1995

NASA /ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

COMPUTATIONAL MODELING OF MAGNETICALLY ACTUATED PROPELLANT ORIENTATION

Prepared By: John I. Hochstein, Ph.D.

Academic Rank: Associate Professor

Institution and Department: The University of Memphis
Department of Mechanical Engineering

NASA/MSFC:

Laboratory: Propulsion Laboratory
Division: Propulsion Systems
Branch: Advanced Propulsion

MSFC Colleague: George R. Schmidt, Ph.D.

INTRODUCTION

Unlike terrestrial applications where gravity positions liquid at the "bottom" of the tank, the location of liquid propellant in spacecraft tanks is uncertain unless specific actions are taken or special features are built into the tank. Some mission events require knowledge of liquid position prior to a particular action: liquid must be positioned over the tank outlet prior to starting the main engines and must be moved away from the tank vent before vapor can be released overboard to reduce pressure. It may also be desirable to positively position liquid to improve propulsion system performance: moving liquid away from the tank walls will dramatically decrease the rate of heat transfer to the propellant, suppressing the boil-off rate, thereby reducing overall mission propellant requirements. The process of moving propellant to a desired position is referred to as propellant orientation or reorientation.

Several techniques have been developed to positively position propellant in spacecraft tanks and each technique imposes additional requirements on vehicle design. Propulsive reorientation relies on small auxiliary thrusters to accelerate the tank. The inertia of the liquid causes it to collect in the aft-end of the tank if the acceleration is forward. This technique requires that additional thrusters be added to the vehicle, that additional propellant be carried in the vehicle, and that an additional operational maneuver be executed. Another technique uses Liquid Acquisition Devices (LAD's) to positively position propellants. These devices rely on surface tension to hold the liquid within special geometries (i.e. vanes, wire-mesh channels, start-baskets). While avoiding some of the penalties of propulsive orientation, this technique requires the addition of complicated hardware inside the propellant tank and performance for long duration missions is uncertain. The subject of the present research is an alternate technique for positively positioning liquid within spacecraft propellant tanks: magnetic fields.

The idea of using electromagnetic fields to position propellants in spacecraft tanks was studied briefly in the 1960's. Electrical fields can produce voltage differentials within the tank that pose a prohibitive safety hazard. Magnetic fields do not pose this risk. Since LOX is paramagnetic (attracted toward a magnet) and LH2 is diamagnetic (repelled from a magnet), a nonuniform magnetic field of sufficient strength could provide a positioning force. Order-of-magnitude analyses showed that magnets based on 1960's technology were prohibitively massive and this option has remained dormant during the intervening years. Recent advances in high-temperature superconducting materials hold the promise of electromagnets with sufficient performance to support cryogenic propellant management tasks. Therefore, a recent initiative was authorized in late 1992 at NASA MSFC to asses the feasibility of using magnetic fields to positively position propellants in spacecraft tanks. The key component of this initiative is the Magnetically-Actuated Propellant Orientation (MAPO) experiment. A mixture of ferrofluid and water will be used to simulate the paramagnetic properties of LOX and the experiment will be flown on the KC-135 aircraft to provide a reduced gravity environment. The influence of a 0.4 Tesla ring magnet on flow into and out of a subscale Plexiglas tank will be recorded on video tape. The first flight is currently scheduled for late September 1995.

Given the complexity of the physical processes involved in the magnetically-actuated orientation process, it is unlikely that analytical solutions to the equations describing these processes can be obtained. While experimentation is essential in establishing basic relationships between the process parameters, the requirement for a reduced gravity environment makes experimentation particularly expensive and time consuming. The most efficient approach to evaluating the feasibility of MAPO is to compliment the experimental program with development of a computational tool with a demonstrated ability to model the process of interest. The goal of the present research is to develop such a tool. Once confidence in its fidelity is established by comparison to data from the MAPO experiment, it can be used to assist in the design of future experiments and to study the parameter space of the process. Ultimately, it is hoped that the computational model can serve as a design tool for full-scale spacecraft applications.

MATHEMATICAL MODEL

Although the practitioner of experimental or computational fluid mechanics may have familiarity with many of the features of the research problem, it is less likely that he/she will have a strong background in the magnetic and paramagnetic aspects of the problem. The author spent considerable time and effort retrieving the background information in these areas and has collected the basic information into a single resource that it is hoped will be of value to other researchers who tackle this problem, "Magnetism and the Flow of Paramagnetic Fluids: An Introduction for the Non-Specialist." In addition to this review of the basic physics, 22 papers related to the flow of paramagnetic fluids and ferrofluids were extracted from the literature and assembled into a reference resource.

LOX and LH2 are reasonably well represented as incompressible, constant property, Newtonian fluids and therefore the flow of interest can be modeled using a modified form of the Navier-Stokes equations

$$\rho\frac{\partial\vec{V}}{\partial t}+\rho\left(\vec{V}\cdot\nabla\right)\vec{V}=-\nabla p+\mu\nabla^{2}\vec{V}+\rho\vec{g}+\mu_{o}\left(\vec{M}\cdot\nabla\right)\vec{H}$$

In addition to the usual flow boundary conditions, the normal stress boundary condition at a gas/liquid interface is given by:

$$\Delta p = \sigma\kappa + \tfrac{1}{2}\mu_o\left[\left(\vec{M}\cdot\hat{n}\right)^2_{liq} - \left(\vec{M}\cdot\hat{n}\right)^2_{gas}\right]$$

where the first term is the "pressure jump" at the interface due to surface tension and the second term is the "magnetic pressure" due to the change in magnetization across the interface.

The magnetic field due to the ring magnetic will be modeled as a magnetic dipole located at the center of the ring.

$$\vec{B} = \frac{\mu_o m}{4\pi r^3}\left[(2\cos\theta)\hat{e}_r + (\sin\theta)\hat{e}_\theta\right] = \mu_o\left(\vec{H} + \vec{M}\right)$$

where $\vec{B}$ is the magnetic flux density, m is the magnetic dipole strength, and r, θ, φ are spherical coordinates with θ measured "down" from an upright z-axis and φ is measured in the x-y plane.

COMPUTATIONAL MODEL

A computational tool for the simulation of magnetically-actuated propellant orientation must be able to solve all of equations and boundary conditions presented in the development of the mathematical model. Further, the tool must be capable of modeling the large interface deformation and mass transport associated with bulk propellant motion within the spacecraft tank. This single requirement eliminates most candidate CFD codes and identifies the RIPPLE code as uniquely well qualified to serve as the foundation for building the desired computational tool. RIPPLE was developed at the Los Alamos National Laboratory under an interagency agreement with NASA and source code is readily available. Except for the Pondermotive force term, the baseline code provides all of the required capabilities. Further, the fidelity of this code in modeling propulsive propellant reorientation has been previously demonstrated, providing strong confidence that it will serve well as a foundation for the present research.

The RIPPLE code models the transient flow of an incompressible Newtonian fluid. The flow field is discretized into finite volumes to form a nonuniform computational mesh. A staggered-grid approximation to the continuity and momentum equations produces a nonlinear system of algebraic equations that is solved using a two-step projection method. Instead of an interface tracking scheme, the VOF technique is use to follow the advection of mass through an Eulerian mesh and special donor-acceptor cell differencing is used for the VOF-function to preserve steep interface shapes. The Continuum Surface Force (CSF) model is used to represent surface tension forces producing a more robust tool than previously developed codes.

The RIPPLE code, and a supporting graphics package known as RGO, were ported to a workstation (SGI 4D/35TG) in the MSFC computational environment. The analysis code contains a sequence of subroutine calls in which each subroutine computes the contribution of a force term to momentum equation. A new subroutine, ponder, has been written to compute the contribution of the Pondermotive force and this subroutine has been inserted into the calling sequence. Additional modifications to support the magnetic model have been accomplished including changes to the I/O subroutines and the common blocks. RGO was also modified to support the new variables introduced by the magnetic model.

TEST CASES

Several test cases have been run to evaluate the new model for the Pondermotive force. To check that the new force model interacted properly with the pressure solver, two cases were constructed in which the magnetic force was specified to be uniform in the coordinate directions, (one case in x-direction and one in y-direction). As expected, constant pressure contours are straight lines, orthogonal to the direction of the force. and equally spaced.

The second set of cases was composed of three analyses in which simple magnetic fields were imposed: dh/dx = constant, dh/dy = constant, and dh/dx = dh/dy = constant. The third case is also the first in which a small void region was provided to test the interaction of the magnetic model and the free surface model. The constant pressure contours predicted for the second two cases are presented in Figure 1. As expected, the constant pressure contours are straight lines orthogonal to the gradient of the magnetic field. The nonlinear dependence of the Pondermotive force on the magnetic intensity ($H\nabla H$) is evident in the concentration of the constant pressure contours toward the region of high field strength, (left and lower-left corner). The deflection of the contours at the wall in the third case is an anomaly in the graphics package. The heavy contour in the upper-right corner of the third case is both a constant pressure contour and the computational prediction for the free-surface shape. As expected, these contours are coincident.

The third set of test cases sought to more rigorously test the interaction between the Pondermotive force model and the free surface/surface tension model. As a representative case, Figure 2 depicts the pressure and velocity fields predicted for the motion of an initially circular void region under the influence of a magnetic field with dh/dx=constant. Although there is no experimental data available for comparison to these calculations, the results seem reasonable and provide confidence that computational tool has the desired basic modeling capabilities required to simulate magnetically-actuated propellant orientation.

The final set of test cases executed this summer were an attempt to begin modeling the flows expected in the MAPO experiment. Measurements of magnetic intensity were made in the neighborhood of the ring magnet and a comparable dipole strength was computed for use in the computational simulation. A model was then constructed in which the dipole was located 0.05 m below the bottom of the tank and along the tank centerline. Given the short period available for this study, it was not possible to obtain a completely successful simulation. Although the predicted pressure contours appear to be reasonable, the velocity fields exhibit a strong vortex near the tank outlet that did not appear in any of the previous tests. Figure 3 depicts the magnetic field, pressure contours, and velocity field shortly after initiating a simplified analysis in which the tank is cylindrical, there is no surface tension, and the initial free surface is flat. As expected, the velocity field in the neighborhood of the free surface appears to be moving the interface toward an equilibrium configuration in which the fluid is higher at the left wall and lower at the right. The vortex in the lower-left corner was not expected and at present cannot be explained.

FUTURE DIRECTIONS

The preceding text describes ten weeks of effort, and, in the author's mind, comes to a sudden halt. This reflects the unfinished nature of the research effort. A reasonably difficult problem has been approached and preliminary tests indicate a good chance of success for the methods and tools developed. The next step must be an understanding of the cause of the unexpected vortex and modification of the computational model as required. Once this is accomplished, the code should be exercised on additional test cases that have been identified during the literature search for which experimental data or analytical solutions are available. The fidelity of the code should then be evaluated by comparing computational predictions to measurements from the MAPO experiment. Successful completion of this research program will produce a valuable tool that can be used for the design of additional experiments, to study the parameter space of the MAPO process, and ultimately as a design tool for full-scale spacecraft applications.

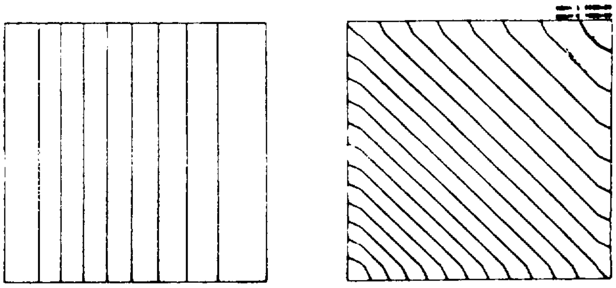


Figure 1

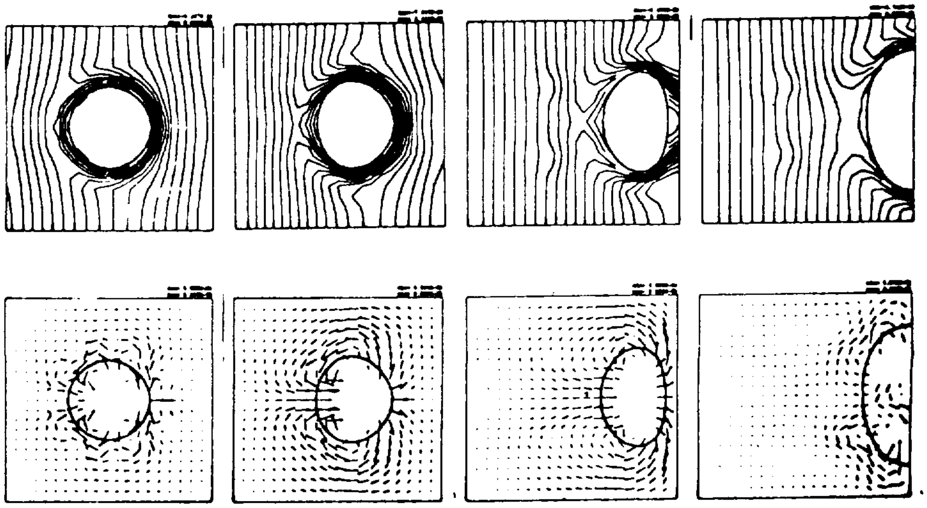
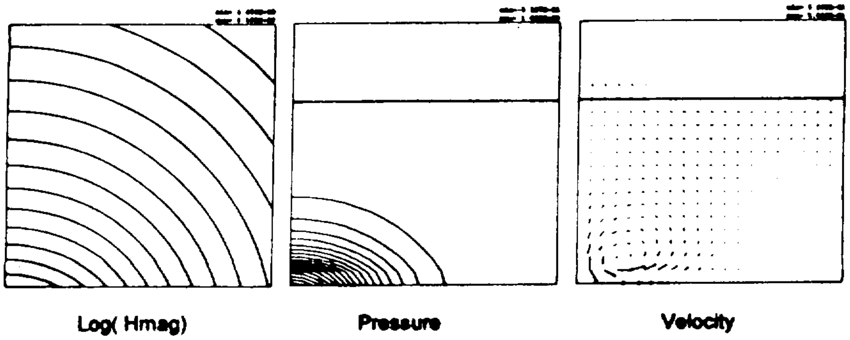


Figure 2



Log(Hmag)

Pressure

Velocity

Figure 3