NCCR - Aramid Sandwich Insulator for Cryogenic Applications

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Abstract: Structural integrity of cryogenic propulsion system in which fuel and oxidizer tanks are connected using truss tubes was well established. The critical issue in the design is the temperature constraint so that temperature is limited to within 20 ± 0.5 K for LH2 tank as against 77 ± 8 K for the LOX. In the present work, based on transient heat transfer analysis for 600s, polyimide foam filled aramid honeycomb core sandwich insulator is designed for common bulkhead instead of truss tubes each for cryogenic and semi cryogenic systems. Non-conducting cryo compatible resin (NCCR) is used to bond the skin and core. Comparison of the back wall temperature for different heat flux and different thermal specifications obtained from test and prediction shows a good agreement. The study shows that a small increase in core height of foam filled sandwich insulator considerably controls the temperature increase of LH2. Test data on flat - wise tensile strength at 77K of NCCR resin used in the honeycomb sandwich insulator shows the values in the acceptable range.

Keywords: Liquid hydrogen, LH2, Liquid oxygen, LOX, Common bulkhead, CB

1 Introduction

Indian Space Research Organisation (ISRO) evolved Expendable Launch Vehicle concept studied in detail. Two Launch vehicle configurations for the Manned and Unmanned Cargo Mission to International Space Station orbit were then reported by Vedachalam et al. [1]. Cryogenic Rocket stages of launch vehicle are widely used because of their versatile advantages such as non-toxic and environment - friendly, high specific impulse. Various studies were reported on the structural integrity of cryogenic and semi-cryogenic propulsion systems in which fuel and oxidizer tanks are either connected by using truss tubes or with a common bulkhead (CB) [1-2]. A sandwich insulator with cork filled inside the metallic honeycomb core for the CB design for cryogenic system was reported in 2007 based on a transient heat transfer analysis [1] and then in 2013, an efficient design for the sandwich insulator with polyimide foam filled inside aramid honeycomb core and aramid skin was reported by Kumar et al. [2]. Such a sandwich insulator was capable of maintaining a thermal gradient of 123K for 1000s for a constant heat flux of 65W/m². The temperature increase in LH2 was expected to be within 1K. Effect of thermal conduct conductance between the skin and core reported by Kumar et al. [3] opens even truss core sandwich option.

A CB suitable for both cryo and semi-cryo is a formidable task as it has an opposite nature of requirement on the design of an insulator on thermal gradients (figure 1). This is mainly due the
difference in thermal gradient of LH2-LOX (= 77-20K) and LOX – Kerosene Tanks (77-300 K). The critical issue in the design of the Liquid Hydrogen (LH2) tank (20 K) is the increase in volume the quantity of LH2 by as much as 15 times for one degree increase in temperature. Consequently, the ullage volume reduces and structural design margin decreases. A CB option for the propellant, Kerosene (300K) as fuel and liquid oxygen (77 K) as the oxidizer is also shown. Once a system on structurally qualified tanks using truss tube option for the LH2-LOX tanks are available, then an alternate design with CB common head can bring up significant payload gain without further basic structural qualification. In such case design of thermal insulator is a mandatory to meet the stringent thermal specification.

For the case of LH2 the design specification for temperature is limited within $20 \pm 0.5 \, \text{K}$ as against $77 \pm 8 \, \text{K}$ corresponding to the LOX temperature.

It may be noted that in the available literature, the sandwich insulator with cryo compatible conducting type resin was used to bond the skin to the core [1-2]. However, no experimental verification was carried out to prove the efficacy of the sandwich insulator to maintain the critical thermal constraint of temperature increase within $\pm 0.5 \, \text{K}$ over a period of 600s.

In the present work, based on transient heat transfer analysis, CB design is carried out for 600s. For both cryogenic or and semi cryogenic systems using polyimide foam filled aramid honeycomb core - sandwich insulator is considered. The top and bottom skin of the sandwich insulator is made out of aramid – epoxy (non conducting cryo compatible NCCR resin) corresponding to the respective different heat flux values and different thermal specifications on the back wall temperature. Thermal properties corresponding to temperature variation in 3-directions are considered for the analysis. A good agreement is obtained between the prediction and test. Study on the effect bond strength of the honeycomb sandwich insulator is also performed.

2 Method of Approach

Sandwich insulator configuration as shown in Figure 1 is considered for the purpose of a CB design for cryogenic and semi-cryogenic Tanks. Transient heat transfer analysis is carried for a period of 600s. The back wall temperature is obtained for respective heat flux.

Heat flux for LH2-LOX $= 65 \, \text{W/m}^2$

Heat flux for LOX – kerosene $= 300 \, \text{W/m}^2$

Detailed finite element analysis for transient heat transfer for thermal profile is reported by Vedachalam et al. and, Kumar et al. [1-2].

The sandwich insulator should provide thermal insulation between two media within 0.5K over 600s. To ensure the design adequacy of the recommended configuration, it is necessary to compare the predicted back wall temperature with the test data for a test configuration. In order to prove the efficacy of the sandwich insulator, test data on thermal profile across the insulator is generated and compared with analysis based on thermal properties that varies with temperature (catalogue values are considered for certain values as given in Table 1.) using liquid nitrogen at 77K. Though LOX- kerosene case may be critical in view of heat flux, temperature rise of LH2 is considered as most critical (< 1K).

2.1 Sandwich insulator for common bulk head

Analysis and test using liquid nitrogen tank condition is carried to compare exposed skin temperature for a period of 600s. The skin thickness, $t_s$ for the CHB and sandwich core thickness, $t_c$ are given in figure 1.
2.2 Parametric study for the design of sandwich insulator of cryogenic tank
In the present study for a heat flux of 65 W/m$^2$ from LOX to LH2 direction and retain LH2 temperature within $20 \pm 0.5$K with the reference temperature of 77K corresponding to LOX is considered for the sizing of the sandwich insulator (figure 1).

2.3 Parametric study for the design of sandwich insulator of semi-cryogenic tank
For a heat flux of 300 W/m$^2$ from kerosene to LOX direction and retain LOX temperature within $77 \pm 8$K with the reference temperature of 300K corresponding to kerosene is taken to ensure the insulator is ensured (figure 1). Core height and skin thicknesses are varied.

2.4 Evaluation of Bond strength between skin and core at 77K
In a sandwich construction the structural integrity is evaluated based on lap shear strength of the resin used to bond between the skin and honeycomb core. Lap shear strengths at room temperature and at 77K (20 minute socking) are determined.

![Figure 1. Conceptual design configurations for sandwich insulator of cryogenic and semi-cryogenic systems](image)

| Semi - Cryogenic stage | Cryogenic stage |
|------------------------|-----------------|
| $t_s$ (CB)             | - 0.18 mm, AA 2219 |
| $t_c$                  | - 0.18 mm, AA 2219 |
| $t_s$ - Aramid honeycomb core height | $t_c$ - Aramid honeycomb core height |
| $t_s$ - Aramid NCCR skin exposed to kerosene | $t_s$ - Aramid NCCR skin exposed to LOX |

$$t_s$ (CB) / $t_c$ / $t_s = 0.18 / 6.5 / 0.42$ mm

2.5 Material properties for heat transfer analysis
Tested and catalog properties on thermal conductivities in three directions of NCCR resin, aramid core filled with polyimide foam, polyimide foam, and bare aramid honeycomb core are given in Table 1. Using the upper and lower bound values in the form of a linear curve, transient heat transfer analysis is carried out.
Table 1 Temperature-dependent thermal properties for the analysis

| Material Description                                      | Temperature (K) | Thermal Conductivity (W/mK) | Specific Heat (J/Kg.K) |
|-----------------------------------------------------------|-----------------|-----------------------------|------------------------|
| | | Kxx | Kyy | Kzz | | | | |
| AA2219 (2800 kg/m³)                                       | 300             | 121.00                       | 121.00                 | 121.00               | 875               |
| | | 350             | 140.00                       | 140.00                 | 140.00               | 900               |
| Aramid- NCCR resin (1240 kg/m³)                           | 77              | 0.90                         | 0.90                  | 0.123               | 1200              |
| | | 300             | 0.13                         | 0.13                  | 0.123               | 1420              |
| Aramid core filled with polyimide foam (61 kg/m³)         | 300             | 0.04                         | 0.04                  | 0.04                | 900               |
| Polyimide foam (64 kg/m³)                                 | 20              | 0.01                         | 0.01                  | 0.01                | 850               |
| | | 300             | 0.04                         | 0.04                  | 0.04                | 900               |
| Bare aramid honeycomb core (21 kg/m³)                     | 300             | 0.042                        | 0.042                 | 0.042               | 900               |

3 Results and Discussion

Results on exposed (A) and back wall temperature (B) of the polyimide foam filled aramid honeycomb core sandwich insulator obtained by test and transient heat transfer analysis for a duration of 600s is compared in figure 2. Comparison of test and analysis results on thermal gradients across sandwich insulator with NCCR and CCR resin systems is provided in Table 2. Effect of back ball temperature for 10 and 20mm core height insulator corresponding cryogenic and semi cryogenic system with reference back wall temperature of 20K and 77K respectively are given in figure 3. for 600s based on finite element transient heat transfer analysis. A comparison of back wall temperature obtained by analysis at 300 and 600s for three different core heights for the cryo and semi cryo systems are compared in Table 3. Test results on lap shear strength of NCCR resin system at room temperature and at 77K are also discussed.

3.1 Comparison of temperature prediction with test data (test configuration)

Based on the transient heat transfer analysis and test data, temperature variation of the exposed skin, $t_e$ (figure 1b) for the sandwich plate of 200 x 200 mm size with thickness of $t_s$ (CB) = 0.18 / $t_c$ = 6.5 / $t_s$ = 0.42 mm for 600s is compared in figure 2. FE model using 3-D finite element analysis with temperature dependent properties, with adiabatic boundary condition over four edges are considered [2]. When the panel was dissected, it was observed that due to capillary action, NCCR resin was flown inside the foam filled core. Hence, the thermal conductivity in the thickness direction of filled aramid core was taken corresponding to the resin value of $K_{zz}$ = 0.123W/mK (table 1). Similar value for the case of conducting resin is 0.27W/mK. A heat transfer coefficient of 3.85W/m²K can be obtained for a given instance of say, 100s from test data that is constant for the entire period considered. From the figure 2, it can be noticed that for a period up to 600s a good agreement is observed between test and analysis. The designed thermal sandwich insulator can sustain a minimum thermal gradient of 175 K with LN2 test condition. Present experimental and analysis studies show that temperature of the exposed skin does change for the conducting resin whose thermal conductivity is twice the non conductive one ([2], Table 2). This may be due to very small resin thickness of 0.15mm.
3.2 Common bulk design for cryogenic and semi-cryogenic stage

Table 3 shows a comparison on the back wall temperatures obtained based on transient heat transfer analysis for 300s and 600s and for cryogenic and semi-cryogenic cases, for respective heat flux (Sec. 2). From figure 3 it can be concluded that for a sandwich insulator design with $t_s = 0.18$, $t_c = 10$, $t_t = 1$ mm meets the design specification of $20 \pm 0.5$ K, based on transient heat transfer finite element analysis for cryogenic common bulkhead.

| Resin type               | Test data on temperature at B in K, figure 2 | FE data on temperature at B in K, figure 2 |
|--------------------------|---------------------------------------------|-------------------------------------------|
| Non-conductive type Resin| $t = 0$ $t = 300s$ $t = 600s$               | $t = 0$ $t = 300s$ $t = 600s$             |
| Reference value at B     | 298.0 254.9 247.3                           | 298.0 249.7 249.2                         |
| Thermal gradient         | 221.0 177.9 170.3                           | 221.0 172.7 172.2                         |
| Conductive type Resin    | $t = 0$ $t = 300s$ $t = 600s$               | $t = 0$ $t = 300s$ $t = 600s$             |
| Reference value at B     | 298.0 256.2 252.7                           | 298.0 249.8 249.2                         |
| Thermal gradient         | 221.0 177.9 170.3                           | 221.0 172.8 172.2                         |
Similarly for the semi cryogenic case, the core height is increased from 10mm to 20mm to meet the design specification of $77\pm 0^\circ$ (figure 3).

![Diagram of sandwich insulator with back wall temperatures](Image)

**Figure 3.** Comparison of back wall temperature between the prediction and test for a test configuration

| Configuration | Cryogenic ($t_s$) (K) | Semi-Cryogenic ($t_s$) (K) |
|---------------|------------------------|-----------------------------|
| Initial Temperature | 20.0 | 77.0 |
| Reference Temperature | 77.0 | 300.0 |

**Back wall temperature at 300s**

| Polyimide form filled sandwich construction | (K) | (K) |
|--------------------------------------------|-----|-----|
| 1. 0.18 / 6.5 / 0.42 mm                   | 22.4| 115.9|
| 2. 0.18 / 6.5 / 1.00 mm                   | 21.0| 96.5 |
| 3. 0.18 / 10 / 1.00 mm                    | 20.2| 86.8 |
| 4. 0.18 / 20 / 1.00 mm                    | 20.0| 78.0 |

**Back wall temperature at 600s**

| Polyimide form filled sandwich construction | (K) | (K) |
|--------------------------------------------|-----|-----|
| 1. 0.18 / 6.5 / 0.42 mm                   | 33.4| 186.1|
| 2. 0.18 / 6.5 / 1.00 mm                   | 25.3| 135.0|
| 3. 0.18 / 10 / 1.00 mm                    | 21.0| 118.5|
| 4. 0.18 / 20 / 1.00 mm                    | 20.1| 84.1 |
3.3 Bond strength assessment of NCCR resin system

For both cryogenic and semi-cryogenic systems, sandwich insulator whose metallic skin of 0.18mm is bonded with the aluminium tank domes. Under ‘g’ load, insulator should not separate. Input for the bond stress requirement of the insulator corresponding to ‘4g’ longitudinal load should be greater than 0.2MPa.

Table 4. Flat - wise tensile strength with NCCR resin

| Specimen | At room temperature | After soaking to 77K for 20minutes |
|----------|---------------------|-----------------------------------|
| 1.       | 0.54MPa             | 0.37MPa                           |
| 2.       | 0.43MPa             | 0.20MPa                           |
| 3.       | Failed prematurely due to improper specimen preparation |

Design criterion: Interfacial bond strength value should be more than aramid honeycomb core shear strength value.

- Minimum Flat-wise tensile strength at RT = 0.43 MPa (Table 4)
- Minimum Flat-wise tensile strength at 77K = 0.20 MPa
- Core shear strength in w direction at RT = 0.21 MPa
- Core shear strength in w direction at 77K = 0.10 MPa (50% reduction)

The design of the sandwich insulator is based on the criterion that interfacial bond (here, the bond between Al dome of LOX or LH2 to 0.18mm Al skin of insulator, (figure 1) should not fail till honeycomb core failure occurs.

4 Conclusions

Based on transient heat transfer analyses, sandwich insulator designed for cryogenic and semi-cryogenic systems have been supported with experimental verification on back wall temperature for the duration of 600s. Comparison of temperature prediction of the exposed bi-directional aramid skin has shown a good agreement with test data using LN2 (77K). It has been concluded from the analysis that for the cryogenic tank, a configuration of $t_0 \text{(CB)} = 0.18$, $t_c = 10$, $t_s = 1 \text{mm}$ (figure 1b) can meet the design specification within $20 \pm 0.5 \text{K}$ for a heat flux of $65\text{W/m}^2$. Similar configuration for semi-cryogenic case is $t_0 \text{(CB)} = 0.18$, $t_c = 20$, $t_s = 1 \text{mm}$ that can meet the design specification of LOX temperature within $77 \pm 8 \text{K}$ for a heat flux of $300\text{W/m}^2$. Both test and analysis results have shown the effect of conducting and nonconducting cryo compatible resin on the back wall temperature is found to be negligibly small. However, it is concluded to recommend NCCR resin system as the temperature rise of LN2 should be less than 0.5K. When compared to the core failure strength, the flat - wise tensile stress for the evaluation of interface strength between the exposed skin to the honeycomb core at 77K meets the design requirement.

References

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