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EFFECT OF PRESSURANT INLET CONFIGURATION ON LIQUID OUTFLOW IN WEIGHTLESSNESS

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16. Abstract

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SUMMARY

An experimental study was conducted to investigate the effect of various pressurant inlet configurations on the draining process during liquid outflow from a cylinder in weightlessness. Both normal gravity measurements and actual outflow tests in a weightless environment are reported. The normal gravity tests were made to set up various internal tank pressure distributions, and the weightless tests were conducted to measure the liquid residuals remaining in the tank at the time of vapor ingestion. The internal tank pressure distributions examined were peaked in the center of the tank, peaked at the tank wall, and nearly uniform throughout the tank. The nearly uniform distribution produced the least distortion of the interface in weightlessness and, therefore, the lowest liquid residuals.

INTRODUCTION

The Lewis Research Center has been conducting experimental investigations of the general problem of liquid outflow from tanks in weightlessness. The overall objectives of these studies were to define some of the problems that may be encountered in orbital refueling and similar liquid-transfer operations in weightlessness and to establish criteria that would aid the solution of these problems.

The initial experimental study of liquid outflow in weightlessness was conducted by Nussle (ref. 1). He reported that the liquid-vapor interface is distorted during outflow and that increasing the outflow rate further distorts the interface causing a reduction in the amount of liquid expelled. He also observed that installing liquid outlet baffles and pressurant inlet baffles reduced the interface distortion and delayed the occurrence of vapor ingestion. The basic problems of interface distortion and vapor ingestion during outflow in weightlessness were studied in considerable detail in references 2 to 5. The effectiveness of various outlet baffle designs in reducing liquid residuals was determined in reference 6. In that study flat plates and perforated baffles were placed over the tank outlet.

This report presents the results of an experimental study conducted to determine the effect of various pressurant inlet configurations on the draining process during liquid outflow from a tank in weightlessness. Internal tank pressure distributions were obtained in normal gravity and liquid residuals at the time of vapor ingestion were measured in weightlessness. The tests were conducted at the Lewis 5- to 10-Second Zero Gravity Facility with a hemispherically bottomed cylinder having a cylindrical drain located on tank centerline.

BACKGROUND

The draining of containers in rocket vehicles and spacecraft systems requires pressurization techniques in which gas is introduced into the ullage space above the liquid. A drain valve located in the outlet line is then opened to initiate the outflow process either to a pressure-fed or a pump system. The interaction of the pressurant gas on the liquid-vapor interface can result in a nonuniform pressure distribution. The dissipation of the energy of the incoming gas into the bulk liquid determines to a considerable degree the efficiency of draining gas-free liquid from the container. To complicate the draining process, the liquid-vapor interface in weightlessness is highly curved prior to the initiation of outflow and is further distorted during draining (ref. 1).

A considerable amount of work, both experimental and analytical, has been done to study the interaction of gas jets impinging on liquid surfaces in normal gravity. These are somewhat related to the problem at hand; however, the effects of surface tension are neglected and the liquid surfaces are flat and stationary. One experimental study has been conducted in weightlessness. This study by Labus (ref. 7) examined the effect of a parabolic-profile, gaseous jet impinging on a liquid surface. He was able to relate the jet momentum to the depth of penetration of the liquid by the jet in a weightless environment. Although the effect of surface tension was included, his study was also limited to a flat and stationary liquid-vapor interface.

The treatment of the overall draining process in weightlessness, considering all the conditions described above, represents a considerable challenge to solve analytically, even with the use of state-of-the-art computer techniques. As a result, a complete analytical solution is not yet available. There is, however, currently in progress an analytical study to obtain the motion of the liquid-vapor interface during draining in weightlessness (and at reduced gravity) but only with a uniform pressure distribution over the free surface.

The present study, therefore, is designed to examine experimentally the draining process in a weightless environment. Studied are several pressurant inlet configurations which result in a wide range of free surface pressure distributions, including a nearly uniform profile. The liquid residuals at the time of vapor ingestion are used to compare the merits of each configuration in weightlessness.

APPARATUS

Pressurant Inlet Configuration

The pressurant inlet configurations used in this study are shown in figure 1.

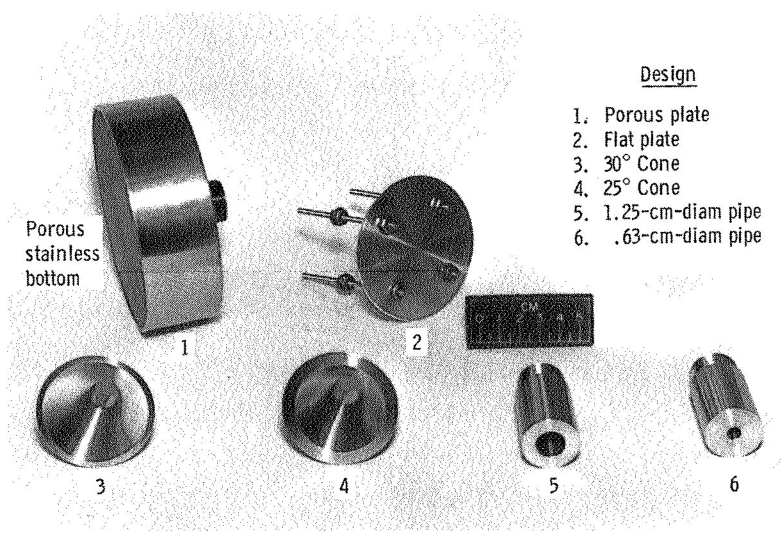

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Figure 1. - Inlet configurations tested.

Design 1 consisted of an enclosed cylindrical plenum chamber having a porous stainless steel bottom. The flat plate design 2 was a solid steel disk (identical in design to that of ref. 3), having a diameter equal to the tank radius. The conical and straight pipe designs shown as designs 3 to 6 are self-explanatory. For each of these devices, the vertical location of its outlet into the tank with respect to the liquid-vapor interface in normal gravity was held constant at one-half the tank radius.

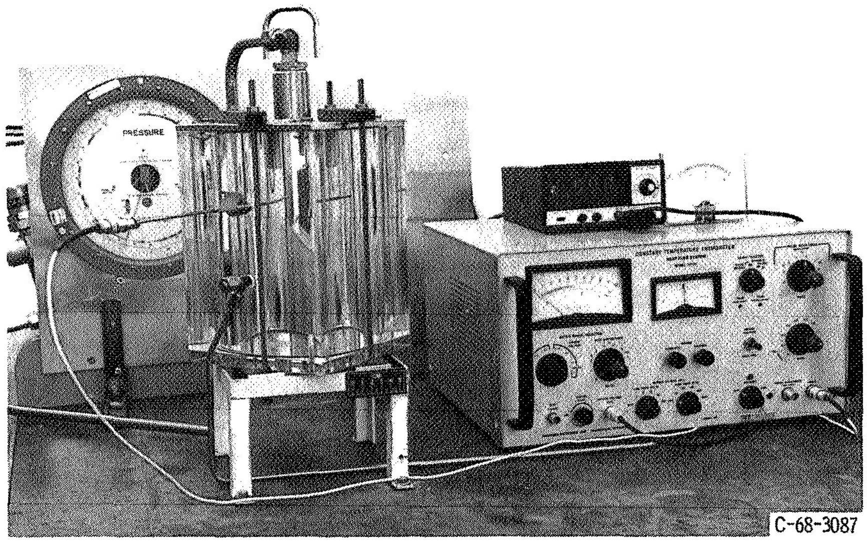


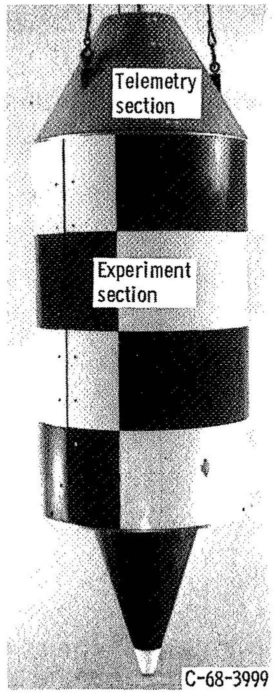
Figure 2. - Normal-gravity experimental apparatus.

Normal Gravity

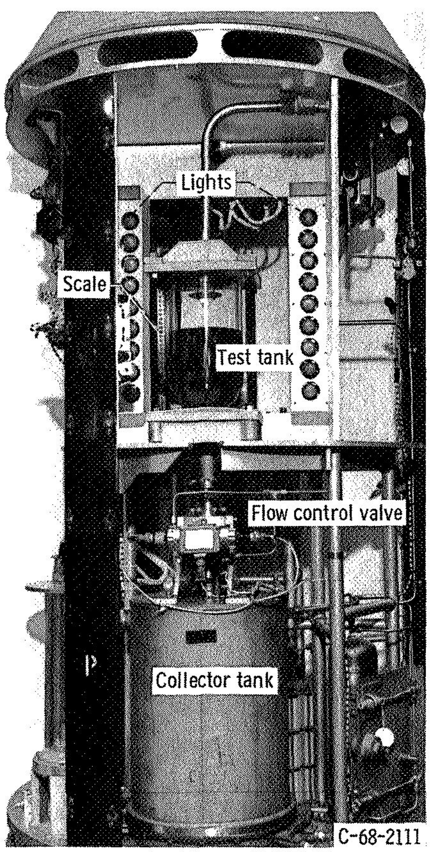
The normal gravity test apparatus illustrated in figure 2 consisted of a plastic test chamber, a pressurization and flow control system, and a mass flow measurement system. The test chamber was a 15-centimeter-diameter cylinder machined from an acrylic plastic block. It had a steel top and an adapter for the pressurant inlet configuration to be tested. The opposite end of the cylinder was fitted with a pressurant exhaust port having a controllable orifice opening. A static-pressure tap was positioned one tank radius from the bottom of the test chamber.

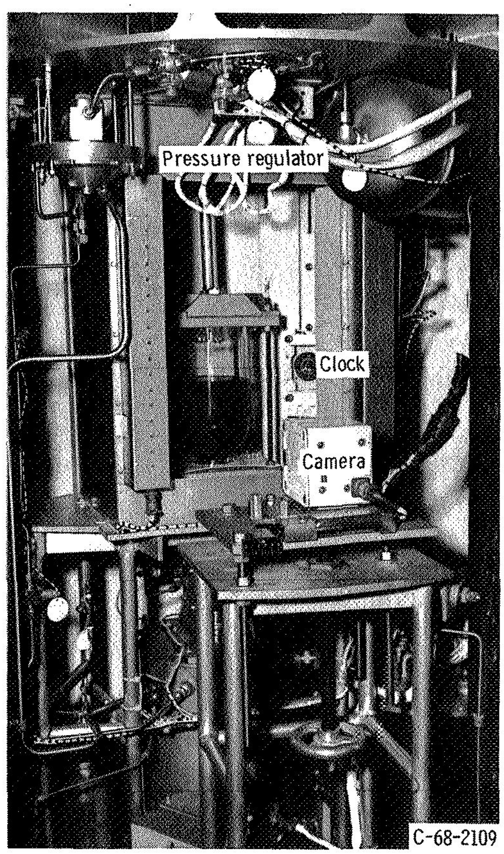
The pressurization and flow control system consisted of a pressure regulator and a supply pressure gage. Filtered air was used as the test fluid (no liquids were employed in these normal gravity tests).

The mass flow measurement system contained a constant-temperature anemometer and a hot-film sensor. The sensor was attached to a probe and installed in the test chamber one tank radius from the top as shown in figure 2. The probe was positioned in a plane 3.75 centimeters below the exit of the pressurant inlet device being tested and traversed the diameter of the chamber. This position coincided with the initial location of the liquid-vapor interface for the outflow tests.



(a) Experiment vehicle.





(b) Experiment section details.

Figure 3. - Experiment system for weightless tests.

Weightlessness

The experimental data on outflow during weightlessness were obtained in the Lewis Research Center's 5- to 10-Second Zero-Gravity Facility which is described in detail in reference 3. Briefly, this facility consists of an evacuated underground test chamber where free-fall tests may be conducted with a minimum air drag on the experiment vehicle; and a ground level service building for the assembly and servicing of the experiment vehicle. The experiment vehicle used is shown in figure 3. It is essentially the same unit (including the test tank) as was used for the tests conducted in reference 3. The only change has been the addition of the various pressurant inlet configurations.

A detailed description of the experiment vehicle system may also be found in reference 3. Basically, this vehicle consisted of a self-contained unit on which were mounted the plastic test tank, the pressurization system and the necessary photographic, data-recovery, and electric-power systems. Ethanol was used as the test liquid because its contact angle of 0° on plastic and its specific surface tension of 28.3 cubic centimeters per second squared very closely simulate these properties for liquid hydrogen (a commonly used propellant).

PROCEDURE

For the normal gravity tests, pressure against liquid flow rate calibrations were first conducted with the experimental system that was to be eventually used in the tests. A liquid outflow rate of 2050 cubic centimeters per second was selected as the one at which all of these comparative tests would be conducted. This flow rate was chosen as the best compromise due to such limitations as experimental time available (5 sec), liquid-vapor interface formation time in weightlessness, and tank size. From the calibration tests, it was determined that a pressure of 20-psi (13.8 N/cm^2) on the liquid surface was required to yield this particular liquid flow rate.

Therefore, all the normal gravity tests were then conducted with 20-psi (13.8-N/cm^2) static pressure in the tank. The gas flow rate out of this tank was controlled by an orifice in the exhaust port. The barometric pressure to which the system was exhausted was recorded. Mass flow measurements were made by recording output voltages of the anemometer at 0.5 centimeter radial increments across the entire tank. These measurements were taken in only one plane and axial symmetry was assumed to exist in the test tank. The complete mass flow measurement system was precalibrated using a closely controlled, well defined airstream.

The procedure for the tests in weightlessness was identical to that used in the tests of reference 3. After the required cleaning process, the test tank was installed in the experimental vehicle and filled with ethanol to a level of 3 tank radii. The entire vehicle was then placed in the test chamber and allowed to free-fall in its evacuated environment. The outflow test was conducted during this 5-second free-fall interval by means of preset timers to operate the various systems. Data were recorded by means of high-speed motion pictures.

DISCUSSION OF RESULTS

Normal Gravity

The pressurant inlet configurations investigated in this study were generally representative of those which result in three types of free surface pressure distributions. These were (a) a distribution which peaks or maximizes near the center of the tank, (b) a distribution which peaks near the tank wall, and (c) a uniform distribution. Since the static pressure in the tank was a fixed value in all the normal gravity tests, the dynamic pressure or velocity head was the dominating parameter affecting fluid motion within the tank and, therefore, was used in comparing the inlet configuration performance in normal gravity.

The results are presented in figure 4. The pressure profiles for the cones and pipes are similar and are characterized by a sharp spike in the center of the tank indicating very little flow in the outer areas. Some improvement, that is, spreading of the incoming flow over a larger area, is noted as one moves from the smaller to the larger pipe and then to the cones.

The distribution observed with the flat-plate baffle, on the other hand, was quite different (fig. 4(c)). It maintained lower average pressures throughout the central portion of the tank and concentrated the higher levels in an annular ring near the wall of the tank. However, here the flow was quite turbulent as it passed over the edge of the plate and caused substantial oscillations on the order of ± 5 percent in the magnitude of any point. (The points indicated in the figure are averages of these fluctuations.)

The nearly uniform distribution was observed with the porous plate (fig. 4(c)). In this case, there was very little flow immediately next to the tank wall (because the porous plate diameter was smaller than the tank diameter) and the energy of the pressurant gas was most evenly distributed throughout the remainder of the tank. The low pressure observed in the central area of the profile with the porous plate may have been caused by the fact that the pressurant enters the plenum containing the porous plate in the radial direction and, therefore, tends to direct the flow toward its outer diameter.

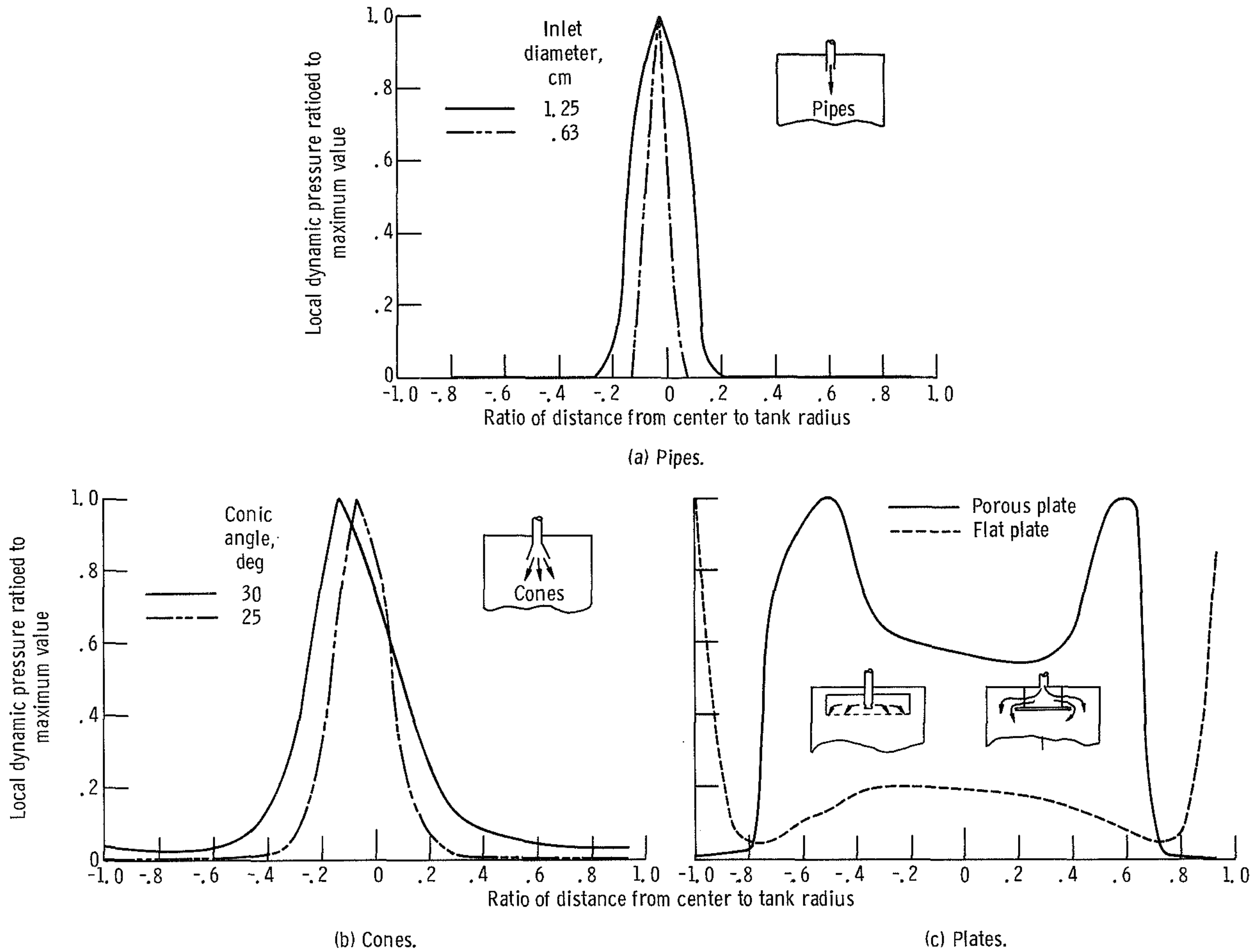


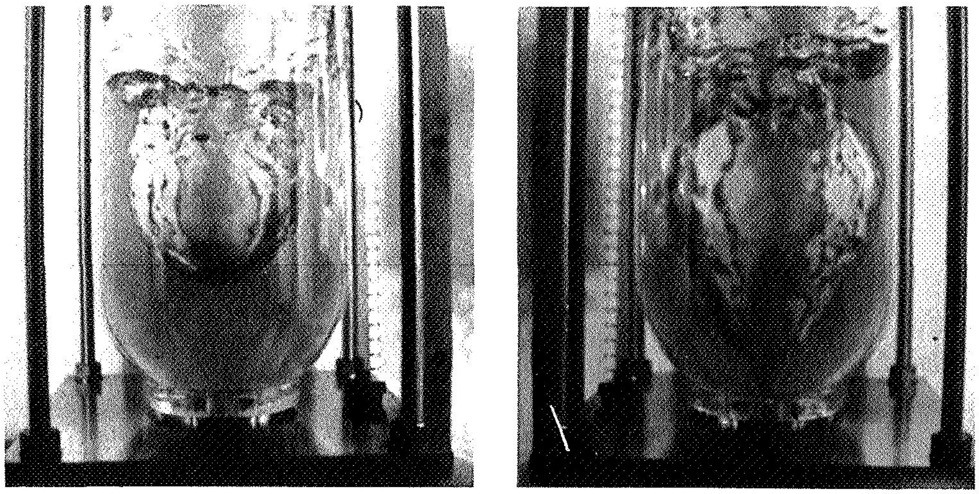
Figure 4. - Dynamic pressure distributions in normal gravity.

Weightlessness

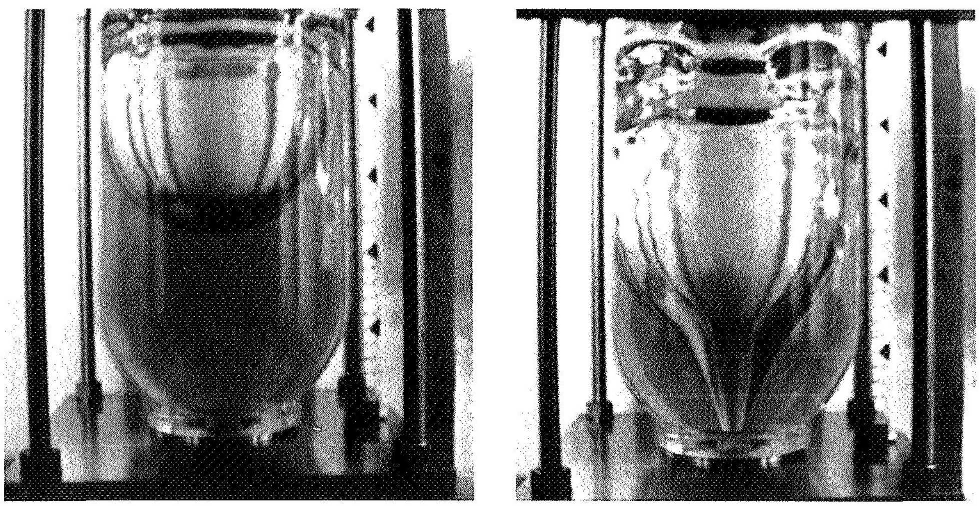
Tests in weightlessness were conducted with four of the six configurations used in the normal-gravity tests. These were the 30° cone and the 1.25-centimeter-diameter pipe for the central peak profile, the flat plate for the wall peak profile, and the porous plate for the uniform distribution. Each test in weightlessness consisted of photographically recording the motion of the liquid-vapor interface as a function of time for a constant flow rate of 2050 cubic centimeters per second.

The liquid-vapor interface shapes during outflow and at the instant of vapor ingestion into the outlet are compared in figure 5 for the various distributions. Selected for comparison in figure 5 are the results obtained with the 30° cone, the flat plate, and the porous plate. Figure 5(a) shows the results obtained with the 30° cone and is also typical of the pictures obtained for outflow with the straight pipe. In both cases, excessive amounts of liquid residuals are evident on the tank wall. The interface shapes are highly irreg-

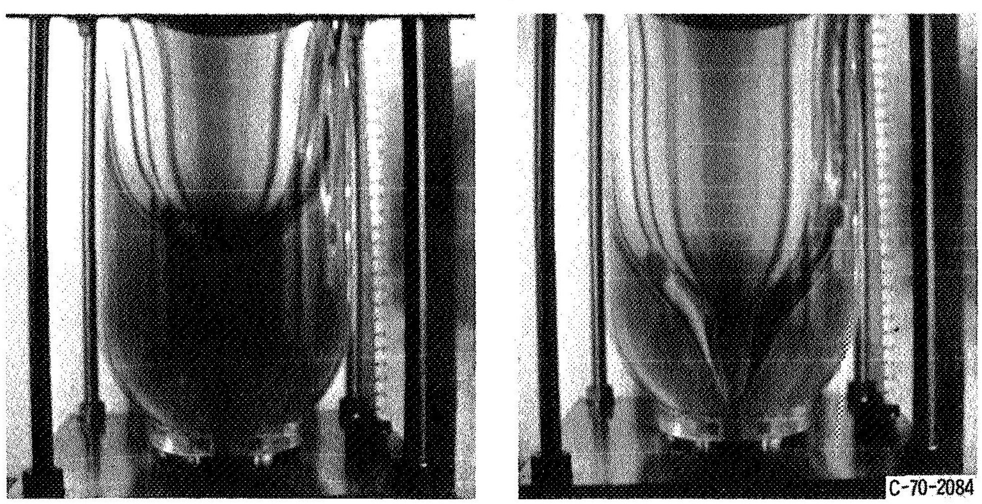
During draining At vapor ingestion



(a) Typical of both 30° cone and straight pipe.



(b) Flat plate.



(c) Porous plate.

Figure 5. - Liquid-vapor interface shapes in weightlessness.

ular and rapidly changing. The liquid is very agitated. The interface shape with the wall peak distribution (fig. 5(b)) is considerably smoother than the shapes obtained with the central peak (cone or straight pipe, fig. 5(a)); however, it still exhibits wave formations especially in the vicinity of the pressurant inlet device. These waves and ripples tend to confirm the normal gravity observations of turbulence near the edge of the flat plate. Note the tendency of the liquid to hang up and collect near the top of the tank. The interface shapes with the uniform pressure distribution, on the other hand, were completely lacking in waves or surface deformations and were very smooth during draining as well as at vapor ingestion (fig. 5(c)). No agitation or liquid collection was observed in these tests. This set of pictures clearly shows that the more even pressure distributions resulted in the smoother interface shapes.

From the films it was possible to calculate and compare the liquid residuals. The residual fraction was used for the comparison, and, as defined in reference 5, this is the residual volume at vapor ingestion divided by the reference volume of $(2/3)\pi R^3$ (where R is the tank radius). The results of these computations are summarized in table I where the residual fractions are listed for each type of velocity profile. For the

TABLE I. - LIQUID RESIDUALS IN WEIGHTLESSNESS

Pressure profiles	Pressurant inlet configuration	Residual fraction[a]
Central peak	1.25-cm-diam pipe	1.93
	30° Cone	1.81
Wall peak	Flat plate	1.09
Uniform	Porous plate	.96

[a]Residual fraction = (Residual volume)/(reference volume or $(2/3)\pi R^3$).

central peak profiles the residuals were on the order of twice the reference volume, and for the wall peak and uniform profiles they were equivalent to the reference volume.

The magnitude of the residuals listed in table I do indeed confirm the observations made in figure 5; that is, the uniform pressure profile results in the least distortion of the interface and, consequently, the least residual liquid volume at the time of vapor ingestion into the outlet. It is also worthy to note, however, that the wall peak profile obtained with the much simpler design of the flat plate baffle was nearly as effective in reducing the residuals as the more complex system with the uniform distribution.

CONCLUDING REMARKS

A study was conducted in both normal gravity and in weightlessness to determine the effect of the incoming pressurant on the liquid-vapor interface during outflow. Draining studies in weightlessness were performed for pressurant inlet configurations which produced three types of internal tank dynamic pressure distributions in normal gravity. These distributions were central peaked, wall peaked, and nearly uniform, and were obtained with pipes and cones, a flat plate, and a porous plate, respectively. As expected, the various distributions considerably affected the liquid surface, with the most uniform profile (obtained with the porous plate) producing the smoothest liquid-vapor interface during draining. However, the considerably simpler flat plate was not much worse. The measured residual fractions ranged from 1.93 for the central peak profile to 0.96 for the uniform profile.

It should be pointed out that these comparisons were made only at one specific flow rate with one given tank geometry and one test fluid. They clearly demonstrate the advantages of maintaining a uniform pressure distribution over the liquid-vapor interface. However, a more detailed study of any proposed pressurant inlet design is needed to fully optimize the pressurization system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 19, 1970,
124-08.

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