Cryogenics 74 (2016) 154–165

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Layered composite thermal insulation system for nonvacuum cryogenic applications

J.E. Fesmire

NASA Kennedy Space Center, Cryogenics Test Laboratory, UB-R1, KSC, FL 32899, USA

ARTICLE INFO

Article history:
Received 4 July 2015
Received in revised form 9 October 2015
Accepted 15 October 2015
Available online 26 October 2015

Keywords:
Thermal insulation
Weathering
Compression
Piping
Valves
Tanks
Space launch vehicles

ABSTRACT

A problem common to both space launch applications and cryogenic propulsion test facilities is providing suitable thermal insulation for complex cryogenic piping, tanks, and components that cannot be vacuum-jacketed or otherwise be broad-area-covered. To meet such requirements and provide a practical solution to the problem, a layered composite insulation system has been developed for nonvacuum applications and extreme environmental exposure conditions. Layered composite insulation system for extreme conditions (or LCX) is particularly suited for complex piping or tank systems that are difficult or practically impossible to insulate by conventional means. Consisting of several functional layers, the aerogel blanket-based system can be tailored to specific thermal and mechanical performance requirements. The operational principle of the system is layer-pairs working in combination. Each layer pair is comprised of a primary insulation layer and a compressible radiant barrier layer. Vacuum-jacketed piping systems, whether part of the ground equipment or the flight vehicle, typically include numerous terminations, disconnects, umbilical connections, or branches that must be insulated by nonvacuum means. Broad-area insulation systems, such as spray foam or rigid foam panels, are often the lightweight materials of choice for vehicle tanks, but the plumbing elements, feedthroughs, appurtenances, and structural supports all create "hot spot" areas that are not readily insulated by similar means. Finally, the design layouts of valve control skids used for launch pads and test stands can be nearly impossible to insulate because of their complexity and high density of components and instrumentation. Primary requirements for such nonvacuum thermal insulation systems include the combination of harsh conditions, including full weather exposure, vibration, and structural loads. Further requirements include reliability and the right level of system breathability for thermal cycling. The LCX system is suitable for temperatures from approximately 4 K to 400 K and can be designed to insulate liquid hydrogen, liquid nitrogen, liquid oxygen, or liquid methane equipment. Laboratory test data for thermal and mechanical performance are presented. Field demonstration cases and examples in operational cryogenic systems are also given.

Published by Elsevier Ltd.

1. Introduction

Thermal insulation of working cryogenic systems, that is, the thermal isolation of the working fluid (a cryogen such as liquid oxygen [LO_2], liquid hydrogen [LH_2], liquefied natural gas [LNG], or liquid methane [LCH_4]), is often only an afterthought in system design, yet that isolation is crucial for the control, safety, and reliability of the system and for the energy efficiency and preservation of the cryogen. As shown in Fig. 1, cryogenic systems in most space launch facilities, propulsion test stands, and other aerospace applications are unavoidably complex. And their challenges are dramatically increased by mechanical/vibration loads, weathering/ascent pressure environments, and requirements for accessibility and maintenance. Furthermore, any successful thermal insulation system must be lightweight and meet a wide range of fire, compatibility, outgassing, and other physical and chemical requirements. High thermal performance (low thermal conductivity) is the overall goal, but it is not always at the top of the list of material requirements.

Ambient-air insulation systems for low-temperature (subambient) applications are difficult to achieve because of moisture ingress, environmental degradation, and thermal stress cracking. Most of the accepted methods for externally applied insulation in outdoor environments are fraught with problems centered on moisture ingress and lack of sealing. In response, the Cryogenics Test Laboratory at Kennedy Space Center (KSC) developed LCX – the layered composite insulation system for extreme environments. LCX maintains high thermal performance in ambient air

http://dx.doi.org/10.1016/j.cryogenics.2015.10.008
0011-2275/Published by Elsevier Ltd.

Fig. 1. Examples of piping complexity in aerospace cryofuel systems: the aft compartment of the Space Shuttle Orbiter Discovery with its main engines removed (left) and the Shuttle External Tank LH_2 Vent Umbilical (right).

or a purged environment, needs no sealed outer envelope (vacuum jacket [VJ]), and can be adapted to a wide range of requirements. The common elements of LCX designs are a primary insulation blanket layer, a compressible radiant barrier layer, and an optional overwrap layer, all of which should be hydrophobic or at least waterproof.

2. Thermal insulation system design

The LCX system's primary insulation blanket layer is preferably hydrophobic, such as an aerogel composite blanket, but can be any suitable flexible insulation material, such as polymeric foam. It can consist of one or more layers of blanket or foam and goes onto the cold inner surface of the tank, piping, or other cold-process object. The compressible barrier layer then goes onto the insulation blanket layer and so forth to create a layered stack (Fig. 2). The compressible barrier layer is also an insulating layer, but is primarily selected to offer the mechanical compliance, compressibility, and placement necessary to enable a good fit of the primary insulation layers with optimal closure of seams and gaps. This layer is a polymeric air-sealed material that includes radiant barrier facings (aluminized plastic film or aluminum foil) in a composite. The outermost compressible barrier layer can incorporate an aluminum foil layer to further conform to complex shapes or to close out the blanket stack around a flange, port, or other component. LCX can be field-applied or prefabricated to meet specifications for piping, tanks, or flat panels.

2.1. Heat transfer considerations (full vacuum pressure range)

The LCX technology builds on prior layered thermal insulation systems intended for vacuum service (vacuum enclosure or the vacuum of space). Multilayer insulation (MLI) systems are composed of highly conductive materials, such as aluminum, in combination with excellent insulating materials, such as lightweight polyester netting or fiberglass paper. Designed and installed in the right way, the two-component MLI systems can provide the ultimate in thermal insulation performance, with heat flux values below 1 W/m^2 and effective thermal conductivity values below 1 mW/m K for the typical boundary conditions of 300 K and 77 K. However, these systems are strictly for vacuum environments or evacuated metal jackets. Although MLI systems can perform as well as the best closed-cell spray foam systems, the materials will not hold up in the ambient (wet) environment beyond the first cooldown.

The KSC Cryogenics Test Laboratory has been developing MLI and other layered, blanket-type insulation systems for the last 15 years [1]. The objective for cryogenic applications is to achieve the best thermal performance according to the specific vacuum environment: high vacuum (HV), soft vacuum (SV), or no vacuum (NV) [2]. Layered composite insulation (LCI) technology has been introduced in the last decade for the ultimate in soft-vacuum performance from 1 to 10 torr [3,4]. For high-vacuum applications, the performance of LCI systems, using three-component architecture within a vacuum envelope or VJ, can be comparable to that of MLI systems. Thus, LCI represents a strategic advantage in that it maintains some effectiveness with degradation in vacuum level. LCI systems designed for soft-vacuum applications do not require expensive, heavy, welded, stainless-steel jackets, but can instead be constructed of inexpensive, lightweight plastics that are glued together for the jackets.

For both MLI systems and LCI systems, the approach is to use a combination of materials to address all modes of heat transfer. The total heat flow (Q) consists of solid conduction, gaseous conduction, bulk-fluid convection, and radiation, as indicated by Eq. (1).

$$Q_{total} = Q_{solid\ conduction} + Q_{gaseous\ conduction} + Q_{convection} + Q_{radiation} \quad (1)$$

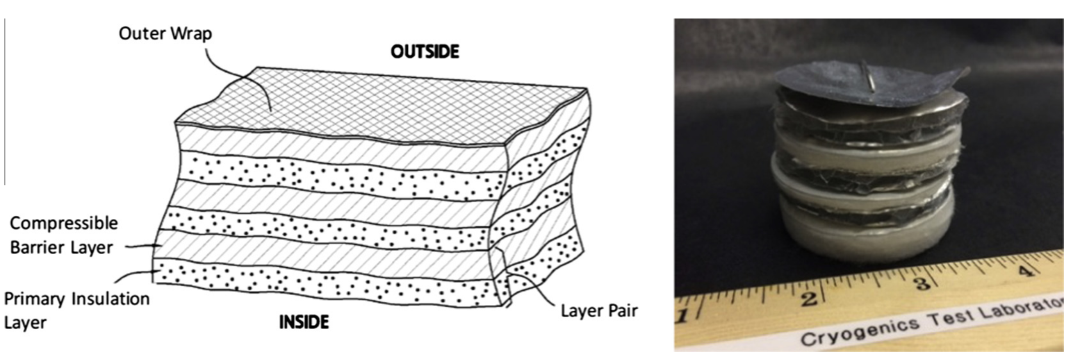

Fig. 2. Basic concept of the LCX system (left) and test specimen construction for laboratory testing (right).