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Design and analysis of liquid hydrogen storage tank for high-altitude long-endurance remotely-operated aircraft

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ABSTRACT

Liquid hydrogen is seen as an outstanding candidate for the fuel of high altitude, long endurance unmanned aircraft. The design of lightweight and super-insulated storage tanks for cryogenic liquid hydrogen is since long identified as crucial to enable the adoption of the liquid hydrogen. The basic structural design of the airborne cryogenic liquid hydrogen tank was completed in this paper. The problem of excessive heat leakage of the traditional support structure was solved by designing and using a new insulating support structure. The thermal performance of the designed tank was evaluated. The structure of the tank was analyzed by the combination of the film container theory and finite element numerical simulation method. The structure of the adiabatic support was analyzed by using the Hertz contact theory and numerical simulation method. A simple and effective structure analysis method for the similar container structure and point-contact support structure was provided. Bases for further structural optimization design of cryogenic liquid hydrogen tank were provided also. Research results showed that: the insulating support can reduce the heat leakage of the support structure more than 85%, while the maximum stress of point-contact supports structure can be 9 times larger than conventional support structure; the tank designed in this paper can meet the structural and thermal requirements for aerospace applications.

Introduction

With the "Global Hawk" coming out, the role of high altitude, long endurance (HALE) unmanned aeronautic vehicles (UAVs) in the military field is highlighted. Hydrogen contains 2.8 times more energy than kerosene for the same weight [1,2]. The mass of the fuel will therefore reduce with approximately the same ratio for a given mission and pay load [3]. Therefore, the liquid hydrogen (LH_2) is an ideal fuel for long-endurance UAVs. The Americans have taken off the hydrogen fuel powered flight UAV "Global Observer" and "Phantom Eye" in 2010 and 2011 respectively, and the cruising time of them are up to 4 days and 7 days separately [4], while the longest cruising

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time record of ordinary fossil fuels powered UAV is only 41 h created by "Global Hawk". The comparison shows the use of LH_2 fuel can greatly improve the cruising time of UAVs.

H_2 has been considered as an aviation fuel in various research projects from as early as 1918 [5]. Whereas the bulk of the studies were theoretical [6–10], flight tests were conducted in the 1950s using a B-57 airplane and in the 1980s using an experimental Tupolev Tu-55 aircraft, which is a modified Tu-154 [11]. During 2005, AeroVironment built and tested the world's first LH_2 powered UAV successfully, which is one of the pioneers in HALE UAV with development of 150 feet wingspan Global Observer HALE aircraft on their merits. The prototype demonstrated the robustness and the practicality involved in enabling the concept of a Global Observer Operation System [12].

The feasibility of lightweight, insulated cryogenic tanks has been identified as a key technical enabler for hydrogen fueled flights since research into the use of H_2 for aviation started [10]. The volume of LH_2 is 4 times of the conventional aviation fuel and LH_2 tank needs to meet the differential pressure and insulation requirements for airborne applications [1,13]. Even nowadays, the design and development of durable, light and super-insulated tanks is still considered as one of the crucial technical challenges confronting the use of LH_2 for airborne applications [6,7,14,15].

Researches of National Aeronautics and Space Administration (NASA) showed that the support structure of the traditional tank has the maximum heat leakage [16–19]. In this paper, basic structural design of liquid hydrogen storage tank was completed in terms of structure, shape and material, and then the basic configurations were determined. The thermal model was established to calculate the thermal performance of the tank. By designing and using an insulating support structure, the heat leakage of the support structure was reduced by more than 85%. Structural strength of the tank was calculated by film theory and checked by the numerical simulation of ANSYS. The Hertz contact theory and ANSYS finite element simulation were applied to analyze the insulating support structure respectively and the results were compared. Finally, a mechanical tensile strength experiment was conducted to further check the strength of the support structure. The results showed that the analysis method and the design of the tank are feasible. In addition, a simple and practical method for the structural analysis of similar structures was provided.

Configuration design

Shape

Adiabatic tanks are generally spherical or cylindrical [2]. Compared to the spherical tank, the cylindrical tank has a larger surface area with an equal capacity, while the pressure inside the cylindrical tank is greater and not equally distributed, so a cylindrical tank requires a larger and thicker wall [1]. What's more, the cylindrical tank needs to minimize sloshing in order to ensure the weight balance of the whole length. These factors cause the mass of cylindrical tank greater than the spherical tank. Therefore, the spherical tank will be better than a cylindrical tank if is installed inside the aircraft and the fuselage can accommodate it.

Structure

As LH_2 is stored at cryogenic conditions near its boiling point, super-insulated cryogenic tanks should be used to store the LH_2 in order to reduce the vaporization of hydrogen. The combined use of the high vacuum Multi Layer Insulation (MLI) and a Vapor-Cooled Shield (VCS) under high vacuum has been proposed as the best configuration to reduce heat leakage effectively [20], so the double vacuum jacket structure with a spiral pipe embedded was used. The spiral pipe acts as a VCS since it decreases heat leakage and boil-off losses significantly [21]. For the adiabatic vacuum jacketed tank, the support structure has the most significant heat leakage [16]. Therefore, a new insulating support structure was used to connect the liner and the shell in this paper. As shown in Fig. 1 and Fig. 2, the interior liner is fixed by point contact between the gasket, tank shell and balls. The contact thermal resistance of the flat-ball model can be estimated using the following formula [22]:

$$R_c = \frac{1}{2a\lambda_c} \tag{1}$$

Where R_c is the contact thermal resistance; a is the contact radius whose value is given in Section 3.1 and λ_c is the harmonic thermal conductivity of the ball and gasket.

Assuming that only four of the eight support structures are tensile or compressive, calculation results showed that the total thermal resistance of each support structure is $R_1 = 759.3(\mathrm{W/K})^{-1}$.

If using the boom or pull rod as support structure, when the length of the rod is 50 mm and the diameter is 8 mm, the heat leakage of this structure is 9.6 times more than that of the insulating support, namely, the heat leakage at the adiabatic support structure is reduced by more than 85% on account of the reduction of the contact area between the support structure and the liner. The new support structure also has an advantage in weight and space. Furthermore, it meets the requirements of the movable liquid hydrogen storage tanks for compact structure.

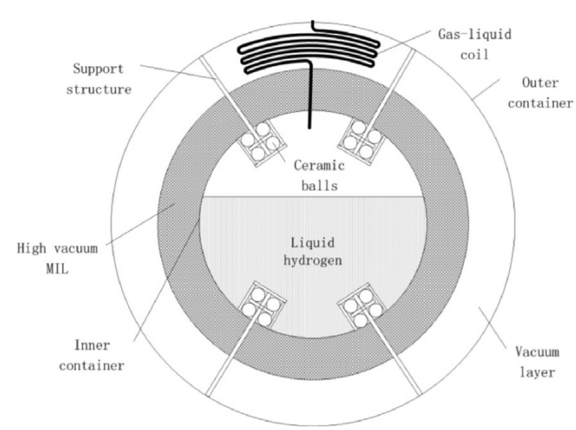

Fig. 1 – Schematic diagram of cryogenic liquid storage tank.