Liquid Management in Low Gravity Using Baffled Rotating Containers

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Abstract

ORBITAL experiments can require control of large masses of liquids for long periods. An example is a proposed relativity experiment (GP-B[1]) for which over 300 kg of liquid helium will be vented during a period of one year. Its configuration must always be sufficiently symmetric to keep acceleration effects at the design center of mass below 9.8×10^{-10} m/s^2. The helium is to be contained in a rotating cylindrical annulus with baffles to locate the helium (Fig. 1).

The system will fail if 1) the interfaces do not attach to the baffles; 2) the interfaces are not at the same mean radius; and 3) the interfaces are hydrodynamically unstable. The first two failure modes are calculated below; the third is beyond the scope of this paper.

Contents

Consider a liquid of density ρ_L partially filling a cylindrical container of radius R_C and length $2(n+1)L$, divided into n layers by baffles. Let the container rotate at ω about its symmetry axis. The remainder of the cylinder contains gas of density $\rho_G << \rho_L$. Denote the interfacial tension by γ and neglect compressibility.

Introduce a gravity field g parallel to ω, in anticipation of simple grounded-based experiments. Let r, ϕ, z denote cylindrical coordinates, with $r=0$ as the cylinder axis and $z=0$ the bottom.

The jump in pressure across the interface in each layer is equal to $\gamma K'$, where K' denotes the mean curvature of the surface. That relation can be written in layer i, in terms of layer dimensionless coordinates x_i and y_i, defined in terms of r and z by

$$z=2(i-1)L+z_iB+R_ix_i$$

$$R=R_i(z)=R_i[1-y_i(x_i)] \tag{1}$$

$$\frac{1}{\Delta}\left[1+\frac{y_i''}{\Delta^2}-\frac{1}{2}F_iy_i(2-y_i)\right]-G_ix_i=1+C_i \tag{2}$$

where the prime denotes differentiation with respect to argument, $F_i=\rho\omega^2R_i^3/\gamma$, $G_i=\rho g R_i^2/\gamma$, $\rho=\rho_L-\rho_G$ is the density contrast and C_i is the axial curvature at the point $x_i=0$.

An interface shape is found by integrating Eq. (2) subject to the boundary condition on the contact angle and the compatibility condition that $x^T-x^B=2(L/R)$. This is done numerically by rewriting the equation as pair of first order equations and applying a fourth-order Runge-Kutta scheme[2] to the system. Note that y' can become large near the wall so that one chooses a constant interval Δs along the interface rather than a constant Δx. The integration begins at $x=0$ (where $y=0=y'$) with a given value of C and continues in the forward direction until $y'=\cot\theta$. This is repeated in the negative direction until $y'=\cot\theta$. The compatibility condition then gives one point in a C vs L/R curve. Decreasing C increases L/R.

C cannot be decreased indefinitely. For any F and G there is a minimum value at which $y^B=1$, corresponding to the "capillary rise" reaching the rotation axis. Decreasing C below this value leads to an apparent change of sign in y'' before y' can reach its boundary value. This critical value of $C, C_{\min}$ has associated with it an $L_{\max}$, and $2L_{\max}$ is the maximum baffle spacing for which an interface can form.

The second type of instability is an interchange instability. Because the layers are interconnected, the liquid pressures at the outside must be equal. If layer i moves out and layer $i+1$ moves in, the sign of the pressure difference $\Delta p=p_{i+1}-p_i$ determines stability. If $\Delta p>(<)0$, the system is unstable (stable). The sign of Δp is determined by a balance between centrifugal and surface tension terms, and the critical condition can be shown to be $\partial p/\partial R=0$, which determines a critical $C=C_{cr}(F,G)$.

Figure 2 shows the two stability boundaries for $G=0$, the GP-B case. (The situation for nonnegligible G is sufficiently complicated that a general analysis seems counterproductive). That container is a cylindrical annulus with inner radius 0.18

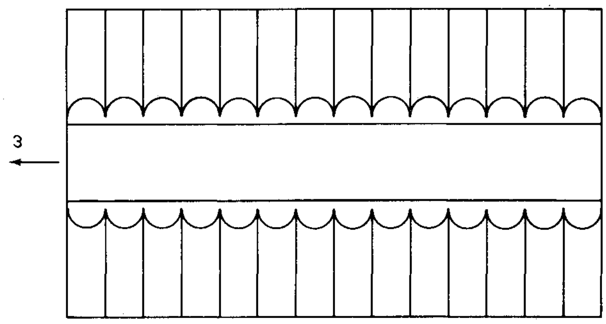

Fig. 1 Schematic of an ideal rotating baffled liquid container. Passages for liquid are provided at the outside edges of the baffles.

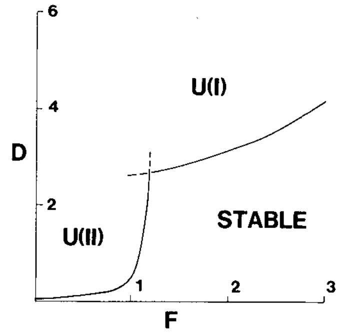

Fig. 2 Type II neutral stability curves for zero gravity. $D=2(L/R)$), F pairs in the U_{II} field can form interfaces, but these are unstable to the interchange instability.

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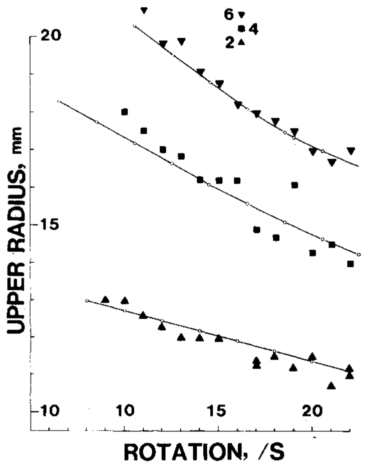

Fig. 3 Experimental upper interface vs ω at fixed void volumes: Δ, 2 ml void volume, □ 4 ml void volume, ▽ 6 ml void volume. The curves are theoretical.

m and outer radius 0.54 m. The overall length is 2.94 m. Let $\rho = 145$ kg/m^3, $\gamma = 5.3 \times 10^{-1}$ N/m and $\omega = 0.01$ s^{-1}.[1] The dewar is initially to be 90% full of liquid helium. Thus $R = 0.242$ m, $F = 0.388$ and $G = 1.57 \times 10^{-5}$, the latter based on the necessity of keeping local gravity to $10^{-10} \times$ normal gravity. For these values of F and G the interchange instability is dominant. The critical spacing is $2L = 18.5$ mm.

The basic idea of the type I instability can be examined in the laboratory. Experiments were done in a petri dish (diameter = 48.06 mm, depth = 8.59 mm) mounted to the top of a Genisco model C-181 turntable. Centering accuracy was better than 0.8 mm. Turntable speed was accurate to better than 5 parts per thousand in the range of interest. The working fluid was ethanol (Pharmco 200 proof ethyl alcohol) colored with Higgens India Ink at 2 drops for 25 ml ethanol. Textbook[3] values for density (800 kg/m^3) and surface tension (0.022 N/m) were used. A contact angle of zero was assumed.

The measured dependent variable was the apparent intersection radius of the fluid with the upper boundary marked with concentric circles spaced at 2-mm intervals. Errors which arise from nonconcentricity and parallax are estimated to be 0.5 mm. The mean position can be estimated somewhat more precisely than 0.5 mm.

The most difficult parameter to control in the experiment is the air volume. Several methods were tried. The final precedure was to 1) fill the container as nearly completely as possible while it spun at 22 s^{-1} (to center the air bubble); 2) withdraw the desired amount of fluid with the container stationary; and 3) plug the hole with paraffin. The last step is necessary because when the hole is unplugged, the ethanol is sufficiently volatile to evaporate at about 1.2 ml/h (measured with the container stationary).

Results are shown in Fig. 3 for air volume of 2, 4, and 6 ml. The symbols denote data and the solid lines joining open circles are calculated results. The calculation predicts bottom exposure for the 6-ml case at rotation rates above 18 s^{-1}. The observations are consistent with the prediction. The four rightmost symbols on the upper curve showed a clearly exposed bottom. The next two were ambiguous. All the others on all the curves showed the bottom covered.

Plans for future work center around short-time, low-gravity experiments using parabolic flight paths from NASA's KC-135. It is hoped that qualitative checks on the interchange instability can be made in such a setting.

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References

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