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QUICK COOLING AND FILLING THROUGH A SINGLE PORT FOR CRYOGENIC TRANSFER OPERATIONS

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ABSTRACT

Improved technology for the efficient transfer of cryogens is needed for future on-orbit fueling and remote Lunar/Mars operations. The cooling and filling of a liquid nitrogen (LN_2) test vessel through a single port were investigated in a series of experiments. A new "in-space" transfer tube design concept was used to demonstrate the ability to quickly cool and load cryogens through a single feed-through connection. Three different fill tube configurations with three different diameters were tested. The tubes providing the quickest cooldown time and the quickest fill time for the test article tank were determined. The results demonstrated a clear trade-off between cooling time and filling time for the optimum tube design. This experimental study is intended to improve technology for future flight tank designs by reducing fill system size, complexity, heat leak rate, and operations time. These results may be applied to Space Shuttle Power Reactant Storage and Distribution (PRSD) System upgrades and other future applications. Further study and experimental analysis for optimization of the fill tube design are in progress.

INTRODUCTION

Investigation of the cryogenic operation of cooling and filling to a tank through a single port is essential to improve technology for future flight tank designs and proposed space exploration missions [1]. A single-port design would substantially reduce the overall heat leak rate into the cryogenic vessel, which in turn reduces the boiloff. For example, liquid oxygen supplies will be necessary for life support, propellants for Mars ascent and return to Earth, and other operations. Cryogenic transfer must occur quickly to minimize boiloff and maximize fuel quantity. Research of the "in-space" transfer of cryogens is essential for future exploration of the solar system [2]. In this experimental research study, nine different stainless-steel tube configurations served as the transfer device test articles. The optimum goal was to determine the best tube configuration that would allow quick cooling, while maintaining minimum boiloff rate. This experimental study was performed at the Cryogenics Test Laboratory at the NASA Kennedy Space Center.

EXPERIMENTAL

A liquid nitrogen boiloff cryostat was used in this study [3]. (See FIGURE 1.) This apparatus simulated a cryogenic tank system by providing a steady-state repeatable platform for the testing and evaluation of each fill tube design. The cryostat includes a 0.5-meter- (m) long cylindrical cold mass that has a capacity of approximately 2.78 kilograms (kg) of near-saturated liquid nitrogen. Temperature sensors were placed in five locations on the cold mass as shown in FIGURE 2. All measurements were monitored and recorded with a customized data acquisition system.

The cold mass assembly was prepared and then installed inside the standard vacuum chamber of the cryostat test apparatus. After final assembly, evacuation and leak checks at high vacuum level (below 10^{-5} torr) were performed. The testing procedure involved heating and vacuum pumping to high vacuum level and then allowing the system to stabilize at ambient temperature conditions [approximately 293 kelvin (K)].

The liquid nitrogen was added to the cold mass and allowed to stabilize until the cryogenic steady-state conditions were achieved. The selected tube configuration was used to cooldown the tank while the time-temperature profile was recorded. The time for sensor T3 to reach liquid nitrogen temperature was designated the cooldown time. The same tube was then used to fill the tank while the time-weight profile was recorded. The fill time corresponds to a 100-percent-full level of the cold mass tank. This process was repeated for all tube designs.

FIGURE 1. Overall view of the cryostat test apparatus.

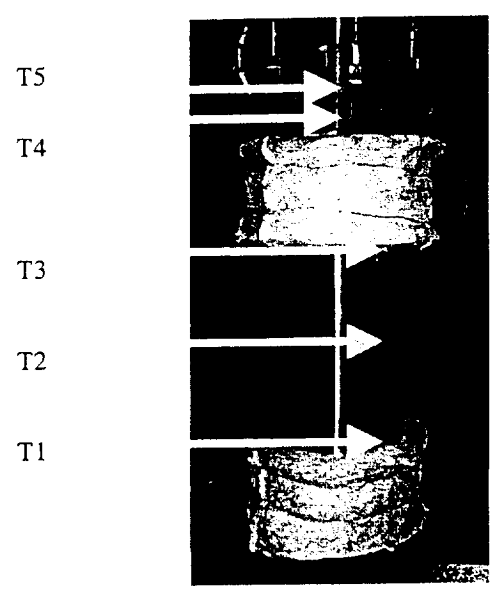

FIGURE 2. Temperature sensors locations on the cold mass assembly.

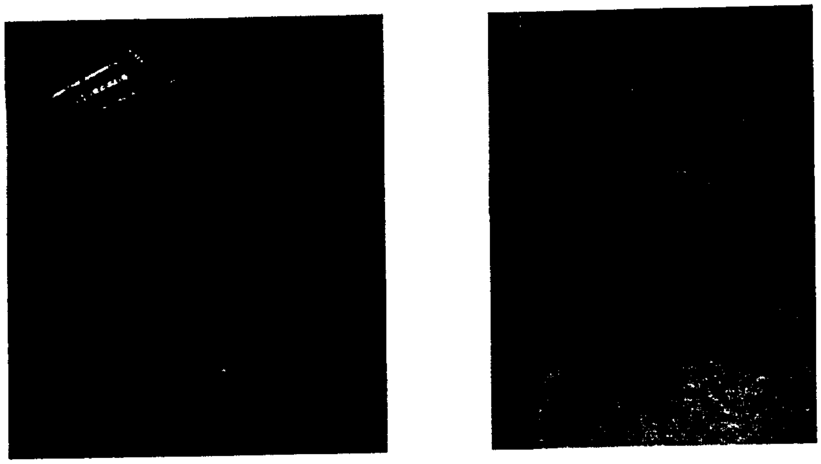

FIGURE 3. a) Filling of cryostat with liquid nitrogen and b) close up view of the funnel after filling.

By using an existing research cryostat system, the setup of the experiment was straightforward and inexpensive. The approach provided a well-insulated tank under consistent and carefully controlled conditions with a highly repeatable total heat leak rate. The experimental parameters are defined as follows:

- Port feed-through design: 12.5-millimeter- (mm) diameter single port for filling and venting
- Temperature boundaries: 293 K and 77 K
- Cold vacuum pressure: $1x\ 10^{-5}$ torr to 760 torr
- Supply pressure of LN_2: 8.1 kilopascal (kPa) (constant liquid head pressure)
- Residual gas: nitrogen
- Vacuum-insulated vessel (cryostat)

Nine 304 stainless-steel seamless tubes with a 0.889-mm wall thickness were used to manufacture the LN_2 fill tubes with the hole configurations as given in TABLE 1.

TABLE 1. Fill tube configurations.

1/4-inch (in) Tube (6.35 mm)	5/16-in Tube (7.9375 mm)	3/8-in Tube (9.525 mm)
[1A] 1 set of 1/8-in holes, spaced 1 in apart, positioned 0.5 in from bottom of the pipe	[1B] 1 set of 5/32-in holes, spaced 1 in apart, positioned 0.5 in from bottom of the pipe	[1C] 1 set of 3/16-in holes, spaced 1 in apart, positioned 0.5 in from bottom of the pipe
[2A] 9 sets of 1/8-in holes, spaced 1 in apart, positioned 0.5 in from bottom to 8.5 in of the pipe	[2B] 9 sets of 5/32-in holes, spaced 1 in apart, positioned 0.5"= in from bottom to 8.5 in of the pipe	[2C] 9 sets of 3/16-in holes, spaced 1 in apart, positioned 0.5 in from bottom to 8.5 in of the pipe
[3A] 27 sets spaced 1 in apart starting from 0.5 in from bottom and descending in hole size (0.125, 0.0669, 0.0335 in) to 26.5 in of the pipe	[3B] 27 sets spaced 1in apart starting from 0.5 in from bottom and descending in hole size (0.15625, 0.0827, 0.0420 in) to 26.5 in of the pipe	[3C] 27 sets spaced 1 in apart starting from 0.5 in from bottom and descending in hole size (0.1875, 0.0995, 0.0520 in) to 26.5 in of the pipe

The diameters of the holes used in manufacturing were proportionally based on the diameter of the tubing. Four holes were drilled and evenly spaced around the circumference of the tube (see FIGURE 4). When the term "hole" is used to define a tube configuration, it means a set of 4 drilled holes (for example, the 9-hole tube would include 9 sets of drilled holes).

RESULTS AND DISCUSSION

The results of this experimental study are summarized in FIGURES 5 and 6. FIGURE 5 shows the variation of the tank temperature with time while FIGURE 6 shows total time required to fill the tank. The tank (or cold mass of the cryostat) capacity is approximately 2.78 kg or 3.44 liters of liquid nitrogen. Nine different fill tube configurations were tested under cryogenic conditions (liquid nitrogen temperature) within a high-vacuum insulated environment. Fill tubes were tested with starting (warm) temperatures ranging from 140 K to 160 K.

By observing sensor T3 (located at the top of the cold mass tank) as it reached approximately 77 K, the cold mass 100-percent-full condition was determined. From FIGURES 5 and 6, the overall fastest tube configuration to cool down and to fill was the 1/4-in tubing with 27 descending holes (3A), at a time of 360 seconds and the 5/16-in tubing with 27 descending holes (3B) at a time of 400 seconds, respectively (see TABLE 2). FIGURE 5 suggests that while tube 3A was faster in overall time, tube 2C initially cooled faster as indicated by the steeper slope of the cooling curve. During testing of tube 3C, the liquid nitrogen was not traveling down the tube, and escaped at the very top of the tube before reaching the bottom. This configuration is therefore acceptable only for the initial filling. The worst tube for cooldown and filling was tube 1A. From observing the temperature sensors on the cold mass, the tank could not be completely cooled. As the liquid nitrogen level approached half full, the liquid kept "flashing off" due to the heat load causing back-pressure buildup. This data is not displayed in FIGURE 5 due to the out-of-range length of time.

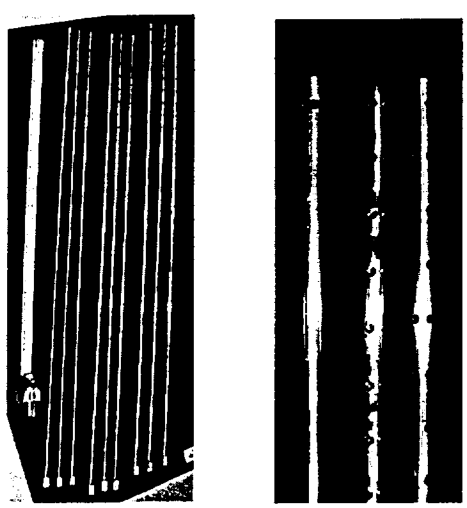

FIGURE 4. Fill tube configurations: a) overall view of the nine different fill tube assemblies and b) close-up view of three of the fill tubes.

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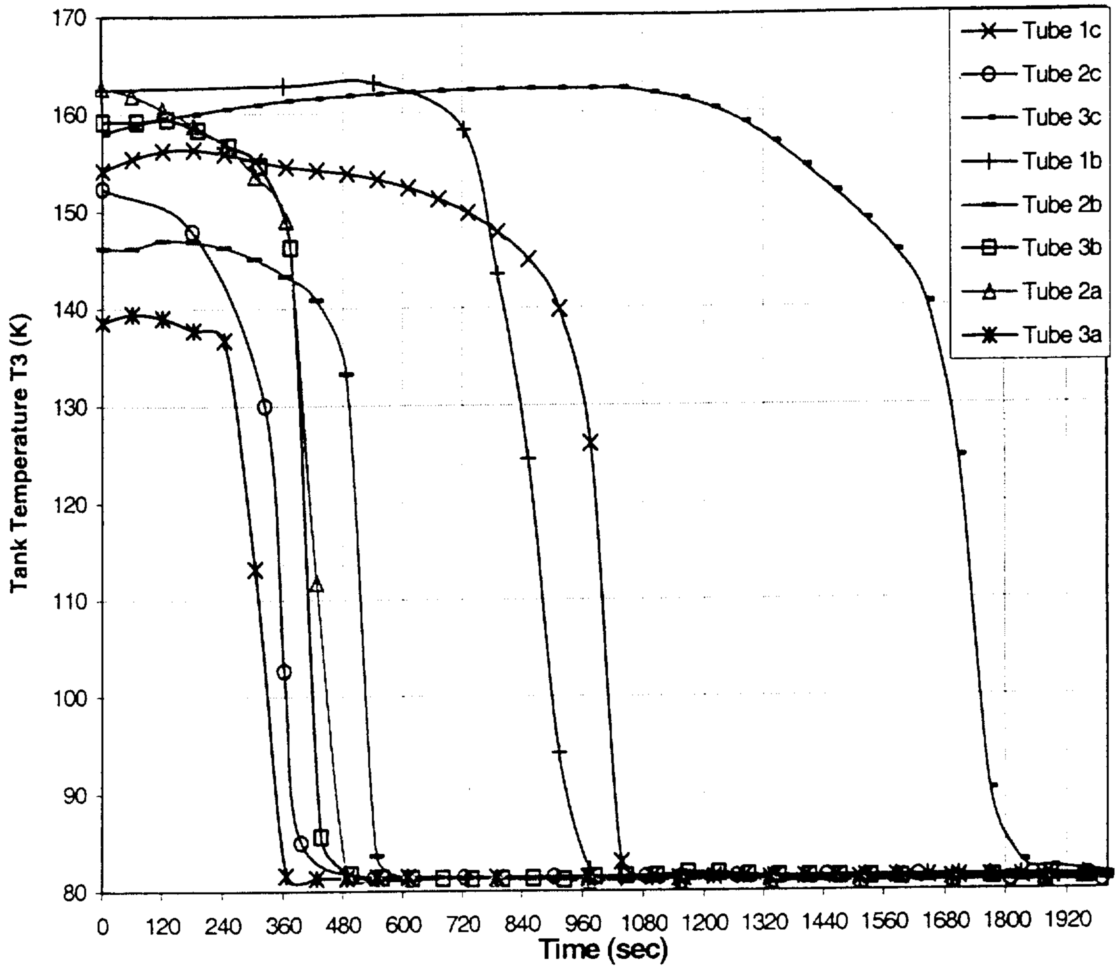

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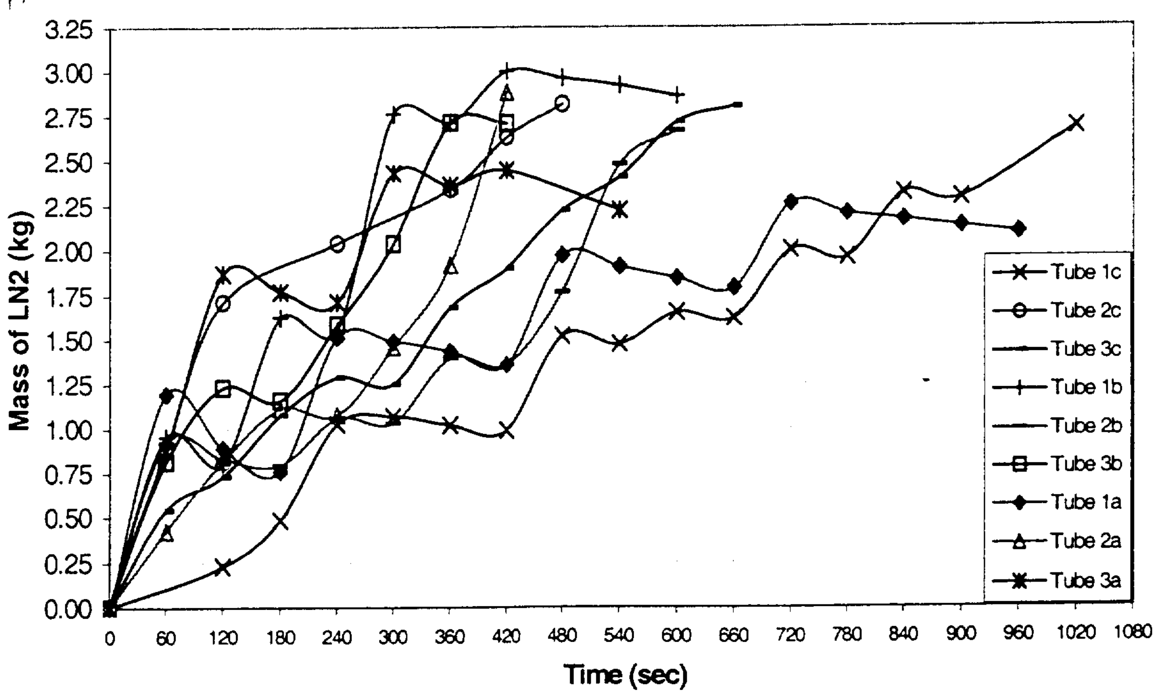

A single test was conducted using the 1/4-in tube with 9 holes (2A) comparing a warm start (~300 K) vs. cold start (~140 K). During the warm start, thermocouple T1 dropped signifcantly and during the cold start it remained steady due to the temperature already atapproximately 80 K. As expected, thermocouple T2 took longer for both warm and cold start, and thermocouple T3 dropped to the very last once cold mass reached 100 percent.

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Tube Diameter	Hole Configuration	Cooldown Time (sec)	Fill Time (sec)
A	1	Never cooled / filled	
	2	480	420
	3	360	500
B	1	960	600
	2	540	600
	3	480	400
C	1	1020	1000
	2	420	480
	3	1800	660

TABLE 2. Summary of times to cool and fill for different fill tube configurations.

CONCLUSIONS

Tube 3A was best for cooldown (3B, 2A, and 2C were also good performers). Tube 3B was best for filling (2A and 2C were also good performers). Tube 3A was best for combined cooling and filling (but 3B and 2C were almost as good). From the data collected, the best fill-tube configuration involved interchanging different tube configurations (for example, using the 9-hole configuration for immediate cooling and switching to the 27-hole tube for filling). To achieve the optimum result for cooling and filling and also for filling (starting with warm tank) and replenishing (starting with cold tank) of the tank, an optimum fill tube should be further investigated. This experiment was conducted to cover cooling and filling time combined. Optimum fill tube design would be different for filling and replenishing only (starting with a cold tank).

A need for further study is suggested by implementing the following:

- Include ambient temperature starting condition and supply a higher, more stable delivery pressure.
- Build a new experimental tank setup that is more representative of an actual in-space cryogenic trans-fill design concept.
- Evaluate the relationship to overall design of tank/transfer system. (The single port concept has many benefits: less heat leak because of fewer paths for solid conduction, less mass, overall simpler and more symmetric design, and better suitability for automated umbilical operations.

Today at the Cryogenics Test Laboratory of the NASA Kennedy Space Center, engineers have implemented the interchangeable 5/16-in tubing with 27 holes (3B) for quick cooling and the 3/8-in tubing with 9 holes (2C) for fast filling of the larger research cryostats. This improvement saves time in the frequent cooling and filling operations of the laboratory.

REFERENCES

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