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# Development and validation of an analytical charge–hold–vent model for cryogenic tank chilldown

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ABSTRACT

To enable future in-space cryogenic fuel depots, efficient methods are required for the tank chilldown and transfer process to minimize the amount of consumed propellant. This paper presents a transient charge–hold–vent (CHV) analytical model which is compared against the single set of liquid hydrogen tank chilldown data. The model solves conservation of mass and energy, uses quasi-unsteady steps in time to simulate natural convection and jet impingement heat transfer, and tracks two-phase fluid thermodynamic properties as the chilldown process evolves. The additional cooling potential made available through a cyclic tank venting process is also calculated in the code. The flexible code can simulate multiple CHV cycles, be used to optimize tank geometry and nozzle location, and provide predictions on the amount of propellant mass used for each cycle. This model compares within 7% of the liquid hydrogen tank chilldown experimental data.

## 1. Introduction

A mission architecture that incorporates the capability to refuel permits a higher payload mass and higher space vehicle transfer velocities which reduce mission duration, an important factor for manned missions. Fuel depots will enable all on board propellant mass to be used, with a planned propellant resupply later in the mission.

Fuel depots as a general system must deal with the unforgiving conditions of space. Low gravity and drastically varying hot/cold environments necessitate specific design considerations. The depot must remain lightweight so as to not burden its launch vehicle and it must remain compact so as to fit within the geometric constraints of the launch vehicle. The vehicles that dock and interact with the depots must have on board tanks that implement much of the same technology as the depot tank. Spray systems, liquid acquisition devices (LADs), and insulation systems are three main components that enable single phase liquid to be transferred and stored in the environment of space.

Before a depot can ever fly, extensive ground testing of its components and procedures must first occur. Fig. 1 illustrates a system for testing cryogenic fluid transfer flight hardware. The setup is outfitted with the necessary components to permit single-phase liquid transfer in low gravity. The receiver tank can be thought of as the fuel tank and the supply tank can be thought of as the depot. Subcooled liquid cryogen exists in the supply tank. The liquid is subcooled to account for heat leak into the system during the transfer process, such that the cryogen remains in the liquid phase upon reaching the receiver tank. The transfer line is regulated with a control valve to allow specification of flow rates, and it permits mass to transfer between the supply and receiver tanks. LADs are fitted to both the supply and receiver tank. LADS allow tanks in low gravity environments to be emptied of liquid without ingesting vapor into the transfer lines. The receiver tank is onboard the customer spacecraft that rendezvous and docks with the depot; the liquid line out permits the spacecraft access to the liquid cryogen once the transfer from the supply tank has terminated.

Before vapor-free cryogen can be transferred into the customer spacecraft, the transfer line and receiver tank must be chilled down to cryogenic temperatures. The most direct, repeatable, and easiest method for chilling down the hardware is to use the sensible and latent energy in the propellant itself. The largest thermal mass is contained in the receiver tank, which is expected to require the longest chill down time. The lines, LADS, vent valve, and spray system are sized to deliver and remove propellant mass quickly. The most cooling potential can be extracted from the fluid by developing a process of mass injections into the sealed tank, followed by a hold period to allow heat to transfer and thermal equilibrium to be reached. Upon reaching equilibrium, the mass inside the tank can be vented off and the process repeated until the tank walls are cooled to a sufficiently low temperature.

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## Nomenclature

| | |
|---|---|
| $A$ | area, crossectional flow area |
| $C_D$ | discharge coefficient |
| $c_p$ | specific heat at constant pressure |
| $D$ | diameter |
| $E$ | major to minor axis ratio |
| $f$ | iteration function, constituent mass fraction |
| $g$ | gravitational constant Gibbs free energy |
| $h_{top}$ | natural convection coefficient of top tank endcap |
| $h_{cyl}$ | natural convection coefficient of cylindrical tank body |
| $h_{bot}$ | natural convection coefficient of bottom tank endcap |
| $h_{jet}$ | forced convection coefficient of jet impingement heat transfer |
| $H_{jet}$ | distance from nozzle to impingement area |
| $m$ | amount of mass in receiver tank |
| $m_i$ | amount of mass injected into receiver tank (charge size) |
| $\dot{m}_i$ | average mass flow rate into receiver tank |
| $m_o$ | amount of mass removed from receiver tank in one sub-vent |
| $m_o^1$ | constant scaling factor for determining the magnitude of $m_o$ for each sub-vent |
| $m_{o,tot}$ | amount of mass removed from receiver tank by parent vent |
| $N_{vent}$ | number of parent vents per CHV cycle |
| $N_{sub\text{-}vent}$ | number of elapsed sub-vents |
| $N_{sub\text{-}vent,max}$ | total number of sub-vents composing a parent vent |
| $N_{\Delta t/sub\text{-}vent}$ | number of timesteps in hold phase per sub-vent |
| $N_{\Delta t/hold}$ | number of timesteps in hold phase between parent vents |
| $P$ | receiver tank pressure |
| $P_a$ | ambient pressure |
| $P^0$ | pressure of reciever tank before a CHV cycle begins |
| $P_s$ | supply tank pressure |
| $\dot{Q}_w$ | heat transfer between fluid contents and tank wall |
| $\dot{Q}_{jet}$ | forced convection heat transfer between impinging nozzle jet and tank contents |
| $\dot{Q}_{top}$ | natural convection heat transfer between top endcap and tank contents |
| $\dot{Q}_{cyl}$ | natural convection heat transfer between cylindrical tank body and tank contents |
| $\dot{Q}_{bot}$ | natural convection heat transfer between bottom endcap and tank contents |
| $\dot{Q}_{leak}$ | heat transfer into tank from environment |
| $\dot{Q}_{cond}$ | receiver tank conduction heat leak |
| $\dot{Q}_{rad}$ | receiver tank radiation heat leak |
| $\dot{Q}_{conv}$ | receiver tank convection heat leak |
| $R$ | gas constant or radial distance |
| $T_a$ | ambient temperature |
| $T_{jet}$ | jet film temperature |
| $T_w$ | receiver tank wall temperature |
| $T_w^0$ | receiver tank wall temperature before a CHV cycle |
| $t_i$ | duration of jet heat transfer |
| $t_t$ | specified transition time from jet heat transfer |
| $V_{jet}$ | jet velocity |
| $\overline{V}_x$ | submerged jet modified average exit velocity |
| $\Delta t$ | time step size |
| *Greek* | |
| $\theta_{jet}$ | fluid jet half angle |
| $\mu$ | dynamic viscosity |
| $\rho$ | density |
| $\tau_t$ | dimensionless transition time from jet impingement heat transfer |
| $\tau_o$ | dimensionless time during a parent vent |

The chill down and transfer process can be optimized in one of two ways. The process can be time optimized, which is advantageous in the presence of large heat leaks and/or strict launch/landing windows, or the process can be optimized to preserve as much fluid mass as possible. Techniques for transferring the liquid from the supply depot have been explored since the 60's, Ref. [1]. Over fifty years have passed but the problem remains the same.

The transfer process can be broken down into two subprocesses. First, the tank must be cooled before liquid can be injected, because injecting relatively cold liquid into a relatively hot closed system will produce unmanageable pressure transients and may cause component failure. Second, the tank must be filled. Specifically designed tank chill down and liquid transfer techniques enable optimized liquid transfer in a low gravity environment, the details of which are not necessarily intuitive. The lack of buoyancy forces contribute to the difficulty of performing a low gravity liquid transfer.

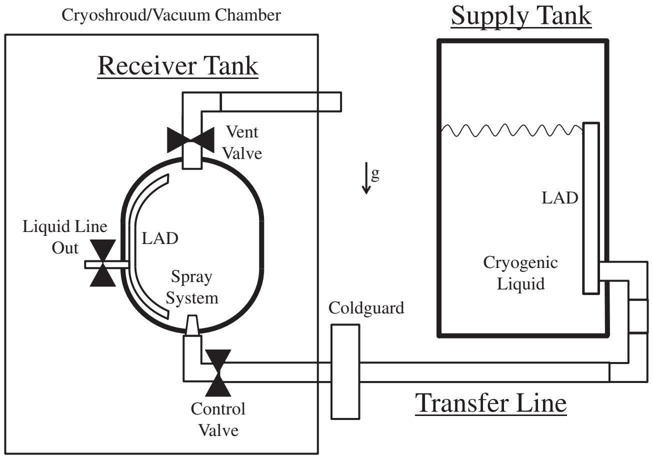

**Fig. 1.** Illustration of flight hardware experimental setup.

If a similar transfer were to occur within Earth's gravity the procedure details become familiar. A vent valve would be left open on top of the warm tank as the cold liquid is injected from the bottom. At first, the liquid would rapidly transfer heat with the wall, boil, and vaporize. The generated vapor would rise to the top of the tank and exit through the open vent valve. Eventually, the tank would cool enough to enable liquid accumulation in the bottom. Liquid will continue to evaporate but at a slower rate than it did initially because less thermal energy remains in the walls of the tank. The rate of liquid entering the tank would be greater than the rate of evaporation, and as a result, the liquid level in the tank rises. Once the tank is brimming with liquid, the vent valve can be shut and the transfer is considered complete. Heat leak into the tank will cause some of the liquid to evaporate and the pressure to rise. The vent valve can be opened to relieve pressure without the risk of losing liquid.

In the above example the chill down and fill occurred simultaneously. Liquid was allowed to flow into the tank at a constant rate until the tank was considered full, even though rapid evaporation occurred initially. The rapid evaporation did not induce a rapid pressure transient because the vapor could escape the tank system as it was being generated. However, the vapor generated during