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DISCHARGE RATE OF CRYOGENS IN MICROGRAVITY: WHAT GROUND BASED EXPERIMENTATION CANNOT RESOLVE

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ABSTRACT

The discharge of cryogenic liquid and vapor from tanks to a vacuum is investigated. The effects of the L/d ratio, mass quality, supply tank transient and gravitational environment are discussed. The discharge of saturated liquid through long ($L/d \geq 10.0$) straight tubes is emphasized.

Normal gravity experiments and existing model results are presented which indicate that the homogeneous equilibrium model provides an accurate description of two-phase critical flow for many conditions likely to be encountered in practical microgravity systems. Nonequilibrium effects are found to produce flow rates greater than homogeneous equilibrium model predictions for, short tubes with high inlet pressure, and long tubes with low inlet pressure. Long tubes with low inlet pressure are also found to be susceptible to blockage from cryogen solidification.

The gravitational environment will not significantly affect mass flow rate when turbulence is present. The gravitational environment is expected to be most important for predicting the flow rate when the flow velocity is low and mass quality is high. Gravity is especially important in the transition regions as the important system parameters change.

NOMENCLATURE

d	diameter (m)
G	mass flux (kg/m^2-s)
L	length (m)
P	pressure (Pa)
Re	Reynolds number, $Re = Gd/\mu$
T	temperature (K)
x	mass quality, $x = m_g/(m_g + m_f)$
μ	viscocity (kg/m-s)

Subscripts

HEQ	homogeneous equilibrium model
i	inlet
t	supply tank

1. TWO-PHASE FLOW OF CRYOGENS IN STRAIGHT TUBES

1.1 The General Two-Phase Flow Problem

An accurate, quantitative description of two-phase flow requires that mass flow rate, pressure drop, and quality can be predicted. A general description of this type for liquid/vapor two-phase flow has not been accomplished for two reasons. One, the diverse nature of the problem does not allow a single model to describe all of the situations which may be encountered. And two, the lack of understanding of the phase change problem, especially nucleation, requires that nearly all models rely on some form of empiricism.

However, the literature contains many articles in which the authors have managed to successfully describe two-phase flow for specific situations. This implies that engineering models are available for many applications. The engineering problem is to find and choose a model which applies to the situation at hand.

1.2 The Influence of the L/d Ratio

1.2.1 Model Applicability

Experiments have been performed in which saturated liquid nitrogen (LN_2) is discharged from a supply tank at low pressures (≤ 3 atmospheres), through straight tubes to an ambient pressure which is below the nitrogen triple point (t.p.) pressure (12.5 kPa). The tubes were round and insulated, and the discharges were vertical up in normal gravity.

These experiments focus on a limited portion of the general two-phase flow problem, but four distinct modeling regions have been identified.

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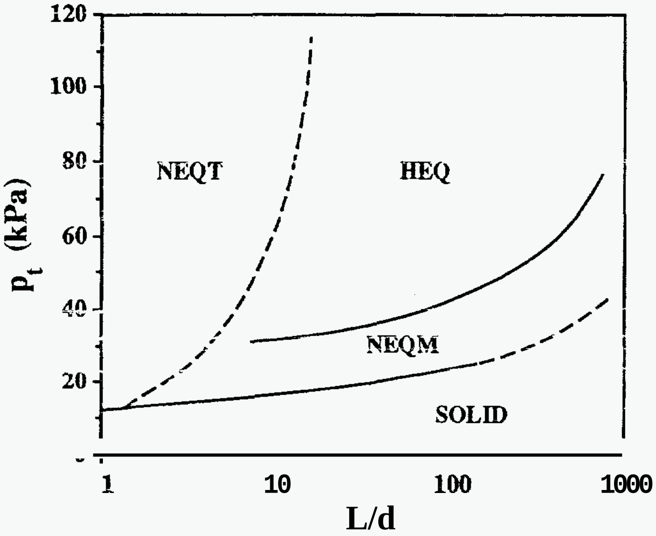

Figure 1. A Mapping of Modeling Regions Based on Tube Inlet Pressure and L/d ratio. The map is based on saturated liquid nitrogen entering a straight tube. The ambient pressure at the discharge end of the tube is taken to be 0.0 kPa. Solid lines are based on experiments, dashed lines are based on the literature and interpolation.

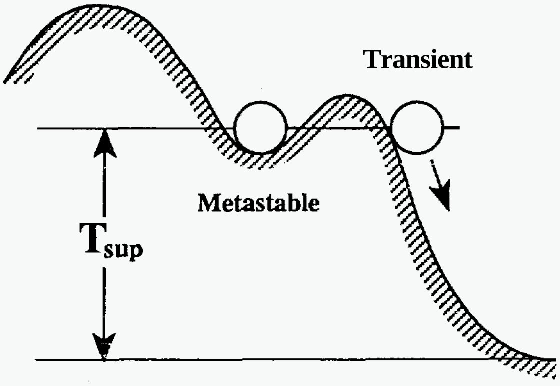

Figure 2. Schematic Showing Metastable and Transient Nonequilibrium States. Both states are shown with the same superheat, but the transient state is changing with time.

1. Nonequilibrium Transient Flow (NEQT).
2. Homogeneous Equilibrium Flow (HEQ).
3. Nonequilibrium Metastable Flow (NEQM).
4. Flow With Solid Formation (SOLID).

Figure 1 is a mapping of these different flow types based on the discharge line entrance pressure and the tube L/d ratio. The ambient pressure at the discharge line exit is taken as 0 kPa, although the pressure inside the tube does not drop to ambient when the flow is critical. The dashed lines on figure 1 are estimates and the solid lines are based on our experimental evidence. The smallest L/d ratio used was 10, which was not short enough to allow us to observe NEQT flow at the low pressures used.

The difference between NEQT and NEQM type flows may be understood by the schematic of figure 2. The metastable state can be maintained indefinitely without outside influences. The transient state is shown with the same superheat as the metastable state, but it is progressing toward a new state which cannot be attained instantaneously. An important consideration in modeling NEQT flow is the description of the nonequilibrium rate of vapor production while for NEQM flows it is most important to describe the the nonequilibrium flashing inception point of the liquid. Both nonequilibrium phenomena may be observed in the same tube, figure 1 indicates where each effect is dominant.

The transition between the NEQT and HEQ areas in figure 1 is affected by the traverse time that a mass element spends inside the tube. The transition line shown is an estimate based on Henry and Fauske's[1] statement that their homogeneous nonequilibrium model provides accurate critical flow rate predictions when $L/d \leq 20$. The NEQT type of critical flow is often discussed and alternate approaches have been offered[2,3]. The homogeneous equilibrium model given by Wallis[4] is simple to implement and is frequently applicable.

The transition between the HEQ and NEQM areas is affected by turbulence. The solid line between these areas on figure 1 is a line of constant Reynolds number ($Re_{i,\mathrm{HEQ}} = 1 \times 10^5$) which is defined below.

$$Re_{i,\mathrm{HEQ}} = \frac{G_{\mathrm{HEQ}} d}{\mu} \tag{1}$$

The subscript i indicates that the Reynolds number is calculated at the tube inlet, and HEQ indicates that the calculation is based on the homogeneous equilibrium model. Turbulent flow is characterized by localized velocity and pressure fluctuations in a flow stream. Jones[5] differentiates between static and dynamic modes of liquid flashing where dynamic flashing is subject to turbulent pressure fluctuations. The magnitude of the fluctuations is affected by the degree of turbulence. At high Reynolds numbers the pressure fluctuations are more pronounced, the local value of liquid superheat is larger, and vaporization is more likely to occur. When the Reynolds number is large enough, the flowing liquid will vaporize with the average superheat in the tube equal to zero and the HEQ model accurately predicts the mass flow rate. As the Reynolds number drops, the

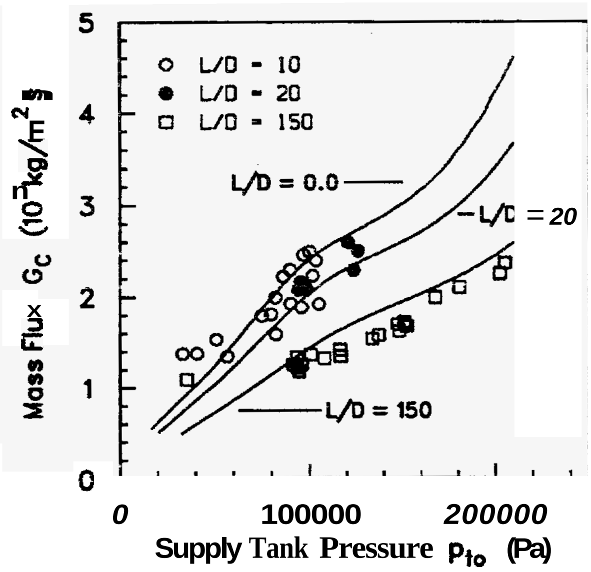

Figure 3. Mass Flux as a Function of Supply Tank Pressure at Various L/d ratios. Shown are the homogeneous equilibrium model and experimental data taken with a 5-mm diameter discharge line. Pure liquid at saturation conditions enters the discharge line.

local superheats are not large enough to cause vaporization at the equilibrium pressure and the liquid flows in a metastable state until the bulk pressure drops farther.

The transition line between the NEQM and SOLID region is based on experiments in which a glass tube was blocked by solidification of initially saturated LN_2. The observed solid was porous and did not completely stop the flow of nitrogen.

As L/d is increased beyond the values of figure 1, the flow will depart from being critical. At these high L/d's the volume fraction of vapor in the tube becomes significant. This effect, in combination with the reduction of turbulence causes interphase slip to become an important parameter, and transitions between annular, slug and bubble flow regimes will be observed.

1.2.2 Normal Gravity Experimental Results

Figure 3 shows experimental LN_2 mass flux measurements as a function of the supply tank pressure for several L/d ratios. The experiments were performed with saturated liquid entering the tube in normal gravity. The supply tank pressure and bulk liquid temperature were monitored but temperatures and pressures were not monitored inside the tube. Note that at the higher pressures, HEQ model predictions and the experimental results agree within about 50 percent, and at low pressures the percentage difference is about 100 percent.

During low pressure experiments in which flow rates are significantly larger than those predicted by the HEQ model, the flow appeared transparent and completely free of vapor (NEQM region). For experiments closely matched by the HEQ model, the flow is not transparent and appears to contain a homogeneous mixture of liquid and vapor (HEQ region). Experiments in which the tube was vibrated after establishing NEQM flow, frequently resulted in a change from the NEQM to the HEQ region. The visible transition was accompanied by a corresponding drop in mass flow rate to HEQ levels.

1.2.3 Practical Systems

From a practical standpoint, HEQ flow systems are easiest to design in the area of liquid management and transfer. HEQ systems are characterized by distributed but significant pressure drops. Most practical L/d ratios will prevent operations in the NEQT region. NEQT systems are characterized by significant localized pressure drops. A system with a NEQM Reynolds number may be tripped into the HEQ region by vibrations, valves, pipe bends etc.

There may be some value to promoting NEQM flow because it is possible to attain larger mass flow rates with lower pressure drops than HEQ flow. This may allow more efficient use of pressurants.

1.2 The Influence of Mass Quality

An additional dimension of mass quality at the tube inlet may be added to the flow map of figure 1. As the quality changes, the location of the transition lines change, and entire modeling regions may appear or disappear. An increase in the inlet quality is somewhat analogous to increasing the L/d ratio, and will cause the transition lines of figure 1 to move to the left. The results of figure 4 show that the NEQT model is not necessary to describe the mass flux for high quality flows because increasing the area of the liquid/vapor interface causes vapor formation to approach equilibrium rates. This is an indication of the HEQ region moving to the left. The flow regimes for which interphase velocity slip is important will also be present at smaller L/d ratios when significant amounts of vapor enter the tube. The NEQM region will diminish in size as the quality increases because the existence of vapor in the flow causes temperature gradients during depressurization resulting in a decrease in the liquid superheat.

Figure 4 shows HEQ and NEQT critical mass flux predictions as functions of tube inlet quality at 171 kPa. Both models predict asymptotically constant mass fluxes

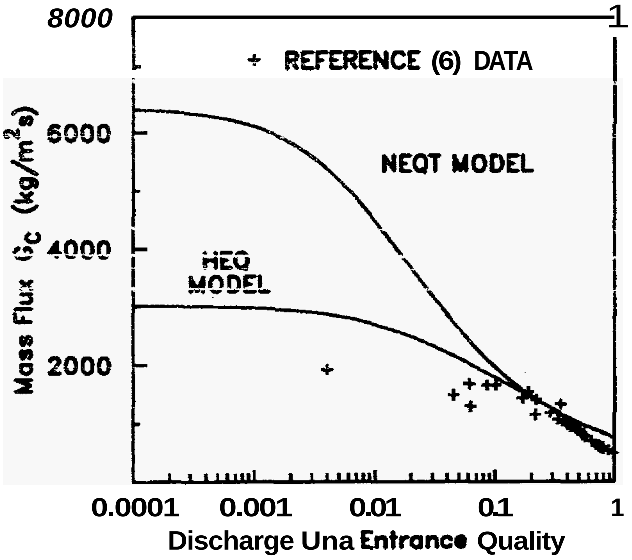

Figure 4. Critical Mass Flux as a Function of Tube Inlet Quality ($p_t = 171$ kPa). Shown are the predictions of Henry and Fauske's NEQT model, the HEQ model, and experimental data collected by Campbell and Overcamp.

when the quality is small. The volume fraction of vapor is approximately 1/2 when $x = 0.01$.

The mass flux predicted by the HEQ model at low qualities is only three times greater than that for pure vapor, and mass flux appears to be a relatively weak function of quality in this region. However, when discharging from a supply tank, the discharge tube inlet quality greatly affects the supply tank pressure transient. The discharge of pure vapor causes the tank pressure to decrease more than the discharge of pure liquid. The difference in supply tank pressure transients is an additive effect which amplifies the effect of quality on the mass flow rate.

1.3 The Influence of Gravity

In the turbulent flow regions, gravitational effects are not important because gravity will not affect the phase distribution, and the gravitational and frictional pressure drops are small compared to the momentum pressure drop. Gravity becomes more important as L/d and/or quality increase. These effects decrease the momentum pressure drop and the relative magnitudes of gravitational and frictional pressure drops become important. Duckler *et al.*[7] note that for many of these normal gravity flow situations, the gravitational pressure drop exceeds the pressure drop due to wall friction, when the tube is inclined upwards only 1° from horizontal.

Gravity also influences the supply tank, which in turn affects the inlet condition (p, x) to the discharge tube.

Because it is difficult to predict the amount of superheating necessary to initiate heterogeneous or homogeneous nucleation, it is also difficult to predict the pressure response of the supply tank 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 mass discharge, or the phases may be distinctly separated due to surface tension and the effects of micro-gravity.

In some cases, 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.

The homogeneous assumption will probably be valid when the volume discharge rate is large and the pressure drop is rapid. This will cause boiling to occur in a violent manner which is likely to mix the liquid and vapor together. However, for slow discharges boiling need not occur and a distinguishable separation of phases may be sustained. The validity (and importance with regard to mass flow rate through the discharge line) of assuming equilibrium between the phases is not clear. Temperature gradients will exist in a tank undergoing depressurization, but they may be negligible in some cases.

2. THE NEED FOR MICROGRAVITY EXPERIMENTATION

The performance of cryogenic discharge experiments in microgravity environments is necessary to gain the tools needed for designing safe, predictable, and efficient systems for use in the exploration and utilization of space. The experimental work which must be accomplished in a microgravity environment follows:

1. *Locate microgravity two-phase* flow *transition* ***re-gions.*** **A** general description of two-phase flow is not possible in normal gravity nor in microgravity. This is due in part to the existence of the various flow regimes where different system parameters are

important in describing the flow. The transitions between the flow regimes usually define the application limits of the various two-phase flow models in normal gravity, and can serve the same purpose in microgravity. As we increase our use of space, adequate models will be developed, or extended from normal gravity models, for use in microgravity environments. Identification of transition regions will make consistent data easier to obtain and model development more efficient.

2. *Determine if new models are necessary for some flow regions, and obtain the data necessary for development.* After transition regions are identified experiments must be performed for the flow regimes of interest in order to verify the applicability of ground based models, or to obtain data for microgravity models. Prior knowledge of the transition regions will allow experiments to be designed such that they operate in only one flow regime. This will increase the value of experimental data and reduce the number of experiments necessary to gain confidence in new models.

3. *Determine supply tank behavior and its influence on discharge tube inlet conditions.* Two-phase flow modeling is necessary for predicting the performance of practical systems. These systems will generally consist of a supply tank discharging to some reservoir or to the surroundings. Predicting overall system performance requires knowledge of the supply tank behavior and its influence on flow through the discharge tube. It is necessary to test the homogeneous supply tank assumption fox limiting cases and to study the possibility of promoting a preferred phase distiibution in the supply tank or at the inlet, to the discharge tube (liquid acquisition devices, baffles etc.).

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