different CBH radii. Carrying out in the same fashion for all possible series, a 3D graph (see Fig. 10) was plotted with mass vs. density vs. radius (the trend is shown), and it can be observed that among all available combinations of density and radius in our 3.2 mm cell size honeycomb combined with foam, the minimum mass corresponds to have a radius of 2.5 m and density of honeycomb as 96 kg/m^3.

So, from the above three comparisons, we can say that the final dimensions of our CBH dome are

- Core thickness= 44.7 mm.
- CBH dome radius= 2.5 m.
- Aluminium face sheet =1.3 mm.

Therefore, we can proceed with these values for further calculation of mass and height reduction. The minimum mass of the CBH dome will correspond to a maximum mass reduction in the launch vehicle.

5. RESULTS

5.1 Result for mass saving

After obtaining the optimum mass of the CBH dome (see Table 1), we calculate mass savings by adding intertank mass and mass of two domes from the developing configuration of a closely stiffened cylinder (intertank) and subtracting the mass of CBH dome from this.

For mass of a closely stiffened type intertank (h=2 m, t_* = 8 mm, R_*=2 m, made of Al-2219-T851)

Density of Al, ρ=2840 kg/m^3

Volume, $V = 2\pi t_* R_* h$

Mass, $m=\rho V$=571 kg

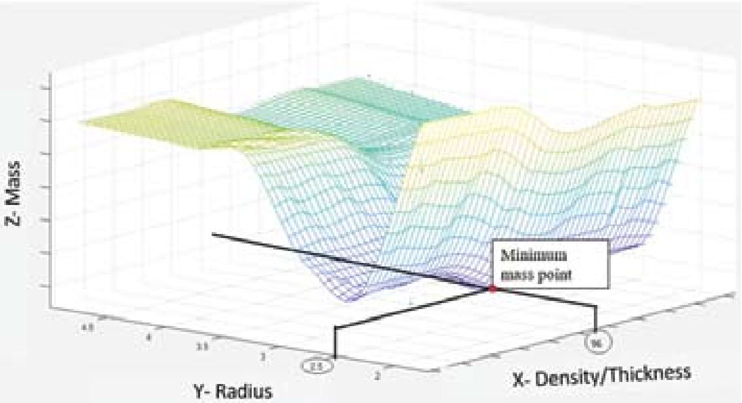

Figure 10. Variation of mass with respect to radius and density.

Table 1. Comparison of mass for each component for different CBH radii

	Aluminium facesheet 1		Sandwich		Aluminium facesheet 2		Net mass
Radius (m)	**Thickness (m)**	**Mass (Kg)**	**Thickness (m)**	**Mass (Kg)**	**Thickness (m)**	**Mass (Kg)**	**(Kg)**
2.0	0.00110	78.47	0.0355	61.26	0.0011	66.00	205.75
2.5	0.00130	56.90	0.0447	58.29	0.0013	57.43	172.62
3.0	0.00165	67.44	0.0525	59.70	0.00165	66.98	194.13
3.5	0.00195	76.40	0.0608	65.45	0.00195	70.44	202.31
4.0	0.0022	84.10	0.0690	71.32	0.0022	83.72	239.16
4.5	0.0025	94.07	0.0772	77.07	0.0025	93.65	264.80
5.0	0.0028	104.22	0.0851	82.26	0.0028	103.73	290.22

Toroidal tank dome:

Thickness = 2 mm

Mass=91.1165 kg (each)

So, for two tanks, mass=192.233 kg (since two such domes are removed)

Total mass removed=192.233+571=763.5 kg

CBH dome mass

Mass of two Al sheets = 56.90+57.43=114.33 kg

Mass of sandwich core structure = 58.29 kg

Mass of common bulkhead dome = 114.33+58.29
= 172.62 kg.

Mass saving = 763.5 - 172.62= 590 kg (approximately, with respect to the closely stiffened type intertank).

The above calculations show that we can make significant savings of upto 590 kg by introducing a CBH tank to our launch vehicles with respect to a closed intertank configuration. As discussed in the introduction section, the closed type intertank configuration exceeds the current truss-type by approximately 100 kg.

Mass saving with respect to the current truss-type configuration of GSLV MkIII will approximately be upto 490 kg.

5.2 Result for Height Savings

Removing the height of the intertank after incorporating CBH while maintaining the same volumes of LOX and LH2, we obtain a height reduction of upto 1.7553 m with respect to both truss type and closed type. From Fig. 5, we can see that when an intertank of height 2 m is removed from the previous configuration, about 0.25 m is used in the CBH tank to compensate for the same cryogenic volume giving an overall height saving of about 1.755 m.

It should be noted that the exact mass and height saving can be concluded after taking into account the design of the connecting skirts, fluid lines, etc. However, the mass saving will still be significant since the CBH dome is the major contributor to these savings.

6. CONCLUSION

The usefulness of introducing CBH to our launch vehicles can be understood by its mass and height saving values obtained. The advantage of these savings had already been discussed before. There will be some initial design and manufacturing complexities associated with it, but they can be eventually overcome by troubleshooting. Few agencies in the past[5,6,7,10] have achieved it to a good maturation level which motivates us to consider the CBH tank as a replacement for our current cryogenic tank configuration.

7. FUTURE WORKS

Hardware development and testing at a small scale can be done though it seems very expensive and complex. LN2 may be used instead of LO2 for safety and operational reasons for these experiments. Several core materials[13] are available to be explored (experimentally) for these applications, which may offer better manufacturing feasibility. The manufacturing feasibility for foam-filled honeycomb is another challenging task, along with determining suitable foam and honeycomb combinations. The design of connecting region (transition of CBH dome to external tank) is yet another design area to be worked on. The probable solution to it may be a decoupled ring interface. ISRO has been using such ring interfaces, but modifications are required in maximizing conduction path and minimizing conduction area when it comes to its usage in CBH cryogenic tanks. The manufacturing feasibility and the NDI techniques[14-15] for each component need to be explored for full-scale development.

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ACKNOWLEDGMENT

The authors express their acknowledgment to LPSC, ISRO, Trivandrum staff members for their constant support and guidance during this work.

CONTRIBUTORS

Mr Yogesh Pratap Singh received his BTech in Mechanical Engineering from National Institute of Technology, Raipur, Chhattisgarh, India, in 2018. Currently, he is a research scholar in the Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India. He was selected for the prestigious Prime Minister's Research Fellowship (PMRF) in 2018 to pursue his PhD at IISc. His areas of interest are robotics, vibration, design, and controls. He has carried out several projects with various research organisations like ISRO, NAL, etc.
He contributed to the research work in problem statements' identification, literature survey, modelling, simulations and preparing the manuscript.

Mr Harjit Singh is currently working as a Scientist/Engineer SF in the Mechanical Design and Analysis entity of LPSC/ISRO Trivandrum. He specialises in the design and structural analysis of aerospace structures. He is a recipient of the Team Excellence Award 2017 and Young Scientist Award 2018 for his contributions to space technologies by ISRO.
He provided many valuable suggestions and feedbacks for the applicability of the CBH concept. He also helped to frame the problem and possible solutions.

Mr Prahlad Kumar Sahu received his BTech in Mechanical Engineering from National Institute of Technology, Raipur, in 2020 and had an internship from ISRO, LPSC, in 2019. He is currently a Software Engineer (R&D Associate) with Dassault Systemes. In the current study, he carried out modelling, simulations, and the post-processing of the results.

Dr R Muthukumar received his PhD (in Aerospace) from Indian Institute of Science, Bangalore, in 2006. He worked in the design, analysis, and development of Mechanical systems for launch vehicles and satellites of ISRO from 1984 to 2020 and retired as Deputy Director, MDA, ISRO, Trivandrum in 2020.
This research work was carried under his supervision. He also helped in reviewing the manuscript.