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Research Paper

Insulation performance of foam during the terrestrial and ascent period

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HIGHLIGHTS

- The minimum thickness of foam for different cryogens are predicted.
- The unsteady heat transfer through foam is studied for the diffusion of CO_2.
- The transient performance of foam is investigated with the variable physical properties considered.
- The performance comparison between foam and foam/MLI is made.

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ABSTRACT

To effectively reduce heat leakage, foam insulation is widely used in refrigeration, energy, chemical, cryogenic system and pipe engineering. The present study is aimed to investigate the thermal performance of foam on cryogenic storage system under variable environmental parameters. The heat transfer model through the foam is introduced in detail. The minimum thicknesses of foam for different cryogens are calculated under the influence of the external free convection during the terrestrial condition. Meanwhile, with carbon dioxide diffusion out of and air invasion in the foam cells, the related unsteady process is studied with coupling the mixture gas heat conduction and the external free convection. While during the liftoff of rocket, foam insulation is subjected to the forced aerodynamic heating. The transient thermal performance of foam is particularly investigated under the influence of aerodynamic heating, with the variable physical properties, flight velocity and acceleration, and environmental parameters considered. Finally, the performance comparison between foam and foam/Multilayer insulation is made. Some valuable conclusions are obtained. The present study is of significance to the insulation design for cryogenic fuel storage.

1. Introduction

Due to great virtues of high specific-impulse, environment friendly and being easy to obtain, cryogenic propellants, such as liquid hydrogen (LH_2) and liquid oxygen (LOX), are widely used in aerospace engineering and launch system [1]. However, as cryogens are usually stored in low temperature, for instance, the storage temperatures of liquid hydrogen and liquid oxygen are < 20 K and < 90 K, it is necessary to reduce the cold loss from low temperature with effective insulation. Meanwhile, accurate prediction on the thermal conductivity of cryogenic insulation is important in thermal design of cryogenic system. Now, cryogenic insulation can be mainly subdivided into five categories, including vacuum insulation, multilayer insulation, powder and fibrous insulation, foam insulation, and special-purpose insulations. As there is no mean distinct between the above five approaches, the present study is concentrated on the study of foam insulation, which has been widely used in refrigeration, energy, chemical, cryogenic processing and pipe engineering. Instead of air, spray-on foam insulation (SOFI) is the most efficient thermal insulation approach because it contains chlorofluorocarbon (CFC) gas or carbon dioxide (CO_2), which is trapped in the closed-cell structures of foam during production. The heat transfer process through SOFI includes solid conduction, gas conduction and radiation across the void spaces. These heat transfer principles are important to the insulation design for phases of terrestrial or space applications, where the isolation of the warm and cold boundaries are contributed greatly to the efficiency of the insulation.

To study the thermal performance of foam insulation, investigators have conducted extensive experimental measurements. Martin [2]

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Nomenclature

C_G, C_R, C_s	empirical coefficients for gas conduction, radiation and solid conduction
c_p	specific heat
Gr	Grashof number
h^*	reference enthalpy
h_r, h_w	enthalpy corresponding to T_r and T_w
Kn	Knudsen number
l, L_c	characteristic length
m	mass
M_{air}, M_{CO_2}	mole mass of air and CO_2
N^*	layer density
$\overline{N}$	layer number
Nu	Nusselt number
Pr	Prandtl number
q_{aero}	aerodynamic heat flux
q_c	convection heat transfer
q_{cond}	heat conduction
q_g	gas conduction
q_r, q_{rad}	radiation heat
q_s	solid conduction
q_t	total heat flux
R_u	universal gas constant, 8.314 J/(mol·K).
Re^*	Reynolds number
T^*	reference temperature
T_c	temperature of cold boundary
T_e	environment temperature
T_h	temperature of hot boundary
T_m	mean temperature of insulation, $(T_H + T_C)/2$
T_r	recovery temperature
T_w	tank wall temperature
t_m, t_s	nominal thickness of Mylar shield and spacer
u_e	flight velocity
V	volume of the cell

Greek symbols

α	convection heat coefficient
α_{aero}	aerodynamic heat coefficient
δ	thickness of the insulation
ε	emissivity factor
ϕ	porosity of the foam
η	volume fraction of air
λ_a	thermal conductivity of air
λ_{air}, λ_{CO_2}	thermal conductivities of air and CO_2
λ_s, λ_g, λ_r	thermal conductivity of solid materials, gas within cavities and radiation
λ_{foam}, λ_{MLI}	thermal conductivity of foam and MLI
ρ_{air}, ρ_{CO_2}	density of air and CO_2
μ	viscosity
ρ_{foam}, ρ_g, ρ_s	density of foam, solid material and gas
σ	Stefan-Boltzmann constant, 5.67×10^{-8} W/(m²·K⁴)
ς	gas molecular mean free path
ξ_m, ξ_s	average specific weight of Mylar shield and spacer
Φ, Ψ	parameters related to Kn

conducted four prelaunch experimental simulations with SOFI being attached to the tank wall. With LH_2 being working fluid and the vacuum chamber and test article environmental shroud under a gaseous nitrogen purge, results showed that the SOFI efficiently prevented the liquefaction of oxygen and nitrogen in terrestrial condition. Afterwards, the thermal performance of a composite insulation consisting of SOFI and Multilayer insulation (MLI) was conducted by Martin et al. [3] in vacuum chamber to simulate the orbit hold environment with the minimum pressure lower to 1.33×10^{-3} Pa. With SOFI covered with 16 layer MLI radiation shield, three vacuum boil-off tests simulating the orbital conditions were conducted. By measuring the SOFI interstitial pressure at the top of the test article, there was obvious pressure drop, which reflected a reduction on the SOFI vapor pressure and rapid cryopumping of any condensable gases trapped within the MLI. Tseng et al. [4] experimentally studied the thermal conductivity of polyurethane foam with the test temperature ranging from 300 K to 20 K. The results showed that while the gases in the foam cells were evacuated, the thermal conductivity of polyurethane foam could be reduced by 70%. Meanwhile, the related research has firstly supplied the available thermal conductivity data < 90 K, which was significant for the design of cryogenic insulation. Wu et al. [5] selected six different sample cell sizes to investigate the thermal conductivity of polyurethane foam with the external pressure ranging from 101,325 Pa to 1.86 Pa. The experimental results showed that the effective thermal conductivity of polyurethane foam decreases as the decrease of cell size. It also turned out that while the external pressure was decreasing, the solid conduction had a larger proportion. Due to the flight cost and limited orbital experiments, both the thermal conductivity of foam and MLI were measured on the multipurpose liquid hydrogen test bed by NASA in 2001 to simulate the space condition [6]. With foam attached on LH_2 tank and covered with MLI, the insulation performance of foam during ground hold and ascent flight conditions were tested. After several ground experiments, it showed that SOFI has successfully prevented the purge gas liquefaction and the expected ground hold heat leak was 63.00 W/m². While it reduced to 0.22 W/m² for the orbit hold tests with the warm boundary temperature of 305 K. Fesmire et al. [7] conducted the cryostat thermal performance test on a 1.0 m-long SOFI specimen of BX-250 material, with a 51-mm thickness and a density of 38 kg/m³. The test experiments showed that for high vacuum to 1.33 Pa, the thermal conductivity of SOFI has a sharp increase with the gas conduction being the dominate heat transfer mode. While the soft vacuum ranges from 13.3 Pa to 1.33×10^4 Pa, free convection becomes the dominant mode of heat transfer. The related thermal conductivity rises slightly. While the soft vacuum is larger than 1.33×10^4 Pa, the thermal conductivity of foam increases moderately due to increased convection within small defects inside the foam. To address the application of SOFI on future launch vehicles, Fesmire et al. [8] investigated the thermal performance of SOFI by using laboratory standard liquid nitrogen (LN_2) boil-off apparatus. The influence factors, including heat transfer temperature difference, moisture and test pressure range were measured and analyzed with the temperature difference of 200–260 K through the 25 cm thickness insulation. It showed that moisture taken into the foam should be considered in detail, which would cause large influences on the insulation performance of foam. Afterwards, Fesmire et al. [9] measured the rigid polyurethane foam under cryogenic conditions and selected three different materials to determine the thermal performance and moisture uptake of foam. It showed that the water vapor was driven into the subsurface due to the extreme thermal gradient, with the final result of water being accumulated in the closed polyurethane foam. With SOFI used on the cryogenic fuel storage tank, the effective thermal conductivity of NCFI 24-124 foam was measured by Barrios and Van Sciver [10]. With the test boundary temperature in the range of 20–300 K, the related thermal conductivity ranges from 0.002 W/(m·K) to 0.1 W/(m·K). Meanwhile, the results showed that the residual gas and condensation have significant effects on the thermal conductivity of SOFI at low temperature. Xue et al. [11] experimentally studied the insulation performance of SOFI and MLI by conducting boil-off tests with LOX under different cold and hot boundary temperatures. Based on their calculations, the evaporation rate during the orbital flight phase could be realized with the 6 cm thickness SOFI + MLI. With a