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Wrapped multilayer insulation design and testing

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ABSTRACT

New vehicles need improved cryogenic propellant storage and transfer capabilities for long duration missions. Multilayer insulation (MLI) for cryogenic propellant feedlines is much less effective than MLI tank insulation, with heat leak into spiral wrapped MLI on pipes 3–10 times higher than conventional tank MLI. Better insulation for cryogenic feed lines is an important enabling technology that could help NASA reach cryogenic propellant storage and transfer requirements. Improved insulation for Ground Support Equipment could reduce cryogen losses during launch vehicle loading. Wrapped-MLI (WMLI) is a high performance multilayer insulation using innovative discrete spacer technology specifically designed for cryogenic transfer lines and Vacuum Jacketed Pipe (VJP) to reduce heat flux.

The poor performance of traditional MLI wrapped on feed lines is due in part to compression of the MLI layers, with increased interlayer contact and heat conduction. WMLI uses discrete spacers that maintain precise layer spacing, with a unique design to reduce heat leak. A Triple Orthogonal Disk spacer was engineered to minimize contact area/length ratio and reduce solid heat conduction for use in concentric MLI configurations.

A new insulation, WMLI, was developed and tested. Novel polymer spacers were designed, analyzed and fabricated; different installation techniques were examined; and rapid prototype nested shell components to speed installation on real world piping were designed and tested. Prototypes were installed on tubing set test fixtures and heat flux measured via calorimetry. WMLI offered superior performance to traditional MLI installed on cryogenic pipe, with 2.2 W/m^2 heat flux compared to 26.6 W/m^2 for traditional spiral wrapped MLI (5 layers, 77–295 K). WMLI as inner insulation in VJP can offer heat leaks as low as 0.09 W/m, compared to industry standard products with 0.31 W/m. WMLI could enable improved spacecraft cryogenic feedlines and industrial hot/cold transfer lines.

1. Introduction

New NASA vehicles and long duration missions using cryogenic propellants need improved cryogen storage, preservation and transfer Ref. [1]. Insulation on cryogenic transfer feedlines is problematic, with current feedline Multi-Layer Insulation (MLI) performance about 10X worse per area than tank MLI insulation Ref. [2]. Heat leak through cryogenic piping can be as much as 80% of the total system heat leak, limiting use of cryogenic spacecraft propulsion systems. Cryogenic propellant transfer lines used as Ground Support Equipment lost about 50% of LH_2 during transfer, chill down and ground hold during an STS launch. Quest Thermal Group LLC, teaming with Ball Aerospace, has developed an advanced insulation system for cryogenic transfer lines called Wrapped MLI (WMLI). Wrapped MLI (WMLI) uses discrete spacers to control layer spacing and reduce heat leak to provide high performance insulation for cryogenic piping and industrial Vacuum Jacketed Pipe.

New developments in cryogenic insulation, such as Integrated MLI (IMLI) with discrete spacers, are leading to higher performing systems, playing a role in providing Reduced or Zero Boil Off of cryogenic propellants. Better insulated piping could provide more efficient cryogenic fluid transfers, improved spacecraft cryogenic propulsion, cryogenic propellant storage and transfer in orbiting fuel depots, and higher performing Ground Support Equipment

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Abbreviations: WMLI, wrapped multilayer insulation; MLI, multilayer insulation; IMLI, integrated Multilayer insulation; SOFI, spray on foam insulation; VJP, Vacuum Jacketed Pipe.

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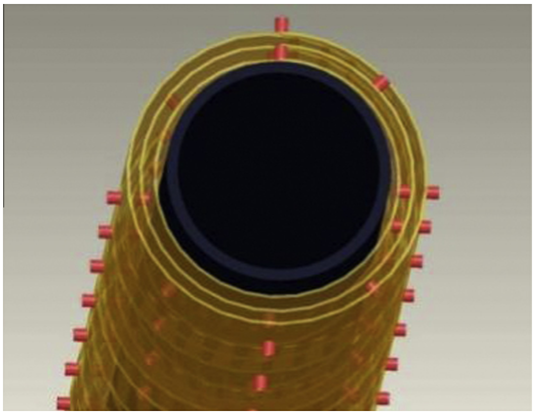

Fig. 1. WMLI conceptual design shows discrete spacers separating radiation barriers.

for loading cryogenic launch vehicles or liquid hydrogen fueled aircraft. Wrapped MLI uses a new spacer engineered to reduce heat leak for insulation installed on small diameter piping. WMLI development included designing several new spacers, modeling them for thermal performance, fabricating rapid prototypes, developing new installation methods, installing on cryogenic piping test fixtures and measuring thermal performance.

Discrete spacer technology provides precise, controlled layer spacing and insulation density, reduces the thermal conductance from layer to layer, and can form a bonded up, robust and repeatable structure. Next generation insulation IMLI uses low thermal conductance polymer micromolded spacers between radiation shield layers Ref. [3]. IMLI systems show a measured heat leak of 0.41 W/m^2 (20 layers, 3.7 cm, 77–293°K) Ref. [4], 37–50% lower heat leak per layer than traditional netting-based MLI, and perform close to their modeled behavior.

Other unique insulation systems have been designed and tested using discrete spacers for Load Responsive MLI that dynamically respond to external pressure and operate both in-air and on-orbit Ref. [5], Load Bearing MLI in which the spacers self-support a Broad Area Cooled shield without the heat leak of tank supports Ref. [6], and MMOD-MLI where the spacers support high strength ballistic layers to provide micrometeoroid/orbital debris shielding.

WMLI has different requirements than large acreage tank MLI, and so a unique, specialized spacer for wrapped insulation with limited space and concentric layers on cryogenic feedlines or industrial hot/cold transfer piping was a focus of this work.

2. Results and discussion

2.1. Wrapped MLI design

The WMLI concept uses discrete spacers to separate radiation barrier layers (Fig. 1). An early WMLI design used a simple glass spherical spacer and had a heat flux nearly four times lower than spiral wrapped traditional MLI insulation. It was thought performance could be further improved with spacers designed to minimize contact area and offer lower thermal conductivity.

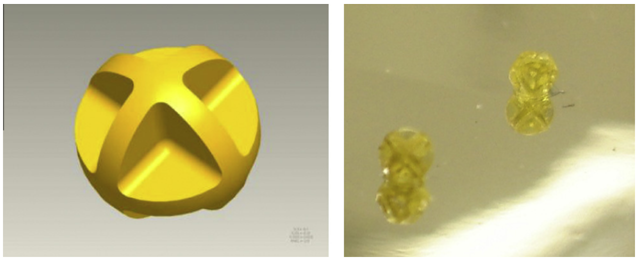

Fig. 3. Triple Orthogonal Disk spacer CAD image (left), and actual TOD spacers showing alignment bonded to a radiation barrier (right).

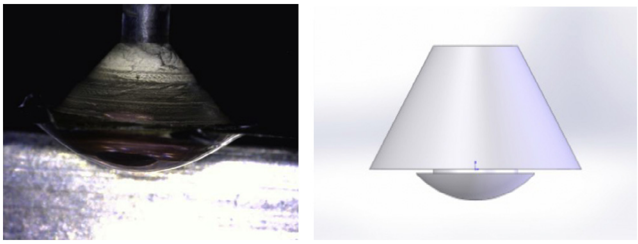

Fig. 4. Post-on-demand fabrication of a spacer; right is conceptual design of microslurry spacer with pass through layer holder; image left is actual formed spacer sitting above and below a radiation layer.

The WMLI system performance is obviously dependent on design and development of a discrete spacer for use on tightly wrapped insulation on piping. Some 15 different micromolded polymer spacers were designed, thermally modeled and considered. The design process included variables such as thermal contact area between spacer and radiation barrier, length of spacer between layers, spacer material thermal conductivity, and optimal height and strength of the spacer. From these initial concepts, several were selected to prototype using stereolithography. See Fig. 2.

The spacer was designed around principles that reduce the effective area/length, minimizing solid heat conductance. The final selected design was a Triple Orthogonal Disk (TOD) spherical polymer spacer that touches adjacent dual aluminized mylar layers on the edges of thin disks, providing for very small contact area and a low effective area/length ratio Ref. [7]. See Fig. 3. The TOD spherical spacer was thoroughly modeled and analyzed, and selected as the spacer design of choice. The TOD spacer was tooled, micromolded, and used to build WMLI prototypes.

During WMLI spacer design, a second novel approach was studied in which “post-on-demand” spacers were formed on-the-fly with a microslurry rapid curing manufacturing process. A slurry allows different materials with different thermal properties to be combined such as microspheres in a polymer curable matrix. This process allows various shapes to be fabricated, and may be a good approach for high volume manufacturing of WMLI. See Fig. 4.

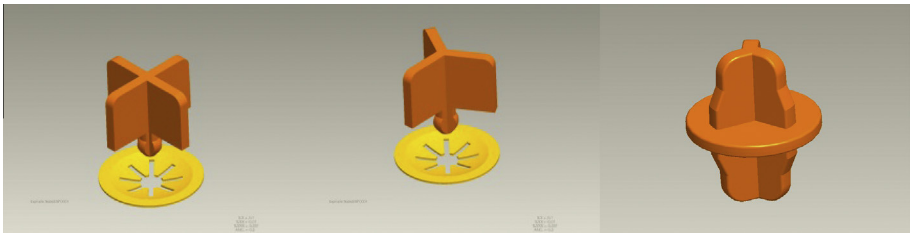

Fig. 2. Spacer designs fabricated using rapid prototyping processes.