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Experimental study on composite insulation system of spray on foam insulation and variable density multilayer insulation

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HIGHLIGHTS

- Composite insulation system of SOFI and MLI/VD-MLI has been analyzed.
- The measured heat flux of VD-MLI is lower than that of MLI by 17.49%.
- Lockheed method needs to be improved in solving the temperature distribution.

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ABSTRACT

The composite insulation system of spray on foam insulation (SOFI) and multilayer insulation (MLI)/variable density multilayer insulation (VDMLI) is regarded as the most promising insulation system for cryogenic propellant in space application. In this paper, the composite insulation system composed of SOFI and MLI/VDMLI is studied in theoretical analysis and experimental testing. A test bed has been built to test the insulation performance of the insulation system. Heat leakage and temperature distribution of the insulation system were measured and analyzed. Theoretical calculation was carried out by "Layer by layer method" and "Lockheed method". Composite insulation system was tested with simulated fluid of liquid nitrogen in high vacuum condition and atmospheric pressure condition, respectively. The test results show that the thermal resistance of SOFI accounts for only 0.12% of the total thermal resistance in high vacuum condition experiment, while 45.37% in atmospheric pressure condition experiment. With 50 layers of reflector, the measured heat leakage of VDMLI is lower than that of MLI by 13.57%, and heat flux decreases by 17.49%. By comparing the experimental results and the calculated value, it can be found that Lockheed method and Layer by layer method are suitable for calculating heat flux through MLI, but need to be improved in solving the temperature distribution.

1. Introduction

With advantages of large thrust, non-toxic and pollution-free, liquid hydrogen (LH_2) and liquid oxygen (LO_2) are regarded as the most promising propellant. Due to the characteristics of low boiling point and ease of evaporation, LH_2 and LO_2 are difficult to store in long-term and mainly used in the upper stage engine of rockets [1–3]. In the future deep space exploration mission, cryogenic propellant is not only to meet the need of short time launch mission, but also to meet the need of long-term on orbit storage. Research on insulation system used in on orbit storage of cryogenic propellant is of great significance for deep space exploration [4]. Future deep space exploration is an urgent need for zero boil-off (ZBO) . The excellent thermodynamic performance of the insulation system is the prerequisite for the realization of ZBO [5].

The composite insulation system of SOFI and MLI is regarded as the most promising insulation system for storage of LH_2 and LO_2 [6]. SOFI plays an important role in the atmospheric pressure state of the ground period, which is sprayed on the wall of the tank. MLI consists of reflector with highly reflecting radiation and insulator with low thermal conductivity. MLI plays a major role in high vacuum state of the orbiting period.

In this paper, the composite insulation system composed of SOFI and MLI is studied in theoretical analysis and experimental testing. For reasons of experimental safety and cost, liquid nitrogen (LN_2) is chosen as test fluid in the experiment.

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Nomenclature

C_g	empirical parameters
C_r	empirical parameters
C_s	empirical parameters
C_0	black body radiation coefficient, 5.67 W/(m^2 K^4)
C_1	empirical parameters
C_2	empirical parameters
D^*	density of spacer materials
A_e	effective area, m^2
f	relative solid density of spacer material;
K	apparent thermal conductivity, W/(m^2 K)
K_g	gas conduction coefficient, W/(m^2 K)
K_r	radiation coefficient, W/(m^2 K)
K_s	solid conduction coefficient, W/(m^2 K)
K_{SPA}	thermal conductivity of spacer material
K_{SOFI}	apparent thermal conductivity of SOFI
L	thickness, mm
L_{REF}	thickness of reflector, mm
L_{SPA}	thickness of spacer, mm
M	mass, kg
n	number of MLI reflector, 1
P	pressure, Pa
P^*	vacuum degree, torr
Q	heat leakage, W
V	volume of the tank, 55 L
q	heat flux, W/m^2
q_v	evaporation flow, mL/min
q_s	heat flux of solid conduction, W/m^2
q_r	heat flux of radiation, W/m^2
R	thermal resistance, m^2 K/W
r	latent heat of liquid nitrogen
T_H	temperature of the hot boundary, K
T_C	temperature of the cold boundary, K
x	layers of spacer between adjacent reflector
Y_1	empirical parameters
Y_2	empirical parameters
Y_3	empirical parameters
z	Layer density of reflector, 1/mm
ε	total hemispherical emissivity
ε_H	emissivity of reflector material near hot wall;
ε_C	emissivity of reflector material near cold wall
σ	Pan Stefan Boltzmann constant
η	daily evaporation rate
Θ	thermal adaptation coefficient
τ	time, 24 $*$ 60 min
ω	empirical parameters
SOFI	spray on foam insulation
MLI	multilayer insulation
VDMLI	variable density multilayer insulation
REF	reflector
SPA	spacer
LNSE	liquid nitrogen storage experiment

2. The test bed and composite insulation system

2.1. The test bed

A test bed for the storage of cryogenic liquid has been built, and the insulation performance of different insulation schemes can be tested. Heat leakage and temperature distribution in different positions of the insulation system can be measured and analyzed. The test bed can be divided into four parts: the vacuum chamber, the vacuum and temperature control system, the tank and outlet pipe and the measurement system. Schematic of the test bed is presented in Fig. 1.

The vacuum chamber consists of stainless steel inner chamber and outer chamber, possessing an interlayer through which fluid can flow. The chamber can support the tank by a steel tube and provide an external environment for the tank with constant ambient temperature and specific vacuum degree. The vacuum and temperature control system consists of vacuum pump units and water-bath. Vacuum pump is connected with the inner chamber. Vacuum degree in chamber can be as high as 6×10^{-4} Pa. The water-bath is connected with interlayer of chamber, and wall temperature can be maintained at a constant value between 273 and 323 K. Measured temperature difference at different positions of the chamber is below 0.3 K in 24 h.

The aluminum alloy (AL2219) tank is spherical and cylindrical in shape with a volume of 0.055 m^3 and a surface area of 0.74 m^2. To simulate on-orbit state, LN_2 in tank was maintained at steady state of 0.6 MPa (96.38 K) in the experiment. In order to shield the solid heat conduction from the neck between the tank and chamber, a heat exchanger (EH I) was set on the neck and its temperature is controlled with the same as the top of the tank by adjustable cold nitrogen flow. Temperature control accuracy of EH I is less than 0.5 K.

Heat leakage of composite insulation system was obtained by static method. The flow rate of nitrogen gas in the tank can be measured by mass flow meter. Platinum resistance thermometers were set at different locations to measure the temperature distribution in insulation system. The vacuum degree of the chamber was measured and recorded by resistance gauge and ionization gauge of compound vacuum gauge. Pressure of cryogenic fluid in the tank and gas at different locations in outlet pipe can be measured by pressure sensors with different measuring range. Main instrument parameters of measurement system are presented in Table 1.

2.2. Composite insulation system

Composite insulation system consists of SOFI and MLI/VDMLI, as shown in Figs. 2 and 3. In the experiment, rigid polyurethane foam is robotically covered on the wall of the tank with an average thickness of 15 mm. The closed cell proportion of SOFI is 98%.

In MLI and VDMLI, double-aluminized polyester foil and non-woven polyester are used as reflector and spacer, respectively, whose parameters are presented in Table 2. In order to reduce operating time, MLI material was previously processed into several modules, and every module contained 10 layers of reflector and corresponding spacer. In VDMLI, density of reflector was adjusted by layers of spacer [7,8].

2.3. Test method and measurement

In the experiment, the vacuum and temperature of the outside of the tank are the two most important physical quantities. The external temperature of the tank was controlled and kept constant by the water-bath. The vacuum degree of the vacuum chamber was controlled by a vacuum pump and maintained at above 6×10^{-4} Pa. For fill level, in each experiment, the tank was filled with liquid nitrogen, and the volume of liquid nitrogen in the tank (55 L) was not less than 52 L to avoid the interference of fill level on the experimental results.