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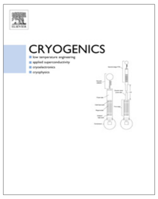

Experimental study of moisture uptake of polyurethane foam subjected to a heat sink below 30 K

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ABSTRACT

Rigid closed-cell foam is widely used to thermally insulate liquid hydrogen and oxygen tanks of space launch vehicles due to its lightweight, mechanical strength and thermal-insulating performance. Up to now, little information is available on the intrusion of moisture into the foam that subjects one side to liquid hydrogen temperatures and the other side to room temperatures and high relative humidity. A novel cryogenic moisture uptake apparatus has been designed and fabricated to measure the moisture uptake into the polyurethane foam. For safety and convenience, two identical single-stage pulse tube cryocoolers instead of liquid hydrogen are used to cool one side of the foam specimen to the lowest temperature of 26 K. Total of eight specimens in three groups, according to whether there is a butt-joint or weathering period, are tested respectively for both 5 h and 9 h. The additional weight due to moisture uptake of the foam for the 26 K cases is compared to previous measurements at 79 K. The results are instructive for the applications of foam to the insulation of liquid hydrogen tanks in space launch vehicles.

1. Introduction

It is a must to provide good thermal insulation for the liquid hydrogen (LH_2) and liquid oxygen (LO_2) tanks on the space launch vehicles to avoid the large boil-off losses. The launch vehicles of CZ-3A and CZ-3B Serials in China [1] use polyurethane (PU) foam with CFC-11 as the blowing agent, while the ARIANDE 5 launcher uses the Polyvinyl Chloride (PVC). The polymethacrylimide (PMA, also known under the trade name Rohacell) foam was reported [2] for the potential usage in the high-speed reusable aircraft with comparable insulation performance to PU foam. The applications and properties of the PU rigid foam is introduced in Ref. [3].

The thermal properties of this foam at different temperatures are definitely the main concern, and have been widely investigated theoretically and experimentally in the past decades. It is recognized that heat transfer through the foam insulation occurs by conduction through the solid matrix and gas as well as by radiation through the whole medium [4,5]. Several models have been developed to predict the effective thermal conductivity, including the geometrical cell model by Placido et al. [4], and the analytical model by Tseng et al. [6]. In the experimental aspect, the thermal diffusivity of rigid PU foams blown with different hydrocarbons was measured by Prociak et al. [7] for calculating the effective thermal conductivity. Tseng et al. [6] tested the conductivity of PU foam with R-141b as the blowing agent in the temperature range from 20 to 300 K based on a two-stage GM cryocooler. The results indicated that the thermal conductivity of the PU foam can be reduced by as much as 70% by evacuating the gases in the foam cells. The thermal conductivity of PU foam designed for ARIANE 5 Launcher is experimentally determined by Fischer et al. [8] at 80 K and 20 K by using the LN_2 and LH_2, respectively. Recently, Barrios et al. [5,9] compared the thermal conductivity of foam for four cases: “as received”, evacuated, conditioned and helium intrusion in the temperature range from 30 K to 300 K. The results verified that the residual gas inside the foam has a predominant effect. The conditioning process with one side at 78 K, which incurs moisture absorption, has little effect on the effective conductivity at the temperatures over 80 K.

In fact, when the foam is exposed to a high-humidity environment and an applied large temperature gradient for a period, it seems to be inevitable that water penetrates into the foam by vapor condensation. As a result, it may degrade the thermal performance and significantly increase the undesired weight. Therefore, it is necessary to determine the amount of water/ice taken into the foam insulation under practical cryogenic conditions of the space vehicles. Unfortunately, less attention has been paid on the effects of moisture uptake and condensation, in particular at cryogenic temperatures. The weight-based amount of water can be surprisingly high, approaching as much as ten times the dry sample

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reported for the expanded bead polystyrene foam (EPS) under near-ambient conditions [10]. Martyn et al. [11] reported the rate of water uptake for the aged PU foam with commercial formulations for nearly one month test period, under the conditions of 273 K on one side and 323 K and 75% RH on the other side. They found that the water content increases linearly with time and the final weight increases over twofold. At the cryogenic conditions, the moisture uptake will be even serious as the cryo-pumping effect is strengthened. Fesmire et al. [12] experimentally verified that the potential added lift-off weight is in the range of 1134–1633 kg with the mass of foam of 2200 kg on the space shuttle external cryogenic tank, for an on-time launch and substantially more weight penalty for a 24-h scrub turnaround and launch. The present authors have built a cryogenic apparatus for the measurement of the moisture uptake of the rigid PU foam at LN_2 temperatures [13]. We explored the effects of the surface thermal protection layer, the thickness, exposed time, cracks and the material density.

The moisture uptake processes are rich in physics. An impressive progress on water uptake mechanism was made recently by Vanderlaan et al. [14], who firstly obtained the 3D images of water content in the conditioned foam samples using the method of MRI. Here, "conditioned" means the sample was launch pad conditioned in a rig that subjects one side to 34 ± 2 °C and >75% RH air and the other side to 77 K for either 9.5 or 69 h. The results demonstrated that the water content is mainly accumulated in the warm half for the 9.5 h cases, while it extends to about 80% of thickness for the 69 h cases. In consideration of the fact that the moisture uptake is mainly driven by cryopumping effects, which will be stronger as the temperature gradient is further enlarged. However, little information is now available on the intrusion of moisture into the foam material under liquid hydrogen (LH_2) temperatures.

This study dedicates to experimentally determine the moisture uptake of the PU foam specimens with the temperature on one side below 30 K. The PU foam was produced by Aerospace Research Institute of Materials and Processing Technology (ARIMT) of China. Two home-made single-stage pulse tube cryocoolers (PTC) in parallel with a cooling power of 15 W/20 K [15] each are used as the heat sink. On the other side, 303 ± 0.5 K and >95% relative humidity (RH) are maintained by using a positive temperature coefficient heater and the ultrasonic humidifier, respectively. A special fabrication was designed to minimize the heat leak to the PTCs from the ambient. The comparison of moisture uptake at 26 K and 79 K [13] is made and analyzed.

2. Materials and experimental apparatus

The tested materials and insulation structure are the same as the descriptions in our previous paper [13]. For completeness, a concise introduction is given here. The insulation structure consists of buffer layer, foam insulation layer and thermal protection layer from the tank wall outward. The buffer layer is actually a thin layer of epoxy cryogenic glue. The rigid foam layer is formed by a spray-on method with the machined thickness of 20 mm and density of about 48 kg/m^3. It has anisotropic closed-cell morphological structure with the cell diameter of about 60 μm. The outer surface of the foam layer is adhesively bonded by a thermal protection layer, which is a thin laminate of Kapton–aluminum–Kapton (KAK) and glass cloth.

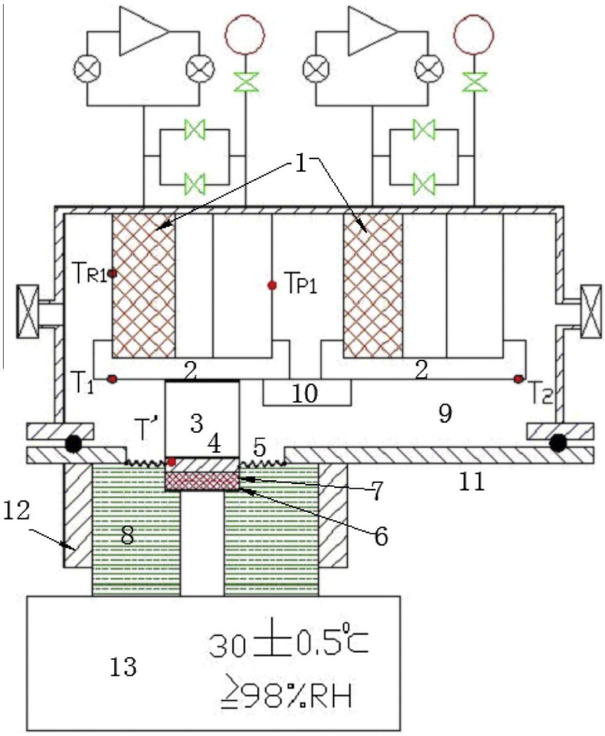

Fig. 1. Schematic of apparatus for moisture uptake of foam cooled by two pulse tube cryocoolers. (1) Pulse tube cryocooler; (2) Cold end; (3) Copper stem; (4) Copper disk; (5) Corrulation plate; (6) O-rings; (7) Specimen; (8) Support; (9) Vaccum; (10) Copper block; (11) Bottom plate; (12) LN_2 reservior; (13) Ambient temperaturn chamber (ATC).

Fig. 1 shows the schematic of the test apparatus, which mainly consists of three parts: the upper cryogenic system, the middle specimen fixing system and the below ambient temperature chamber (ATC). The cryogenic system mainly comprises two identical single-stage GM type PTCs, an oxygen-free copper stem, a corrugation plate and a vacuum chamber. Two cold ends (2) are thermally bridged by a copper block (10). Indium films are filled between the copper block and each cold end for good thermal contact. The vacuum chamber consists of the above cuboidal cover and bottom plate (11), which are seal connected by a Teflon gasket instead of the O-ring, in consideration of the possible low temperature on the bottom plate. It is a challenge to transfer heat to the cryocoolers, which are installed in a vacuum chamber. A copper stem (3) with diameter of 80 mm and length of 40 mm is employed to connect the cold end (2) and a copper disk (4) with thickness of 8 mm and diameter of 80 mm. The contact surfaces of the copper stem are also covered by indium films in order to decrease the contact thermal resistance. Considering the thermal contraction during the cryogenic operation and also to decrease the conductive heat losses, a thin-wall corrugation plate (5) made of 304 stainless steel is specially designed and soldered with the copper disk (4) and the bottom plate. The corrugation plate can vertically move up and down slightly and withstand the pressure difference between the ambience and the vacuum.

The temperatures in each PTC cold end (T_1 and T_2) and middle of the regenerator (T_{R1}) and the pulse tube (T_{P1}), as well as the copper disk (T') are measured by calibrated Rh–Fe resistance temperature sensors with accuracy of 0.1 K. Specifically, a short trough is made on the upper surface of the copper disk (4) to hold the sensor. The surface below the copper disk is relatively lower about 3 mm than the wave crest of the corrugation, to guarantee the specimen can be always pressed on the disk tightly.

It is necessary to minimize the heat leak through the fixing structure of the specimen in order to reach cryogenic temperatures. The heat leak is primarily due to: (a) the conduction in the vertical direction through the tested foam specimen (7); (b) the conduction in the radial direction through the corrugation plane (5) to the central copper disk (4); (c) the convective heat transfer