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Pressurization of Cryogens: A Review of Current Technology and its Applicability to Low-Gravity Conditions

N.T. Van Dresar
Lewis Research Center
Cleveland, Ohio

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PRESSURIZATION OF CRYOGENS: A REVIEW OF CURRENT TECHNOLOGY AND ITS APPLICABILITY TO LOW-GRAVITY CONDITIONS

N. T. Van Dresar*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

A review of the technology, history, and current status for pressurized expulsion of cryogenic tankage is presented. Use of tank pressurization to expel cryogenic fluids will continue to be studied for future spacecraft applications over a range of operating conditions in the low-gravity environment. The review examines experimental test results and analytical model development for quiescent and agitated conditions in normal-gravity, followed by a discussion of pressurization and expulsion in low-gravity. Validated, one-dimensional, finite difference codes exist for the prediction of pressurant mass requirements within the range of quiescent normal-gravity test data. To date, the effects of liquid sloshing have been characterized by tests in normal-gravity, but analytical models capable of predicting pressurant gas requirements remain unavailable. Efforts to develop multidimensional modeling capabilities in both normal and low-gravity have recently occurred. Low-gravity cryogenic fluid transfer experiments are needed to obtain low-gravity pressurized expulsion data. This data is required to guide analytical model development and to verify code performance.

Nomenclature

Bo	Bond number
C	ratio of wall to gas effective thermal conductivity
c_p	specific heat at constant pressure
D	equivalent tank diameter
g	acceleration level
h_c	gas-to-tank wall free convection heat transfer coefficient
h_i	inlet gas specific enthalpy
h_s	saturated gas specific enthalpy
L	characteristic length
M	molecular weight
m_t	interfacial mass transfer
Δm	required pressurant mass
P	tank pressure during expulsion
$p_1 \ldots p_8$	fitted constants - Eq. (2)
Q	heat transferred from gas - Eq. (1)
Q	ratio of total ambient heat input to effective gas thermal capacitance - Eq. (2)
$\dot{q}$	tank wall external heat flux
R	gas constant
S	modified Stanton number
T_s	saturation temperature at initial pressure
T_0	pressurant inlet temperature
t	thickness
ΔV	volume change of gas phase
w_p	total pressurant mass
w_p^0	total pressurant mass under conditions of zero heat and mass transfer
w_p/w_p^0	collapse factor
θ_T	outflow time
ρ	density
σ	surface tension

subscripts:

L	liquid
G	gas
w	wall

superscripts:

0	at inlet temperature and tank pressure

*member, AIAA

Introduction

Potential applications of low-gravity (low-g) transfer of cryogenic fluids include fluid resupply of satellites, space station subsystem fluid replenishment, on-orbit fueling of space transfer vehicles, and resupply of strategic defense systems. Fluid transfer processes become more difficult to conduct in the low-g environment of space due to the uncertain separation of liquid and vapor phases. Numerous schemes have been proposed for low-g transfer of cryogenic liquids from a supply tank[1]. One of the concepts, supply tank pressurization and liquid expulsion, is examined in this paper. It is generally accepted within the aerospace community that pressurized transfer of cryogens will be required in future low-g applications. Tank pressurization is a component of an overall fluid transfer process, and must be combined with other low-g technologies such as propellant positioning, liquid acquisition, transfer line and receiver tank chilldown, and vented or unvented filling of a receiver tank.

Tank pressurization involves the introduction of a pressurant gas into the vapor space or ullage of a supply tank to increase tank pressure. This first step is known as ramp pressurization, ullage compression, or prepressurization. During the next step, liquid expulsion, additional gas is injected into the tank to displace the liquid during outflow and maintain tank pressure. Either the gaseous phase of the liquid or a noncondensible gas may be used as the pressurant. If a noncondensible pressurant is selected, the gas should have a low solubility limit in the liquid; otherwise large quantities of pressurant could dissolve into the liquid. The pressurant may be produced by vaporization of some of the stored liquid (autogenous pressurization) or it may be supplied by an external source such as high pressure gas bottles. Generally, external pressurization allows more rapid pressurization and transfer; however it increases the weight of the pressurization subsystem. In situations employing a cold noncondensible gas, the pressurant may conceivably be employed to provide liquid cooling. Other tank pressurization options (see Ring[2], Ch. 16), such as the injection of hypergolic reactants or polytropic expansion (blowdown), are not considered here.

Pressurization combined with fluid pumping has been employed to supply cryogenic propellants to the engines of numerous launch vehicles, such as the Space Shuttle, Saturn, and Centaur. Gaseous pressurant is added to maintain the necessary net positive suction head (NPSH) during pumping and to maintain the structural rigidity of the propellant tank. Specification of tank pressure operating limits requires determination of propellant feed requirements and structural loading requirements. These requirements will vary with propellant head (acceleration and liquid level), external pressure, aerodynamic heating, and other factors (see Ring[2], Ch. 18). Knowledge of the pressurant gas requirements is of particular importance to optimize the weight of the pressurization subsystem. In the Saturn V, S-IC stage, for example, the propellant tank pressurization system weight was large in comparison to that of other subsystems[3].

Effective tank pressurization provides the necessary liquid subcooling to avoid excessive vapor formation in both the supply tank and transfer lines. During liquid outflow, the liquid remaining in the tank will boil if the pressure drops below the saturation pressure due to expansion of the ullage region. Vapor generation within the fluid transfer path (liquid acquisition device, transfer line, pump, etc.) will adversely affect performance or lead to failure of the supply operation. Therefore, transfer of cryogens in normal or low-g requires pressurization of the supply tank to prevent flashing or boiling of the cryogen.

In past applications of tank pressurization, spacecraft designers have been primarily concerned with supplying propellants such as liquid oxygen and liquid hydrogen to rocket engines during operational times on the order of minutes. Under high acceleration conditions, the liquids are settled in a known position and characterized by a rather well defined liquid vapor interface. The nearly flat interface is normal to the acceleration vector, and relatively free of turbulence or large scale motion other than that due to sloshing or liquid outflow. These conditions are well suited to ground testing and have been successfully modeled for many cases. The modeling effort is simplified by the short operational times, allowing the neglect of some heat and mass transfer effects. An intense analytical and experimental research effort was conducted in the 1960's and 1970's to determine pressurant requirements, optimize pressurization subsystem design, and determine operating parameters for launch vehicles. This earlier work serves as the foundation for development of liquid supply technology for reduced gravity applications. In this paper, the high acceleration launch vehicle environment is considered similar to that of normal-gravity; however, captive firing tests of rocket engines pose different requirements on the pressurization subsystem than actual flight (Ring[2], Ch. 18).

When considering the application of pressurized transfer of cryogens in the space environment, it is recognized that operating environments will often be different from the earlier work described above. Tank-to-tank transfer times for operations such as an unvented fill process will be much longer than the rapid expulsion of propellants in launch vehicles, thus accentuating the influence of heat and mass transfer between liquid, vapor, and tank wall. Furthermore, liquid sloshing may occur during spacecraft maneuvers such as docking, attitude control, or other routine activities. Finally, the low-g environment will lead to conditions where fluid statics and dynamics are controlled by capillary phenomena. All of these factors affect the tank pressurization and expulsion processes and are the subject of later discussion.

Thermodynamic models are used to obtain the range of possible pressurant consumption[4]. These models circumvent the need for understanding of the heat and mass transfer phenomena by examining cases where the exchange occurs at either infinite or infinitesimal rates. The idealized case is defined as a process without heat and mass transfer from the pressurant; this represents the "minimum gas requirement" provided heat input or vapor generation within the tank is insignificant. A "maximum gas requirement" is defined to occur when the pressurant achieves thermal equilibrium with the tank liquid and vapor at saturation conditions at the tank pressure. (Thermal equilibrium is very undesirable as the liquid is expelled from the tank as a saturated liquid. Any additional heat input to the liquid at this state will likely lead to vapor formation and possibly subsequent failure of the liquid supply system.) The range of pressurant requirements for expelling a nearly full tank of liquid hydrogen[4], for example, ranges from a factor of approximately two at a transfer pressure of 20 psia to a factor of five at 120 psia; a considerable range of uncertainty for predicted pressurant mass. Presently, analytical models which narrow the range of uncertainty have been validated only for limited ranges of parameters in normal-gravity. The present lack of experimental low-g data will prevent validation of low-g models as they undergo development.

Normal-Gravity: Quiescent Liquid-Vapor Interface

Pressurized expulsion has been studied extensively under settled fluid conditions in normal-gravity. A review of this work up to 1965 has been published by Clark[5]. The required amount of pressurant gas is not simply a function of the displaced liquid volume, inlet gas temperature, and tank pressure, since the inlet gas transfers heat and is cooled on contact with the colder tank wall and internal hardware. In addition, the initial ullage must be compressed to the higher transfer pressure and evaporation or condensation may occur at the liquid-vapor interface. Conventional practice is to introduce the pressurizing gas into the vapor space of a supply tank via a diffuser which reduces gas injection velocities and thus minimizes interaction of the warm gas with the cold liquid and tank wall. This practice mitigates cooling and condensation of the gas therefore reducing the amount of gas required to expel a given liquid quantity. Additionally, proper dispersion of the pressurant gas minimizes undesired heating of the liquid.

Results from ground based experiments indicate the most important parameters influencing pressurizing gas requirements. General conclusions are stated in the following quote from Clark[5]:

> "Perhaps the most significant variables affecting pressurant requirements are inlet gas temperature and pressure. Minimum residual gas mass is achieved by maximizing the inlet gas temperature, minimizing its pressure, and selecting a pressurant with low molecular weight and high heat capacity. Heat transfer with the tank wall is dominant in most vessels and interfacial heat transfer with the liquid is not significant. The liquid at the interface will be at the saturation temperature corresponding to the total gas pressure, thus providing a heated layer of liquid near the interface. Any disturbance which disrupts this layer results in rapid condensation of the gas and loss in gas pressure."

A thermodynamic, or lumped-system, analysis may be used to estimate pressurant requirements. Equation 1 was proposed by Gluck and Kline[6] for determining pressurant mass. The three terms on the right hand side account for the volume of liquid displaced, interfacial mass transfer, and heat loss from the gas. The dependence on gas specific heat, molecular weight, tank pressure, and inlet temperature (enthalpy) are evident.

$$\Delta m = \frac{\left(c_p M/R\right) P \Delta V + c_p T_s m_t + Q}{\left(h_i - h_s\right) + c_p T_s} \qquad (1)$$

The heat transfer phenomena to be considered might include conduction, free and forced convection, aerodynamic heating, radiation, and chemical reaction. For the gas-to-wall convective heat transfer coefficient, different values are expected depending on the pressurant, flow rate, and geometrical factors. Interfacial mass transfer may be either evaporation or condensation. In addition, condensation of pressurant on the cold wall exposed during liquid expulsion is possible, as is evaporation or boiling of the cryogen due to environmental heat input.

In 1965, Epstein[7] published a correlation to predict pressurant requirements for liquid hydrogen and oxygen in cylindrical tanks. The pressurant can be either autogenous or helium. This correlation was extended in 1968 to include any axisymmetric tank shape and liquid nitrogen and fluorine propellants[8]. The form of the correlation is:

$$\frac{w_P}{w_P^0} = \left\{\left(\frac{T_0}{T_s} - 1\right)\left[1 - \exp\left(-p_1 C^{p_2}\right)\right]\left[1 - \exp\left(-p_3 S^{p_4}\right)\right] + 1\right\} \times \exp\left[-p_5\left(\frac{1}{1+C}\right)^{p_6}\left(\frac{S}{1+S}\right)^{p_7} Q^{p_8}\right] \qquad (2)$$

where

$$w_P^0 = \rho_G^0 \, \Delta V$$

$$C = \frac{\left(\rho c_p t\right)_w}{\left(\rho c_p\right)_G^0 D}\left(\frac{T_s}{T_0}\right)$$

$$S = \frac{h_c \, \theta_T}{\left(\rho c_p\right)_G^0 D}\left(\frac{T_s}{T_0}\right)$$

$$Q = \frac{\dot{q} \, \theta_T}{\left(\rho c_p\right)_G^0 D T_0}$$

The dimensionless quantities, C, S, and Q are obtained from theory[7,9] and represent the ratio of wall-to-gas effective thermal capacity, the modified Stanton Number, and the ratio of total ambient heat input to effective thermal capacitance of the gas, respectively. Heat transfer coefficients for the gas-to-wall heat transfer are based on free convection. Readers are referred to the reference for values of the curve fit constants p_1 to p_8 and for the range of applicable variables such as tank size, outflow time, and pressurant inlet-to-saturation temperature ratio. The predicted collapse factor, w_p/w_p^0, from Eq. 2 is reported to be within ±12 percent of experimental data for both small (less than 100 ft^3) and large (greater than 1,000 ft^3) tank sizes for the given range of variables. Use of the correlation is not recommended when: outside the range of variables, sloshing occurs, an inefficient diffuser is employed, the initial ullage volume exceeds 20 percent, or ambient wall heat fluxes cause appreciable propellant evaporation.

Application of numerical techniques to the analysis of pressurized expulsion began with the development of the "Rocketdyne Program"[5,9] in the early 1960's. This program was updated by the Marshall Space Flight Center[3,5] as experimental data for large scale systems became available. Concurrently, another finite-difference code was developed by Roudebush[10] at the Lewis Research Center. The Roudebush code has also undergone revision; separate versions[11] exist for the ramp and expulsion processes, and they have been modified for use with slush hydrogen[12-15]. The Rocketdyne and Roudebush codes are similar in that they solve the continuity and energy equations in one dimension (the axial direction) for a cylindrical coordinate system. For axisymmetric propellant tanks in normal or high acceleration levels, the one-dimensional modeling has often been appropriate. Radial temperature and velocity gradients are often negligible provided that the incoming pressurant is properly diffused. (An example where the radial gradients are significant is when pressurant is introduced via a straight pipe injector[16].) Under such conditions, the dominant energy exchange is between the ullage and tank wall. Roudebush[10] found free convection correlations to work well for pressurization with gaseous hydrogen and helium. With heavier molecular weight gases (oxygen), better results were obtained with the Rocketdyne code by specifying combined free and forced convection for the gas-to-wall heat transfer. Nein and Thompson[3] were able to predict pressurant requirements and ullage temperature gradients with an accuracy of ±5 percent over a tank size range of four orders of magnitude using the Rocketdyne program. This required determination of 14 constants (with additional parameters set to zero). Computational programs today continue to be either limited by simplifying assumptions or dependant upon parameters requiring experimental verification.

More recently, modeling of the pressurization process has been extended with multidimensional computational techniques. In a study by Sasmal, et al.[17], the FLOW-3D code[18] was used to model ramp pressurization in a spherical tank at normal-gravity. The FLOW-3D code was selected because it features models for compressible flow, a two-fluid interface, thermal buoyancy, surface tension, and turbulent flow, plus time dependent boundary conditions. Preliminary results have been obtained for the case where the liquid hydrogen surface is modeled as a solid boundary without interfacial mass transfer. Heat transfer rates to the wall and liquid interface are specified to match calculated values from a one-dimensional[12] code. An interesting result is the increased penetration of the inlet jet as the initial tank pressure is reduced, leading to substantial variations in the ullage flow and temperature fields. Other results show that for reduced initial ullage pressures (slush hydrogen) significant flow velocities and higher temperatures occur near the interface which requires consideration of mass transfer and variable heat flux boundary conditions. Accurate model definition could be improved with better experimental data; measurements required include inlet pressure, temperature and mass flow rate history, initial temperature distribution, heat loss history to wall and liquid interface, and interfacial mass transfer rate. It is recognized that some measurements are difficult to obtain. Many problems involving transport phenomena at boundaries remain the same as for one-dimensional modeling.

Normal-Gravity: Agitated Liquid-Vapor Interface

Under conditions such as liquid sloshing, the liquid-vapor interface assumes a dynamic nature due to externally applied forces. The potential for enhancement of heat and mass transfer between the liquid, vapor, and tank wall is large. Thus, the thermodynamics of the pressurization and expulsion processes may be greatly altered. Analytical modeling of sloshing is difficult, and has been limited to fluid dynamics without energy transfer. However, tank pressurization and expulsion under conditions of vigorous fluid motion in normal-gravity has been the subject of several experimental studies[19-21].

Experimental results published by DeWitt and McIntire[19] for sloshing at the natural frequency show an increase in condensible gas pressurant requirements due to slosh wave splashing and increased cyclic interaction between the cold wall and warm ullage. The wall is cooled upon contact with the sloshing liquid and then promotes condensation of the ullage gas as it is reexposed to the ullage region. The effect of sloshing was worsened when baffles were present. In this situation, splashing of the liquid due to the presence of baffles appeared to increase ullage condensation thus driving up the pressurant requirements. For liquid methane sloshing in a spherical tank at its natural frequency, methane pressurant consumption was increased above the requirements for the static liquid condition by an approximate factor of 3 in an unbaffled tank and by a factor of about 4 to 5 with baffles. With sloshing, 6 to 12 times as much condensed mass was observed and more than 50 to more than 70 percent of the liquid showed signs of heating - an undesirable result in applications requiring subcooled liquids. DeWitt and McIntire[19] also report results for sloshing with noncondensible pressurants. For these tests, small reductions (5-16 percent) in pressurant requirements compared to the static case were obtained for sloshing with and without baffles. This was attributed to increased evaporation of the liquid propellent during sloshing.

Not all tests with sloshing have indicated such a substantial effect on the pressurant requirements. Tests of liquid hydrogen pressurized with gaseous hydrogen by Coxe and Tatom[21] over a range of sloshing frequency and amplitude showed little difference from a no slosh condition. Their tests were conducted in a cylindrical tank outfitted with slosh baffles and high external heat input. Although sloshing did not appreciably affect gas requirements, pronounced propellant heating was observed when the tank was sloshed at near its natural frequency, thus indicating enhanced interfacial heat transfer. Nein and Thompson[3] reported that prepressurization with a noncondensible gas helps to reduce the pressure decay during vigorous sloshing near the first critical mode. They theorized that the pressurant added prior to expulsion occupies a buffer zone nearest the liquid surface and prevents contact between the liquid and condensible ullage gas.

In expulsion tests with liquid and slush hydrogen, Tomsik, et al.[22] found that fluid mixing increased condensation and therefore pressurant requirements when hydrogen pressurant was employed. When helium gas was used for both prepressurization and expulsion, or for prepressurization followed by expulsion using gaseous hydrogen, pressurant requirements with fluid mixing were similar to quiescent conditions. In addition, hydrogen pressurant consumption was reduced during expulsion for both quiescent and mixed conditions if helium was used for prepressurization.

Another ground-based experiment that results in an agitated liquid-vapor interface involves the submerged injection of pressurant. The buoyant bubble motion induces convective heat and mass transfer at the bubble interface in addition to disrupting the liquid free surface as the bubbles coalesce with the ullage region. When a noncondensible gas is injected, the sensible heat loss of the gas bubbles results in evaporation of propellent. This technique has been successfully used to reduce the requirement for externally supplied pressurant[23]. Worst case test simulations with submerged injection of autogenous pressurant have been performed by Stochl, et al.[24]. The worst case test is characterized by thermal equilibrium of the liquid and injected propellent and produces the maximum pressurant requirement. It is possible to approach this condition by injecting the pressurant well below the liquid-vapor interface, thus promoting collapse of the pressurant bubbles before coalescence with the ullage region occurs. In liquid hydrogen expulsion tests, pressurant requirements closely match predictions based on thermal equilibrium and 90 percent of the pressurant energy is lost to liquid heating[24].

Low-Gravity

Tank pressurization will be a vital component of cryogenic fluid transfer in low-g. It provides the driving force for liquid transfer and promotes liquid thermodynamic subcooling. Presently, low-g pressurization technology exists for storable propellants, but not cryogens. The development of low-g pressurization technology has the same objectives as earlier launch vehicle technology programs: to determine (and minimize) the mass of pressurant gas required to pressurize and expel fluid from supply tank under various operating conditions and to determine the resulting degree of liquid heating.

Static liquid orientation in low-g is characterized by the Bond number, defined as the ratio of gravity to surface tension forces:

$$Bo = \frac{\rho_L L^2 g}{\sigma} \tag{3}$$

where the characteristic liquid-vapor interface length is taken as the ullage region radius. Cryogenic tankage in space will often be characterized by small Bond numbers. Spherical or highly curved interface configurations will be encountered. The dominance of capillary forces, combined with the surface wetting characteristics of cryogens, will reduce the amount of direct gas-to-wall contact area and increase liquid-vapor interfacial area, thus altering heat and mass transfer during the pressurization and expulsion processes. Interfacial heat and mass transfer may be augmented by instabilities of the liquid-vapor interface arising from imposed disturbances. Accelerations in low-g vary in magnitude and direction due to crew motions, vibrations, excitation of natural frequencies, spacecraft maneuvering, and other causes[25]. Increased fluid motion persistence makes sloshing and resulting pressure collapse a greater concern in low-g. Most low-g tankage will be fitted with propellant management devices[26] to control sloshing and to assure liquid delivery at the outlet. Pressurant gas must be injected in a way that prevents disruption of the successful operation of such devices. For example, warm gas impinging on a screened liquid acquisition device (LAD) could cause dryout and subsequent breakdown of the capillary screen surface or the formation of vapor within the LAD. Transfer pressure must not exceed bubble point limits for LADs.

In well characterized ground-based systems, use of warm gas is desirable as it reduces the mass requirement.

The capability to diffuse the pressurant results in maximum stratification of the ullage and minimizes interfacial heat and mass transfer, thus reducing condensation and liquid heating. Lack of stratification due to reduced buoyancy in low-g could lead to exorbitant pressurant requirements. In situations with an indeterminant ullage location, the pressurization process can result in direct injection of the gas into the liquid region. This could lead to inefficient pressurization due to localized superheating of the liquid or the formation of an additional vapor region in the tank.

One-g results show that rapid pressurization requires less pressurant mass than slow pressurization. As the pressurization and expulsion durations increase, more time is available for the ullage to cool and approach thermal equilibrium. This effect will be a concern in low-g transfer due to slower outflow rates (transfer times for unvented fills may be on the order of hours) and the need for long pressurized states during receiver tank chilldown, for example. Some low-g cryogen transfers may require partial expulsion of the supply tank contents. Here, the impact of the pressurization process on post-transfer thermal reconditioning needs to be examined. Heat added to the remaining tank contents will have to be removed to return the fluid to a baseline storage condition. Subsequent repressurization of the storage tank will involve pressurization of a larger ullage volume. Reconditioning will be more difficult to perform if noncondensible gas is present in the tank.

A number of cryogenic flight experiments have been proposed by NASA to investigate pressurized tank expulsion and other cryogenic fluid management technologies (see Glover[27]). However, none have resulted in an actual low-g experiment over the past 25 years. Evaluation of experimental data would allow calculation of collapse factors and characteristic heat and mass transfer coefficients. This data in turn would provide limited validation of lumped parameter models (e.g., Rudland, et al.[28]) that are being developed for pressurized expulsion. Table 1 lists experimental parameters of interest for a low-g pressurized expulsion experiment. Epstein-style correlations[8] will require much experimentation covering the range of parameters listed in Table 1 before they can be used with confidence.

Preliminary modeling of the tank pressurization and expulsion processes using multidimensional finite difference techniques has been initiated by users of the FLOW-3D code[18]. An analysis[29] of thermal stratification during ramp pressurization as a function of gravity level has shown that radial variations become significant as the gravity level decreases. In the analysis, a thin slice of the ullage region was modeled (quasi two-dimensional). The liquid interface was assumed to remain planar and at constant temperature (both assumptions are clearly questionable, but result in simplification of boundary condition specification). Attempts to include the liquid phase in the analysis resulted in code instabilities attributed to "impedance mismatch" arising from the large density difference of liquid and vapor. Nonetheless, some interesting results were obtained: multidimensional effects were observed at acceleration levels below 0.1g and pressurant-ullage gas mixing increased with reduced initial tank pressure. It was noted that convergence criteria and mesh size largely impact results at low gravitational levels. Clearly, more effort is necessary to develop multidimensional models for low-g pressurized expulsion and cryogenic fluid management technologies in general.

Table 1 - Low-Gravity Experiment Parameters

Pressurant (condensible, noncondensible)
Gas temperature
Gas flow rate
Liquid outflow rate
Fill level
Tank geometry
Liquid orientation
Initial pressure
Expulsion pressure
Imposed acceleration level
Level of induced disturbances

Closing Remarks

Expulsion of cryogens in normal-gravity has been extensively studied and led to the development of well validated one-dimensional codes for short expulsion times, quiescent liquid surfaces, and well diffused inlet gas. The one-dimensional models can not be relied upon when a disturbed liquid-vapor interface is present, or when the inlet gas is not well diffused. The codes remain to be validated for longer pressurization and expulsion times where increased heat and mass transfer is likely. Multidimensional models may provide improved predictive capabilities over wider ranges of operating conditions as refinement of these models continues. Both one and multidimensional models are bound by limitations in our understanding of interfacial transport phenomena, and require empiricism to provide accurate representation of heat and mass transfer at boundaries.

Space experiments are needed to determine effects of low-gravity on the pressurization and expulsion processes and provide insight into the fluid and thermal physics. Low-gravity data will initially allow determination of transport coefficients for both lumped parameter and multidimensional finite-difference models. Refinement of the models will require experiments with parametric variation of the dominant parameters. Proper scaling using relevant dimensionless groups is necessary to maximize the value of experimental data. Experiments using simulant fluids may be less costly, but will require additional trade-offs involving scaling issues.

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N.T. Van Dresar

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A review of the technology, history, and current status for pressurized expulsion of cryogenic tankage is presented. Use of tank pressurization to expel cryogenic fluids will continue to be studied for future spacecraft applications over a range of operating conditions in the low-gravity environment. The review examines experimental test results and analytical model development for quiescent and agitated conditions in normal-gravity, followed by a discussion of pressurization and expulsion in low-gravity. Validated, one-dimensional, finite difference codes exist for the prediction of pressurant mass requirements within the range of quiescent normal-gravity test data. To date, the effects of liquid sloshing have been characterized by tests in normal-gravity, but analytical models capable of predicting pressurant gas requirements remain unavailable. Efforts to develop multidimensional modeling capabilities in both normal and low-gravity have recently occurred. Low-gravity cryogenic fluid transfer experiments are needed to obtain low-gravity pressurized expulsion data. This data is required to guide analytical model development and to verify code performance.

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