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A Small-Scale Drop Tower for Low-Gravity Fluids Laboratories*

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A small drop tower and low-gravity fluids experiment suitable for use in fluid mechanics laboratory courses are described. Liquid–gas interfaces in the absence of gravity are present in many aspects of space flight; thus experiments which address the basic physics of two-phase low-gravity fluid mechanics are likely to be of use to engineering students. The facility is inexpensive, and a standard video-recorder may be used for data acquisition.

EDUCATIONAL SUMMARY

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in low-gravity fluid mechanics—specifically, the surface tension dominated conditions found in fuel tanks in orbiting spacecraft.
2. The paper describes new equipment useful in undergraduate or graduate fluid mechanics laboratory courses.
3. Undergraduate or graduate students are involved in the use of the equipment.
4. Demonstration of the feasibility of a low-cost drop tower is a new aspect of this contribution.
5. The material presented can be incorporated into a general fluid mechanics course for aerospace engineering students. Specialization is possible too: at Purdue, we offer a graduate course in low-gravity fluid dynamics.
6. Good texts in low-g fluids are scarce. Myshkis *et al.*, *Low-Gravity Fluid Dynamics* (1987) is the most rigorous and reliable.
7. Have the concepts presented here been tested in the classroom. The tower has been used by undergraduates and graduates alike. It is practical, and attention to detail pays off. If you can afford to electronically synchronize a camera to a set time after the magnet shut-off, this will greatly increase the quality of the data.
8. Low-*g* fluid physics are traditionally not included in aerospace engineering curriculum. A laboratory-course experiment such as this one can provide students with exposure to the topic.

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INTRODUCTION

APPLICATIONS involving liquid–gas interfaces and two-phase fluid flows in the absence of gravity are becoming more common. Control of liquid fuels and oxidizers in tanks [1, 2], boiling and heat transfer [3, 4], cryogenic liquid storage [5] and transfer in orbit, and a range of materials processing [6] applications are examples of such fluid phenomena. As the space programs of various countries continue to grow, it is likely that the number of low-gravity fluids applications will grow. Thus, the task of educating engineers has begun to include exposure to low-gravity fluid mechanics.

The basic fluid physics involved in the unique aspect of many of these applications include the surface tension and contact forces [7]. These forces may be the dominant forces on the fluids when a liquid–gas interface exists in a low-gravity environment. In terrestrial fluid mechanics, surface tension may also be of importance. Capillaries, some gravity waves [8], atomization [9], and nucleate boiling are examples of such terrestrial topics. In addition to the dominance of surface tension forces on low-gravity interfaces, there exist thermocapillary forces in many materials-processing applications. That is, a variation of temperature along a liquid–gas interface produces a variation of the surface tension along the interface. This effect may drive fluid motion (thermocapillary or Marangoni convection), and may lead to instabilities in some flows.

A simple and relevant liquid–gas interface geometry in low-gravity is formed when liquid covers one end of an arbitrary cylinder cross-section while gas covers the other. This seemingly simple geometry is presently the topic of research [10] and is a necessary introduction to more complex phenomena [2, 3]. The presence or absence of stability, symmetry and uniqueness of the interface is such a simple geometry in low gravity may be very informative to students. Attributes of this and other low-gravity fluid phenomena may be studied experimentally in a small, relatively inexpensive drop tower. The term 'low gravity' is used in place of the colloquial 'zero gravity', because in a drop tower there are always some residual accelerations. These preclude the creation of a perfect 'zero-gravity' environment.

A description of the drop tower, analysis to justify the design, data from a demonstration experiment suitable for fluid dynamics laboratory classes, and a discussion of the results are presented in this paper. Inexpensive materials and common video-recording equipment combine to form an easily constructed low-gravity experimental facility.

DROP TOWER DESIGN

The basic operating principle of the drop tower is simple. In the absence of aerodynamic drag, the only force on a body that is dropped is gravity. Thus the body accelerates downward at the rate $g_0 = 9.8\ \text{m/sec}^2$. Consider the body to be a sealed container filled with some liquid and some gas. Then the container, liquid and gas are accelerating uniformly at the rate g_0. After sufficient time for the 1 *g* interfaces to adapt to the new low-*g* environment, the low-gravity liquid–gas interface (meniscus), and the solid–liquid–gas interface (contact line) are formed. As discussed below, the duration of the drop and the mass of the liquid in the container typically determine the length of time required for the equilibrium low-gravity interface to be formed. Figure 1 shows the components and the geometry of the drop tower. The test cell is held at the top by an electromagnet while the tower is evacuated. Then the current to the magnet is switched off, releasing the test cell, which falls through the field of view of the video camera. A strobe light in approximate synchronization with the framing rate of the video camera permits a clear video image to be recorded.

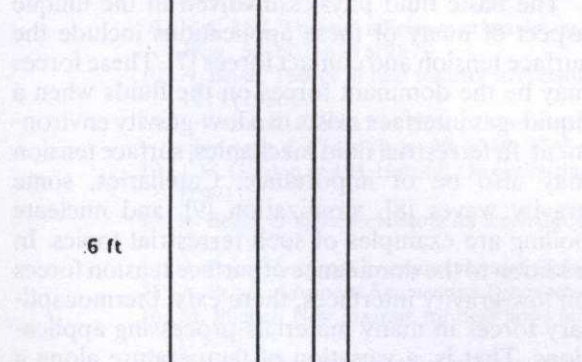

Fig. 1. Schematic of the drop tower and imaging arrangement. Levelers are threaded rods and are used to align the tower vertically. Vacuum pump is not shown.

In the presence of aerodynamic drag, the fluids inside the test cell experience some residual acceleration. Thus the drop tower should be evacuated to reduce drag. As discussed in detail below, even a non-evacuated drop tower can be useful in a lab course for illustrating certain physical principles and scaling laws.

Drop duration and g-levels

Integrating Newton's second law twice shows that the duration of the drop in the absence of drag increases with the square root of the drop height. That is, a test cell accelerating downwards at g_0 falls through a height h in the time $t = \sqrt{2h/g_0}$. For example, a 1 m drop requires little more than 0.3 sec. With aerodynamic drag, the drop duration increases slightly at the expense of the *g*-environment inside the test cell. That is, the test cell now accelerates downwards at a rate of $g_0 - D/m$, where $D = C_D(1/2)\rho V^2$ is the drag force, m is the mass of the test cell and ρ is the mass density of the air through which the test cell falls. The drag coefficient is $C_D = C_D(Re)$ and is typically a function of the Reynolds number, $Re = \rho V d/\mu$. The velocity of the test cell is V, diameter, d, and the coefficient of viscosity is μ. The coefficient of drag is a characteristic of the shape of the body, but one can use the $C_D(Re)$ data of a sphere from an elementary fluid mechanics textbook for purposes of illustration and as a conservative estimate. Such an exercise shows that it is possible to reduce the aerodynamic drag to levels that have negligible effect on a stable zero Bond number interface. The Bond number is the ratio of gravitational and surface tension induced pressures, $Bo = (\rho_L - \rho_G)gr_0^2/\sigma$. Here ρ_L is the liquid density, ρ_G is the gas density, g is the acceleration, r_0 is the characteristic length scale, and σ is the surface tension of the liquid–gas interface. For example, if aerodynamic drag leads to an acceleration of 2% of the gravitational acceleration at the earth's surface, then for water and air ($\sigma = 73$ dyne/cm) in a 2 cm diameter cylinder, the Bond number is approximately 0.25. Using the Bond number and a computer code such as discussed below in the section on numerical modeling, the maximum deviation of the interface from the ideal zero-drag spherical interface is found to be approximately $0.003r_0$. Thus while it is safe to assume that the aerodynamic drag has a negligible effect on the drop duration ($g_0 \gg D/m$), it is not possible to neglect the effect of aerodynamic drag on the g-environment at atmospheric conditions.

Accelerations due to aerodynamic drag can easily be reduced by adding ballast to the test cell by evacuating the drop tower. Worst-case maximum g-levels due to a tumbling-like rotation encountered in the drop may be inferred from tower geometry. That is, the amount of rotation required for the test cell to strike the tower divided by the drop duration is the maximum possible angular velocity of the test cell. Photographs of the test cell at a given time in the drop can be used to refine the estimate of the rotation rate of each individual drop. The simplest properties to control in this design are the mass of the test cell and the density of the air. Adding mass to the test cell decreases the drag force per unit mass, thereby reducing the residual accelerations in the test cell. The drag of the test cell is reduced by evacuating the tower. While it is true that reducing the density of a flow will tend to decrease the Reynolds number and therefore increase the drag coefficient, this relation is generally weaker than linear. Therefore, the net effect of decreasing density is generally to lower the drag force on the object in the flow.

Determination of precisely what justifies a sufficiently long test duration for a given liquid–gas interface to reach equilibrium is a difficult task [10]. Dynamic contact lines, like those during the motion from 1-g to low-g interfaces, are not nearly as well understood as static contact lines [11]. Contamination and particulates cause changes in the wetting behavior [12] of the contact surface. An initial estimate of the necessary drop duration may be made by considering how long the contact forces would take to accelerate the liquid in the cell through a distance equal to the expected height of the low-g meniscus (Δ in Fig. 3). Of course, time is required for the damping of the impulsively started fluid motion. Because this damping differs for every container and liquid volume, there is not a single satisfactory answer for how much time is sufficient [10]. This presents a topic that ambitious students can examine in a facility such as this one. Multiple drops of a test cell should provide a repeatable interface if equilibrium is reached, thereby providing feedback for use in refining the analysis. Drops of various sized, geometrically similar test cells will produce practical data demonstrating how the necessary drop duration scales with the liquid volume and length scale of the test cell. The authors' observations are that a 1 cm diameter test cell with of the order of 1 cm^3 of water and alcohol can provide satisfactory interface shapes for lab exercises in a 1.5 m evacuated tower.

IMPLEMENTATION

In contrast with large drop towers, such as those at NASA's Lewis Research Center, this educational drop tower does not drop instrumentation with the experiment. Rather, interfaces between a liquid and a gas are photographed through the transparent tower and test cell. The tower constructed by the authors has a diameter of 102 mm (4 in.) and a height of approximately 1800 mm (72 in.). The tower is acrylic so that the experiment may be photographed during the drop. The tower is evacuated during the drop to reduce aerodynamic drag. The experiment package is initially held and subsequently released with an electromagnet. A cushion of soft foam is used as the decelerator at the base of the tower. Thin (5 mm), dense foam lines the walls for two diameters above the foam cushion. This lining prevents damage to the tube or the test cell as the test cell rebounds at the end of the drop. The test cell may take many forms, including a test tube with stopper for drops in an unevacuated tower. For evacuated drops, bear in mind that the test cell is a pressure vessel, and must be constructed accordingly. Figure 2 is a diagram of one possible cell design, slightly improved from our present test cells. Retrieval of the test cell using a permanent magnet and string is found to be a practical method.

Strobe lighting illuminates the test cell from the side opposite the camera. Prior to releasing the experiment, it is a simple matter to adjust the strobe frequency to match the framing rate of the video

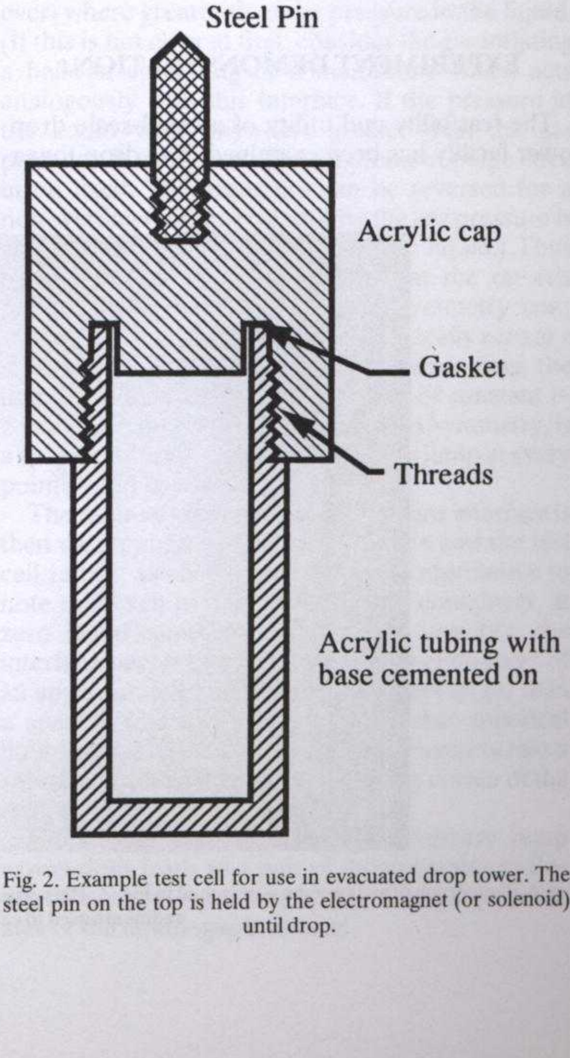

Fig. 2. Example test cell for use in evacuated drop tower. The steel pin on the top is held by the electromagnet (or solenoid) until drop.

camera. Standard home video will provide sufficient quality images for the simplest of experiments. It is recommended that a Super-VHS system be used for superior data acquisition and ease of transfer to a PC via a frame-grabber card. A wide range of such cards and software are commercially available for a comparably wide range of prices. Once the image data is in the computer, many types of data processing may be performed, including determination of interface shape, comparison of interfaces in subsequent images to study interface movement, contact line determination and contact angle measurement by fluid instability [10]. Effects of scaling involving Bond number and Reynolds number (viscous damping of fluid motion) may be studied by the use of a series of geometrically similar and dimensionally different test containers. For laboratories operating with a small budget, the PC-based image acquisition could be avoided and students could make approximate measurements by hand from the video monitor for some of the experiments.

Students may be introduced to additional details of experiment design and image (data) processing by analyzing the ray bending through curved containers and tower walls, variation of contact angle with surfactants, and corresponding numerical solution of interface shape, as illustrated below. The facility is also suitable for the study of interface trends for different gases and liquids, and even for liquid–liquid interfaces.

EXPERIMENT DEMONSTRATION

The feasibility and utility of a small-scale drop tower facility has been examined. The drop tower described above has been constructed, and is used to study liquid–gas interfaces in sealed cylindrical test cells. In the absence of accelerations, the interface is a circular cylindrical container (and some polygonal containers) will be spherical. Because the spherical interface has constant curvature, the pressure difference across the interface will be constant. From Fig. 3, it can be seen that the contact angle and the test cell radius determine the radius of the spherical interface. Note that, in this instance, the magnitude of the surface tension does not affect the interface radius.

Figure 4 shows one stroboscopic image of this simple experiment. This image is recorded on a

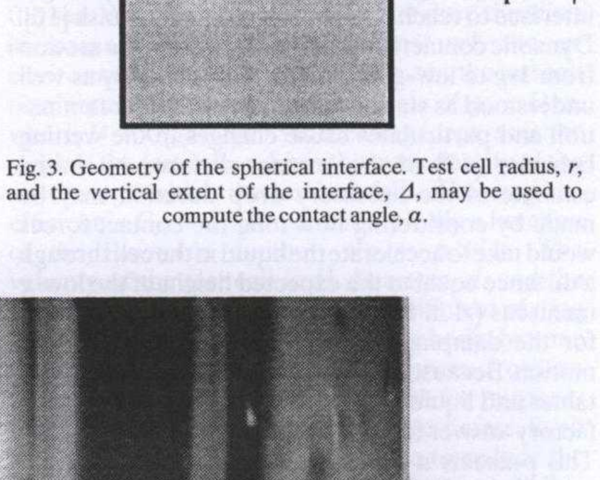

Fig. 3. Geometry of the spherical interface. Test cell radius, r, and the vertical extent of the interface, Δ, may be used to compute the contact angle, α.

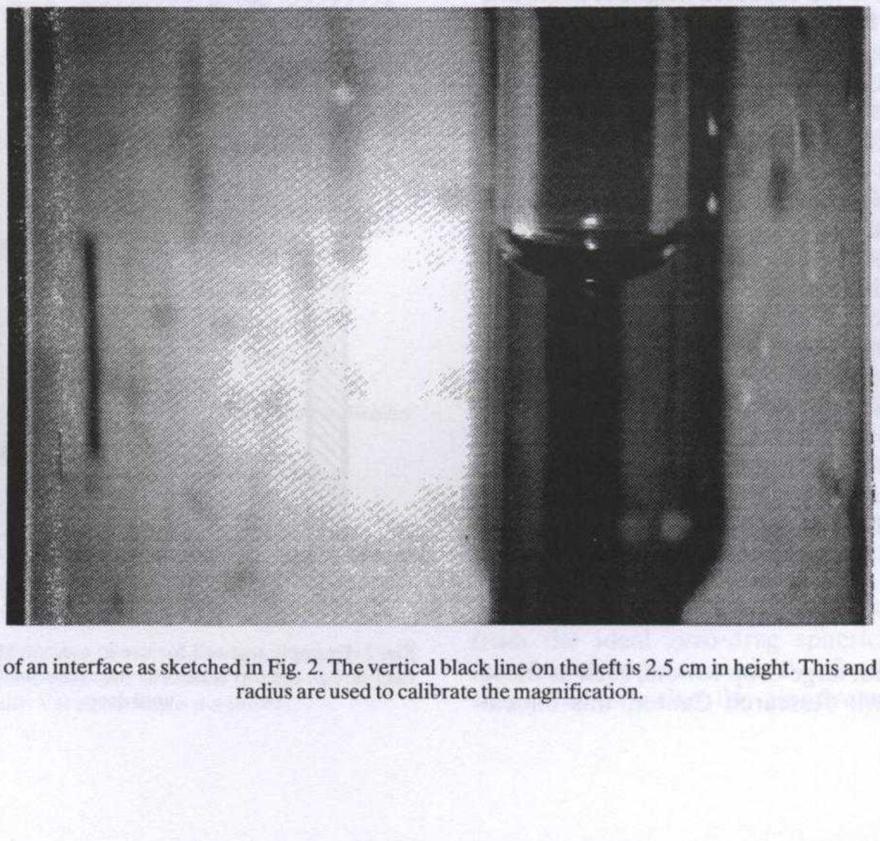

Fig. 4. Photograph of an interface as sketched in Fig. 2. The vertical black line on the left is 2.5 cm in height. This and the known test cell radius are used to calibrate the magnification.

Super-VHS recorder, and digitized from the video tape by a PC-based frame grabber. This arrangement eliminates the requirement to synchronize a camera with the drop of the test cell. For a strobe running at 30 Hz, and a test cell traveling at approximately 5 m/sec at the end of the drop, the cell moves approximately 15 cm between frames. Thus if the field of view of the camera is at least 15 cm, the odds are very good that one good frame will be acquired for each drop. Spending more money would certainly open up more avenues for improving this part of the experiment; in this case the authors acquired a good clear image in approximately 40% of the drops.

In this simplest experiment, one can measure the distance from the top of the interface to the bottom. From that distance the radius of the interface, and hence the contact angle, may be computed. For the experiment illustrated in Fig. 4, the liquid is a mixture of 70% isopropyl alcohol and 30% water, by volume. The computed contact angle is 51° ± 3°. There may be considerable variation in the results found by the students in a lab class. The interface is sensitive to many subtle and currently poorly understood effects, including accelerations from a poor release [10], the motion of the interface when approaching the static state [11] and the cleanliness of the test cell and fluids [12].

The above experiment demonstrates the feasibility and utility of a small-scale drop tower facility for engineering laboratory classes. Even though the tower is not designed as a research-quality facility, a considerable range of phemomena may be examined by the students. Untidy issues in engineering, such as the sensitivity to particulate content of the liquid, may be directly addressed by the students. Even some phenomena used in actual flight hardware, such as the pumping action of vanes in surface tension propellant management devices [1], can be simulated.

Numerical modeling

As part of laboratory assignments or experiment feasibility studies, students may find it beneficial to examine numerical solutions of the shape of the liquid–gas interface. A wide range of combinations of contact angle, surface tension and residual acceleration may be modeled with a relatively simple code. The authors find that use of a general-purpose engineering software package, such as MATLAB, permits students rapidly to determine a variety of low-g liquid–gas interfaces possible in the experimental test cell.

One method for the students to analyze the equilibrium liquid–gas interfaces is to solve for the axisymmetric solution for both fluids in a container [13], in this case, the test cell. Solution starts from Laplace's relation for the pressure jump, ΔP, across the interface,

$$\sigma(k_1 + k_2) = \Delta P \qquad (1)$$

where k_1 and k_2 are the principle curvatures of the surface, and σ is the surface tension of the liquid–gas interface. In an axisymmetric surface, such as the liquid-gas interface, one of the principle curvatures is $k_1 = (\sin\phi)/r$, where ϕ is the orientation of the surface in the r–z plane, as shown in Fig. 3. This figure shows a plane of constant θ in an (r, θ, z) cylindrical coordinate system. The remaining curvature, $k_2 = \mathrm{d}\phi/\mathrm{d}s$, where s is the arc length, is found to be

$$k_2 = \frac{r'z'' - r''z'}{\left[(r')^2 + (z')^2\right]^{3/2}} = r'z'' - r''z' \qquad (2)$$

In this equation, the primes represent differentiation with respect to the arc length, s, in the r–z plane.

The pressure difference, ΔP, in this example is formed by the surface tension and by an approximately steady-state acceleration of the test cell. Any aerodynamic drag on the exterior of the test cell creates an acceleration (drag force per unit mass) that causes pressure to decrease with height in the liquid in the container. From a quasi-steady point of view, this is a hydrostatic pressure field, analogous to how pressure increases with depth in the traditional load-on-a-dam problem. A second source of pressure jump is the curvature at the centerline of the interface. That is, the pressure in the gas is, for a liquid which wets the solid walls, everywhere greater than the pressure in the liquid. (If this is not clear at first, consider the gas inflating a balloon consisting of a membrane which acts analogously with this interface. If the pressure in the liquid were anywhere greater than the gas pressure, it would cause the balloon to bulge back in on itself. The argument can be reversed for a non-wetting fluid to explain why the gas pressure is always less than the pressure in the liquid.) Thus there must exist some curvature at the on-axis point. Note that because of the symmetry constraint, $\mathrm{d}r/\mathrm{d}z$ of the interface is identically zero at $r = 0$. In the absence of any aerodynamic drag, the liquid–gas interface will be a surface of constant r–z plane curvature, which due to the axisymmetry, is a spherical surface. Thus the pressure jump at every point would be uniform.

The radius of the spherical liquid–gas interface is then determined by the contact angle and the test cell radius, as shown in Fig. 3. It is informative to note that even in non-axisymmetric containers, at zero Bond number (perfect 'zero gravity'), the interface becomes a spherical cap in containers of an appropriately small size. Containers larger than a specific size will not form the stable spherical liquid–gas interface, but rather will demonstrate a solution in which the liquid wets every corner of the cell [7].

Combining the curvature and pressure jump expressions leads to a pair of second-order ordinary differential equations for the r and z coordinates of the liquid–gas interface:

$$\tilde{r}'' = -\tilde{z}'\left(\tilde{k}_0 - Bo\,\tilde{z} - \tilde{z}'/\tilde{r}\right)$$
$$\tilde{z}'' = -\tilde{r}'\left(\tilde{k}_0 - Bo\,\tilde{z} - \tilde{z}'/\tilde{r}\right) \qquad (3)$$

The pressure jump at the centerline is $(\Delta P)_0$. It is a useful student exercise to perform dimensional analysis on the pair of equations to determine the governing dimensionless parameters and equations. The cell radius, r_1, is chosen as the characteristic radius, leading to non-dimensional equations.

$$r'' = -z'\left(-\frac{\rho g}{\sigma}z + \frac{(\Delta P)_0}{\sigma} - \frac{z'}{r}\right)$$
$$z'' = r'\left(-\frac{\rho g}{\sigma}z + \frac{(\Delta P)_0}{\sigma} - \frac{z'}{r}\right) \qquad (4)$$

Here the tilde above the coordinates denotes non-dimensionalization by r_1. The Bond number, $Bo = \rho g r_1^2/\sigma$, and the non-dimensionalized centerline pressure difference, $\tilde{k}_0 = (r_1(\Delta P)_0/\sigma)$, are the two parameters which govern the solution. The initial conditions for the equations are $\tilde{r}(0) = 0$, $\tilde{z}(0) = 0$ (an arbitrary choice), $\tilde{z}'(0) = 0$, and $\tilde{r}''(0) = \tilde{k}_0$. Note that the condition $\tilde{z}'(0) = 0$ causes $\tilde{r}'(0) = 1$.

In this example, once the Bond number and $\tilde{k}0$ are specified, the code uses a numerical shooting method that varies the centerline pressure differential, $\tilde{k}_0$, to find the correct equilibrium interface. The equations are integrated from the centerline outwards. At each step the curvature and the orientation of the surface, ϕ, are computed, and from those the incremental changes in $\tilde{r}$ and $\tilde{z}$. A simple Taylor series is a practical method for inexperienced students to implement. It is worth noting that a predictor–corrector method based on constant curvature arcs of fixed ds or dϕ shows superior performance to the Taylor series method with only a slight increase in programming complexity. Either integration algorithm stops when either the wall is reached, $\tilde{r} = 1$, or the interface becomes vertical, $\phi = \pi/2$.

If the interface reaches the wall, the slope is compared to the specific contact angle. When the slope is too flat, the centerline curvature is increased and integration begins anew. Similarly, when the slope is too steep, the centerline curvature is decreased. Note that the case in which the interface turns up to $\phi \geq \pi/2$ before reaching the wall also causes a reduction in curvature. Once candidate interface reaching the wall with slopes too steep and too low are found the algorithm switches to the bisection solver, which continually divides the interval between the appropriate centerline curvature guesses in order to converge on the correct contact angle at the cell wall. That is, with one guess of $\tilde{k}_0$ giving too small a contact angle at the wall, and one too large, the correct solution has a value of $\tilde{k}_0$ between the $\tilde{k}_0$ values for the bounding solutions. While the bisection solver method converges slower than a more elaborate scheme [14], it is dependable once the solution is bounded. Once bounded, a Newton solver also works well in many cases. (Example codes for this and similar geo-

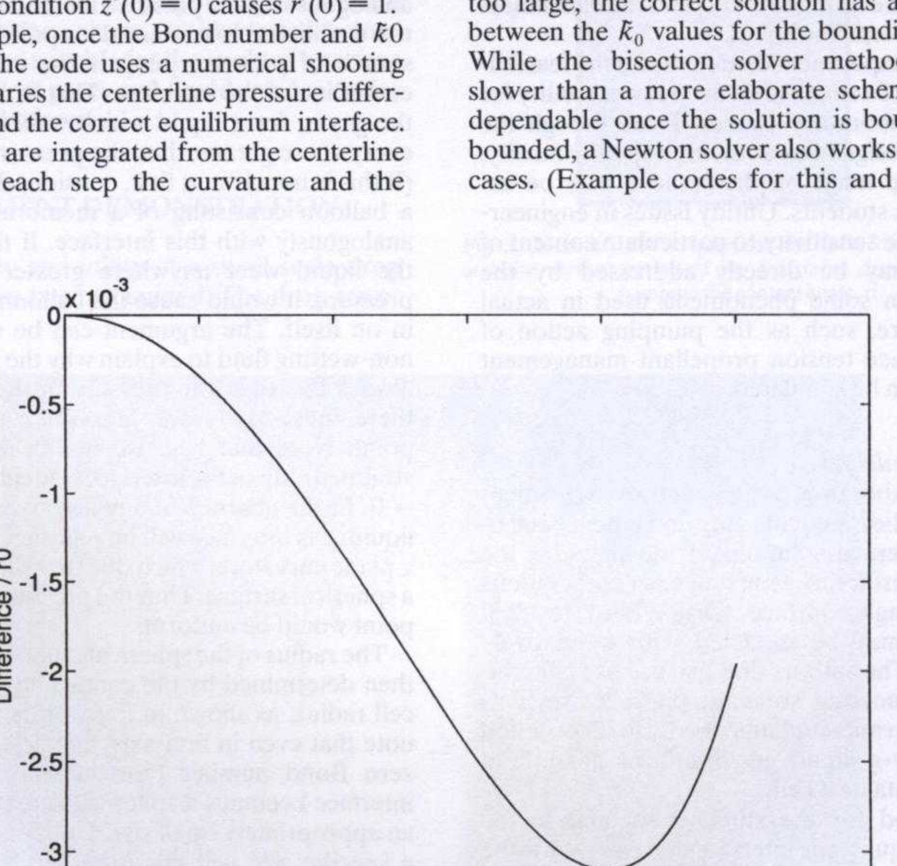

Fig. 5. Illustration of the sensitivity of the zero-g to aerodynamic drag. This data is computed with the code discussed in the section on numerical modeling.

metries are available electronically from the first author at COLLICOT@ECN.PURDUE.EDU.)

Figure 5 shows the difference in vertical (z) location between a zero Bond number interface and an interface at a Bond number of approximately 0.27. This corresponds to a steady aerodynamic drag force per mass of 0.02 g. Note that the differences between 0 g and 0.02 g, as plotted in Fig. 5, are a small fraction of the total vertical extent of the meniscus. Thus a small amount of aerodynamic drag *per mass* will not destroy the experiments. Remember that ballast mass will decrease the drag per mass independent of the aerodynamic drag coefficient.

The cylindrical test-cell geometry is but the simplest possible drop tower experiment. Other experiments that may be both modeled and dropped by students are a cylindrical test cell with a central post, a polygonal container, or perhaps even a spinning cell. A central post simply alters the initial conditions, leading to different interface shapes with new surface areas and volumes. Many polygonal containers with liquid gas will have a spherical interface in zero gravity [7]. Spin is modeled in the numerical solution by including the r^2 pressure field found in a fluid spinning in a solid body rotation. The experiment with a spinning test cell is more difficult; to drop a spinning test cell in the drop-tower would require a complex mechanism to spin-up and then release the test cell. For numerical modeling of equilibrium liquid–gas interfaces which are not axisymmetric, one may find it desirable to pursue energy-method solutions for the shape of the interface, such as possible with the substantial Surface Evolver code [14].

CONCLUSIONS

Because requirements for specialized hardware are minimal, a small-scale (approximately 2 m) low-gravity drop tower can be relatively inexpensive to assemble. Equipment which typically exists in a fluids laboratory (strobe light, video-recorder, small vacuum pump, DC power supply for the electromagnet, etc.) comprise most of the equipment, thus permitting the facility to be constructed using shared equipment to reduce cost. Floor space is minimal, and a 2 m height can provide sufficient test time without the need for high-bay laboratory space.

A short-duration drop tower is shown to be a feasible and illustrative laboratory course experiment facility. This is demonstrated with experiments in sealed cylindrical test cells. The contact angle of liquid–gas–solid interfaces are determined from measurements of the low-g interface shape. More complex geometries and fluid mechanics may be examined by students using such a facility. Associated theoretical exercises for students could include examination of the dimensional analysis, tolerable residual g-levels for a given experiment and numerical solution of Laplace's condition for the liquid–vapor interface.

The continuing human presence in orbit, propellant management in any orbiting or interplanetary craft, and materials processing research in space require engineers with knowledge of low-gravity fluids behavior. The experimental facility described may provide engineering students with their first practical experience in these relevant fluid physics.

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Robert Chambers attended Purdue University from 1988 to 1993, where he studied aeronautical and astronautical engineering with emphasis in aerodynamics and propulsion. While in college, he spent three summers performing satellite mission analysis for Hughes Aircraft Company in Los Angeles. After earning a bachelors degree in May 1992 and a masters in May 1993, he moved to New Jersey where he now works in satellite manufacturing for Martin Marietta Astro-space. Mr Chambers has received several honors and distinctions to date, including two first-place design awards at Purdue, a university undergraduate academic scholarship, and a graduate study fellowship from Hughes.