ZERO-BOIL-OFF LIQUID HYDROGEN STORAGE TANKS

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Abstract

Using densified liquid hydrogen as a cryogenic propellant for launch vehicle applications can reduce fuel tank volumes, decrease vapor pressures, and improve cooling capacity over the normal boiling point propellant. A densified liquid hydrogen test bed has been developed using Gifford-McMahon cryocooler to refrigerate hydrogen inside the 150L storage tank at the Florida Solar Energy Center (FSEC). The test bed has an integrated refrigeration and storage system with multiple capabilities including hydrogen liquefaction, densification, and zero-boil-off (ZBO) storage test. The test bed has successfully demonstrated hydrogen liquefaction and densification processes at 16.5K followed by long term ZBO liquid hydrogen storage. This report contains the design considerations, the detailed system descriptions, and the results obtained during initial hydrogen liquefaction, densification and ZBO storage tests.

Introduction

The Florida Solar Energy Center and NASA Kennedy Space Center have performed collaborative research processes for increasing the density of cryogenic propellants for launch vehicle applications. Technologies that provide for the densification, conditioning, transfer and storage of cryogenic propellants can reduce gross lift-off weight of a launch vehicle by up to 20% or increase its payload capacity[1]. By using densified propellants, one can expect reduced external tank volumes, decreased vapor pressures, and increased enthalpy gain before boil off. NASA Kennedy Space Center has years of experience handling cryogenic propellants, but all with saturated liquids. This work focuses on using existing cryogenic technology to densify hydrogen, and developing a test bed where densified propellant handling techniques can be researched. Various research efforts for the development of densified propellants technology in NASA are reviewed in previous report by the same author [2-3].

FSEC and NASA KSC have designed the hydrogen densification system, and Cryogenic Technical Services (CTS) of Longmont, Colorado fabricated and delivered it to the FSEC in late 2003. In addition to the test bed, various data acquisition systems, power and water utility lines, emergency hydrogen vent line and remote alarm system were prepared to start running the system in safe environment. As a preliminary densification test, a nitrogen liquefaction and densification test was performed to exercise subatmospheric operating condition for subcooled cryogen. Then, the hydrogen densification test bed successfully demonstrated hydrogen liquefaction and densification as well as ZBO storage test. This report includes the test bed design considerations, the detailed system descriptions, major experimental results of the hydrogen densification and ZBO storage test, and future research plans will be also discussed later.

Hydrogen Densification Test Bed

Design Considerations

To achieve demonstration goals of hydrogen liquefaction, densification and ZBO storage test with limited cryocooler cooling power available, various thermal and mechanical design considerations were required at the initial design stage. The volume of inner storage vessel was limited to 150 Liter by the facility safety regulation code. The aspect ratio of the vessel was optimized by vessel material, operating temperature, thermal analysis of heat conduction and radiation heat transfer from ambient. Heat pipe technology was selected to extend the cold head of cryocooler down to the bottom of storage vessel. Operating temperature, pressure and thermodynamic properties of working fluid in the heat pipe can provide heat pipe design parameters such as material choices and dimensions. A couple of bundles of copper braids at the bottom of the heat pipe were considered to increase surface area so that more efficient heat exchange between hydrogen and heat sink can be expected. Pressure build-up unit (PBU) was employed to control internal vessel pressure by evaporating stored liquid hydrogen without any vent loss. It also allows self-pressurization of the system in a short period of time to drain and/or transfer stored liquid hydrogen to other storage tanks and applications. The top plate of the vessel and its dewar necks were designed to maximize reconfiguration flexibility with flanged connections on the cryocooler interface and the outer vessel. This design allows full access to reveal components such as the cryocooler cold head, heat pipe, and copper braids structures out of the vessel when repairs and future modifications are needed. Thermal insulation design was one of the most important issues to minimize heat loads on the system. Sophisticated design efforts in dewar necks, inner vessel support, baffles, instrumentation lines, fluid supply and drain lines, valves, and appropriate use of multilayer insulations minimized heat loads on the cryocooler.

System Descriptions

The hydrogen densification test bed consists of cryocooler, helium compressor for cryocooler, 150 L double-walled vacuum jacketed cryostat, LN_2 precooler bath, vacuum pump system, gas supply and vent lines, vacuum jacketed liquid hydrogen supply and drain line, and data acquisition system. FIGURE 1 depicts various components of the test bed.

The cryocooler constitutes the heart of the hydrogen densification test bed. Cryomech AL-330 single-stage Gifford-McMahon(G-M) cryocooler was selected and installed on the top of the storage vessel. It has an expected cooling capacity of 40 W at 20 K and 25 W at 15 K [4]. The water-cooled type helium compressor uses 7 kW of power and provides 2 MPa of helium gas to the G-M cryocooler. The cryostat has been designed to store 150 L of densified liquid hydrogen in its inner stainless steel tank with additional ullage space. To minimize convective heat transfer between inner vessel and outer jacket, a combination of mechanical and turbo molecular vacuum pumps generates 10^{-6} Torr of high vacuum. Total loss including radiation, conduction through the support structure and instrumentation lines is estimated to less than 8.3W at 15 K. TABLE 1 shows the detail of heat loads estimation on the cryocooler.

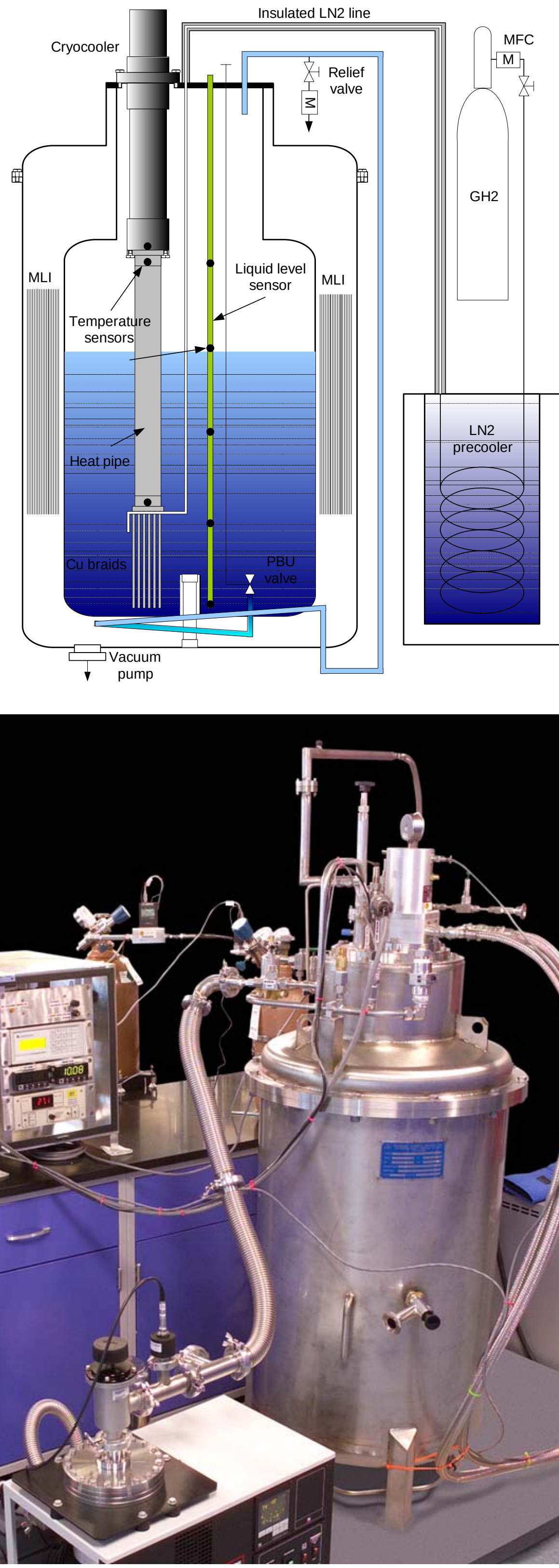


FIGURE 1. A 150L liquid hydrogen densification and zero-boil-off storage system at FSEC.

TABLE 1. Heat loads estimation on the cryocooler at 15K

Component	Heat Load
MLI	2.2 W
Instruments	2.7 W
Support	0.3 W
PBU line	0.1 W
Other lines	3 W
Total	**8.3 W**

The entire assembly is designed to be easily modified, if needed, with flanged connections on the cryocooler interface and the outer jacket. Since the cold head of the cryocooler is not long enough to reach the bottom of the storage tank, a heat pipe is used. The heat pipe is located at the bottom of the cold head and extends the cryocooler cold head to the bottom of the inner vessel. This pipe uses hydrogen gas as working fluid. Three silicon diode temperature sensors are installed on the cryocooler cold head, top and bottom end of the heat pipe, respectively. A gas supply line is wrapped around the bottom of the heat pipe so that supplied gas can be precooled, liquefied and densified at heat pipe temperature. Also, more than 2,500 pieces of thin copper braids per bundle are attached to the bottom of the heat pipe to increase the contact surface between heat pipe and fluids.

One capacitance-type liquid level sensor (AMI, Model 185) is installed to measure liquid level in the storage tank. Also, five calibrated silicon diode sensors are installed on a 0.75m long fiber glass tube along the vertical axis of the storage tank to provide vertical temperature profiles in the tank.

A pressure build-up (PBU) unit controls internal pressure by evaporation of stored liquid without any vent loss. The PBU unit consists of a cryogenic valve, a pressure regulator and evaporation coils at the bottom of cryostat. Opening the PBU valve allows stored cryogenic liquid to be evaporated in the PBU coil by exchanging heat with ambient temperature. It results in an increase of storage tank pressure without imposing any external pressure.

A vacuum-jacketed cryogenic liquid transfer line mounted on the top flange supplies cryogen to the storage tank or drains liquid out of the storage tank. Using an additional gas supply line and the PBU unit, one can easily transfer cryogenic liquid into or out of the storage tank. An adjustable relief valve, a rupture disk and a manual venting valve are installed in the gas supply line, PBU coil and manual vent manifold for operational safety and emergency vent process. The relief valve and the rupture disk are set to 412(= 45 psig) and 446 kPa (= 50 psig), respectively to prevent the system from over-pressurization. FIGURE 2 depicts various system components installed at the top and bottom of the heat pipe area, and detailed configurations of each component are listed in TABLE 2.

TABLE 2. Summary of system configurations

Component	Material	Dimension (OD x H or L)
Inner vessel	SA 240 304	0.51 m x 0.91 m
Outer vessel	SA 240 304	0.61 m x 1.14 m
Heat pipe	SA 269 304	0.07 m x 0.68 m
Support	G-10/11	35 mm x 159 mm
Braids	C110(ETP) copper cable	0.254 mm x 178 mm x 2500 strands x 6 bundles
Insulation	MLI	40-45 layers

In the test bed, various sensors are installed to study the thermo-physical behavior of densified hydrogen. Three pressure transducers measure the inner storage vessel, annular vacuum space and heat pipe pressure. Low and high vacuum gauges depict the pressures of the mechanical and turbo molecular vacuum pumps. Two mass flow meters installed at gas supply and vent lines measure the rate of liquefaction and heat leak rate. Eight temperature sensors measure the liquid level stored in the tank, cryocooler cold head temperature and heat pipe temperatures. Signals from these instruments are sent to National Instrument Field Point data acquisition modules. A Labview 7 Real-time module performs all the real-time data processing, display and storage of the data on a PC. All data acquisition Field Point modules can be monitored and controlled by intranet and internet network connections from any remote location.

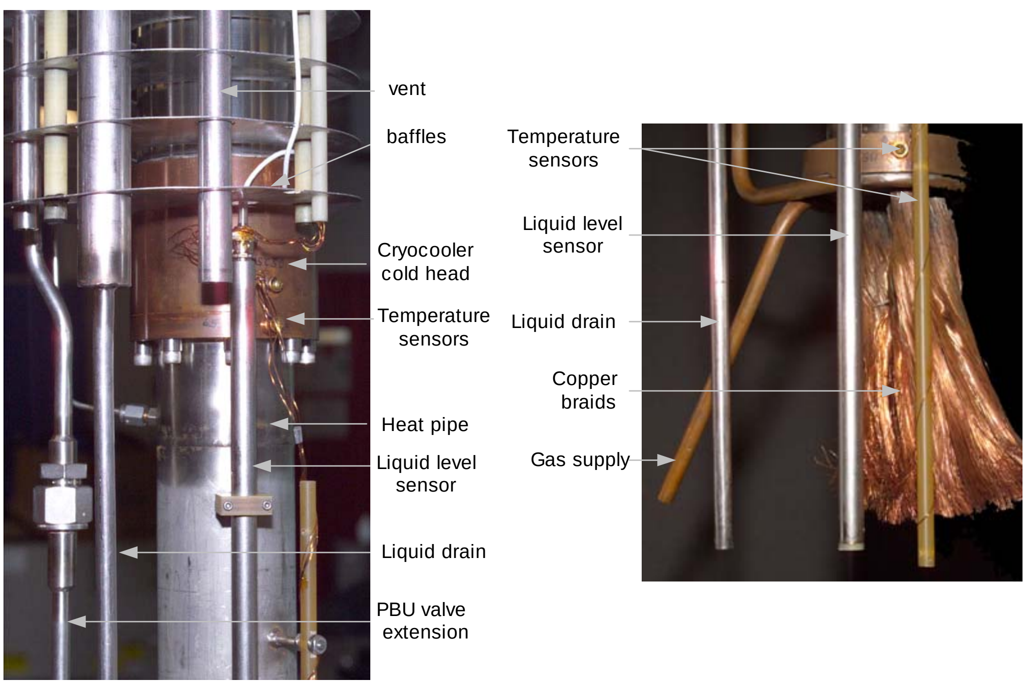


FIGURE 2. Component arrangements at the top and bottom of the heat pipe in detail.

Test Descriptions

The test bed needs multiple purge processes to remove any impurity through the entire system before the cryocooler starts. The heat pipe, the inner vessel and every flow path in the system has to be purged by 200 kPa dry nitrogen gas, and evacuated to 10^{-4} Torr of high vacuum. The test starts with a chill down process using LN_2 to cool the inner vessel to save cool-down time, as opposed to using the cryocooler refrigeration power. At the start of the test, all valves on the system are closed, and a portable 160 L LN_2 dewar is connected to the liquid fill & drain line. LN_2 supply begins while the system manual vent valve is opened. The LN_2 supplied through a vacuum jacketed transfer line cools the inner vessel and the heat pipe down to about 77 K in a short period of time. After the inner vessel pressure becomes stable, the LN_2 stored is drained to LN_2 precooler bath for future use to precool ambient hydrogen gas.

Once LN_2 is drained, the system experiences multiple purge processes again to remove the liquid nitrogen and residual cold nitrogen gas using gaseous helium and vacuum pump. After the purge process, the heat pipe is charged with hydrogen gas up to pre-determined pressure or mass. The amount of hydrogen charged in the heat pipe is obtained from pressure-volume-temperature relations of hydrogen and mass conservations. In this test, 5.6g of hydrogen which corresponds to 20 mm liquid level of 16K densified liquid hydrogen in the heat pipe is charged. After the heat pipe is charged with required amount of gas hydrogen, the cryocooler starts its operation. Within an hour, the lower heat pipe temperature completes its cooldown to ~15 K. The temperature differences between the cold head and the heat pipe end is approximately 0.7 K, which is very efficient considering there is thermal contact resistance between the top of the pipe and the cold head, and thermal resistance down the length of the pipe. The inner vessel pressure remains below 10^{-5} Torr because of cryopumping effect on the cold head and the heat pipe surfaces. The cold head temperature often shows temperature oscillations of a magnitude near 1.5 K, which are damped out by the thermal mass of the heat pipe.

Hydrogen gas at room temperature is slowly introduced into the vessel through the LN_2 precooler bath, and its mass flow rate and pressure increases are recorded. The introduced gaseous hydrogen flows through the coiled copper tube soldered at the bottom of the heat pipe, releases heat to the lower heat pipe, and then becomes cold gaseous and/or liquid hydrogen. Also, the copper braids soldered at the bottom of the heat pipe enhance heat transfer between the lower heat pipe and hydrogen. The temperature and pressure profiles are driven by the mass flow rate into the vessel, since the enthalpy from the warm gas introduces the energy in the system while the cryocooler tries to remove this thermal energy. Accurate control of the mass flow rate of gaseous hydrogen is important to maintain the inner vessel pressure below 273.7 kPa (= 25 psig) for safe operation.

Results and Discussions

Hydrogen Liquefaction and Densification Test

The cryocooler refrigerates hydrogen gas, and in turn, the natural convection effect of the cold gas cools the inner storage vessel until it becomes sufficiently cold enough to

TABLE 3. Comparison between densification rate estimations and test results.

Cold head temperature	Cooling power	Densification rate without LN_2 precooling	Densification rate with LN_2 precooling
15K	25W	4.9 L/day	17 L/day
16.5K, estimation	30W	6.5 L/day	23 L/day
16.5K, measured	30W	***~ 7.2 L/day***	***~ 25 L/day***
20K	40W	10 L/day	36 L/day

*15K, 16.5K estimation, and 20K operations are estimated based on 8.3W of heat load on the cryocooler.

store liquid hydrogen. For initial liquefaction and densification tests, a total of 13.7 m^3 or 1.13 kg of gaseous hydrogen was introduced into the tank. FIGURE 3 shows temperature variations of the cold head and densified hydrogen in the inner vessel when the system becomes close to a steady-state densification condition of 16.5K at the saturation pressure of 26 kPa (= 3.8 psia). FIGURE 3 indicates that the densified liquid hydrogen is stored up to the 'bottom' sensor of the inner vessel, and the remainder is cold gaseous hydrogen. The measured thermodynamic properties allow us to estimate the state of the hydrogen inside, and the quality of the stored hydrogen is found to be 4.8%, or a total liquid mass of 1.075 kg. It is converted to about 14.4 L of 16.5 K densified liquid hydrogen. The density of the saturated liquid at 16.5K is 74.7 kg/m^3, and an increase of 5.6 % over the NBP of hydrogen. TABLE 3 summarizes overall densification test results, when LN_2 precooler bath was used and not used. The initial test results indicate that actual heat load on the cryocooler was less than 8.3W.

ZBO Liquid Hydrogen Storage Test

The ZBO storage test was performed with the 14.4 L densified liquid hydrogen stored in the tank by turning the cryocooler on and off. FIGURE 4 shows the pressure and temperature changes during the ZBO storage test. After the cryocooler was turned off, the pressure was increased to 207 kPa (= 30 psia) within 7 hrs, and the densified liquid hydrogen at the bottom of the tank found another equilibrium state at elevated pressure. After the cryocooler was turned on again, the temperatures and pressure were recovered to previous conditions within ~1 and 8 hrs, respectively. In the ZBO test, it is demonstrated that the system can be maintained at least 8~9 hrs without the cryocooler operation before the relief valve starts to releases boil-off gas, and 1 hr/day of the cryocooler operation can provide enough refrigeration power to maintain the densified liquid hydrogen for a long time without any boil-off loss. The ZBO storage test was repeated once a day for a week to show the system reliability. When several Hurricanes hit the state of Florida in late 2004, the test bed and researchers successfully exercised the emergency draining and the system evacuation procedure which is a part of predocumented facility evacuation routines.

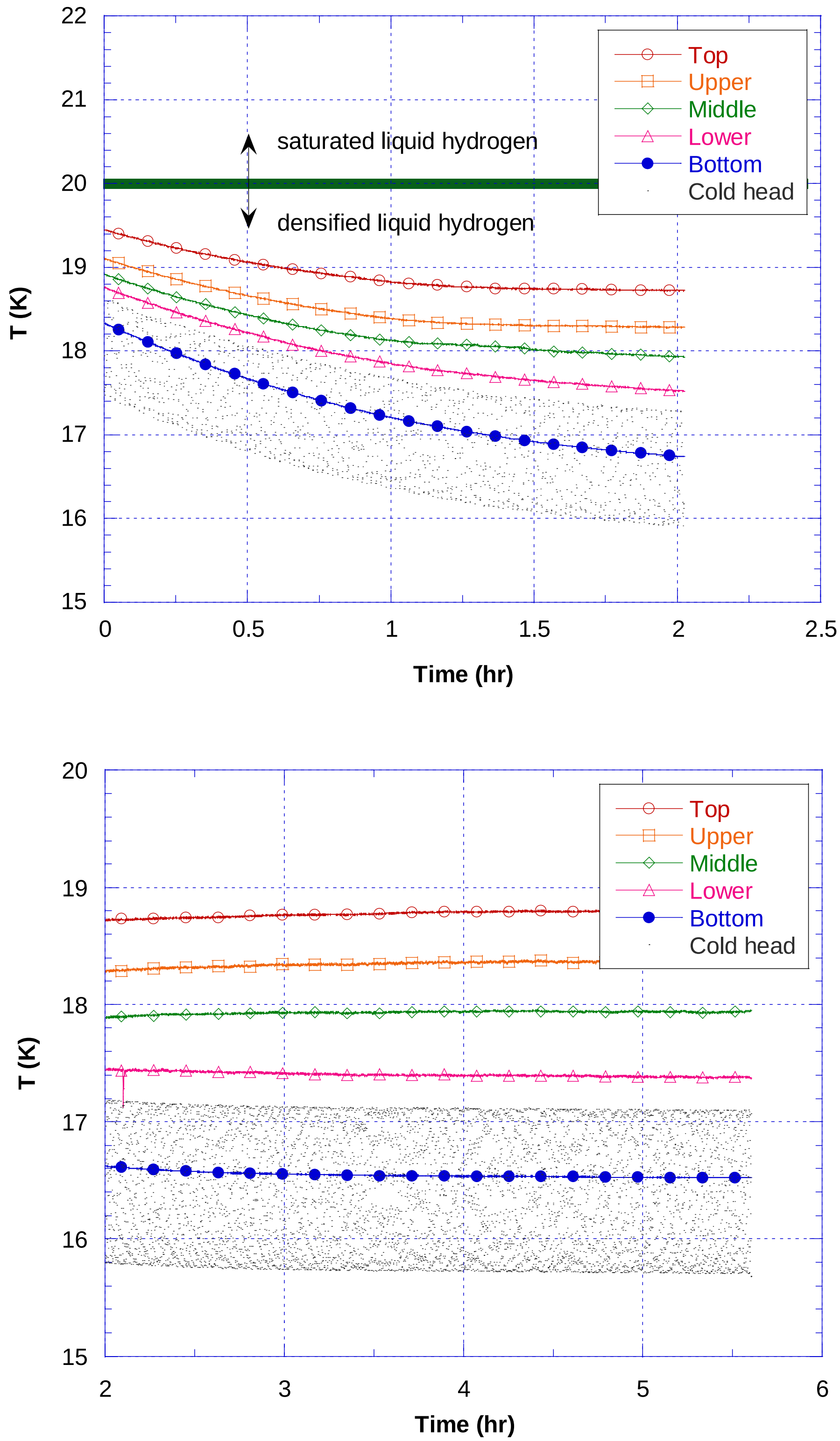
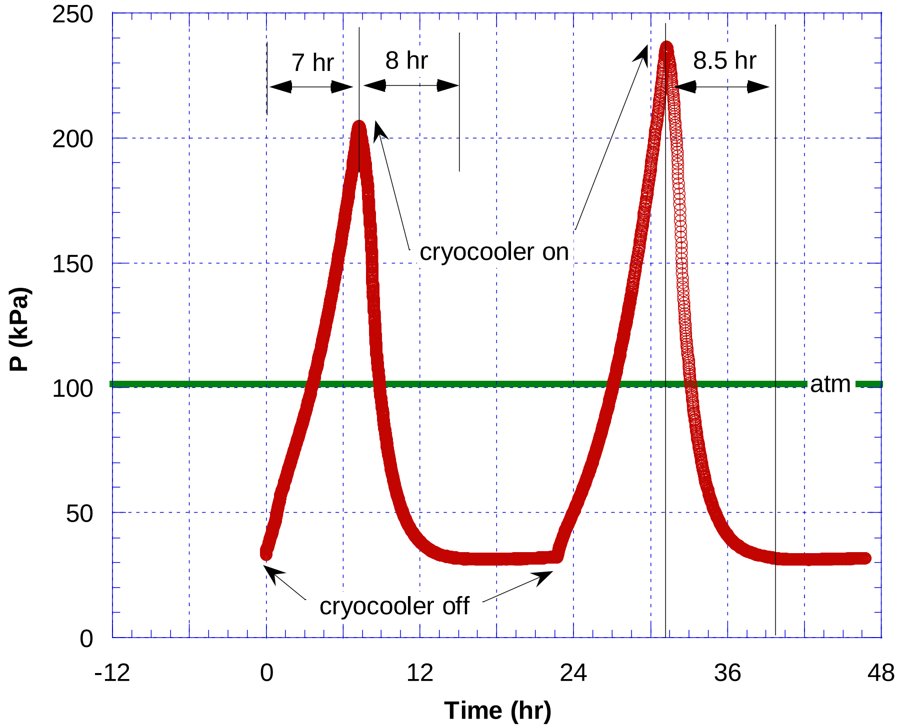


FIGURE 3. Temperature changes of the cold head and densified hydrogen during the densification test.



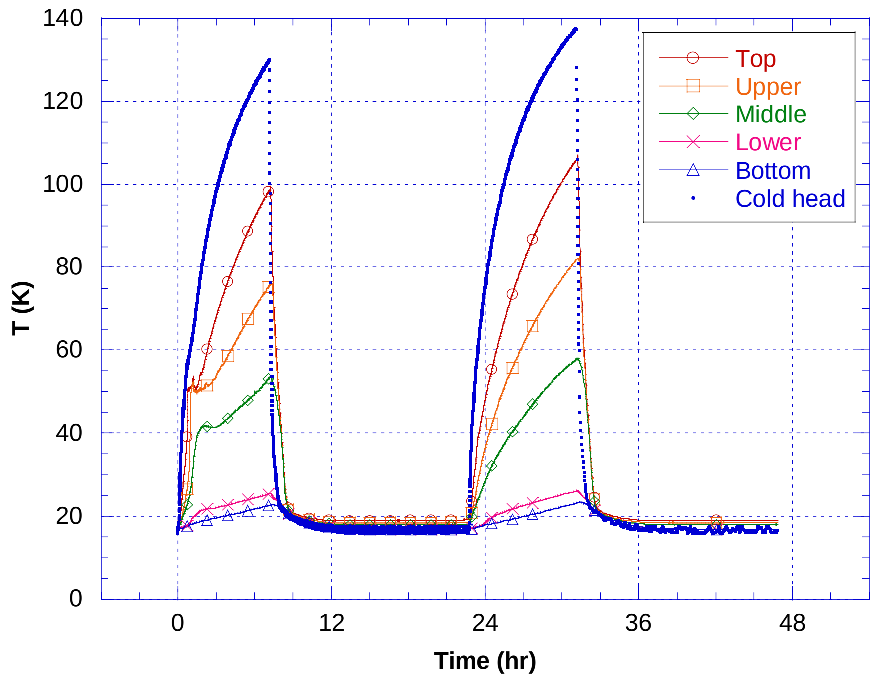


FIGURE 4. Pressure and temperature changes during ZBO storage test.

FIGURE 5. The densified hydrogen testing field facility at FSEC.

Conclusion

Researchers at the Florida Solar Energy Center and NASA KSC have developed a hydrogen densification test bed to investigate hydrogen densification and ZBO liquid hydrogen storage technology. The test bed successfully performed 7.2~25 L/day of 16.5K densified liquid hydrogen demonstration from ambient gaseous hydrogen using a G-M cryocooler. A series of ZBO storage tests proved that the system can store densified liquid hydrogen without any boil-off loss by ~ 1 hr/day of the cryocooler operation.

Future work

The FSEC has prepared the densified hydrogen testing field facility that combines hydrogen production, purification, storage, and application test sites as shown in FIGURE 5. At the facility, the hydrogen densification test bed can be integrated with a fuel cell backup power system to demonstrate a self-sustained densified liquid hydrogen storage technology. This facility allows us to handle larger quantity of liquid hydrogen than current laboratory so that advanced handling techniques such as pressure control, thermal stratification, and recovery of chill down losses can be investigated. To increase hydrogen liquefaction rate and remove inherent conversion heat during long-term storage, in-line type ortho-to-para hydrogen converter can be integrated at the LN2 bath. Development of vapor-cooled-shield (VCS) structure combined with in-line type para-to-ortho hydrogen converter in the storage tank can extend storage time before boil-off. The endothermic process of para-to-ortho hydrogen conversion through the VCS can reduce heat leak into the inner storage tank. FIGURE 6 shows the schematic of it.

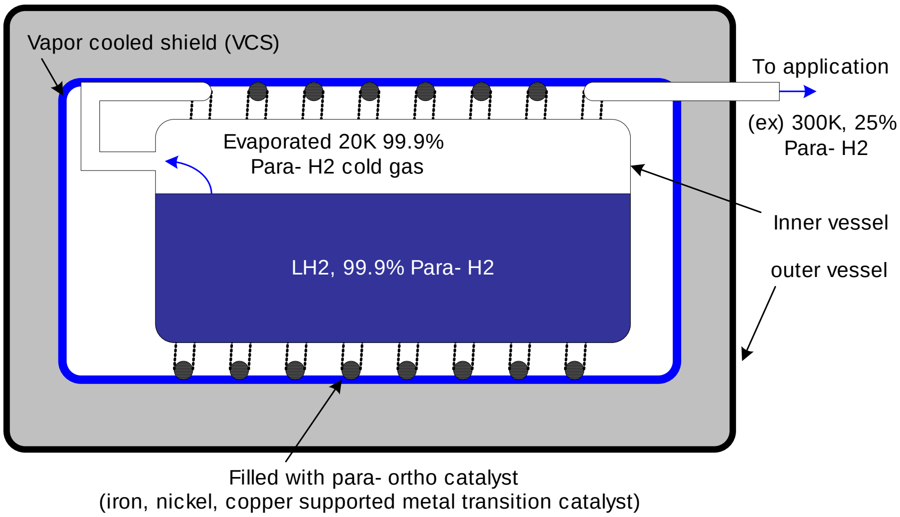


Figure 6. A schematic diagram of vapor cooled shield combined with in-line para-to-ortho hydrogen converter for ZBO storage tank.

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