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A Summary of the Slush Hydrogen Technology Program for the National Aero-Space Plane

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A SUMMARY OF THE SLUSH HYDROGEN TECHNOLOGY PROGRAM FOR THE NATIONAL AERO-SPACE PLANE

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Abstract

Slush hydrogen, a mixture of solid and liquid hydrogen, offers advantages of higher density (16 percent) and higher heat capacity (18 percent) than normal boiling point hydrogen. The combination of increased density and heat capacity of slush hydrogen provided a potential to decrease the gross takeoff weight of the National Aero-Space Plane (NASP) and therefore slush hydrogen was selected as the propellant. However, no large-scale data was available on the production, transfer, and tank pressure control characteristics required to use slush hydrogen as a fuel. Extensive testing has been performed at the NASA Lewis Research Center K-Site and Small Scale Hydrogen Test Facility between 1990 and the present to provide a database for the use of slush hydrogen. This paper summarizes the results of this testing.

Introduction

The overall objective of the Slush Hydrogen Technology Program was to establish a database for slush and liquid hydrogen to allow definition of the NASP fuel and pressurization subsystems. Although small scale studies were conducted by the Air Force and the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) in the 1960's and 1970's (references 1 and 2), little data on large scale production, transfer, and in-tank thermodynamics of slush hydrogen existed prior to the NASP program.

An extensive program was started at NASA Lewis Research Center to expand the experimental slush hydrogen database. Modifications to the existing K-Site facility began in the late 1980's and the first large scale slush hydrogen test series began in September, 1990. To date, four test series have been performed in the K-Site facility. Recently, a Small Scale Hydrogen Test Facility was established at NASA Plum Brook Station to enable lower cost experimentation. Small scale testing focusing on the optimization of the slush hydrogen production process has been performed.

Facility Description

K-Site Facility

The K-Site facility is located at NASA Plum Brook Station in Sandusky, Ohio. The facility was originally designed and built in the 1970's to allow experimental evaluation of flow dynamics and thermal protection subsystems for cryogenic propellant tankage. Large scale slush generation capabilities were added to the facility in the late 1980's making K-Site the only known operational slush hydrogen facility. The facility includes the test building which houses a 25 ft. diameter vacuum chamber, the remotely located control room, the cryogenic and gas storage areas, and the slush hydrogen production subsystem.

All large scale slush hydrogen production, transfer, and in-tank thermodynamic studies are performed at the K-Site facility. All testing is conducted in the facility's 25 ft. diameter stainless steel vacuum chamber. The nominal vacuum inside the chamber is maintained at 10^{-6} torr during testing by four diffusion pumps. The test tank is a 5 ft. diameter spherical tank constructed of 6061 aluminum with 0.31 in. thick walls. It is supported from a cradle structure and hung with stainless steel flexure straps from a rail support system in the vacuum chamber.

The stainless steel flexure plates allows one degree of freedom for shaking of the test tank during sloshing studies. A shaker shaft penetrates the rear of the vacuum chamber and translates along roller supports and is attached to the mid-line of the test tank. The shaft is driven by a hydraulic shaker mechanism capable of six inches of total tank displacement at one Hertz.

Test tank instrumentation provides measurements of the tank wall and fluid temperatures, liquid level, and fluid density. The test tank is also equipped with a viewport and video camera which allows for visual observation and recording of the inside of the tank during testing.

Slush hydrogen is produced in a 1300 gallon upright cylindrical vacuum jacketed slush generator. It is equipped with a mixer and instrumentation including a densimeter, liquid level probe, and multiple silicon diode temperature sensors. The slush hydrogen is generated by the evaporative cooling freeze/thaw process. A 6000 cfm vacuum pumping subsystem is used for the freeze/thaw process.

Following production, the slush hydrogen is pressure transferred from the generator through a cryogenic transfer system to the 5 ft. diameter spherical test tank. The cryogenic transfer system consists of approximately 125 ft. of 1.5 in. diameter vacuum jacketed pipe and various valves, fittings and flex lines. Instrumentation monitors pressure and solid loss during the transfer process.

The test tank is pressurized by two separate pressurant gas systems: 1) main pressurant gas and 2) recirculation gas. The recirculation gas simulates the returning excess gaseous hydrogen which is generated during the low speed operation of the engines in the NASP vehicle. Main pressurant gas is supplied to the ullage space of the test tank through a hemispherical diffuser and can be either hydrogen or helium. Main pressurant gas can be conditioned to approximately 620°R using a steam heat exchanger, 150°R using a liquid nitrogen heat exchanger, or 70°R using a liquid hydrogen heat exchanger. Recirculation gas can be conditioned by a liquid nitrogen heat exchanger to approximately 150°R.

More details on the K-Site facility and the slush production system can be found in reference 3.

Small Scale Hydrogen Test Facility

The Small Scale Hydrogen Test Facility was constructed inside the main test building at K-Site in 1993 for slush production optimization studies.

The facility uses the existing K-Site propellant supply system, a 778 cfm vacuum pumping system, and the remotely located control room for operation of the facility and data recording. The Small Scale Hydrogen Test Facility consists of a slush generator, instrumentation, vacuum jacketed transfer lines, and supporting equipment. The following cryogens can be used at the facility: liquid hydrogen, liquid nitrogen, and liquid oxygen. The following gases are also available at the facility: hydrogen, helium, and nitrogen.

The slush generator/test tank, shown in Figure 1, is an upright cylindrical dewar with a total volume of 200 gallons. Within the vacuum space are several inches of multilayer insulation material. The inner vessel wall consists of a low thermal conductivity plastic for the first 24 inches from the top and remainder of the structure is aluminum.

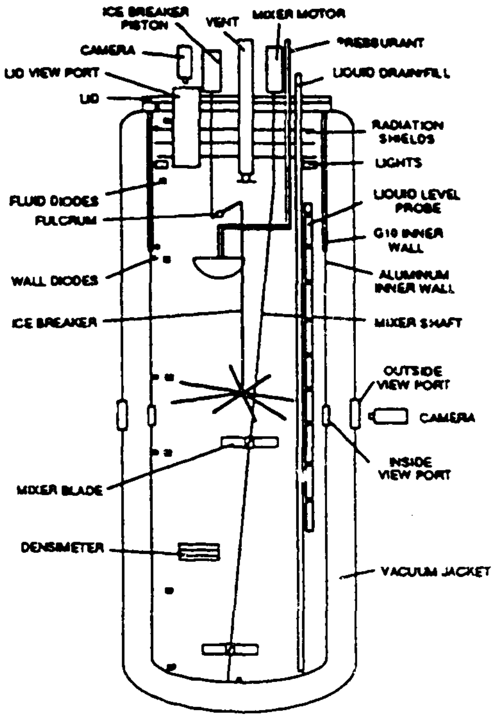

Figure 1: Small Scale Hydrogen Facility Slush Generator/Test Tank

The lid of the test dewar is a flat aluminum plate with multiple penetrations for liquid and gas supplies, pressure taps, and electrical and instrumentation feedthroughs. Below the lid are 3 layers of the low thermal conductivity plastic covered with aluminized mylar. This aluminized mylar acts as a radiation shield to reduce the heat leak into the dewar from the lid. The radiation shields extend down into the tank for approximately 7.5 inches. A stainless steel support ring hangs from the lid and provides support for internal hardware and instrumentation.

The test dewar has four viewports, two on the top of the lid and two at the midpoint of the dewar. The two side viewports are 2 inches in diameter. The viewport assembly consists of an inner sapphire window and outer quartz window. The inner sapphire window is sealed with indium. The outer quartz windows are removable and are sealed with an O-ring. The lid viewports are constructed out of two Pyrex glass discs separated by an evacuated fiberglass tube. The top disc is sealed with an O-ring and the bottom disc is epoxied to the end of the fiberglass tube.

A mixer in the test dewar insures a homogeneous mixture of solids and liquid. It has two sets of 9 inch diameter, 4-bladed, 45° pitch mixing blades attached to a shaft that runs the length of the dewar. The mixer is driven by a pneumatic motor located on the outside of the lid. The maximum speed of the mixer is 550 rpm. Also on the interior of the dewar is a 1 kW heater. This heater provides a method of simulating a heat leak and warming up the dewar after testing is complete.

A vacuum in the test dewar is attained by using the 778 cfm vacuum pump connected to the test dewar through a 4 inch diameter stainless steel vent line. This vacuum pumping system is used for conducting the freeze/thaw, and the continuous freeze production studies. A 36 kW heater is used at the inlet of the vacuum pump to protect it from the cold hydrogen gas. Flow through this system is measured using an orifice and a thermoconductivity type flowmeter with a range of 0 to 6,000 cfm. Vent gases from the dewar can be channeled to either an atmospheric vent system or a tank pressure control system. The tank pressure control system provides for automatic closed loop test tank pressure control. Vent gases from this system are routed through a vent gas measurement system which uses flowmeters and orifices to measure the vent gas flow rate. The system has several flow paths which provide different measurement ranges. In all, the system has the capability of measuring up to 45,000 cfm.

Either hydrogen or helium pressurant gas can be supplied to the dewar. The pressurant gas system is capable of supplying 0.25 lbm/sec of either hydrogen or helium. Flows are measured using a standard orifice run along with absolute and differential pressures, and temperature measurements.

Instrumentation within the dewar measures temperature, pressure, liquid level, and density. Seven silicon diodes spaced approximately 12 inches apart on a vertical rake provide both liquid and ullage gas temperatures. Seven silicon diodes are mounted on the wall and seven silicon diodes can be mounted on various pieces of hardware within the dewar.

A low cost, high quality LeRC designed and fabricated capacitance type densimeter measures the slush hydrogen density within the test dewar. A capacitance type liquid level probe located within the dewar was also designed and fabricated by LeRC. The liquid level probe signal is compensated for changes in dewar pressure and fluid temperature which affect the accuracy of capacitance type devices.

Discussion/Results of Slush Production Studies

Freeze/Thaw Production

All large scale production studies were performed with the K-Site 1300 gallon slush generator using the evaporative cooling freeze/thaw production technique. In the freeze/thaw production method the generator pressure is lowered by use of a vacuum pump to the triple point of hydrogen (1.02 psia and 24.8°R). A layer of solid hydrogen forms on the liquid surface. Following the formation of the layer of solid hydrogen, the pressure in the generator is allowed to increase and the solids sink into the liquid. The generator mixer is used to maintain a homogeneous mixture of solids and liquid. This process is repeated until the solid fraction reaches the desired level. The change in pressure from the freeze through the thaw portion of the cycle can be increased through addition of gaseous helium or hydrogen to the generator ullage.

An empirical study was conducted to optimize the freeze/thaw production process for the given slush generation system. This empirical study involved the parameters of freeze time, thaw time, pressure, and speed and direction of the mixer. The goal was a cycle which provided a complete surface freeze and a thaw with minimum adhesion of solids on the wall of the generator.

In general, the direction of the mixer, whether pushing the slush mixture upward or downward, had an effect on the thaw portion of the cycle. An upward mixer direction provided more liquid force to break up the bridged surface during the thaw cycle. Higher mixer speeds provided a more thorough mixture and ensured a better measurement of the average density of the mixture. The change in pressure from the freeze through the thaw portion affected the formation of the solid layer. The adhesion of solids to the generator surfaces decreased with increasing pressure. In general, gaseous helium was used as the pressurant during the thaw portion of the cycle. More details on this empirical study can be found in references 4.

Another test series documented the differences between gaseous helium and gaseous hydrogen on the thaw portion of the production process. In general, the addition of gaseous hydrogen to raise the generator pressure during the thaw process resulted in a decrease in the rate of slush production, when compared to gaseous helium processing. This is due to the fact that the gaseous hydrogen condenses on the solid surface which puts energy back into the slush.

The Small Scale Hydrogen Test Facility was established to study the parameters needed in the optimization of the slush production process. To the author's knowledge no analytical or theoretical work has been conducted on predicting an optimal freeze/thaw slush production technique for any given slush production facility configuration.

As a starting point in the optimization study, a theoretical dimensional analysis of the freeze/thaw production process was developed. The dimensional analysis began by defining the main parameter of interest: total time (T_t) to produce a given amount of 50 percent solid fraction slush hydrogen, starting with triple point liquid. The parameters defined as being pertinent to the problem are listed in equation 1.

$$T_t = f(T_{min}, T_{th}, T_{fr}, V, D_g, L, h, J_o, \rho_s) \qquad (1)$$

where: $T_{min} = \frac{m_v}{\rho_v V}$ = minimum production time

$J_o = \rho_s (\Omega D_B)^2 D_B$ = liquid momentum

T_{th} = thaw time
T_{fr} = freeze time
V = vacuum pump flow rate
D_g = generator diameter
D_B = mixer blade diameter
L = triple point liquid level
h = distance between the triple point liquid level and the nearest mixing blade below the liquid surface
ρ_s = final density of the slush
ρ_v = density of the vapor entering the vacuum pump
Ω = mixer speed
m_v = the amount of vapor that must be removed to produce the desired amount of slush. (reference 5)

From the nondimensional groups that can be formed from these parameters, one can be defined as representing the freeze process, and one the thaw process. If these are assumed to be the major factors, then:

$$\frac{T_t}{T_{min}} = f\left[\left[\frac{VT_{fr}}{D_g^2 L}\right]^{N_1}\left[\frac{J_o T_{th}^2}{\rho_s h D_g^2}\right]^{N_2}\right] \qquad (2)$$

The individual and combined effects of these two nondimensional groups on T_t/T_{min} as T_{th} and T_{fr} increase is shown in Figure 2. For increased freeze time the freeze parameter and the total production time (T_t) decrease. For increased thaw time the thaw parameter and the total production time increase. The combined effect of the two groupings indicate a minimum production time can be achieved with a certain combination of freeze and thaw times.

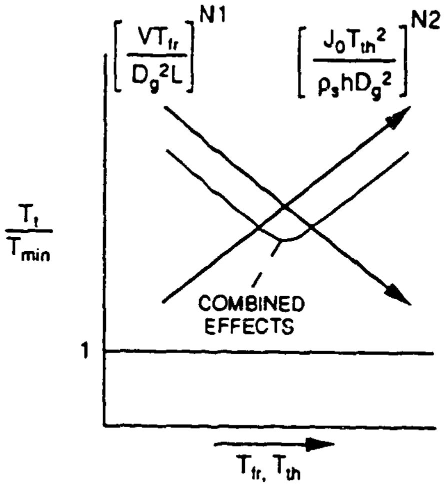

Figure 2: Graphical Representation of Optimal Freeze/Thaw

Based on limited K-Site production data, N_1 and N_2 were determined to be:

N_1 = -1
N_2 = 1/4

Substituting these N values into equation 2 and combining terms results in:

$$\frac{T_t}{Tmin} = f\left[\frac{\Omega^{0.5} D_b^{0.75} D_g^{1.5} T_{th}^{0.5} L}{h^{0.25} V T_{fr}}\right] \qquad (3)$$

Figure 3 is a plot of equation 3 using K-Site data. Because the dimensional analysis was not developed prior to the first test series, several measurements were lacking in the slush production system. Assumptions based on theory were used where empirical data was not available. While the data appears to fit the trends developed with the dimensional analysis, further testing is desired to eliminate the need for assumptions.

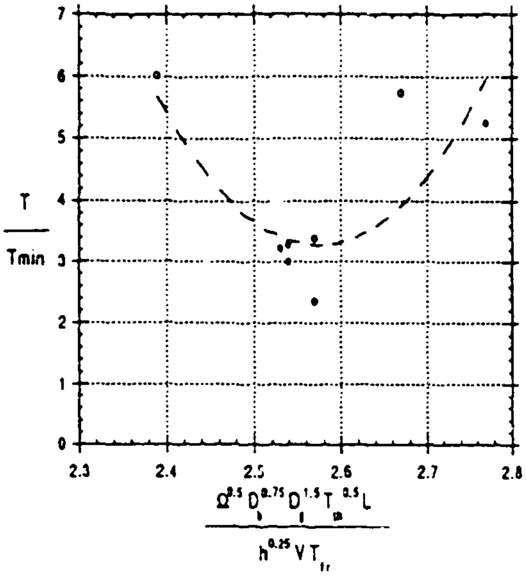

Figure 3: Freeze/Thaw Production Data

Continuous Freeze Production

The goal of a continuous freeze production technique is to provide an alternate method of obtaining a homogeneous mixture of solid and liquid hydrogen. The current large scale freeze/thaw production technique requires approximately 58 percent of the total production time thawing to produce a batch of 50 percent solid fraction slush hydrogen. Eliminating the thaw time would result in a significant reduction in the time to produce a batch of slush hydrogen.

A continuous freeze production technique involving an ice breaker has been studied at the Small Scale Hydrogen Test Facility. The ice breaker consisted of a device with spokes driven by a pneumatically actuated piston. The ice breaker is cycled above and below the surface as solids form, breaking up the solid surface.

Initial test results indicate that the continuous freeze production technique can be used to generate a batch of slush hydrogen in less time and without the need for gaseous helium to assist in the thaw process. A direct comparison of the continuous freeze and the freeze/thaw production techniques requires further testing. The freeze/thaw production technique has not been performed at the Small Scale Hydrogen Test Facility. This testing is required to make a comparison of the two techniques using the same slush production system.

Discussion/Results of Pressurized Transfer Studies

Pressurized transfers were evaluated during the first two test series at the K-Site Facility. These studies evaluated both the pressurization and transfer process. The discussion here represents only a brief synopsis of the results. Specific details can be found in references 3 and 4.

The pressurized transfer of slush hydrogen was successfully demonstrated. Some flow stagnation occurred at low differential transfer pressures and with a non-uniform batch of slush hydrogen. Calculations performed comparing the flow characteristics of the two fluids indicate that the difference in volumetric flow rate between slush hydrogen and normal boiling point hydrogen are small (reference 6). Results indicate that slush hydrogen and normal boiling point hydrogen exhibit similar volumetric flow rates for a given pressure drop, which indicates that the flow characteristics of slush hydrogen should be predictable using standard liquid hydrogen correlations.

Solid loss during a pressurized transfer was also evaluated. In general, the solid fraction loss was less than 15 percent for initial solid fraction near 50 percent. FLUSH (Flow of Slush) is an analytical model developed to calculate pressure drop and solid hydrogen loss in slush hydrogen flow systems. Comparison of the test data to FLUSH predictions shows significant scatter. This may be due to the uncertainties associated with measuring the density of slush hydrogen. More work is required to develop reliable and accurate slush hydrogen density sensor instrumentation.

Pressurant gas requirements during pressurization and expulsion were evaluated on a quiescent tank during two test series performed at the K-Site Facility. Parameters such as mass transfer at the liquid vapor interface, pressurant gas type and temperature, and condensation of the ullage gas at the tank wall all affect the amount of pressurant gas required.

Both a single component ullage, either gaseous helium or gaseous hydrogen, and a double component ullage, gaseous helium and gaseous hydrogen, were evaluated. Pressure levels ranged between 25 and 50 psia and pressurant gas temperatures of 240°R, 520°R, and 620°R were evaluated. Pressurant gas requirements decreased for increased temperature and pressure. Pressurant gas requirements were higher for gaseous helium than for gaseous hydrogen under similar conditions.

One interesting result was the combination pressurant gas results. In all cases the helium/hydrogen pressurant gas combinations showed the lowest mass of pressurant gas required for similar conditions when compared to either gaseous helium only or gaseous hydrogen only. Concentration profiles revealed a layer of helium at the liquid surface. This gaseous helium layer may have reduced the amount of hydrogen pressurant gas condensing on the liquid surface, thereby reducing the amount of pressurant mass required. It should be noted that the layer of helium present at the liquid surface may have been a result of the test procedure, i.e. the tank was pressurized with gaseous helium first followed by gaseous hydrogen in all cases. Pressurant gas requirements for a tank pressurized with gaseous hydrogen followed by gaseous helium or a mixed stream of gaseous helium and hydrogen was not evaluated.

Discussion/Results of Propellant Subsystem Related Studies

Propellant subsystem related issues such as sloshing, recirculation, and thermal conditioning were evaluated at the K-Site Facility.

Sloshing

Any flight vehicle using slush hydrogen could be subjected to severe dynamic conditions resulting from air turbulence, flight maneuvers, or emergency situations such as engine unstart. These situations could create sloshing of the hydrogen fuel that may result in tank pressure decay (ullage collapse) due to increased surface agitation, and the associated increased interfacial heat and mass transfer. With the vapor pressure of the fuel well below sea level atmospheric pressure, excessive cooling of the ullage gas can cause the tank pressure to decay below the local ambient pressure. The risk of subatmospheric pressure might require unacceptably heavy tank structures.

The objectives of the slosh tests were to investigate tank pressure response during sloshing and to identify the relationship between tank pressure response and the following: fluid type, slosh frequency and amplitude, initial ullage volume, heat addition, ramp pressure, and pressurant gas type. Reference 7 contains the details of slosh parameter and test results.

Test tank pressure response was investigated for two slosh conditions: (1) mild rippling (stable slosh) which may result from taxiing and take-off maneuvers, and (2) violent splashing (unstable slosh) which may result from dynamic conditions resulting from flight maneuvers and air turbulence. Initial fill ranges varied from 4 to 54 percent ullage. Tests were performed using either gaseous helium or gaseous hydrogen pressurant gas. To aid in the slush hydrogen slosh predictions, a commercially available fluid dynamics code, FLOW 3D, was modified by the code developer to include: 1) two component ullage; 2) interfacial heat and mass transfer at the liquid-vapor interface; and 3) the addition of heat from the tank wall.

The primary parameter affecting interfacial heat and mass transfer is the amount of subcooling available at the interface on the liquid side. This is dictated by the fluid circulation induced by the sloshing. For the mild rippling (stable slosh), little circulation of the bulk liquid occurred; whereas, significant mixing and destratification of the liquid occurred for violent splashing (unstable slosh). It is important to note that during mild slosh (stable), a thermally stratified layer of liquid hydrogen was present above the slush because of the tendency of the solid particles to settle. This relatively thick layer of liquid hydrogen was at saturated temperature (based on tank pressure). There is a fairly linear temperature gradient to 25°R at the slush/liquid interface. In the violent slosh (unstable) the thermal stratification described above was either nonexistent or much less pronounced. The magnitude of pressure decay appeared to be directly proportional to ullage volume for unstable slosh. For stable slosh, however, it appeared that the magnitude of pressure decay is inversely proportional to the ullage volume.

During sloshing, larger pressure decays were observed with gaseous hydrogen as a pressurant gas. This is the result of the mass transfer at the tank ullage interface. Hydrogen vapor will condense during sloshing, whereas, helium gas will not. Slush hydrogen exhibits greater pressure decay/collapse than liquid hydrogen under similar slosh conditions because of the greater subcooling available.

Recirculation

Recirculation is a process to condense excess hydrogen gas, generated by cooling requirements during the low speed system of the NASF engines, in slush hydrogen in the main fuel tanks. Recirculation is preferred over venting the excess gas overboard because the gas could control the pressure of the fuel tank.

The performance of a Jet Entrainment Mixer (JEM) and a Bubbler Bar as direct contact condensation devices was investigated during these studies. The principle of the JEM design (basically an ejector) is condense gaseous hydrogen by mixing it with slush hydrogen in a nozzle and convert the momentum change in the condensation flow into pressure head and push the exit flow away from the JEMs. In the Bubbler Bar design, the subcooled liquid hydrogen is drawn toward the gaseous hydrogen injection primarily by natural convection with the warm liquid rising and the subcooled fluid flowing down toward the Bubbler Bar.

A JEM consists of three sections: (1) the converging entrance section which accelerates the entrained (or secondary) flow (subcooled liquid hydrogen) to mix with the gaseous recirculation (or primary) flow, (2) the straight mixing section which provides complete condensation and mixing of the entrained flow with the primary flow, and (3) the diverging section for pressure recovery. The JEM performance is characterized by the entrainment ratio, defined as the ratio of secondary flow rate to primary flow rate.

The objectives of the tests for the JEM and the Bubbler Bar were to obtain performance data for the individual devices and to qualitatively understand the recirculation concept for the proposed tank pressure control scenario. Tests conducted on the JEMs and Bubbler Bar showed successful condensation of 0.045 lbm/sec of gaseous hydrogen.

The data obtained from the JEM tests has been used to develop a dimensionless model that predicts entrainment ratio for the area ratio of the JEM tested. The model is a function of density ratio and Jakob number, a function of the degree of subcooling of the secondary flow. Since the density of the secondary flow is limited to between 4.3 and 5.2 lbm/ft3, the primary flow rate (recirculating gaseous hydrogen) is an important parameter in terms of the entrainment ratio. The analytical and experimental results both support this fact. The experimental data also indicated that the secondary liquid temperature is also an important parameter in determining entrainment ratio. The data has also been used to develop a model that predicts the thermodynamic conditions at which condensation of the gaseous hydrogen no longer occurs. The model involves the test tank pressure and the Jakob number.

The Bubbler Bar test results show that the direct contact condensation with the given bubbler bar design can take place in slush hydrogen until approximately 2°R subcooling remains. The data also indicates a trend of increased subcooling remaining with increased recirculation flow rates. Theoretical models have not been developed to predict the thermodynamic conditions at which condensation no longer occurs. More theoretical and experimental work is needed for predicting Bubbler Bar performance, including thermodynamic conditions at which the Bubbler Bar will no longer condense gaseous hydrogen.

The tank pressure typically dropped 10 to 20 psid when gaseous hydrogen recirculation with the JEMs was initiated. The Bubbler Bar, in general, did not create as large a pressure drop as the JEMs. It was later reasoned that this was a result of excessive heat and mass transfer at the liquid/vapor interface caused by the combination of warm pressurant gas and the excessive surface motion caused by the JEM flow. A hydrogen heat exchanger was added in series with the nitrogen heat exchanger for the pressurant gas. The modification reduced the pressurant temperatures from approximately 160°R to approximately 70°R. Because the JEM orientation (inclined 30° toward the liquid surface) could not be changed, little could be done to resolve the excessive surface motion. Pressure drops on the order of 10 psid were recorded during operation of the JEMs despite the lower pressurant gas temperature.

Flight vehicle pressure drops may differ from those recorded in these tests because of the scaling, hardware, and operational differences between the K-Site Facility test tank and a flight type tank.

Thermal Conditioning

Thermal analyses indicated that tank material temperature limits for the NASP vehicle would be exceeded if active measures were not taken to cool the tank wall during periods of high aerodynamic heating. A spray bar was designed to provide a spray pattern to cover the specific geometry of the tank wall at a flow rate necessary to sustain liquid coverage of the wall without dry-out from the external heat loads. Solid-free liquid hydrogen should be provided to the spray bar using the main boost pumps or a dedicated pump with a screened (filtered) inlet to prevent the ingestion of solids. The performance of the spray bar is affected by tank geometry, the thermal capacity of the tank material, the external heat leak rate, and the distribution of the heat flux around the tank geometry.

The primary objectives of the spray bar and screen/filter tests were to ensure that triple point liquid hydrogen, free of hydrogen solids, could be delivered to the spray bar through a screened inlet of the boost pump. The spray bar tank wall cooling effects were also to be observed, although the test data was understood to not be representative of the vehicle spray bar performance because of known limitations of the test tank as compared to the flight tank.

A self-contained pump and spray bar system was chosen for the spray bar and screen/filter concept demonstration tests. The pump had a variable speed motor which was manually adjusted to provide flow rates to the spray bar between 5 and 50 gpm. The spray bar configuration was selected specifically to fit onto the top portion of the tank wall. The spray bar was a ring shaped tube located in the ullage area of the test tank at approximately the 10 percent ullage level. It contained drilled holes which were arranged in an array to spray the walls only. The screen assembly incorporated a cylindrical screen that permitted radial inward flow. The screen open area was determined to anticipate significant solid blockage and at the same time still allow the desired flow to pass through with a small pressure drop.

With slush hydrogen, the measured screen pressure drop were essentially zero psid even at a flow rate of 50 gpm. The spray did a reasonably good job of cooling the wall in the sprayed area to approximately 40°R.

Conclusions

The National Aero-Space Plane Slush Hydrogen Technology Program has dramatically improved the viability of slush hydrogen as a possible fuel for future flight vehicles. Large scale production has been successfully demonstrated and work is ongoing at the NASA Lewis Research Center to optimize the slush hydrogen production process. Key issues such as sloshing, recirculation, and thermal conditioning have been evaluated and, with proper design and evaluation, there is no current known reason slush hydrogen should not be considered as a viable fuel for future vehicles.

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13. ABSTRACT ***(Maximum 200 words)***

Slush hydrogen, a mixture of solid and liquid hydrogen, offers advantages of higher density (16 percent) and higher heat capacity (18 percent) than normal boiling point hydrogen. The combination of increased density and heat capacity of slush hydrogen provided a potential to decrease the gross takeoff weight of the National Aero-Space Plane (NASP) and therefore slush hydrogen was selected as the propellant. However, no large-scale data was available on the production, transfer and tank pressure control chracteristics required to use slush hydrogen as a fuel. Extensive testing has been performed at the NASA Lewis Research Center K-Site and Small Scale Hydrogen Test Facility between 1990 and the present to provide a database for the use of slush hydrogen. This paper summarizes the results of this testing.

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