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EFFECT OF OUTLET BAFFLING ON LIQUID RESIDUALS FOR OUTFLOW FROM CYLINDERS IN WEIGHTLESSNESS

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16. Abstract

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SUMMARY

An experimental investigation was conducted in a weightless environment to study the effect of outlet baffles in reducing liquid residuals after draining from cylindrical tanks. Residuals were compared for two baffle positions and four baffle configurations. Comparisons are made with previous results obtained for unbaffled tanks. The results showed that the liquid residual remaining in a tank after draining in weightlessness can be reduced to about 60 percent of the unbaffled case for some of the systems tested. Also discussed are the pressure losses associated with each baffle configuration.

INTRODUCTION

The Lewis Research Center has been conducting experimental investigations of the general problem of liquid outflow from tanks in a weightless environment. The overall objectives of these studies are 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 will 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 resulted in an increased distortion of the interface which caused a reduction in the amount of liquid expelled. He also reported that installing a baffle over the tank outlet delayed the ingestion of vapor into the tank outlet and thus decreased the amount of liquid remaining in the tank. Further studies of interface distortion and vapor ingestion during outflow were reported in references 2 to 8.

This study was undertaken to expand the outlet baffling work of reference 1 by obtaining a more quantitative measure of the effectiveness of several flat plate baffles located over the tank outlet. The primary variables in these tests were the baffle diameter and its axial position relative to the tank outlet.

The results of this study are presented in terms of the amount of liquid remaining in the tank as functions of baffle size and position, and outflow rate. The experimental study was conducted in the Lewis Research Center's 2.2-Second Zero Gravity Facility with a flat bottomed cylindrical tank. The tank was constructed with a cylindrical outlet located on the tank centerline. Comparisons of the data obtained in this study with the data obtained in reference 7 (an experimental study with no outlet baffles) are also presented.

SYMBOLS

B	baffle radius, cm
h_i	initial liquid height, cm
Q_o	volumetric outflow rate, cm^3/sec
R	tank radius, cm
r_o	outlet radius, cm
t	time, sec
V_o	outflow velocity (liquid velocity in outlet line), cm/sec
β	specific surface tension, σ/ρ, cm^3/sec^2
ρ	density, g/cm^3
σ	surface tension, dynes/cm
μ	viscosity, g/(cm)(sec)

APPARATUS AND PROCEDURE

Test Facility

The experimental data for this study were obtained in the Lewis Research Center's 2.2-Second Zero Gravity Facility. A detailed description of this facility and its mode of operation may be found in reference 7. It consists basically of a drop tower in which experiments are conducted with the use of recoverable, freely falling experiment packages. In this manner, a 2.2-second period of weightlessness may be obtained.

Experiment Systems

Experiment package. - The experiment package shown in figure 1 was used in conducting these tests. It contained all the necessary electric, pneumatic, and photographic systems required to perform the proper operations and recover the test data. It is the same unit that was used in conducting the studies of reference 7.

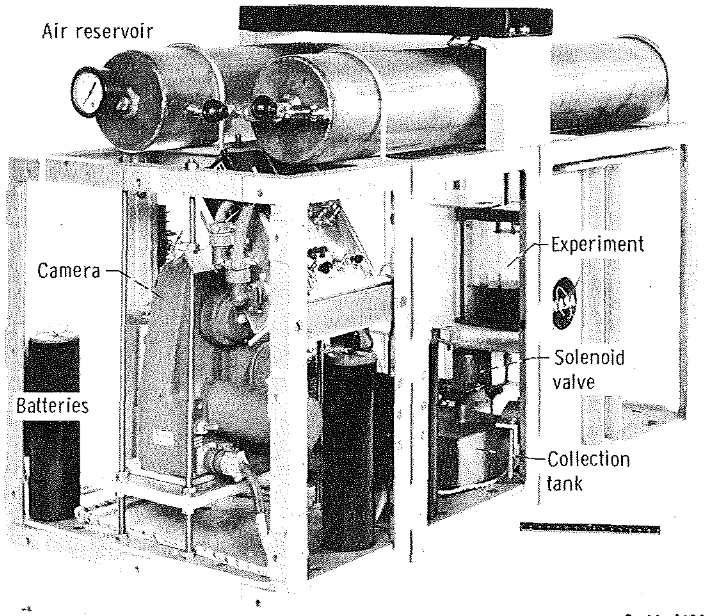
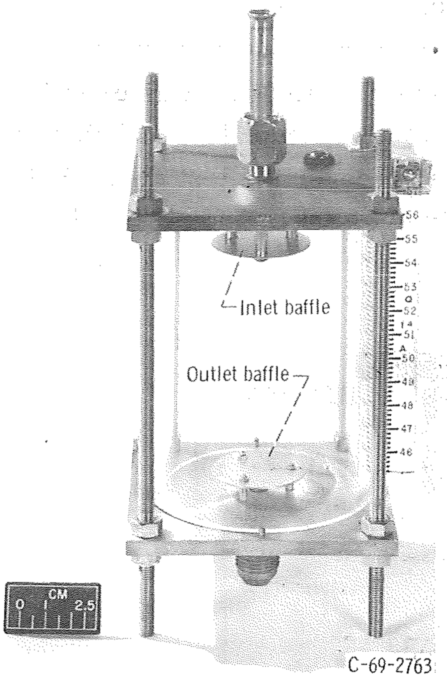


Figure 1. - Experiment package.

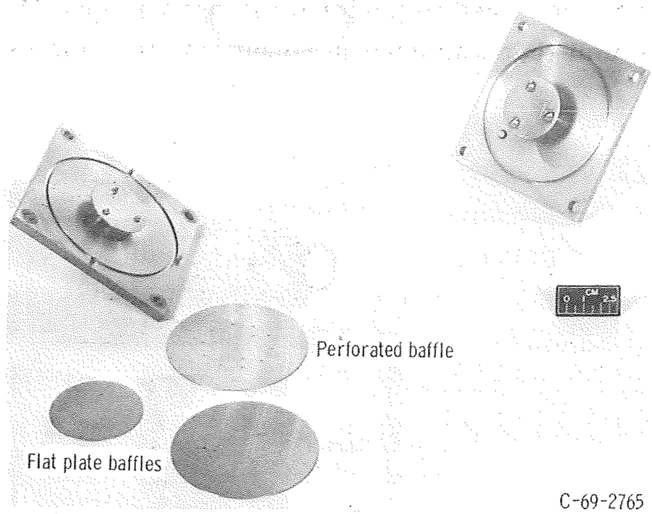
Test tank. - The test tank was a flat bottomed right circular cylinder 4 centimeters in radius. This tank, shown in figure 2(a), was machined from cast acrylic plastic and was fitted with a concentric cylindrical outlet 0.4 centimeter in radius (one tenth of the tank radius). A flat disk 2 centimeters in radius was positioned 2 centimeters below the pressurant inlet port to minimize the effect of the incoming gas on the liquid-vapor interface. Except for the outlet baffles, this tank is identical to that used in the study of reference 7.

Outlet baffles. - The outlet baffles tested in this study are shown along with the disassembled tank parts in figure 2(b). The baffles tested were

(1) Flat plate baffles with baffle- to tank-radius ratios B/R of 0.485, 0.635, and 0.980



(a) Assembled tank.



(b) Tank parts with various outlet baffles.

Figure 2. - Experiment tank.

(2) A perforated baffle which was a flat plate baffle of $B/R = 1.0$ that had 10 equally spaced 0.127-centimeter-diameter holes on a 2-centimeter-radius circle. The total open flow area of the perforated baffle and the solid baffle with $B/R = 0.980$ was equal to the area of the tank outlet. The pins used to support the baffles allowed the positioning of the baffles at either 1 or 2 outlet radii above the tank bottom (0.4 or 0.8 cm).

Test liquid. - The liquid chosen for these tests was anhydrous ethanol with the following properties (at 20° C): surface tension $\sigma = 22.3$ dynes/centimeter; density $\rho = 0.789$ gram/centimeter^3; viscosity $\mu = 1.2\times10^{-2}$ gram/(cm)(sec). This liquid exhibited a 0° contact angle with the tank surface. To improve the quality of the photographic data, a small amount of dye was added to the test liquid. Addition of this dye had no measurable effect on the liquid properties.

Test Procedure

The procedures used for these tests, such as the preparation, calibration, operation of the equipment, and data recovery were identical to that employed in the study of reference 7 where these procedures are described in considerable detail. Briefly, the procedure consisted of conducting a normal gravity, pressurized outflow calibration test, followed by an outflow test conducted at the same pressure in a weightless environment. In both cases, the motion of the liquid-vapor interface was photographically recorded. The position of the normal gravity flat liquid-vapor interface was then plotted as a function of time from which an average outflow velocity was calculated. This normal gravity calibration test was necessary because in weightlessness the liquid-vapor interface distorts from its equilibrium configuration during outflow (ref. 1) and it is, therefore, not possible to determine an average flow rate.

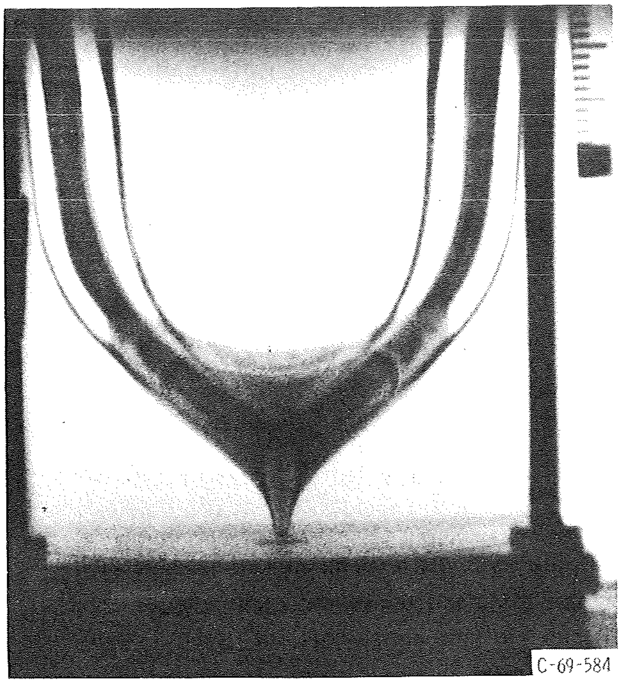
It was assumed that, for a given pressure in the air reservoir, the resulting outflow rate was the same in weightlessness as for the normal-gravity test. This assumption has been previously verified by the author (ref. 3).

For each weightless test, the experiment package was allowed to free fall and sufficient time before initiation of outflow was allowed for the liquid-vapor interface to approach its zero gravity configuration. Since the time required for the interface to come to complete static equilibrium was too long to permit a draining test to follow in the 2.2 seconds available, outflow was initiated when the interface centerline reached its low point in its first pass through equilibrium. This time was calculated from the empirical equation $t = 0.62\left(R^3/\beta\right)^{1/2}\Big/\left[1 + 2\left(\mu^2/\rho\sigma R\right)^{1/4}\right]$ given in reference 8. The interface centerline velocity at this time is zero. The liquid residuals after draining in weightlessness were easily calculated from the outflow rates and the total draining times. The total draining time was measured from the initiation of outflow to the time of vapor ingestion into the outlet.

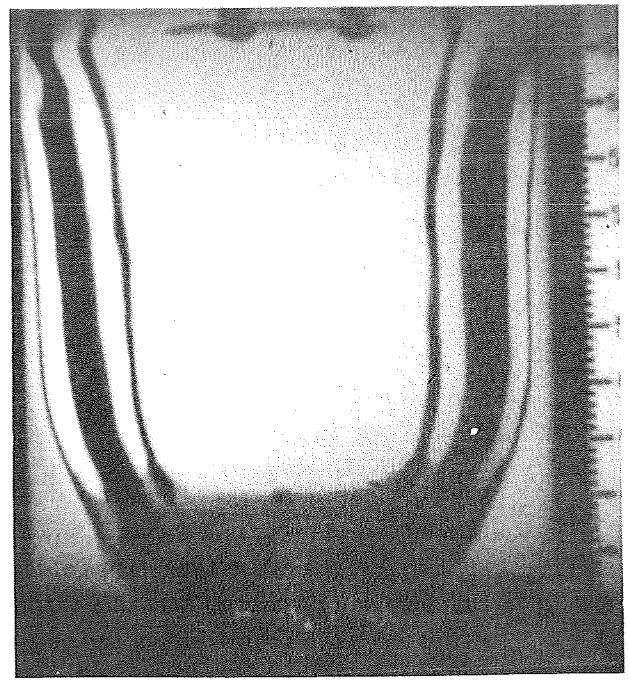
RESULTS AND DISCUSSION

Interface Shapes at Vapor Ingestion with Baffling

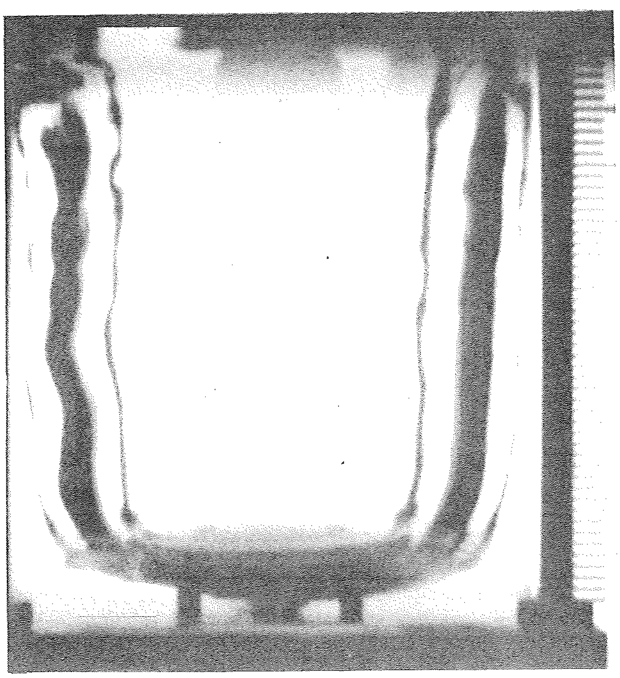
As already noted, this study is very closely related to the study of the unbaffled tanks reported in reference 7. Therefore, these results will be most meaningful when compared to those of reference 7. Presented in figure 3 are photographs of the liquid-vapor interface at the instant of vapor ingestion in a weightless environment. Figure 3(a) shows the typical shape of the liquid-vapor interface at vapor ingestion as observed in reference 7. The results obtained in this study are presented in figures 3(b) to (e) for the flat plate baffles and the perforated baffle. It is apparent from these pictures that the interface shape is changed by the baffles and the amount of liquid remaining in the tank at vapor ingestion (residual) is decreased, with the greatest decrease observed for the largest baffle. This decrease in residual is in agreement with the observations of reference 1.



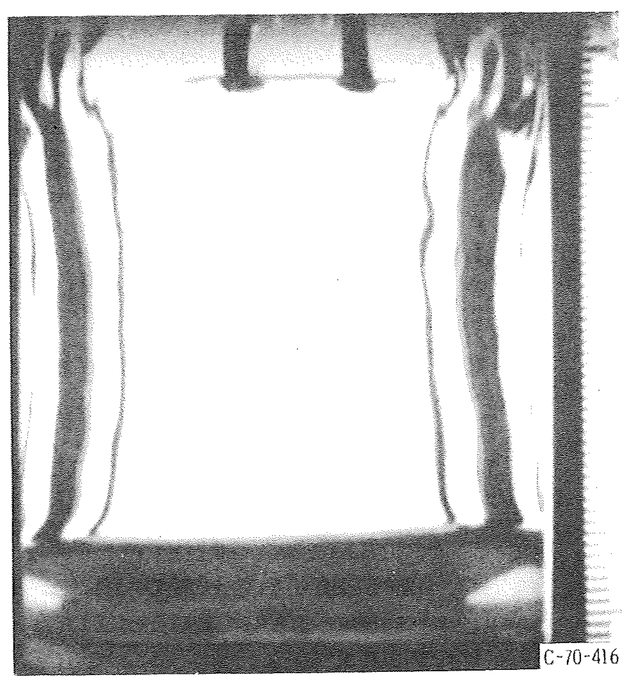
(a) Without baffle.



(b) Baffle- to tank-radius ratio, $B/_R$ = 0.485.

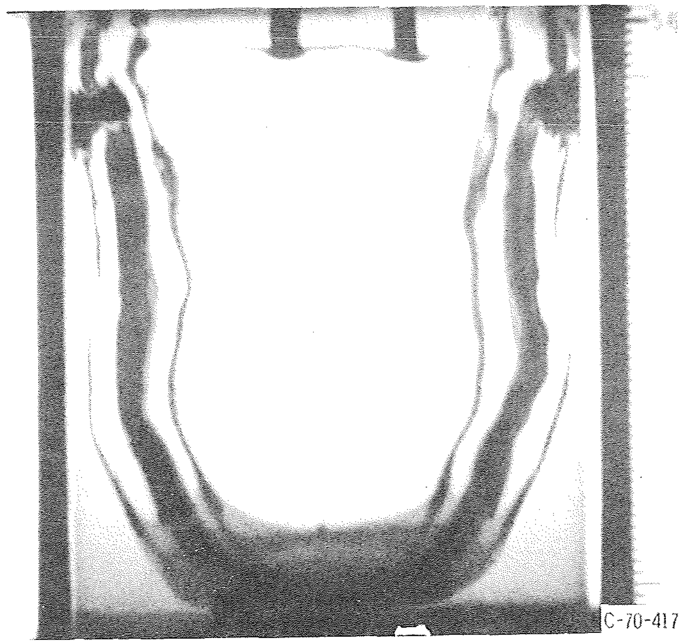


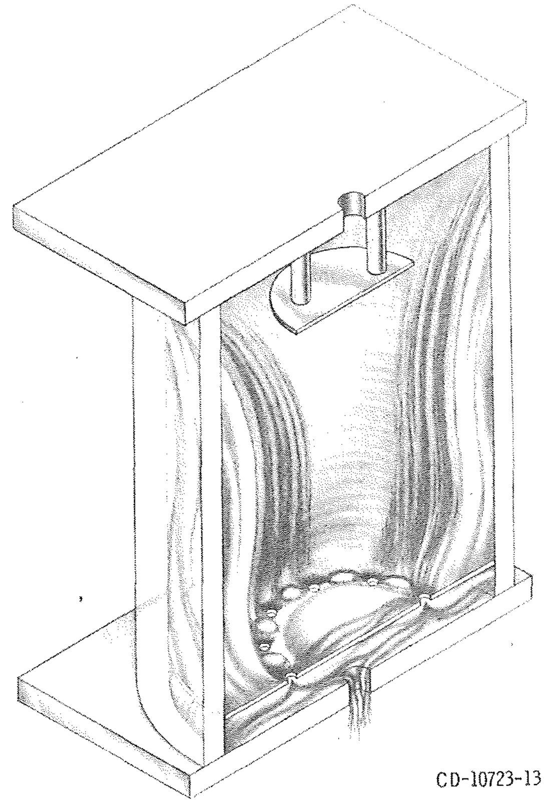
(c) Baffle- to tank-radius ratio, $B/_R$ = 0.635.



(d) Baffle- to tank-radius ratio, $B/_R$ = 0.980.

Figure 3. - Photographs of vapor ingestion in weightlessness with and without outlet port baffling.





(e) Perforated baffle.

Figure 3. - Concluded.

Effect of Baffle Design on Liquid Residuals

In order to obtain a more quantitative measure by which one may compare the relative merits of the various baffles, the liquid residuals were calculated from known initial volumes, flow rates, and outflow times for the flat plate baffles and the perforated baffle.

These residuals are compared in a form where the residual fraction was plotted as a function of the outflow Weber number. The residual fraction was defined as the ratio of the residual liquid volume to a reference volume. This reference volume is equivalent to a tank filled to a depth of one diameter. Each of these tests, as well as the majority of the data for reference 7, was obtained with an initial fill depth of one diameter. The outflow Weber number $Q_o^2/\beta R^3$ used here also corresponds to that developed and used in reference 7 to correlate the liquid residual data of that study.

Flat plate baffle design. - Presented in figure 4 are the results obtained with a flat plate baffle having a baffle- to tank-radius ratio of 0.485 positioned at one and two tank outlet radii above the outlet. The residual fraction ranged from about 0.50 at the lower Weber numbers to about 0.58 at a Weber number of 330. These results indicate that positioning the flat plate baffle at two radii (0.8 cm) above the outlet port results in no difference in liquid residuals from the case where the baffle was positioned at one outlet radius (0.4 cm) above the tank bottom.

The residual fraction obtained for the unbaffled case of reference 7 (dashed line in fig. 4) ranged up to 0.74 at the higher Weber numbers. In comparison then, the baffle

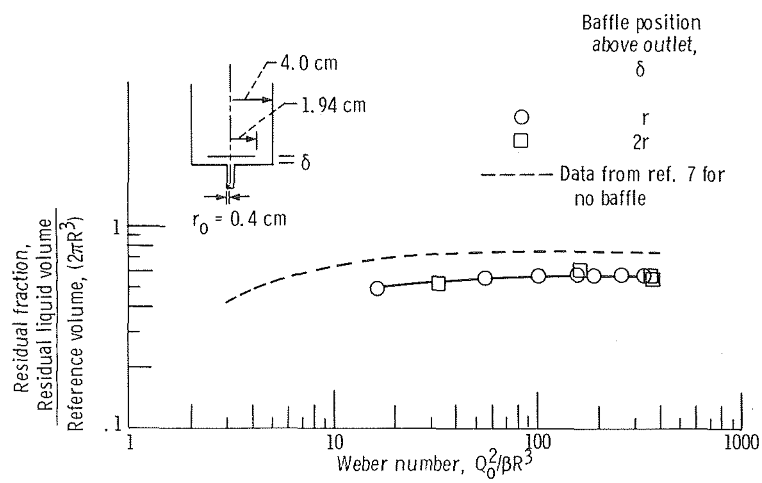


Figure 4. - Effect of baffle position above outlet on liquid residuals for flat plate baffle. (Baffle- to tank-radius ratio B/R = 0.485).

system (B/R = 0.485) reduced the liquid residuals remaining at vapor ingestion to approximately 80 percent of the no baffle case at the same flow rate at a baffle position of either one or two outlet radii above the tank outlet.

In addition to the tests described above with B/R = 0.485, data were obtained for the flat plate baffles with baffle- to tank-radius ratios of 0.635 and 0.980 at a vertical baffle position of 0.8 centimeter (two outlet radii) above the outlet. The largest of these baffles, as described in the section APPARATUS AND PROCEDURE, was sized such that the open area was equivalent to the outlet cross-sectional area. The results are presented and again compared with the no baffle case in figure 5. The results shown in figure 5 indicate a systematic reduction of residuals with increases in baffle- to tank-radius ratio B/R.

When one considers the initial hemispherical liquid-vapor interface, it is evident that in the unbaffled case the shortest distance from the tank bottom to the vapor space is directly above the tank outlet. By installing a larger diameter baffle, the effective drain location is moved to an area of more liquid depth which in turn increases the dis-

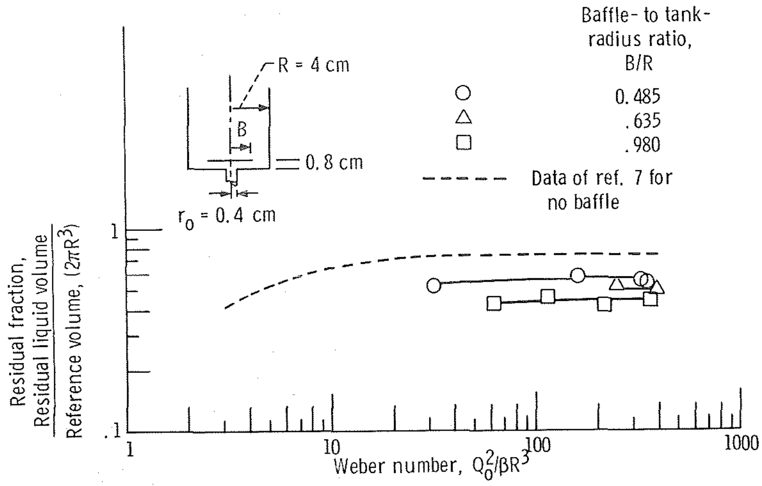


Figure 5. - Effect of baffle- to tank-radius ratio on residuals for flat plate baffle.

tance from the drain to the interface and, therefore, the outflow time. This delays the time of vapor ingestion into the drain (fig. 3(a)). As a result, the residual fraction remaining with the largest baffle was 60 percent of the no baffle case (fig. 5). The residual fraction with the intermediate size baffles falls between the others as expected.

Perforated baffle design. - The perforated baffle was tested and compared in the same manner as the solid flat plate baffles. The resulting residual fractions are presented in figure 6. This particular baffle had an open flow area equal to that of the solid baffle with $B/R = 0.98$ (equal to the outlet cross-sectional area). The line representing the data for the best flat plate baffle is also shown in figure 6 for comparison. It is obvious from the data that the perforated baffle is an improvement over the no baffle case but is not as effective in reducing the residual fraction as the largest solid

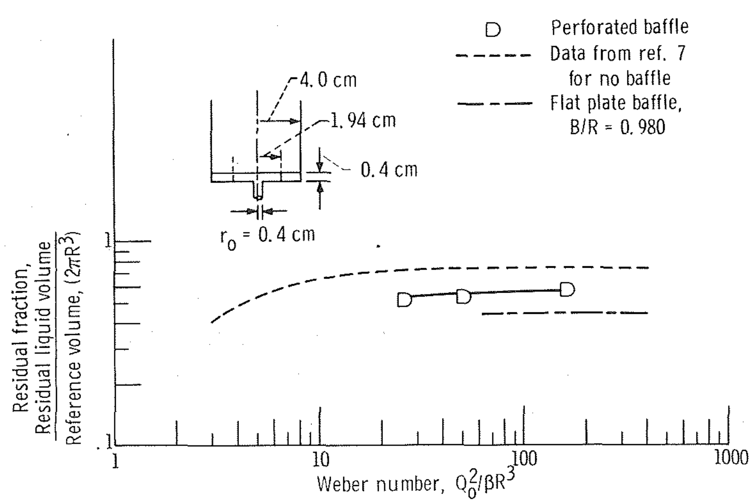


Figure 6. - Effect of perforated baffle on liquid residuals.

baffle with the same flow area. It may be worthy to note that any number of other perforation patterns or designs could have been tested. This particular design was chosen arbitrarily and is not necessarily the best. It is presented only as a guide for comparison.

Pressure Losses Due to Baffling

As a secondary objective of this study, observations were made of the pressures required to obtain the various flow rates with each of the baffle configurations. These pressure requirements were then compared with the no baffle cases of reference 7. Within the ranges tested, the pressure required to obtain a given flow rate was very nearly the same for all the flat plate baffles (within the 5-percent accuracy of the system) as for the no baffle case. For the perforated baffle, however, the pressures required for the same flow rates were on the order of 6 to 7 times greater than those required for the unbaffled system.

It is evident from these tests that, while the open flow areas were the same for the largest flat plate baffle and the perforated baffle, the use of the largest flat plate baffle resulted in the least residuals with the smallest pressure loss.

CONCLUDING REMARKS

An experimental study was conducted to investigate the effect of tank outlet baffling on the liquid remaining in a tank after draining in a weightless environment. The tank used was a flat bottomed cylinder, 4 centimeters in radius, filled with ethanol to an initial liquid level of two tank radii. Two baffle designs, a flat plate and a perforated plate, were tested over a range of outflow rates. The baffle positions and their sizes relative to the tank radius were varied.

As expected, the largest radius flat plate baffle performed the best of all the ones tested. It should be noted that even with this "best" performance almost half of the initial liquid volume still remained in the tank at the time of vapor ingestion, which makes this a very inefficient outflow system. On the other hand, the residuals with this largest baffle were 60 percent of that observed for the tank with no baffle at all. For the flat plate design, decreasing the baffle-to tank-radius ratio to 0.485 increased the liquid residuals to about 80 percent of the no baffle case. No effect was observed when the vertical position of a given baffle was changed from one to two outlet radii above the drain. For all the flat plate baffles, very little additional pressure losses were observed when compared to the system pressure drop for draining with no baffle.

The liquid residual for the perforated baffle was about the same as with the smaller flat plate baffles. However, the pressure losses associated with this system were 6 to 7 times those observed for the no baffle case (at the same flow rate).

These tests have been aimed at experimentally obtaining some quantitative measure of baffle effectiveness during outflow under actual weightless conditions and to expand on the initial qualitative studies of reference 1. They were conducted with some very simple baffle designs and were not intended for the scaling or optimizing of complex draining systems.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 5, 1970,
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