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T. P. Purwin and M. Kaviany
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan
Ann Arbor, Michigan, 48109

J. C. Aydelott
Cryogenic Fluids Technology Office
NASA Lewis Research Center
Cleveland, Ohio, 44135

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ABSTRACT

Transient discharge of liquid cryogens from partially filled tanks under micro-gravity is considered. The discharge is made to a low pressure site through a straight tube. The ultimate objective of the study is to predict the transient mass flow rate $\dot{m}(t)$. In addition to $\dot{m}(t)$, the pressure history in the tank $p_t(t)$ is of interest, since the pressure falls below the triple point toward the end of the dump, causing solidification in the tank and/or the discharge line. As first steps, experiments have been performed in normal gravity and attempts are made to predict $\dot{m}(t)$ and $p_t(t)$ under this condition. Experiments are performed with liquid nitrogen dumped to sites with pressures below the triple point. Homogeneous, equilibrium and non-equilibrium, two-phase critical flow models are compared to the experimental results. Equilibrium and non-equilibrium tank pressure history models are also compared to experimental data.

NOMENCLATURE

A	cross-sectional area (m^2)
d	diameter (m)
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2s)
k	thermal conductivity (W/mK)
L	length (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
N	Henry-Fauske correlation parameter
p	pressure (Pa)
q	heat transfer rate (W)
Ra	Rayleigh number, $Ra = \frac{g\beta(T_i - T_\infty)L^3}{\nu\alpha}$
T	temperature (K)
t	time (s)
V	volume (m^3)
v	specific volume (m^3/kg)
x	quality, $x = \frac{m_g}{m_g + m_f}$

Greek Letters

α	thermal diffusivity (m^2/s)
β	volumetric thermal expansion coefficient (K^{-1})
ν	kinematic viscosity (m^2/s)

Subscripts

c	critical
E	equilibrium
ep	discharge line exit plane
f	liquid phase
fg	property difference between phases
g	vapor phase
i	liquid/vapor interface
l	discharge line
o	stagnation
t	supply tank
∞	bulk value

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1. INTRODUCTION

The objective of this study is to predict $\dot{m}(t)$ for a tank discharging to a low pressure site, in a micro-gravity environment. The pressure difference between the supply tank and the dump site is large enough that, in general, the flow becomes critical in the discharge line. It is believed that the critical flow rate is determined by the state of the liquid/vapor mixture entering the discharge line, with the gravity having negligible effects.

The first step toward this goal is to produce, measure, and predict critical flow rates with the entrance states similar to those realized in micro-gravity environments. Experiments have provided evidence that there is likely to be a temperature difference between the phases at the entrance to the discharge line. This implies that the state of the liquid/vapor mixture is not defined by two properties (as is the case for thermodynamic equilibrium). Each phase must be described separately, although they are at the same pressure. In order to perform experiments which encompass all the possible micro-gravity entrance states, the temperature difference between the phases must be varied, as well as the pressure and quality. Experiments are being performed in which liquid nitrogen ($x = 0$) is dumped to vacuum through long tubes. We report on the measurements made so far. After adequate $x = 0$ data is obtained, experiments will be performed in which $\dot{m}$ will be measured for saturated vapor flow ($x = 1$), and finally for discharge line entrance qualities between zero and one. Since it is difficult to maintain the liquid and vapor in thermodynamic equilibrium, the inter-phase temperature difference will be used as a parameter. When these data are collected, they will be used to arrive at a model that predicts $\dot{m}$ as a function of the discharge line entrance conditions.

When $\dot{m}$ can be predicted for all necessary discharge line entrance conditions, the problem of predicting $\dot{m}(t)$ will become dependent on determining the discharge line entrance conditions with respect to time. An effort has been made to understand the non-equilibrium aspects of the supply tank behavior, and the limiting cases of the pressure history $p_t(t)$ have been determined. It is expected that $p_t(t)$ and liquid/vapor phase temperature data will provide a method of determining the quality entering the discharge line. And conversely, $p_t(t)$ and the line entrance quality can provide an indication of the temperature difference between the phases.

In a micro-gravity environment, the supply tank liquid/vapor dynamics may strongly influence the liquid/vapor mixture quality which enters the discharge line. It is expected that the internal structure of the supply tank and the specific location of the discharge line entrance will influence x significantly. The transient tank hydrodynamics, non-equilibrium and phase distributions which depend strongly on the gravity, have not been studied for this discharge problem. However, these behaviors should be known for accurate predictions of x and the extent of non-equilibrium at the discharge line entrance.

The problem addressed, concerns the interaction of a discharge line with a transient supply tank in normal and micro-gravity. This paper is organized such that the problem of predicting the mass flow rate through the discharge line is discussed first, under the major heading *Mass Flow Rate*. The other major heading is *Supply Tank*, in which the in-tank transient and its effects on the mass flow rate are considered. Under each of the major headings, separate consideration is given to normal gravity and micro-gravity, experiments and predictions.

2. MASS FLOW RATE

Depending on the discharge line entrance and exit pressures, the following three different flow phenomena can occur:

Critical Flow – Under this condition there exists what is considered mass limiting flow, characterized by $\dot{m}$ being independent of the dumpsite pressure. It is for this case that experimental data is presented. The following mass flow rate discussion also focuses on critical flow. In this study the assumption is made that the critical flow is a well mixed, turbulent flow.

Non-critical Liquid/Vapor Flow – This type of flow is characterized by the variation in $\dot{m}$ with changes in dumpsite pressure. Single-component, non-critical flow has been the subject of many investigations. Some of the correlations are examined by Steiner and Schlünder.[1] Accurate descriptions of the flow requires an understanding of the flow regimes. A recent mapping of the air/water flow regimes, in micro-gravity, is presented by Duckler *et. al.*[2]

Flow at or Below Triple Point Pressure – This phenomena is characterized by solidification of the liquid/vapor inside the discharge line and has not been extensively studied. The solidification of nitrogen in the discharge line has been observed in our experiments.

2.1 Normal Gravity

2.1.1 Experiment

The experimental apparatus is shown in Figure 1. The apparatus includes two vacuum insulated, silvered glass dewars with viewing slits, set inside one another. The outer dewar (insulating dewar) is filled with liquid nitrogen (LN2) and provides additional insulation for the inner dewar. The inner dewar is the supply tank for the experiment and has a volume V_t of 3.9 liters. The supply tank is fitted with an insulating head which contains ports for filling, venting, pressure and temperature monitoring, and the discharge line. The discharge line is a straight, sharp edged glass tube, $80cm$ long, placed vertically. The discharge line is vacuum insulated from inside the supply tank to downstream of the exit. The discharge lines are interchangeable and have been used with two different inside diameters ($d_l = 1mm$ and $d_l = 5mm$). The discharge line is connected through the control valve to a high capacity vacuum system capable of handling vapor flow rates in excess of $10m^3/min$ at $12kPa$. The supply tank is filled with LN2 from the storage reservoir which is a $0.2m^3$ tank maintained at approximately $2atm$ of pressure through a passive venting system. A VCR camera with an internal clock is set up to monitor the supply tank liquid level, pressure p_t, and temperatures.

The experimental procedure is to remove the air from the system by introducing warm nitrogen, then subjecting the system to vacuum. The supply tank is then filled with liquid nitrogen until the entrance of the discharge line is submerged and p_t is allowed to stabilize. When the pressure is stable, the control valve is opened and the system transient (supply tank pressure and liquid level with respect to time) is recorded by the camera. The rate of change of liquid depth is used to determine $\dot{m}$

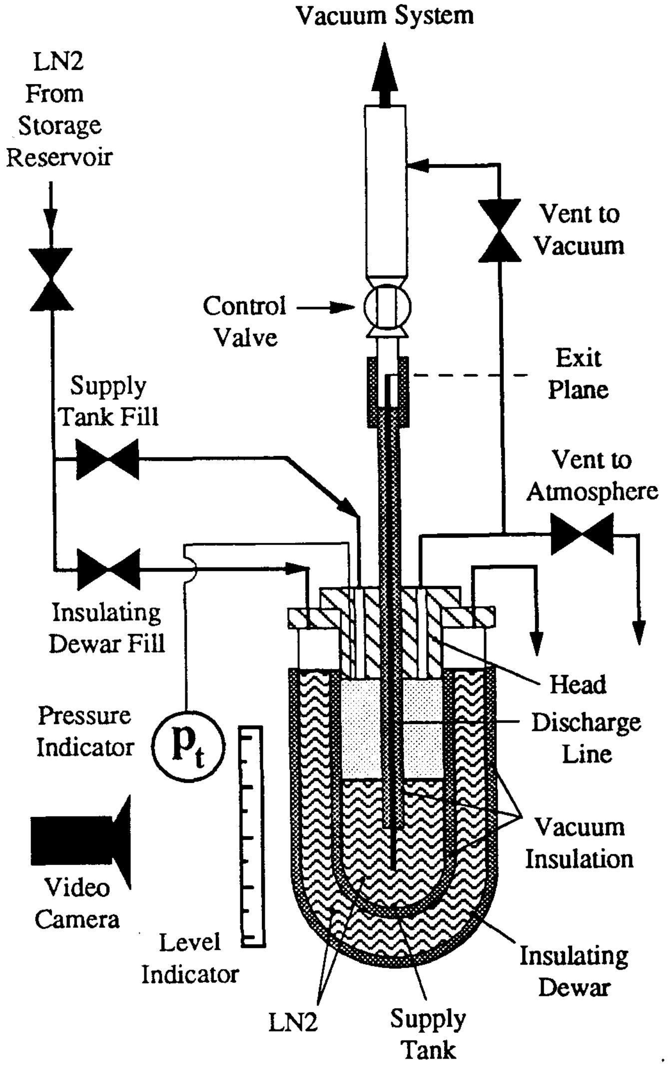

Figure 1. Experimental Apparatus.

and mass flux G ($G = \dot{m}/A_l$, where A_l is the area of the discharge line).

Both, the flow rate $\dot{m}(t)$ and the pressure $p_t(t)$ data are recorded. The results of typical experiments for discharge line diameters of $1mm$ and $5mm$ are shown in Figures 2a and 2b. The mass flow rate $\dot{m}$ is not significantly affected by the supply tank pressure change p_t, and the mass flux data are averaged over the entire dumping period.

The G_c data in figure 3 exhibit considerable scatter. These are our most recent experiments and the data scatter is less severe than in our earlier work. The data in the literature also exhibits some scatter, especially at low qualities.[3,4] We believe that some of the inconsistency is due to the difficulty in starting experiments from an equilibrium condition. The high G_c measured may be associated with a possible subcooled liquid being discharged. The low G_c measured may be associated with a possible superheated liquid being discharged. The most recent experiments have been performed with considerable care to ensure that the liquid and vapor are near equilibrium. The experimental apparatus has been improved by reducing the heat leak to the vapor. However, complete confidence in the initial state of the liquid/vapor mixture does not yet exist due to the current lack of accurate temperature measurements in the system. Chromel-Constantan thermocouples in use have an accuracy of $\pm 2K$ which potentially allow a deviation of $\pm 25kPa$ from the saturation pressure (in the experimental range). We intend to install a single silicon diode temperature detector (accuracy is $\pm .25K$) in the dewar for monitoring the liquid temperature.

Most of the $d_l = 5mm$ mass flux data are lower than the $d_l = 1mm$ data (figure 3). Figures 2a and 2b show that the pressure drop for the $d_l = 5mm$ discharge is much larger and occurs faster than for the $d_l = 1mm$ tube. This implies that the liquid entering the discharge line is more superheated for the $d_l = 5mm$ case, and may lead to larger amounts of vapor formation in the discharge line. The presence of larger volume fractions of vapor in the discharge line will reduce the mass flux and is a possible explanation for the lower mass flux through the larger diameter tube.

In an effort to determine the lowest supply tank pres-

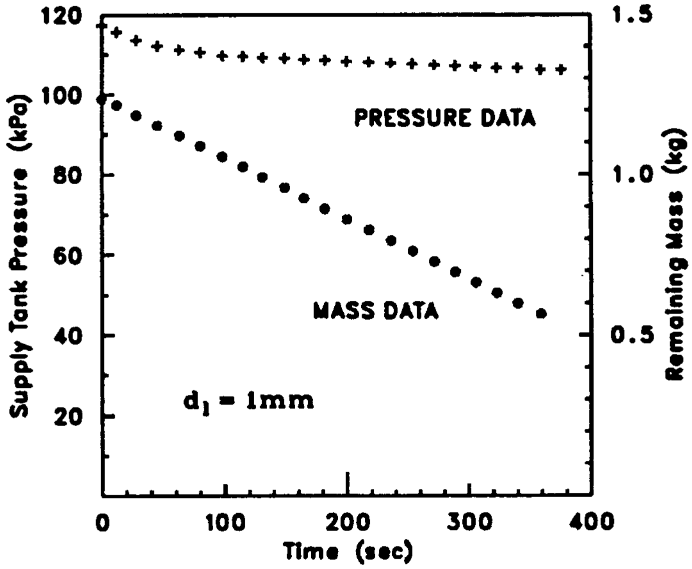

Figure 2a. Supply Tank Mass and Pressure Data.

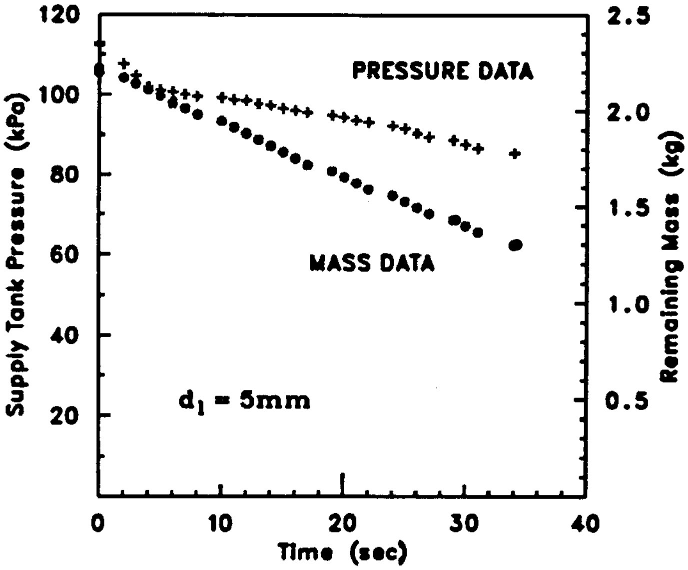

Figure 2b. Supply Tank Mass and Pressure Data.

sure which yet results in a critical flow, experiments have been performed which show that the flow is critical when the supply tank pressure is $\geq 25kPa$, with the dumpsite pressure below the triple point (t.p.) pressure ($12.5kPa$). Solidification in the discharge line has not been observed during these stated critical flow conditions. Solidification and plugging of the line has been observed when the supply tank pressure is less than $25kPa$, the dumpsite pressure is less than t.p. pressure, and pure liquid is entering the discharge line. Plugging means that the solid which is formed remains stationary in the discharge line. The solid plugs are porous and nitrogen continues to flow through the discharge line at lower mass flow rates. Discharge line plugging is less likely for high quality flows because a very small volume of solid is formed from a given volume of vapor (at the t.p. pressure) compared to that formed from the same volume of liquid.

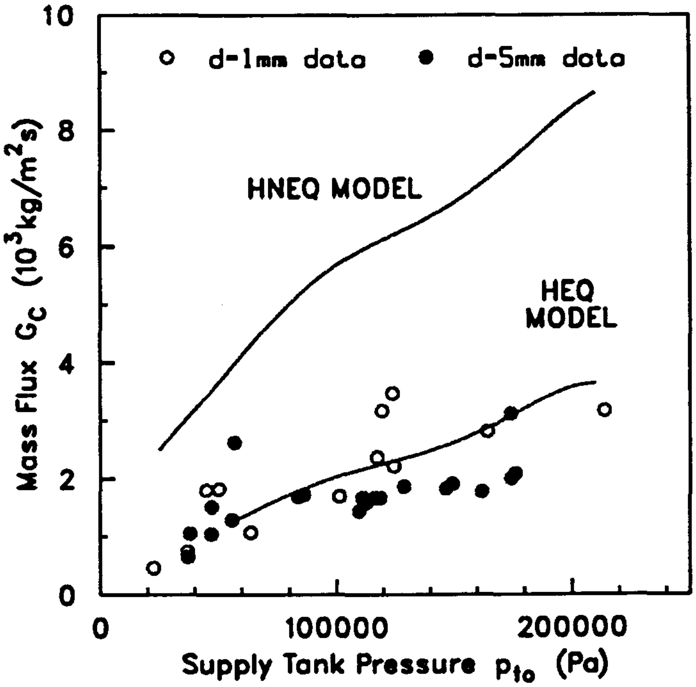

Figure 3. Critical Mass Flux as a Function of Supply Tank Pressure ($x = 0$).

2.1.2 Prediction

Two existing critical flow rate models are considered. The homogeneous, equilibrium model (HEQ) and the homogeneous non-equilibrium model (HNEQ). Both models employ the homogeneous assumption, that is, the liquid/vapor mixture in the discharge line is well mixed and there is no velocity difference (no slip) between the phases. This allows the use of uniform average values for the properties of the two-phase mixture at any given cross section in the discharge line, corresponding to a single phase "pseudofluid".[5] This is an acceptable assumption because the flow is turbulent at the high flow rates associated with the critical flow. For instance, the densities are mass averaged based on the thermodynamic quality, because the velocities of both phases are assumed to be equal. The continuity, momentum, and energy equations are then written as if there were only one fluid present. Homogeneous models give the following equation for the critical mass flux G_c.

$$G_c = -\left\{ \frac{dx}{dp}(v_{fg}) + x\left(\frac{dv_g}{dp} - \frac{dv_f}{dp}\right) + \frac{dv_f}{dp} \right\}_{ep}^{-1/2} \qquad (1)$$

where the subscript ep indicates that evaluation must be performed at the exit plane (analogous to the throat of a nozzle) of the discharge line. Equation (1) can be arrived at by using the sonic velocity as the limiting velocity or by maximizing the mass flow rate. The differences between equilibrium and non-equilibrium models arise from different interpretations of the terms in equation (1).

Both models take $\frac{dv_f}{dp} = 0$. The equilibrium model used here assumes that the liquid and vapor portions of the pseudofluid are always in thermodynamic equilibrium and that the depressurization process inside the discharge line is isentropic.

The non-equilibrium model presently employed is that which was developed by Henry and Fauske, and is widely referenced in the literature.[6,7,8] This non-equilibrium model differs from the equilibrium model in that it assumes that any vapor entering the discharge line expands as an ideal gas in an isentropic process until the exit plane is reached, at which time the gas expands as a polytropic real gas with the polytropic exponent as determined by Tangren *et. al.*[9] More significantly, a correlating parameter is introduced which tends to depress the value of quality as compared to the value produced by the equilibrium model. This correlation is

$$x = N x_E^2 \tag{2}$$

where x_E is the equilibrium value of quality, N is a correlating parameter taken to be 20 for short, constant-area ducts, and x is the non-equilibrium model value of the quality as used in equation (1). The non-equilibrium model results in a substantial increase in G_c, over the equilibrium model, at low discharge line entrance qualities.

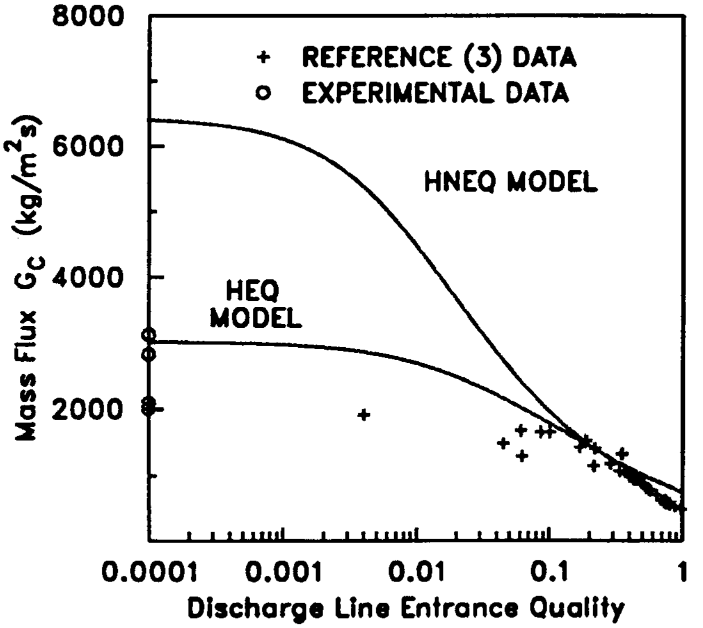

Figure 4. Critical Mass Flux as a Function of Discharge Line Entrance Quality ($p_t = 171kPa$).

The predictions of the homogeneous equilibrium and non-equilibrium models for the critical mass flux, are plotted in figures 3 and 4. Figure 3 shows G_c as a function of the supply tank pressure when $x = 0$, and figure 4 shows G_c as a function of quality for one supply tank pressure ($171kPa$). Experimental results (including results from reference 3) are also plotted on these figures. Figure 4 shows that both models asymptotically approach a maximum flow rate as the quality becomes very small and we have included our $x = 0$ data on the figure, for comparison. Figure 3 shows that most mass flux measurements have fallen below the rates predicted by the homogeneous equilibrium model, and that using a larger diameter tube does not necessarily provide greater mass flux. Other researchers have indicated that, for large L_l/d_l ratios, G_c tends toward an asymptotic minimum.[7,10] Our experiments are with $L_l/d_l = 150-750$, which are much larger than those used by others. Sozzi and Sutherland have collected mass flux data significantly below the homogeneous model predictions, for $L_l/d_l > 20$ and a discharge line entrance quality equal to zero.[10]

It appears that the homogeneous equilibrium model reasonably predicts the flow rate for conditions in our experiments i.e., decreasing supply tank pressure, long tubes and $x = 0$.

2.2 Micro-Gravity

2.2.1 Experiment

An oxygen dumping experiment has been performed aboard the NASA Space Shuttle.[11] During this experiment, a system which initially consisted of subcooled liquid oxygen (no vapor present) was dumped to outer space while the shuttle was in its orbit. The mass of the oxygen was recorded before and after (final mass ≈ 0) the dump, and the system pressure was monitored during dumping.

2.2.2 Prediction

We do not expect to change our critical flow rate predictions for use in a micro-gravity environment. Although we have not settled on the proper model for the normal gravity, we believe that when we are able to predict the normal gravity critical flow, based on the discharge line inlet conditions (pressure, quality, and the temperature of each phase), the same models can be applied to micro-gravity conditions. This is because the gravitational pressure drop during critical flow is of negligible importance in normal gravity and will be of less importance in a micro-gravity environment. Gravitational effects as discussed in reference (2) may be significant when non-critical liquid/vapor flow is encountered.

Mass flow analyses of the shuttle experiment mentioned earlier has been performed, by others, using the Lockhart/Martinelli two-phase flow correlation in combination with an entropy maximization procedure (similar to the single-phase, Fanno flow determination) at the discharge line exit plane.[12] This prediction method coupled with supply tank behavior assumptions (homogeneous equilibrium tank), resulted in an accurate estimate of the time necessary to complete the oxygen dump.[11] Unfortunately, mass data as a function of time is unavailable, therefore, the accuracy of the transient predictions are unknown.

This model has been adapted for predicting the performance of our normal gravity system and has been found to yield mass flow rate results similar to the homogeneous equilibrium model.

3. SUPPLY TANK

The supply tank description centers on the pressure history of the tank (tank pressure as a function of time). Tank pressure is chosen over its temperature because the pressure gradients in the tank are much less significant than the temperature gradients, allowing the pressure transient $p_t(t)$ to provide some indication of the overall in-tank behavior.

During the dumping process the tank pressure transient tends to exhibit what is referred to as the pressure plateau. The pressure plateau exists when, for an extended period of time (50–90% of the total dump time), the in-tank pressure remains constant or decreases slowly with time (figures 5a and 5b). The pressure plateau appears when the rate of vapor formation inside the tank is volumetrically equal to the discharge rate from the tank. For cryogenic fluids at low pressures, the liquid contains much more energy per unit volume than the vapor phase. The available liquid energy makes the pressure plateau physically possible from an energy point of view. The mass transfer from liquid to vapor requires heat transfer. Modes of heat transfer are conduction, convection, and homogeneous or heterogeneous boiling.

If the heat transfer rate is large enough and no temperature gradients develop in the tank, an equilibrium process takes place, and the pressure plateau exists at the saturation pressure. In practice, the pressure drops, with its rate governed by the heat transfer rate. As the pressure falls farther below saturation, the rate of heat transfer increases due to the presence of larger temperature gradients (increased conduction and convection) and the addition of new mechanisms (bubble nucleation and growth). It is also possible for the discharge to be completed without ever reaching a pressure plateau.

For a given $\dot{m}$, $p_t(t)$ will be dependent on the state of the liquid/vapor mixture entering the discharge line, and the rate of vapor formation inside the tank (where the rate of vapor formation is dependent on the heat transfer rate q). The highest possible pressure inside the tank at a given time is the equilibrium pressure. In the equilibrium case, the supply tank state (defined by x and p_E here) is a function only of the mass remaining in the tank (assuming an adiabatic process in the tank). Heat transfer causing vapor formation takes place at whichever rate is necessary for the tank to remain in thermodynamic equilibrium. The lowest possible pressure inside the supply tank will be produced by the discharge of pure vapor ($x = 1$) from the tank while the q causing the production of new vapor is at its minimum. Maximum, minimum and intermediate heat transfer rates are discussed below.

Maximum Heat Transfer Rate – During an equilibrium supply tank process, enough heat transfer takes place to ensure that no temperature gradients exist inside of the tank. The rate of heat transfer causing the vapor formation is determined by the mass flow rates of the liquid and vapor out of the tank. In practice, equilibrium processes cannot be attained, but they may be approached by low discharge rates or by large rates of heat transfer (e.g. mixing). This condition is the same in normal and micro-gravity.

Minimum Heat Transfer Rate – The minimum possi-

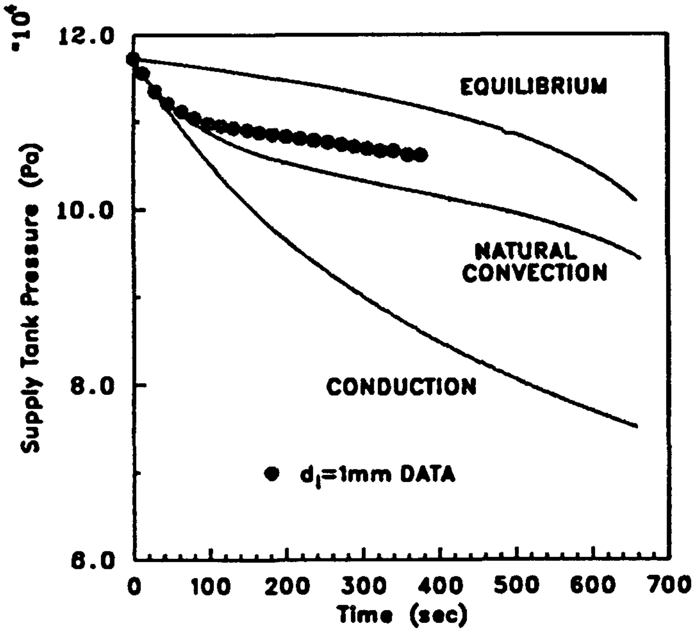

Figure 5a. Supply Tank Pressure Transient, Experiment and Models.

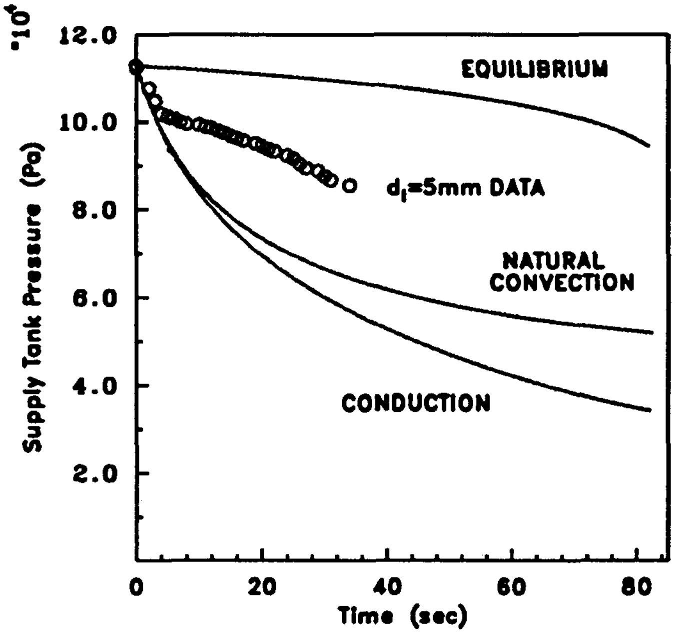

Figure 5b. Supply Tank Pressure Transient, Experiment and Models.

ble heat transfer rate is by conduction only. The conduction heat transfer rate is affected by the liquid/vapor interface temperature T_i and area A_i. If the interface area is small, as for settled liquids, the conduction q will be lower than for a system with a large interface area (such as vapor bubbles mixed throughout a liquid). This condition is the same in normal and micro-gravity.

Intermediate Heat Transfer Rate - This is the most likely scenario. Heat transfer rates may approach those necessary to maintain equilibrium. A non-equilibrium temperature distribution is necessary to maintain the heat transfer rate and the pressure plateau. Modes of heat transfer can be conduction to large interface areas, boiling caused by heterogeneous or homogeneous nucleations, and forced or natural convection.

3.1 Normal Gravity

3.1.1 Experiment

Several experimental supply tank transients $p_t(t)$ have been recorded while dumping liquid nitrogen from a closed supply tank under normal gravity. Typical transients for each discharge line diameter are shown in figures 5a and 5b. All transients have exhibited non-equilibrium behavior with heat transfer rates described as intermediate. When dumping through the $d_l = 1mm$ tube, the liquid/vapor interface appears quite calm. When dumping through the $d_l = 5mm$ tube, the interface sloshes about and significant in-tank liquid velocities are promoted by the higher discharge rates. Natural circulation flow has been observed (from the light refraction through transient nonuniform density fields) in the supply tank, as the pressure drops. The natural circulation initiates almost immediately $(< 1s)$ after the beginning of the experiments.

3.1.2 Prediction

Three models have been used to describe the supply tank pressure transient, $p_t(t)$ under normal gravity. All of the models below assume that the vapor phase is saturated ($x = 1$) at any given pressure, and the vapor temperature is uniform throughout. The models also employ the assumption that the liquid temperature at the interface is equal to the vapor saturation temperature.

Equilibrium – This is the model which corresponds to maximum heat transfer rates, and is valid in any gravitational environment. The model is implemented by assuming that the supply tank remains in thermodynamic equilibrium while the mass content of the tank decreases, and the specific entropy (kJ/kgK) remains constant. This model predicts the maximum possible supply tank pressure for a given mass remaining. In figures 5a and 5b, the model predictions are based on the experimental flow rates and the predictions are continued until the simulated mass remaining is less than 0.1% of the original mass of nitrogen in the supply tank.

Natural Convection – The natural convection description of the supply tank transient provides a low $p_t(t)$ limit for our experiments. The particular correlation used is for horizontal liquid layers cooled from above.[13] This gives

$$q = \frac{0.15kA(Ra^{1/3})(T_i - T_{f\infty})}{L} \tag{3}$$

for determining the heat transfer rate and, therefore, the vapor generation rate. L is a characteristic length which drops out because a factor of L^3 is contained in the Rayleigh Number. The natural circulation model does well in describing $p_t(t)$ when discharge is through the $1mm$ diameter tube, but does not predict enough heat transfer to closely model the transient associated with the $5mm$ diameter tube. This indicates that forced convection is significant when dumping through the larger tube, but the natural convection approach can be used to find the lower bound for the supply tank pressure.

Conduction – The conduction model assumes that the rate of vapor formation is determined by the conduction heat transfer rate to the liquid/vapor interface. Only heat conducted to the interface provides the latent heat necessary for vapor formation from the liquid. The heat diffusion equation is solved for a one dimensional system which is exposed to a varying surface temperature. A finite difference scheme has been employed, and the surface temperature is taken to be the saturation temperature at the vapor pressure. This model predicts the lowest possible $p_t(t)$ under normal and micro-gravity environments.

3.2 Micro-Gravity

3.2.1 Experiment

The Space Shuttle experiment mentioned earlier shows a $p_t(t)$ similar to our ground-based experiments, and can be said to exhibit the characteristics of the intermediate heat transfer described above. The pressure was lower than equilibrium, but higher than would be predicted due to the conduction above. It is expected that the heat transfer was caused by boiling and the subsequent convection (boiling causes mixing). The mixing of liquid and vapor also serves to increase conduction heat transfer because there is more liquid/vapor interface area than for a system in which the liquid is settled.

3.2.2 Prediction

Limiting case pressure transients (equilibrium and minimum q) can be predicted for the discharge of tanks in a micro-gravity environment. It is expected that boiling will cause $p_t(t)$ to behave similar to our normal gravity results (intermediate heat transfer rates). Because it is difficult to predict the amount of superheating necessary to initiate heterogeneous or homogeneous nucleation, it is also difficult to predict the magnitude of the pressure plateau in a micro-gravity environment.

The phase distribution in the supply tank prior to initiating the dumping process is unknown in micro-gravity. It is possible that the liquid and vapor phases are mixed together prior to the mass discharge, or the phases may be distinctly separated due to surface tension and the effects of micro-gravity.

If the phases are initially separated, it may be reasonable to assume that, shortly after a micro-gravity tank begins depressurization, boiling initiates and causes the liquid to "foam" into the vapor space creating a homogeneous mixture of liquid and vapor. The basis for this assumption is that, in the absence of gravity, a disturbance such as boiling will cause the interface surface to break apart, and the liquid and vapor will become more evenly distributed throughout the tank. It may be further assumed that the liquid and vapor phases are at the same temperature (thermodynamic equilibrium). This is the homogeneous equilibrium model for the supply tank transient which was used in reference (11) to predict $\dot{m}(t)$ and $p_t(t)$ for an oxygen dumping experiment under micro-gravity. The homogeneous mixture assumption led to the assumption that the liquid/vapor mixture entering the discharge line was at the same quality as the supply tank. Their estimate of $p_t(t)$ is high, while the total time from initiation of the dump until the tank was empty is accurately predicted. The homogeneous equilibrium supply tank model has been used with some success for making mass flow predictions, without accurately portraying the physics in the tank. First, there must be a temperature difference between the phases in order to have the non-equilibrium type of pressure transient which was observed. The equilibrium assumption leads to an incorrect description of the state of the liquid and vapor entering the discharge line. Secondly, the homogeneous assumption can lead to inaccurate prediction of the quality at the discharge line entrance. The homogeneous assumption may be acceptable when the mass flow rates are large compared with the tank diameter and the liquid and vapor exhibit violent motion inside the tank, but for ordinary transients, we expect that there will be some preferred nonhomogeneous phase distribution in the supply tank. The distribution will be determined by the location of the discharge line inside the tank, and the tank and discharge line geometry, as well as the initial states of the liquid and vapor.

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