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HELIUM II SLOSH IN LOW GRAVITY

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ABSTRACT

This paper describes the status and plans for the work being performed under NASA NRA contract NASW-4803 so that members of the Microgravity Fluid Dynamics Discipline Working Group are aware of this program. The contract is a cross-disciplinary research program and is administered under the Low Temperature Microgravity Research Program at the Jet Propulsion Laboratory.

The purpose of the project is to perform low-gravity verification experiments on the slosh behavior of He II to use in the development of a CFD model that incorporates the two-fluid physics of He II. The two-fluid code predicts a different fluid motion response in low-gravity environment from that predicted by a single-fluid model, while the 1g response is identical for the both types of model.

INTRODUCTION

The motion of helium II in the low-gravity environment of an orbiting satellite is of critical importance for the design of the satellite attitude and translation control systems. Space vehicle designers are particularly interested in the frequency of oscillation and damping rate of the fundamental slosh mode as well as the cross-axis coupling, if any, induced by rotation of the satellite. There is concern and uncertainty about the potential for persistent fluid slosh motion due to the absence of viscosity in the superfluid component of helium II.

CFD CODE DEVELOPMENT

A superfluid helium (SFHe) simulation has been developed based on the commercial CFD code FLOW-3D from Flow Science in Los Alamos, NM. The SFHe code incorporates Landau's two-fluid model, a critical-velocity threshold, mutual friction between the two fluid components and a new method of reconciling the motion of the two independent components at the free surface.

Two-Fluid Model

The SFHe model calculates independent fluid velocities and cell fluid contents for the normal and superfluid components of the helium II. At each time step, the motion of each component is calculated separately, with allowance for mutual friction as described later. The total pressure in the void and fluid is allocated to the components

based on their relative proportions. Calculations for each component's motion are based on its partial pressure, while output pressures are a summation of the two.

The time step process calculates an intermediate explicit estimate of the new velocity $\tilde{u}^{n+1}$ using the Navier-Stokes equation without the pressure term. The pressure term is incorporated in the second step of the process, where the cell pressures at the new time are adjusted in an iterative loop to force the divergence to zero for each full cell in the tank. This converts the $\tilde{u}^{n+1}$ velocity estimate to a final value u^{n+1} at the t+1 time step.

Critical Velocity

The empirical equation described by Van Sciver (1986) and Putterman (1974)

$$v_c \approx d^{-1/4} \quad \text{(cgs)}$$

is used to calculate the critical velocity above which the two components interact through mutual friction. This formula is based on the flow of the helium II through a small circular or rectangular tube; as such, it is really a one-dimensional flow field under study. In this simulation, the critical velocity is determined by the smallest separation distance between surfaces in the vicinity of the cell. This threshold value is then compared to the magnitude of the total velocity vector, ignoring the relative orientation of the flow to the surface. This avoids discontinuities in the linking of the components based on small variations in flow direction.

Mutual Friction

The formulation proposed by Gorter and Mellink (1949)

$$\vec{F}_{sn} = A\,\rho_s\,\rho_n\,v_{sn}^2\,(\vec{v}_s - \vec{v}_n)$$

is used to calculate the amount of coupling between the two components when the differential velocities exceed the critical velocity. Again, as in the case of the critical velocity, the experimental work in this area has been done with small one-dimensional apparatus. In the three-dimensional model, the mutual friction force in each orthogonal direction is calculated using the normal and superfluid component velocities in that direction alone. This avoids the pitfall of having the mutual friction accelerate the fluid in one direction because of a high velocity value in a perpendicular direction.

Motion of Free Surface

One of the concerns unique to this type of simulation is calculating the position of the free surface of the fluid. The interaction of the normal and superfluid components at the free surface is not well understood and there were no models of free surface behavior found in the literature. The general consensus seems to be that the free surface should assume an intermediate position between the shapes predicted for a pure

normal fluid and a frictionless superfluid. Figure 2 shows a thought experiment where a rotating bucket of helium has the normal fluid in solid-body rotation while the superfluid has not spun up and is stationary. In this condition, the equilibrium shape of the surface for each component is different but the two-fluid model requires a common surface for both components.

As shown in figure 1, the SFHe simulation independently calculates the new surface position of each component for each time step and then calculates a weighted-average of the two positions based on the relative proportions of the components. This enforces the requirement of a single common interface while allowing the two components to flow as required by their independent velocity fields. This weighted averaging is not a conservative operation, since the component velocities in the affected cells are not adjusted after the fluid content is changed, but this is consistent with the experimental behavior observed by Mehl and Zimmermann (1968) and Reppy and Depatie (1964).

1-G VERIFICATION TESTS WITH JPL SFHE DEWAR

A series of ground slosh experiments was performed by the author at JPL using their SFHe dewar shown in figure 3 as a verification of the code in 1-g. The dewar was moved laterally to create a slosh wave oscillating in the plane of the test cell and the slosh amplitude decay curve was calculated An exponential curve has been fitted to the combined results of tests at common temperature and fill levels as shown in figure 4 for the runs at 1.7 K. The two-fluid model predicts a slosh frequency (2.63-2.86 Hz) and damping rate (-0.0110 and -0.0114 at 1.7 K) that is identical to that of a single-fluid CFD code; both types of model match the experimental results (2.45-2.77 Hz for all cases and -0.0115 at 1.7 K) within 5 percent. Figure 5 shows the experimental damping coefficient test results for the various temperatures and fill ratios tested. The lack of significant differences between the predictions of the two-fluid and the single-fluid models in either frequency or damping suggests that the 1-g acceleration field is far more influential than the friction or surface tension effects that are unique to the two-fluid model.

LOW-G SLOSH PREDICTIONS FOR GP-B DEWAR

One of the aspects of fluid response studied in the internal project was the impulse response of a large rotating tank that is partially filled with liquid helium. For the purpose of the computer runs, the dimensions and fluid temperature of the Gravity Probe-B dewar were used. The fluid velocity field and the overall force are plotted for both the single-fluid simulation and the two-fluid SFHe model.

Contrary to the results of the CFD simulations in 1g, zero gravity simulations show marked differences in the fluid motion predicted by the single-fluid and two-fluid models. Figures 6 & 7 show the fluid velocity fields 160 seconds after the application of a lateral impulse to the GP-B dewar while it is rotating at 1 rpm. The single-fluid model predicts an symmetrical oscillating flow field while the two-fluid model predicts that the fluid converts to a rotating velocity field with the fluid flowing against the direction

of rotation of the tank in inertial space. In addition, the two components show a difference in their directions of flow.

PLANNED LOW-G EXPERIMENTAL WORK TO BE PERFORMED UNDER NASW-4803

Based on the 1-g experiments and the low-gravity simulations performed to date, it is necessary to perform low-gravity experiments to be able to verify the performance of the SFHe simulation. This contract was awarded to build a SFHe dewar and perform slosh experiments on the KC-135. The dewar that I used for the ground tests was previously used to perform slosh experiments on the KC-135; JPL is in the process of refurbishing the dewar and its support equipment package. The current plan is to build a new SFHe test cell from Lexan with stainless steel tubes support tubes and retrofit this into the existing dewar. Development tests are currently being performed to develop a method of sealing the Lexan-to-steel interface.

CONCLUSIONS

This work is still in its equipment development phase. I am working closely with Peter Mason and Bob Chave at JPL to coordinate the equipment design and integration. It may be possible to perform the first KC-135 experiments this summer.

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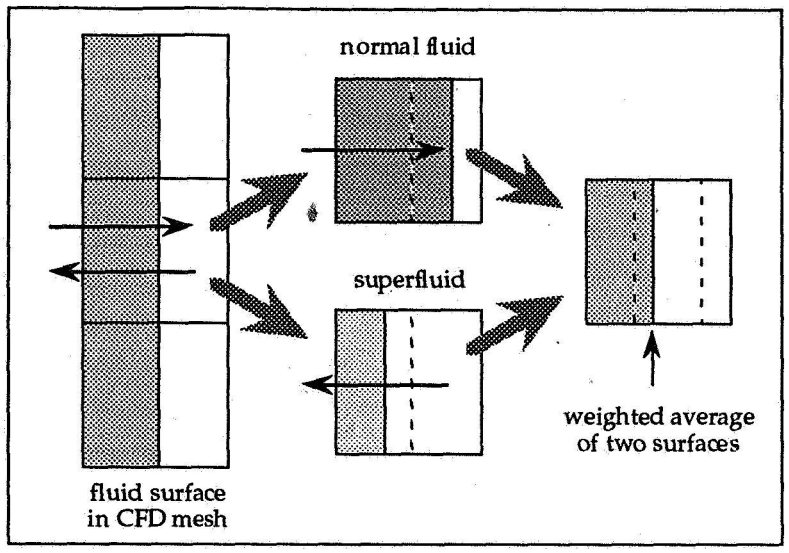
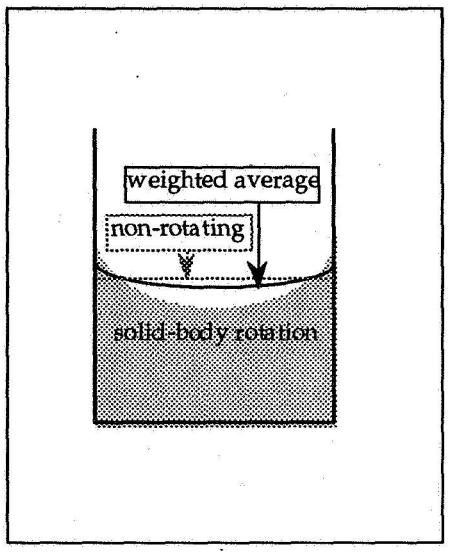


Motion of He II Components at Surface
Figure 1



Rotating Bucket of He II
Figure 2

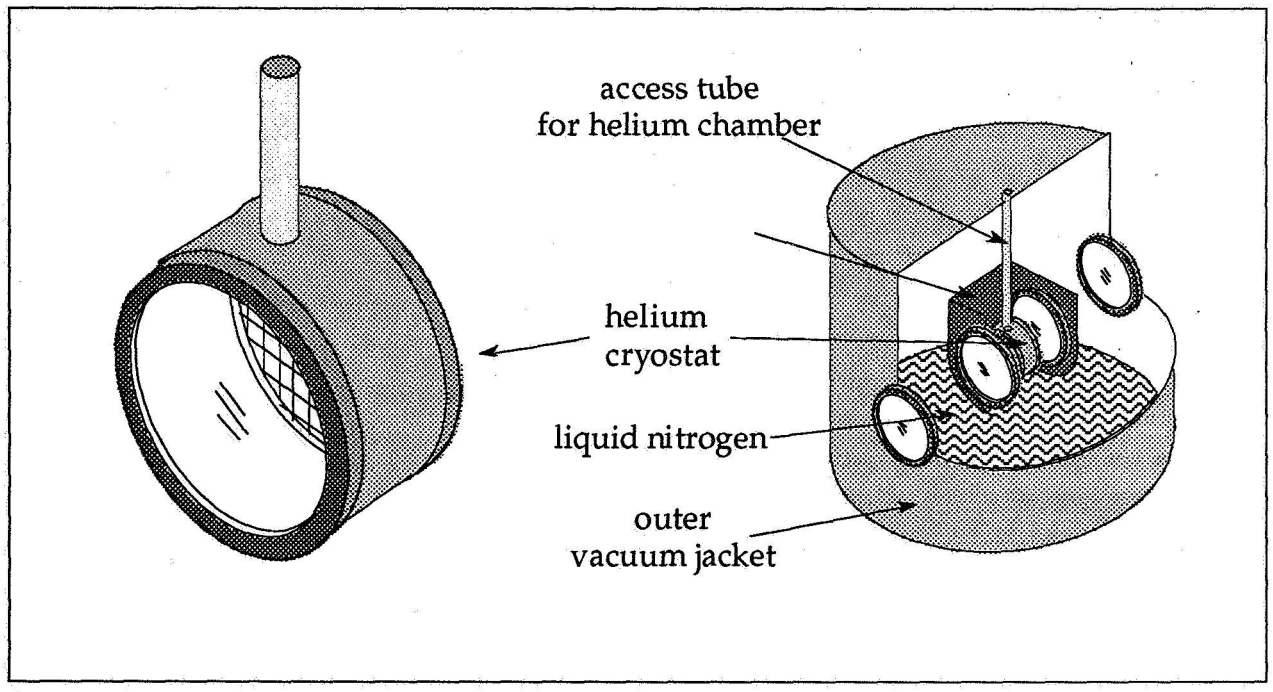
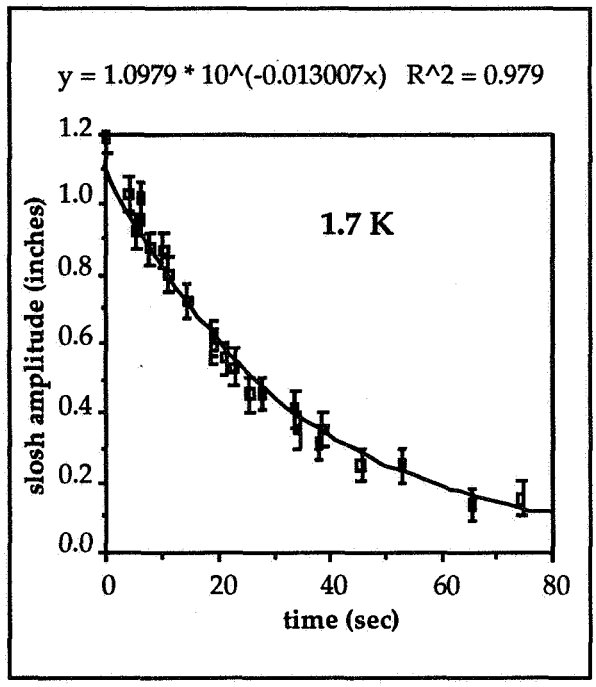
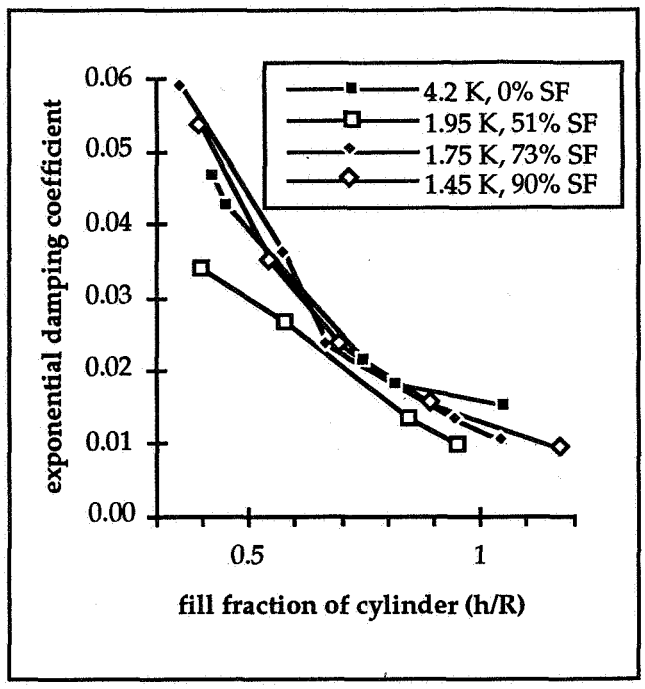


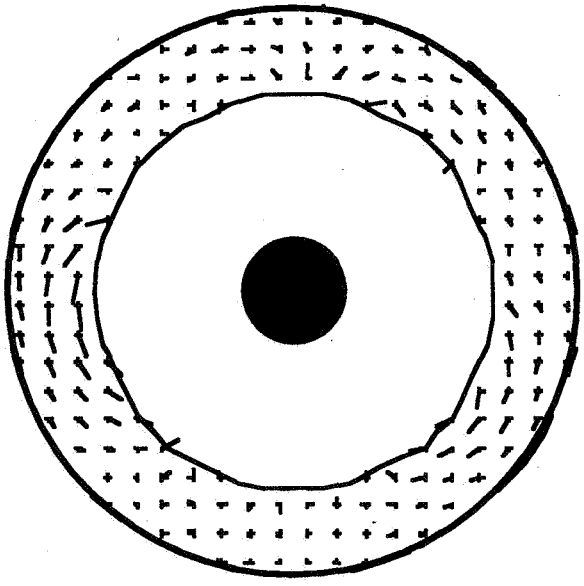
Figure 3 JPL He II Dewar



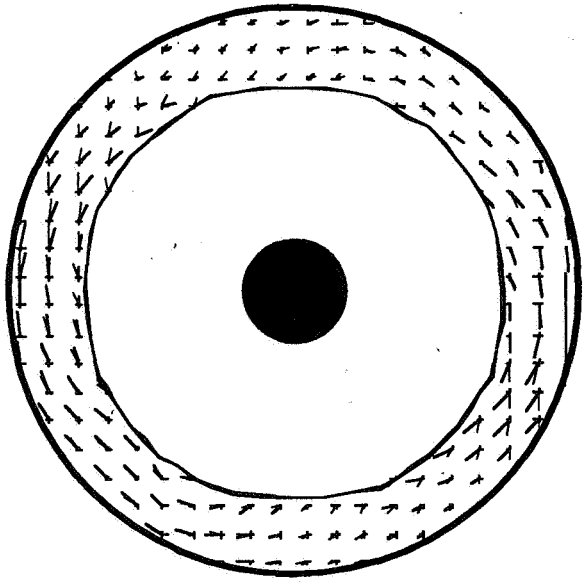
1.7 K Raw Data and Fitted Curve
Figure 4



Damping Coefficients in JPL Dewar
Figure 5



Fluid Velocity Field in Single-Fluid Model
Figure 6



Fluid Velocity Field in Two-Fluid Model
Figure 7