Pressure Testing on an Integrated Thermal Structural Cryogenic Tank Fabricated by Friction Stir Welding

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by

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Abstract

Thermal structural cryogenic tanks in general have been steadily in demand since the use of LN_2 and LH_2 as fuels has taken precedence. These and other cryogenic liquids have shifted the way storage and fuel tanks have to be fabricated and designed. The upside of having cryogenic fuels is the volume and energy densities compared to everyday gasoline. The potential downside to having these cryogenic fuels is their storage temperature and the pressure that these fuels cause when reaching boil off state.
This paper will be reporting the results of thermal, stress and pressure analysis of such a thermal structure. This integrated thermal structure was fabricated by means of friction stir welding and refill friction stir spot welding of aluminum to Polyphenylsulfone (injected molded PPSU). This design utilizes Polyphenylsulfone a thermoplastics as both a thermal and structural component of the tank wall.

Introduction

The design of this cryogenic tank included analytical examinations of the thermal and structural capacities of the tank. The thermal analysis involved the thermal resistance model for a cylinder and looked at what the surface temperature on the outer aluminum skin and the heat flux through the wall would be based on that model and on the different possible tank designs. This approximation will be compared to real time experiment that uses the Clausius-Clapeyron relation.

The structural analysis used the von Mises failure theory to attempt to predict at what pressure the tank would burst. This will be compared to the hydrostatic burst test to accurately obtain the burst pressure of the tank.

Procedure

The Thermal Resistance Model

The thermal resistance is defined as the ratio of the temperature difference, dT, to the heat transfer Q. Ohm's law states that the electrical resistance is defined as the ratio of the voltage drop across a resistor to the current flow across the resistor. The insulation from the PPSU and the aero-gel acted as a resistor. The equation represents the model and it is given by

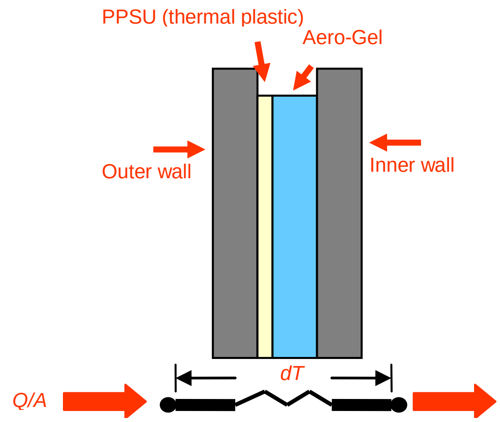


Figure 1 - Thermal Resistance Model

DV = I R or R = DV/ I (Ohm's Law) DT = (Q/A) R or R = DT / (Q/A)

Where (Q/A) is the heat transfer. By using the thermal resistance model for a cylinder the heat flux from the outer wall through the PPSU and Aero gel.

The Clausius-Clapeyron Relation

This relation will be used to calculate the heat flux coming in through the walls of the tank. This experiment will fill the tank up with liquid nitrogen until it reaches a steady boil off level. Then the gas flow will be vented through a series of chambers to measure the rate at which the liquid nitrogen is boiling off at. This rate can be used in the ideal gas law to calculate how many moles of nitrogen is boiling off. Using this rate we can plug in these variables to the Clausius-Claperyon relation to calculate the heat flux. In figure 2 is sketch of test setup.

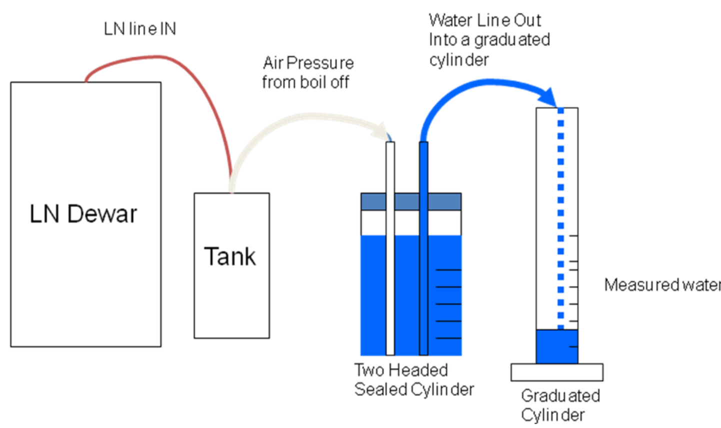


Figure 2 - Clausis-Clapeyron Test Setup

This relation characterizes a discontinuous phase transition between two phases of matter. On a pressure – temperature graph, a line separating the two phases is known as the coexistence curve. The Clausius-Clapeyron relation calculates the slope of this curve mathematically,

$$dP / dT = L / T \Delta V$$

Where dP / dT is the slope of the coexistence curve and L is the latent heat, T is the temperature and ΔV is volume change of the transition.

The von Mises failure theory

The Von-Mises yield surfaces in principal stress coordinate circumscribes a cylinder with radius around the hydrostatic axis. Also shown is Tresca's hexagonal yield surface. The Von-Mises failure theory calculates the burst pressure based on the alloy, the thickness and the strength. This data modeling tool is an approximation but is useful in helping getting a safety range for actual burst strength.

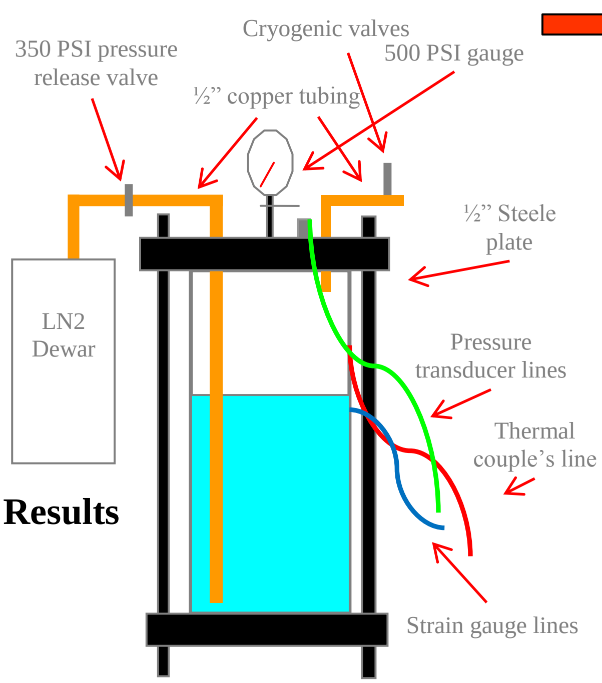
Hydrostatic Burst Test

The hydrostatic burst test will be conducted on the cryogenic tank that was fabricated. The test will seal off all vents except for a water inlet. There also was an inlet for a pressure transducer that will be measuring the pressure in the tank. The water will be pumped in using a pressure washer that is capable of generating a load of 3000 PSI. This should take the pressure well beyond the burst pressure of the tank. The pressure transducer is capable of reading up to 3000 PSI accurately.

Final Design

The final design to perform the thermal cycle and burst pressure test was carefully crafted and designed. The design includes 1/2" copper tubing to pump in and vent out the liquid nitrogen. There were a total of nine thermal couples attached to the tank walls.

Design to application



Results

Figure 3 - Final Design layout

Heat flux calculations

The thermal cycle test was conducted and results were obtained. In the first experimentation results were inconclusive. The design of the tank did not take into consideration for a heat leak through the end caps of the tank. This design was intended only to test the multilayered wall structure. The problem in testing the tank was that the cryogenic temperature would leak out through the end caps and up the outer wall of the tank. This made testing the tank almost impossible. So alterations to the tank were made based on the problem. In the Figure 4 give a visual concept to how the heat leak was occurring. Alterations to the outer wall were made and were cut from the end caps.

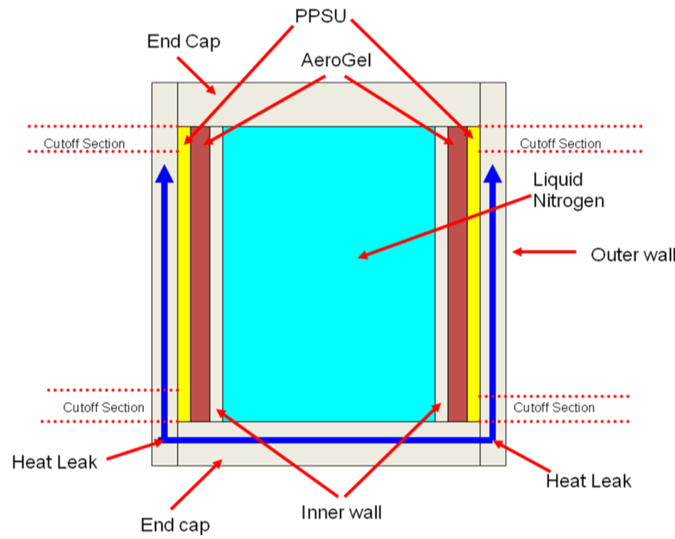


Figure 4 – Alteration to tank

This made the end cap and outer wall connection nonexistent. Also a layer of Styrofoam was placed on the end caps to work as an insulator. It is important to note again that this was a test of the wall design and not the end caps. The test was redone and the data was more consistent. From the data a heat flux of 6 W/m^2 K was calculated. The thermal resistance model predicted that a heat flux of 60 W/m^2 K was obtained. The approximation was off by a power of 10.

Burst test calculations

The bust test was conducted after the thermal testing was done. From the von-misses theory the burst pressure of the tank was calculated to be 900 PSI. The hydrostatic burst pressure from the tank was 518 PSI. The hydrostatic burst test also held the pressure of the tank at about 40% of the calculated burst strength for about 10 minutes. Figure 5 shows the pressure curve on a graph. This was about 43% of the calculated burst pressure from the von-misses theory.

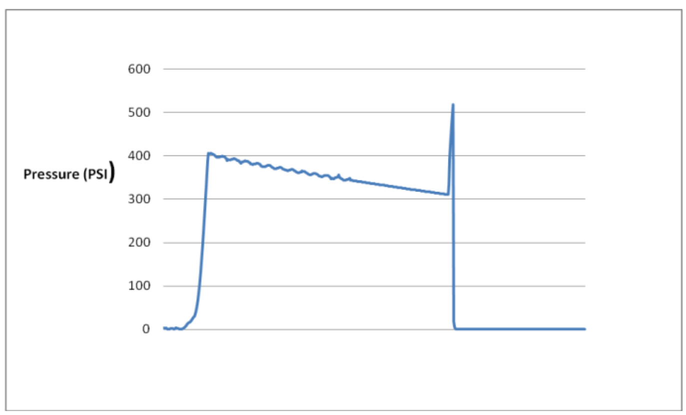


Figure 5 – Pressure Curve Hydrostatic Burst Test

Conclusion

The conclusions here are mixed and further examination of the tank was conducted. This was an investigation on to see why the burst of the tank was such a low pressure from the calculated one. The metallurgy of the weld uncovered some voids in the weld. These voids also known as worm holes were existence off and on throughout the weld. Figure 6 shows a worm hole that was in the weld of the tank. The worm hole is exactly where worm holes form on friction stir welds. That exact cause of this defect is unknown but could be from bad clamping or bad parameters of the friction stir weld. This worm hole defect is the cause of the low burst pressure.

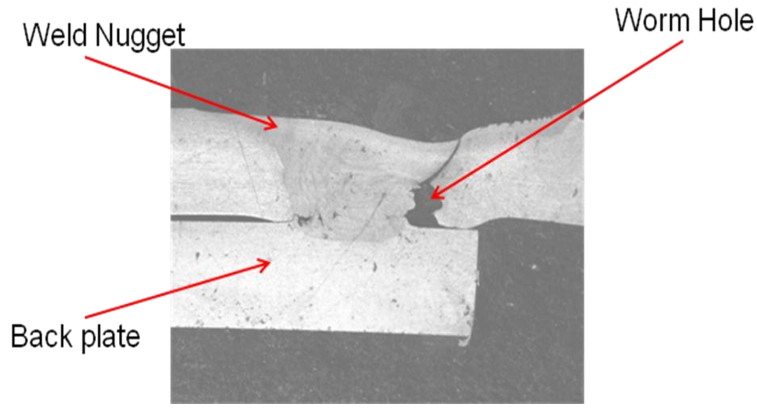


Figure 6 – Worm Hole Macro

The heat flux calculations are off by about a factor 10 further investigation on the thermal model and the Clausis-Clapeyron equations were conducted. All calculations from the model and the equations were sound and no further investigations were needed. A heat flux of 6 W/M^2 K is considered and average heat flux for cryogenic storage units.

References

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