Modeling of Impulsive Propellant Reorientation

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The impulsive propellant reorientation process is modeled using the ECLIPSE code. Brief descriptions of the process and the computational model are presented. Code validation is documented via comparison to experimental data for small-scale tanks. Predictions of reorientation performance are presented for two tanks designed for use in flight experiments and for a proposed full-scale orbit transfer vehicle tank. A dimensionless parameter is developed to correlate reorientation performance in geometrically similar tanks. Its success is demonstrated.

Nomenclature

a	= acceleration
Bo	= Bond number
F	= volume-of-fluid function
Fr	= Froude number
g	= body force per unit mass, typically gravitational
h	= length dimension, typically tank length
h^*	= nondimensional length (h/R)
p	= pressure
R	= tank radius
Re	= Reynolds number
Se	= settling number
t, T	= time
u, v	= x and y velocity components, respectively
v_f	= velocity of liquid leading edge
We	= Weber number
x, y	= spatial coordinates, Cartesian or axisymmetric (x in radial direction)
θ	= fractional cell volume open to flow
μ	= dynamic viscosity
ν	= kinematic viscosity
ξ	= switching integer
ρ	= density
σ	= surface tension

Introduction

THE ECLIPSE code (Energy Calculations of Liquid Propellants in a Space Environment) is being developed as one component of a reduced-gravity fluid management technology program.[1] The long-range goal of a general tool for computational modeling of liquid propellant behavior in a reduced gravity environment is being pursued in stages with each stage corresponding to a problem of current interest to designers of advanced spacecraft. The ability of ECLIPSE to model jet-induced mixing in propellant tanks[2,3] and propellant tank self-pressurization[4] has been documented. The focus of the work being reported in this paper is the modeling of liquid motion induced by a sudden change in the acceleration environment.

During coast in low Earth orbit (LEO), liquid propellants collect in the forward end of the propellant tank due to atmospheric drag on the spacecraft. The process of positioning the liquid over the tank outlet by firing auxiliary thrusters is known as impulsive reorientation or settling. Since impulsive reorientation requires the expenditure of propellant, it is important to optimize the process to minimize the associated propellant requirements. If the thrust level is too low, the propellant may not reposition. If it is too high, a large geyser may form and vapor pockets may be trapped in the pool. Proper spacecraft design and operation requires a good understanding of the process and the parameters that control it.

Small-scale experiments have been performed in the NASA Lewis Research Center drop tower and in the zero-gravity (zero-g) facility to examine liquid motion induced by accelerations that model the reorientation process. The experiments were performed in transparent tanks and the fluid motion induced by these accelerations was recorded via high-speed photography. These experiments identified liquid-vapor interface shapes for a zero-g environment.[5] Records of fluid motion induced in partially filled tanks due to an imposed acceleration were produced.[6] Further studies conducted by Sumner[7] examined the energy expended to accomplish reorientation. A performance map for the reorientation process in these small-scale tanks was developed. This reference provides substantial detail for a number of acceleration levels and tank fillings and the results reported therein have served as the basis for code validation.

Prediction of reorientation performance has relied on two tools. The simplest is a rigid-body dynamics analysis that assumes the propellant pool to behave as a single solid body. Although this analysis is simple to perform, it is such a coarse assumption that large safety factors must be provided when it is used for design purposes. The second tool is described by Sumner[7] and is based on an empirical analysis developed by Salzman.[8] The computational procedure is an empirically based approach using a Weber-number criterion to preclude geysering and results in calculation of a liquid leading-edge velocity. Sumner extended the analysis to include small geysers. Although predictions based on this method correlated well with reported experimental results, it does not start from

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first principles and its application is limited to similar geometries and conditions.

ECLIPSE Code

The ECLIPSE code is a descendant of the family of SOLA codes written at the Los Alamos National Laboratory. In particular, the NASA-VOF2D code[9] was used as the foundation upon which ECLIPSE was built. The baseline code solves the laminar hydrodynamic problem using the volume-of-fluid (VOF) algorithm to determine the location of the free surface. The computational model uses a VOF function F to track the free surface, and a cell blockage function θ to model partial cell blockage. Equations expressing conservation of mass, the force-momentum balance, and the F-transport equation can be written:

$$\frac{1}{\xi_x}\frac{\partial(x^{\xi}\theta u)}{\partial_x}+\frac{\partial(\theta v)}{\partial y}=0 \tag{1}$$

Table 1 I. E. Sumner's test conditions modeled using ECLIPSE

Test no.	R, cm	FR	Fluid	FL, %	a, cm/s^2	Bo	Geyser
1	1.65	4.00	TCTFE	71	16.7	3.9	Small
5	2.00	2.25	Ethanol	62	29.4	4.2	Small
6	2.00	2.25	Ethanol	29	29.4	4.2	Large
7	2.00	2.25	Methanol	51	29.4	4.1	Moderate
8	2.00	2.25	Methanol	33	29.4	4.1	Large
12	3.22	2.14	Ethanol	71	10.8	4.0	None

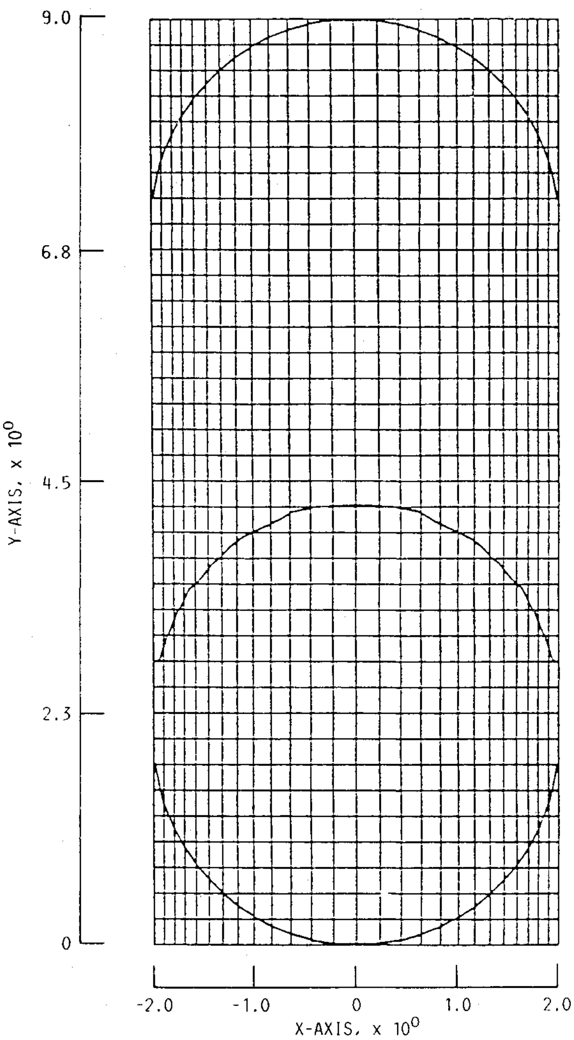

Fig. 1 Typical computational mesh for small-scaled tanks.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g_x-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\xi\left(\frac{1}{x}\frac{\partial u}{\partial x}-\frac{u}{x^2}\right)\right] \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=g_y-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\xi\left(\frac{1}{x}\frac{\partial v}{\partial x}\right)\right] \tag{3}$$

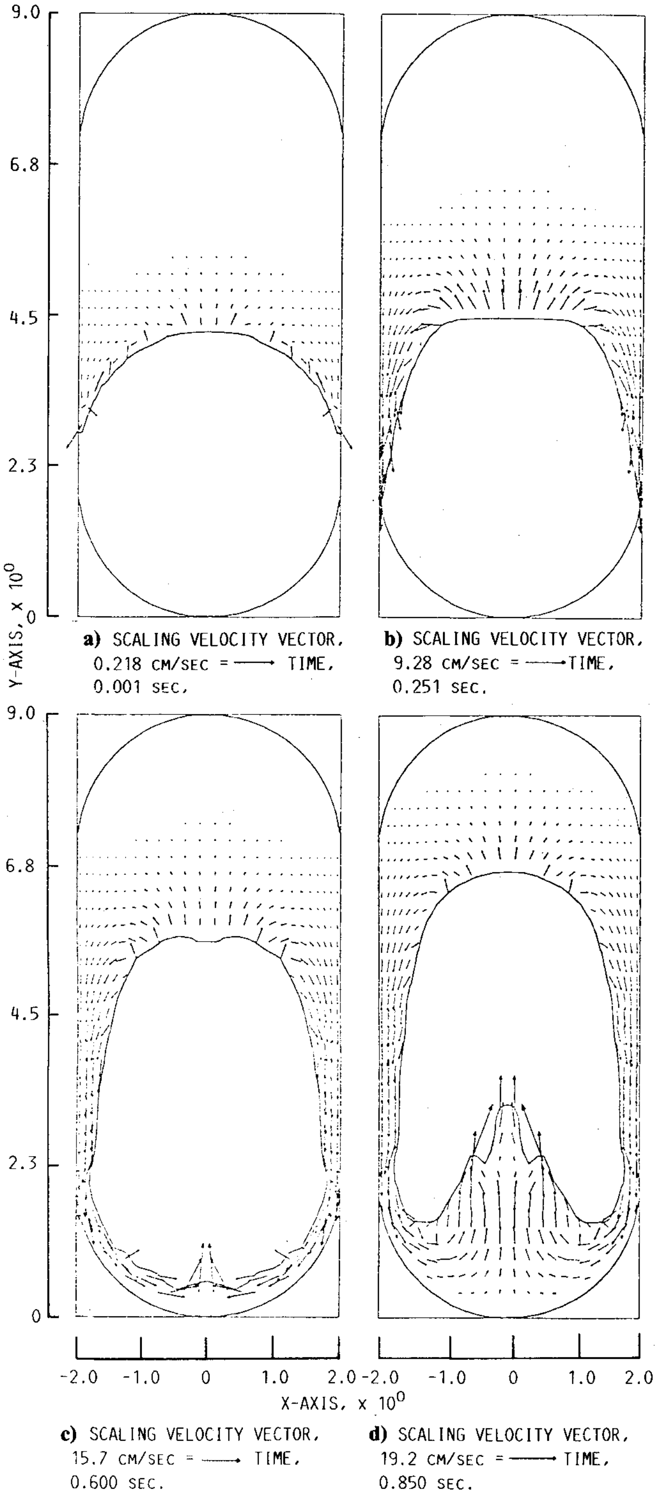

Fig. 2 Propellant motion for test 5. Note: Velocity vectors scaled to maximum velocity in field.

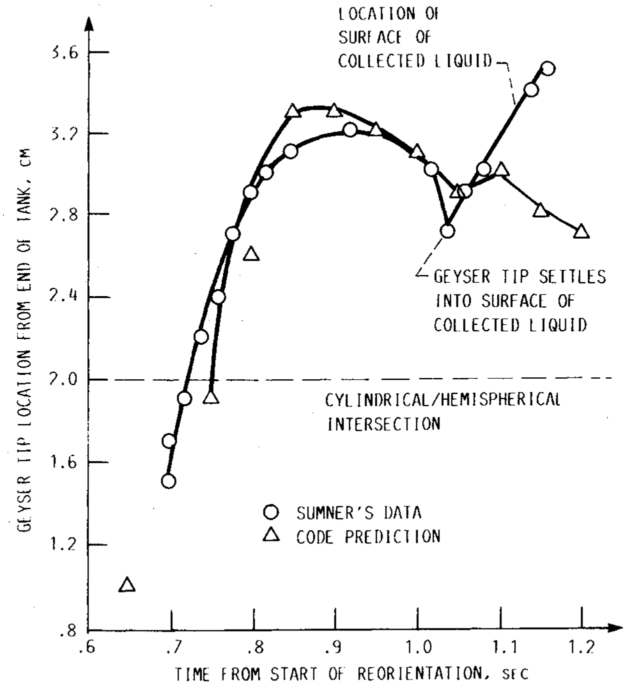

Fig. 3 Geyser tip location vs time for test 5.

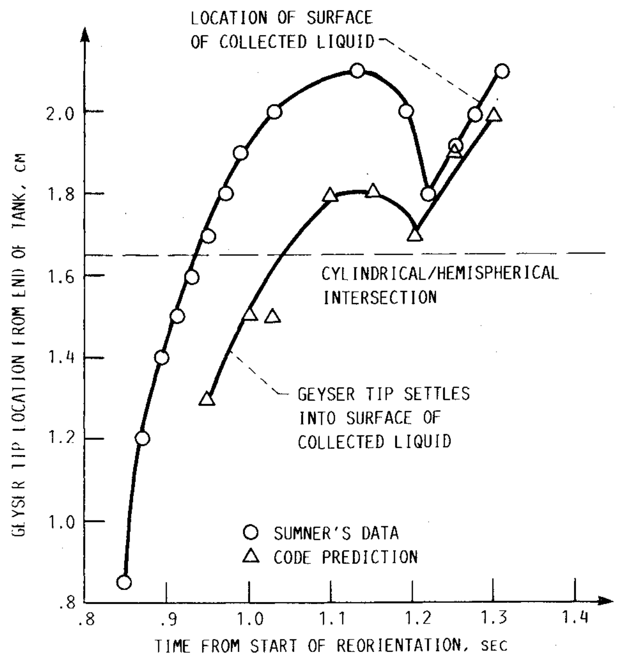

Fig. 4 Geyser tip location vs time for test 1.

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} + v\frac{\partial F}{\partial y} = 0 \tag{4}$$

The equations are discretized using finite difference procedures applied to a staggered grid with velocities defined at the cell faces and pressure at the cell center. The SOLA algorithm is used to march the solution through time. The VOF algorithm is used to determine both the location and the local radius of curvature of the free surface. The curvature is then used to compute an appropriate surface tension force that is imposed on the field as an equivalent pressure. The solution marches through time and an automatic step-size adjustment limited by stability criteria is provided.

Although many features such as heat transfer and thermodynamic models have been added during the development of ECLIPSE, only minor modifications to the baseline code were required to study impulsive reorientation. The routine that provides an initial low-g fluid configuration has been modified so that the liquid can be positioned at either end of the tank. A set of variables have been incorporated to impose a time-dependent acceleration environment on the fluid in the tank. The ability to terminate execution based on criteria for com-

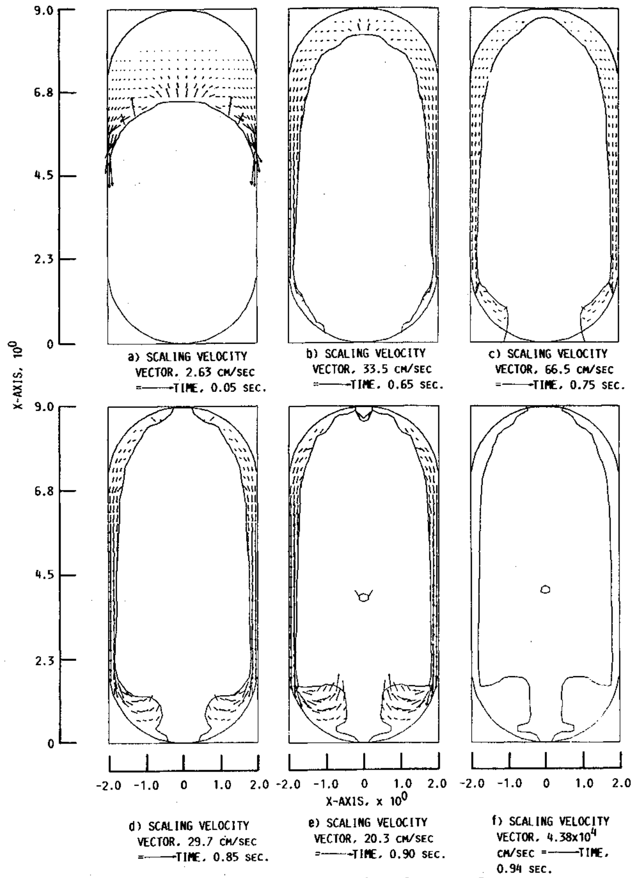

Fig. 5 Propellant motion for test 8.

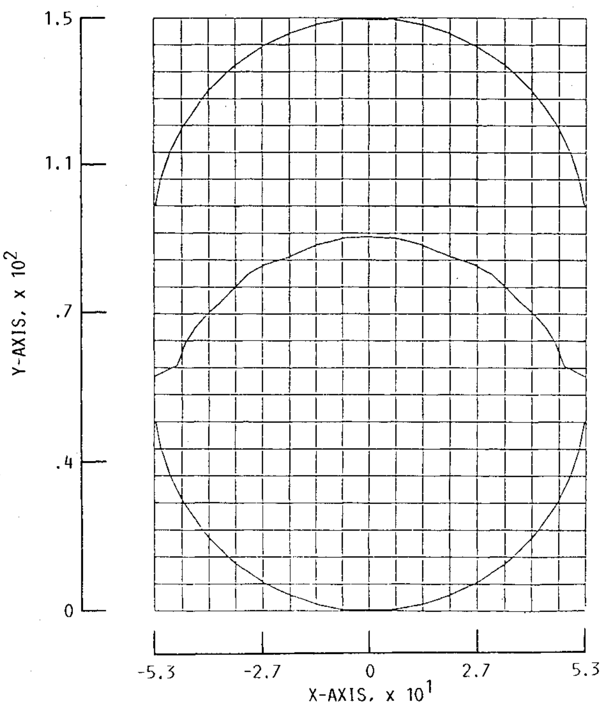

Fig. 6 Boeing SB OTV propellant tank, 0.25 scale.

pletion of reorientation has been incorporated into the code. Finally, additional output options have been added to enhance the tracking of variables of specific interest to the study of the reorientation process.

Code Validation

Six cases were selected from Sumner[7] to serve as verification that ECLIPSE accurately models the impulsive reorientation process. A summary of the test conditions is presented in Table 1. The fineness ratio *FR* is the ratio of tank axial length to tank radius. The percentage of the tank occupied by liquid is recorded in the column labeled *FL*. TCTFE is trichlorotrifluoroethane, *R* is the tank radius, and the balance of the variables are self-explanatory. These cases were selected to provide a range of geyser formation from large to nonobservable.

A typical computational mesh used to model these cases is presented in Fig. 1. The liquid is shown at the top of the tank in a zero-*g* configuration. The mesh has been refined near the maximum tank radius to assure a smooth transition of the flow from the barrel section into the head. Although all figures presented in this report show a full cross section through the tank, the code solves the problem in cylindrical coordinates and therefore only half of the number of cells depicted are required to perform the computations.

A sequence of flowfields computed for the conditions specified for test 5 is displayed in Fig. 2. A comparison between computational prediction and experimental observation of geyser tip location as a function of time is presented in Fig. 3. ECLIPSE predicts formation of a geyser with a maximum height of 3.2 cm, whereas Sumner reports a maximum geyser height of 3.3 cm. ECLIPSE predicts dissipation of the geyser into the rising free surface at approximately 1.05 s, whereas Sumner reports this event at approximately 1.10 s. A comparison between computational prediction and experimental observation of geyser tip location as a function of time for test 1 is shown in Fig. 4. Patag[10] presents comparisons between the experimental data and the computational predictions for the balance of the cases. With the except of test 8, good agreement between experimental data and computational predictions was obtained. The parameters specified for test 8 combine to induce large leading-edge velocities as the liquid moves along the tank walls. At geyser inception at the bottom of the tank, the free surface model in ECLIPSE fails to track correctly the formation of a pool and the initial growth of the geyser. Computed flowfields for test 8 are shown in Fig. 5. It should be noted that the kinetic energy imparted to the liquid is significantly higher than for the other cases. As such, it is highly inefficient and would require an excessive expenditure of propellant to produce these conditions in a real spacecraft. Since the current study is focused on optimization of the reorientation process, the inability of ECLIPSE to successfully model test 8 is not viewed as a significant handicap.

Based on the evidence presented in the preceding paragraphs, it was concluded that ECLIPSE is a suitable tool for modeling pulsed settling.

Scale Model OTV Tanks

One component of the LeRC reduced-gravity fluid-management technology program is development of a flight experiment to examine a variety of fluid-management issues. When the computational modeling effort was initiated, this experiment was know as the cryogenic fluid-management facility[1] (CFMF), but it has since been renamed the cryogenic on-orbit liquid depot, storage, acquisition, and transfer satellite[11] (COLD-SAT). The original design used a 0.25-scale model of

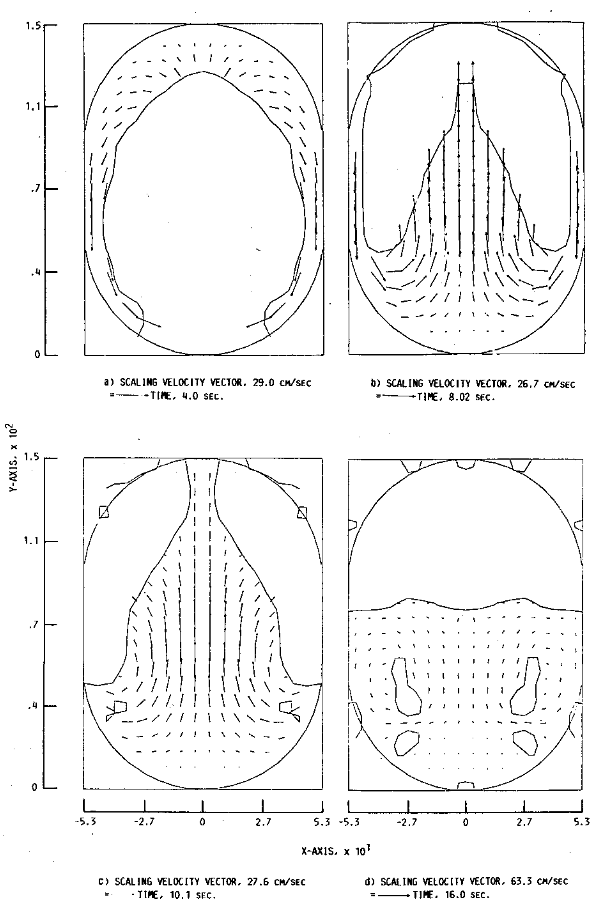

Fig. 7 Propellant motion with $A = 8.0 \times 10^{-3}\,g$. Note: Velocity vectors scaled to maximum velocity in field.

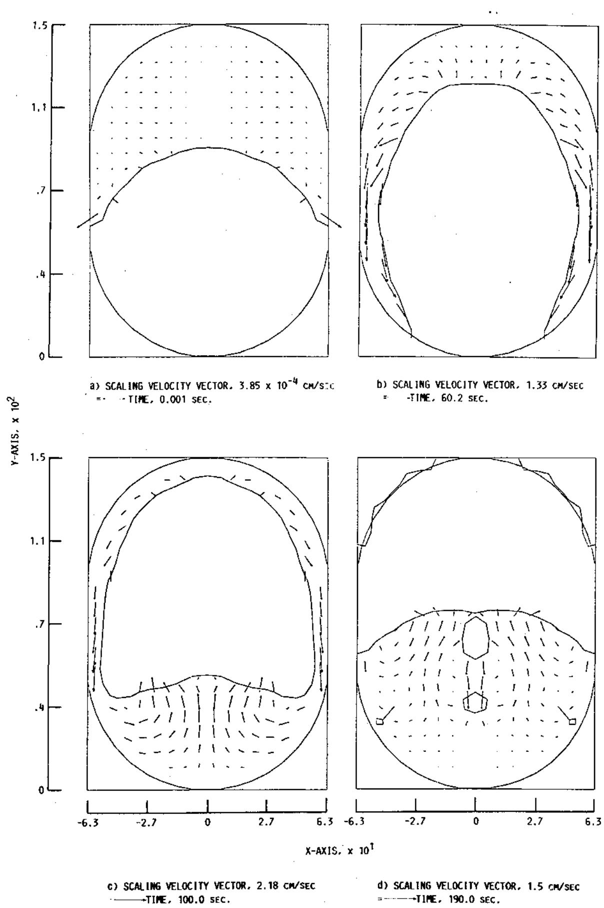

Fig. 8 Propellant motion with $A = 3.7 \times 10^{-5}\,g$. Note: Velocity vectors scaled to maximum velocity in field.

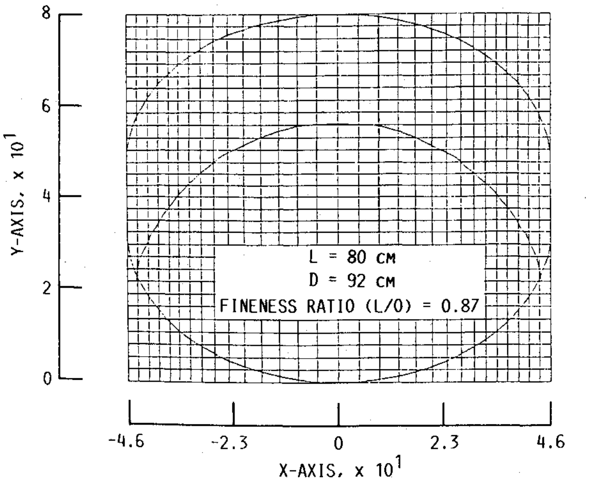

Fig. 9 Boeing short SB OTV propellant tank, 0.215 scale.

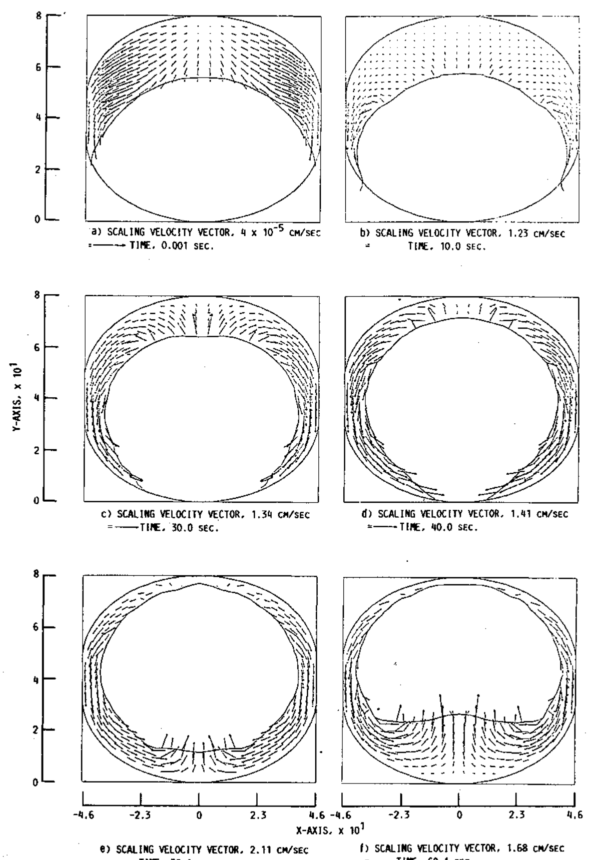

Fig. 10 Propellant motion for 0.215 scale Boeing SB OTV (50% full, imposed acceleration is 3.92×10^{-2} cm/s).

a propellant tank proposed by Boeing for a space-based orbit transfer vehicle (OTV). This tank was selected as a prototype for studying the effect of acceleration level on reorientation performance. The design of the experiment relied on two Shuttle reaction control system (RCS) thrusters to provide an acceleration environment of 7.85 cm/s^2 (8×10^{-3} g).

For the code-validation phase, the investigator reviewed graphical displays of the flowfield evolution and judged settling to be achieved when a sufficient quantity of liquid had collected into a pool at the "bottom" of the tank. To eliminate the subjective nature of this evaluation, and to minimize

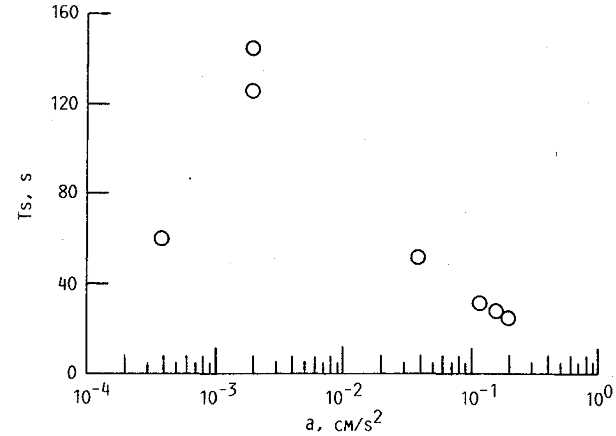

Fig. 11 Settling time vs acceleration, small-scale tank (50% full).

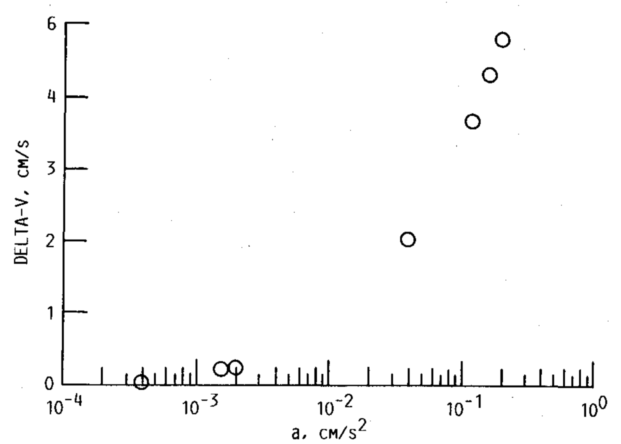

Fig. 12 Delta-v vs acceleration, small-scale tank (50% full).

the computational expense associated with each analysis, a settling criterion based on a measurable quantity was introduced. A typical motivation for settling is to position liquid over the tank outlet prior to main engine firing to prevent vapor ingestion. Since the depth of the pool at the tank centerline can be tracked as the flowfield evolves, the liquid is considered settled when this depth exceeds 20% of the total tank length. Although this figure is somewhat arbitrary, it seems reasonable, and selection of a more refined criterion is probably dependent on the particular application. The settling time is defined as the elapsed time between initiation of thrust and satisfaction of this criterion. This choice of settling time seems satisfactory for the majority of cases.

Figure 6 shows the shape and dimensions of the 0.25 tank as well as the computational mesh used to analyze the propellant motion within it. The analyses were performed for a tank 50% full of liquid hydrogen with all of the propellant initially collected at the top of the tank. Figure 6 shows the corresponding shape of the initial free surface. Figure 7 displays a sequence of flowfields that occur during the reorientation process. The liquid leading edge moves rapidly toward the bottom of the tank. A large geyser forms within 8 s of thrust initiation. The geyser is so severe that the liquid rebounds from the top of the tank before collecting into a pool after approximately 16 s have elapsed. The liquid motion has been so violent that significant vapor pockets have been encapsulated in the pool. If this process occurred in a real propulsion application, it might be necessary to extend the thruster firing period to insure that the vapor pockets are expelled from the pool before the main rocket is started.

Reference 7 indicates that optimal reorientation for the 0.25 tank should occur for an acceleration level of approximately 3.6×10^{-3} cm/s^2 (3.7×10^{-5} g). This level is predicted to be optimal in the sense that it minimizes expenditure of propellant. Figure 8 presents a sequence of flowfields corresponding to this acceleration level. The liquid moves smoothly toward the bottom of the tank collecting into a sizeable pool within 1.5 min. A moderate geyser was formed but no significant vapor pockets were trapped within the pool. After approximately 3 min, almost all of the liquid has collected in the bottom of the tank. Sumner proposed that the reorientation process be judged complete when either the geyser settles back into the pool or the liquid film has cleared the tank wall. The propellant expenditure to accomplish reorientation is roughly proportional to the vehicle delta-v incurred during reorientation. The value of delta-v is easily computed by multiplying the specified acceleration by the elapsed time required to accomplish reorientation. Using the RCS thrusters results in a vehicle delta-v of 125 cm/s, whereas the optimal acceleration level corresponds to a delta-v of 6.5 cm/s, a fuel savings factor of almost 20:1.

As the design of COLD-SAT evolved, the experiment changed from a Shuttle cargo-bay experiment to one that will fly as an independent satellite. One consequence of this evolution is that the tank scale and shape were changed to more accurately emulate current OTV design concepts and to minimize tank thermal mass. The resulting tank geometry is presented in Fig. 9. This is a 0.215-scale model of a tank known as the Boeing Short SB OTV. Analyses therefore shifted to this new tank using the computational mesh shown in Fig. 9. Acceleration environments between 2×10^{-5} and 1 cm/s^2 were studied for a tank 50% full of liquid hydrogen. Figure 10 presents a sequence of flowfields depicting the reorientation process for an imposed acceleration of 3.92×10^{-2} cm/s^2 (4.00×10^{-5} g). Settling time and vehicle delta-v were focused on as the key parameters representing settling performance. Settling time is of obvious interest for the scheduling of orbital maneuvers. Vehicle delta-v is used as a measure of efficiency since it is directly correlated to the propellant expenditure. Figure 11 displays the relationship predicted between settling time and acceleration level. Figure 12 displays the relationship between vehicle delta-v and acceleration level.

Full-Scale OTV Tank

On completion of the small-scale tank analyses, attention was focused on a full-scale Boeing Short SB OTV. Modeling of the reorientation processes in this tank covered a range of acceleration environments from 1.57×10^{-4} cm/s^2 ($1.60 \times 10^{-7} g$) to 7.85×10^{-1} cm/s^2 ($8.00 \times 10^{-4} g$) and included tanks 25, 50, and 75% filled with liquid hydrogen. The same mesh was used for these analyses as was used for the scale model of the same shape. Figure 13 shows a sequence of velocity fields predicted for a 75% full tank subject to an imposed acceleration environment of 1.96×10^{-2} cm/s^2 (2.00×10^{-5} g). Figures 14–16 display the relationship between settling time and acceleration level for the three fill levels. Figures 17–19 display the relationship between vehicle delta-v and acceleration level. The trends are not surprising, but ECLIPSE now provides a far more accurate tool for trading settling time vs propellant expenditure than was previously available.

The data presented clearly indicate that as the imposed acceleration level decreases, the vehicle delta-v required to accomplish settling also decreases. Since decreasing values of delta-v correspond to less propellant expenditure, it might appear that the lowest possible acceleration is desirable. Two factors mitigate against this conclusion. First, orbital maneuvers may need to be accomplished within a short elapsed time to satisfy mission requirements. At low acceleration levels, the

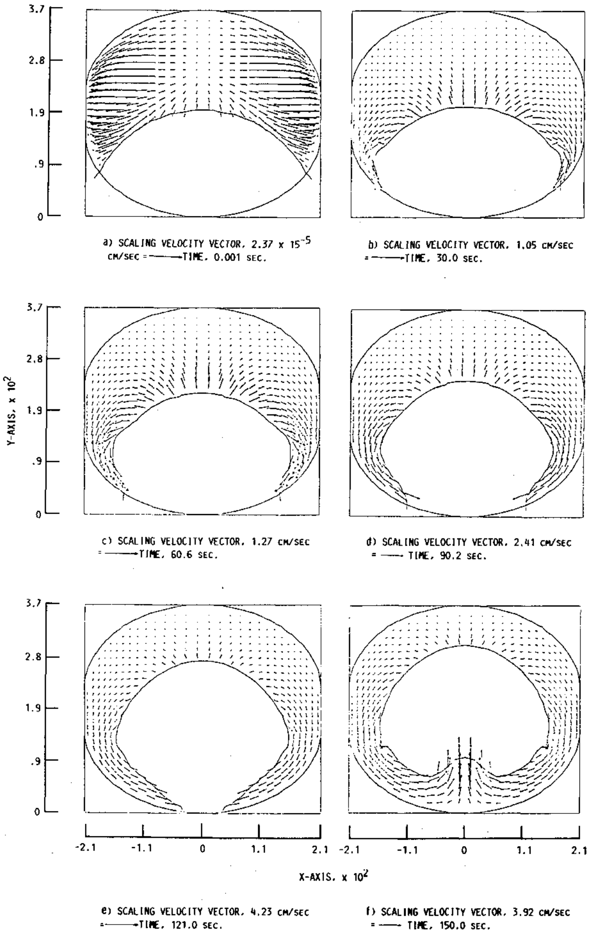

Fig. 13 Propellant motion for full-scale Boeing SB OTV (75% full, imposed acceleration is 1.96×10^{-2} cm/s^2).

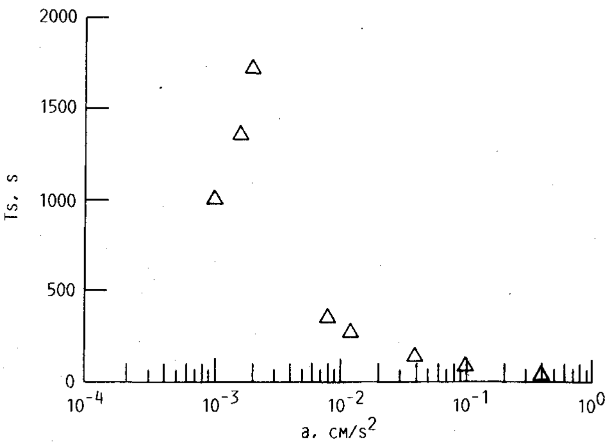

Fig. 14 Settling time vs acceleration, full-scale tank (25% full).

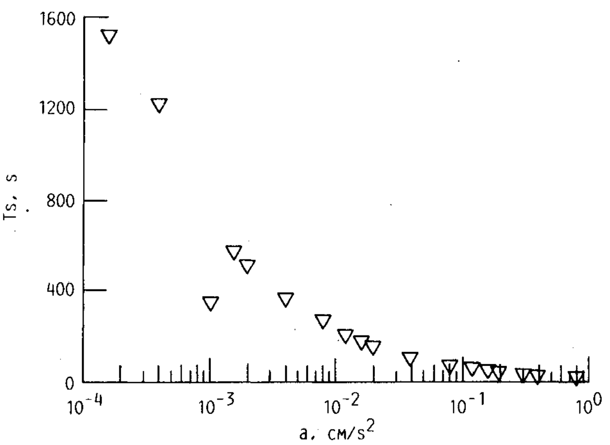

Fig. 15 Settling time vs acceleration, full-scale tank (50% full).

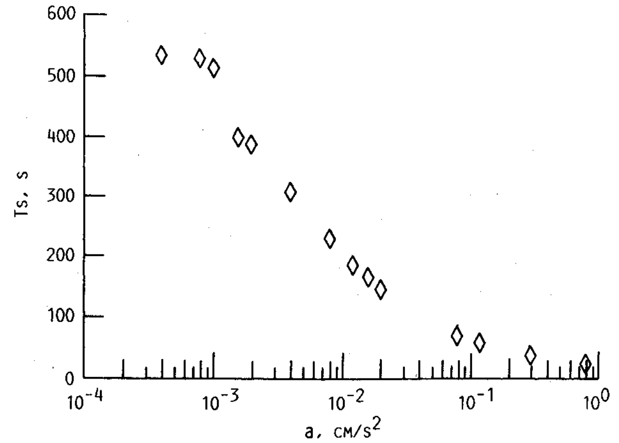

Fig. 16 Settling time vs acceleration, full-scale tank (75% full).

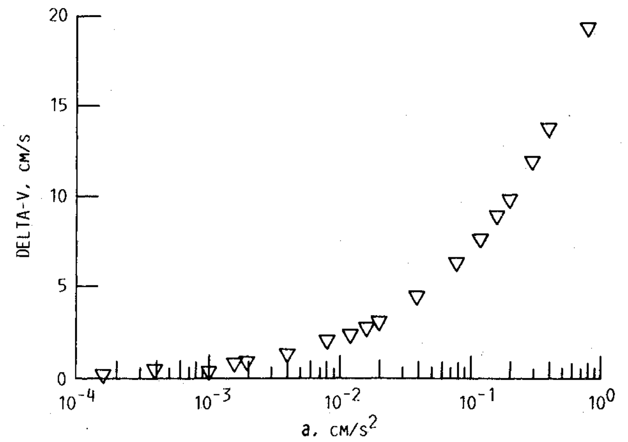

Fig. 18 Delta-v vs acceleration, full-scale tank (50% full).

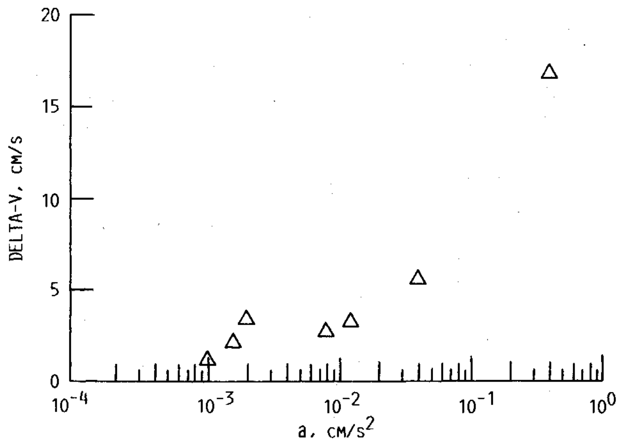

Fig. 17 Delta-v vs acceleration, full-scale tank (25% full).

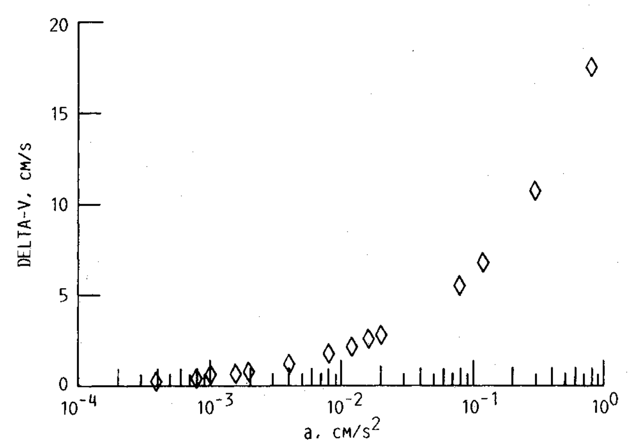

Fig. 19 Delta-v vs acceleration, full-scale tank (75% full).

settling time in full-scale tanks can be on the order of minutes. Second, it has been shown that a critical Bond number exists below which the acceleration forces are insufficient to overcome the stabilizing effect of surface tension and the fluid will not settle at all. This critical value is 0.842 for a tank with cylindrical walls and a fluid with a zero contact angle.[12] Therefore, although ECLIPSE can be used to study the relationship between propellant expenditure and settling time, other factors must be considered in selecting the thrust levels for a particular mission.

Dimensionless Scaling of Reorientation

Since ECLIPSE provides a tool capable of modeling the reorientation process in both scale model tanks and full-scale tanks, it became possible to search for a dimensionless parameter capable of scaling experimental results from small-scale tanks to full-scale spacecraft tanks. In particular, the results for the scale model Boeing SB OTV tank and for the full-scale tank were used as the basis for this investigation. Following the suggestions of previous investigators, the first attempt at correlation used the Bond number based on tank diameter as the scaling parameter. The data did not collapse using this scaling parameter.

The relevant physical variables that one might expect to affect the reorientation process are

$$\text{delta-}v = f(\rho, \mu, \sigma, R, h, a, v_f)$$

Vehicle delta-v was selected as the focus of attention since it is proportional to the fuel expenditure required to accomplish reorientation. A Buckingham Pi analysis[10] suggests that the reorientation phenomenon may be correlated by the following dimensionless groups:

$$\text{delta-}v = f(Bo, Fr, h^*, Se)$$

where

$$h^* = h/R$$

$$Se = \frac{\mu(Ra)^{1/2}}{\sigma} = \text{settling number}$$

The most successful attempt at correlating delta-v with these parameters was to use Se by itself. The settling number can be written as a function of more recognized dimensionless parameters:

$$Se = \frac{(BoWe)^{1/2}}{Re}$$

When viewed in this light, it is seen as representing the ratio of viscous and gravitational forces to surface tension forces.

The proof of a proposed correlating parameter is in the viewing of the results. Figure 20 shows the relationship between vehicle delta-v and Se for the Boeing Short SB OTV with a tank filling of 50%. A single straight line passes through all 24 data points. Unfortunately, the analyses performed for the scale model tank included only a few cases with 25 and 75% fillings. Although these analyses also correlate into a straight line, they are too few to claim as support for the correlating parameter. They are, however, distinctly different

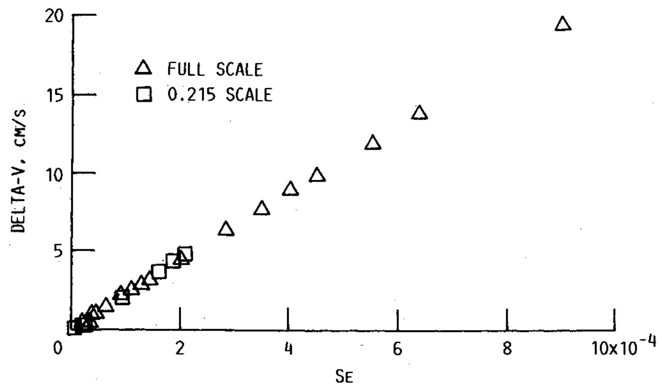

Fig. 20 Delta-v vs Se, fill level = 50%.

lines from each other and from the 50% case. Therefore, it appears that Se is a suitable correlating parameter for relating reorientation performance from small-scale to full-scale geometrically similar tanks, containing the same fluid and with the same volume fraction of liquid.

Summary of Results

The ECLIPSE code has been used to model the process of impulsive reorientation. The accuracy of computational predictions was evaluated by comparison to experimental data for reorientation in small-scale tanks with shapes typical of spacecraft propellant tanks. The model correctly predicted the extent of geyser formation and the elapsed time required to accomplish settling. Based on the comparisons, ECLIPSE was judged to be a suitable tool for studying impulsive reorientation in cryogenic propellant tanks.

Reorientation of liquid hydrogen in flight-experiment tanks was analyzed. These tanks have elliptical heads connected by a cylindrical barrel section and are representative of vehicle propellant tanks. ECLIPSE was able to model the reorientation without difficulty and provided significant insight into the process. For one tank, it was demonstrated that if the existing design was replaced with one producing an optimal acceleration environment, propellant expenditure could be reduced by a factor of almost 20. For the other tank, a range of acceleration environments was investigated and a summary of the results is reported.

Reorientation in a full-scale OTV tank was modeled for three different tank fillings across a range of acceleration environments. A summary of the results for these cases is presented.

A dimensionless parameter called the settling number Se is proposed for correlating the reorientation process between geometrically similar tanks with the same liquid volume fraction. To test the proposed parameter, computational predictions of vehicle delta-v acquired during settling for a full-scale spacecraft tank and for a 0.215-scale model were plotted against Se. All data points were found to scale directly with Se.

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