Experimental Study of the Effects of Low Bond Number Sloshing on Thermal Stratification

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Theme

A SERIES of experiments was performed to determine the effects of low Bond number (ratio of gravitational forces to surface tension forces) sloshing on thermally stratified liquids contained in right circular cylindrical tanks. Specifically, the principal objective of the study was to identify which, if any, of the three lateral sloshing modes that exist near the first natural frequency of the liquid surface disrupt the stratified layer and cause it to mix with the bulk liquid.

Contents

Thermal stratification is a nonuniform thermal energy distribution along the acceleration axis of a liquid container. The major feature of this distribution is a layer of liquid, called the "stratified layer," which exists near the free surface and which has an average temperature higher than that of the bulk liquid. The mechanics of the stratification process are described in a number of works such as that by Clark.[1] The dimensionless temperature moment is used in this study to quantify the degree of thermal stratification. Vliet[2] defined this variable as

$$M_T{}^* = \frac{M_T - M_{\bar{T}}}{M_{\bar{T}}} = \frac{\int_0^h (T - T_0) y \, dy - \left(\frac{h^2}{2}\right)(\bar{T} - T_0)}{\left(\frac{h^2}{2}\right)(\bar{T} - T_0)} \tag{1}$$

Where M_T is the temperature moment (defined as shown above), $M_{\bar{T}}$ is the value the temperature moment assumes if the liquid is completely mixed in an adiabatic process, T is the temperature, T_0 is the initial temperature and $\bar{T}$ is the adiabatic mixing temperature.

Sloshing is generally defined as any free surface wave oscillations caused by motions of a liquid container. This investigation, however, was limited to oscillations near the first natural frequency of the liquid surface that are excited by sinusoidal motions perpendicular to the longitudinal axis of the tank. Three distinct modes of sloshing caused by such lateral motions exist near the natural frequencies of the free surface: 1) stable planar, 2) unstable nonplanar, and 3) stable nonplanar. Detailed descriptions of these modes and the conditions necessary for their appearance are given by Hutton.[3]

The problem of interest is defined by the following conditions: 1) right circular cylindrical tank with no baffles, 2) no wall or bottom heating and negligible interfacial effects, 3) incompressible liquid, 4) no draining or filling of the tank during sloshing, 5) "moderately low" Bond number regime ($10 \leq BO \leq 100$), 6) steady acceleration vector coincident with the longitudinal axis of the tank and oriented such that the liquid does not tend to migrate to the other end of the tank, 7) liquid does not boil, 8) lateral vibrations, and 9) sinusoidal forcing function.

The experiments were performed in a 1 g environment using water in a 0.875-in.-diam by 6-in.-long tank to achieve a value of the Bond number (16.65) representative of large cryogenic tankage in Earth orbit. The tank was mounted directly on the head of an electrodynamic shaker and vibrated in a direction perpendicular to its longitudinal axis. The liquid temperature histories were measured with ten 38 gage copper-constantan thermocouples mounted through holes drilled in the tank wall. The thermal stratification was obtained by using a syringe to

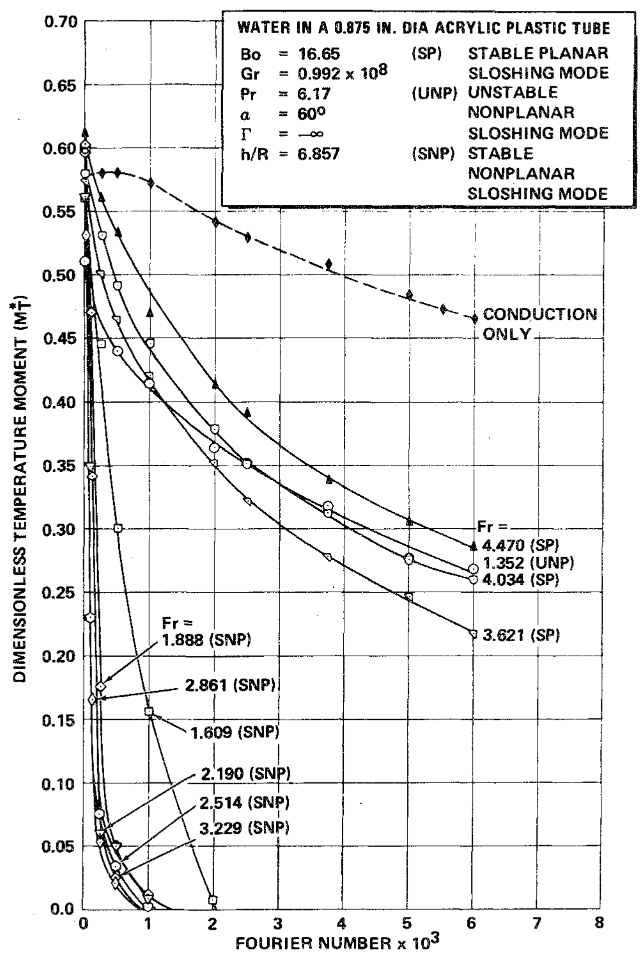

Fig. 1 Sloshing test results—excitation amplitude-to-radius ratio of 0.2286.

Received October 10, 1972; synoptic received April 20, 1973. Full paper available from National Technical Information Service, Springfield, Va., 22151, as N73-21283 at the standard price (available upon request).

Index categories: Fuel and Propellant Storage, Transfer, and Control Systems; Wave Motion and Sloshing.

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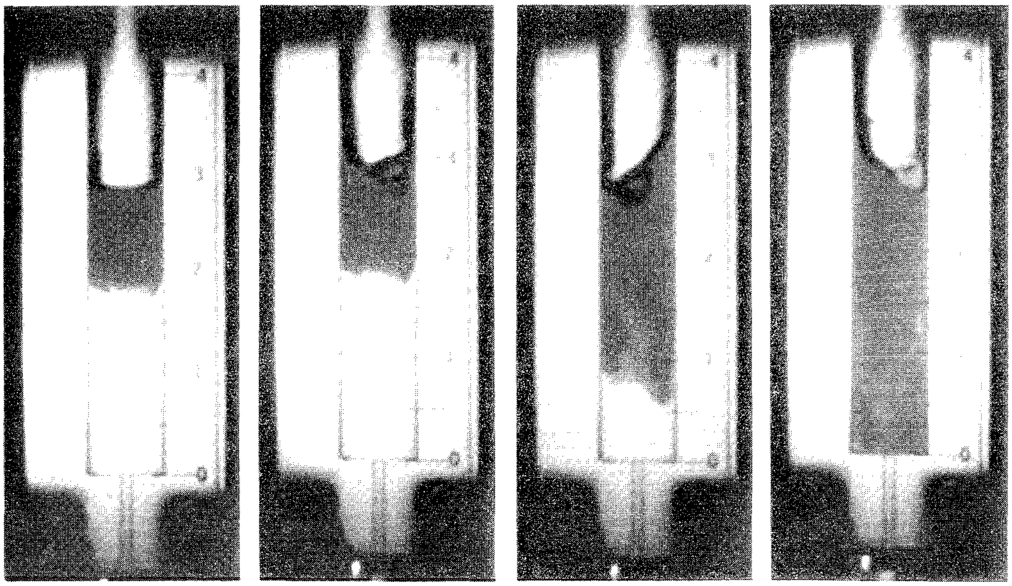

Fig. 2 Destratification with stable nonplanar sloshing.

deposit a 0.75-in. layer of hot (212°F) water on top of a 2.25-in. column of cold (32°F) water previously loaded in the tank with another syringe. A small balsa wood block placed on the surface of the cold water minimized mixing during the deposition of the hot layer. This block was removed from the tank immediately after the loading procedure was completed.

Fifty-four sloshing tests were completed with each test lasting 240 sec. The sloshing mode for each test was determined visually and the lowest natural frequency of the liquid surface was found to be approximately 6 cps which corresponds to a Froude number of 1.609. Since some destratification can be achieved by conduction only without any sloshing taking place, it was also necessary to run a conduction test. This test was identical to the sloshing tests except that the tank was not vibrated. It serves as a limiting case for this investigation since conduction alone will always result in less destratification than combined conduction and sloshing.

The effects of low Bond number sloshing on stratification ranged from a very small degree of destratification, to complete destratification. Typical test results encompassing this entire range of destratification are shown in dimensionless form in Fig. 1. The pronounced groupings of the dimensionless temperature ratio curves show that, for a given excitation amplitude-to-radius ratio, the destratification is a strong function of the Froude number since this parameter determines the sloshing mode. Furthermore, these results also show that the best destratification was achieved at values of the Froude number for which the liquid sloshed in the stable nonplanar mode.

Upon completion of each of several sloshing tests, the sloshing was terminated but the temperatures were recorded for an additional 60 sec. In no instance did the stratification increase after the sloshing had been stopped, indicating that thorough mixing was obtained by the sloshing process.

Several sloshing tests were run after adding a small amount of red dye to the stratified layer in order to observe it mixing with the bulk liquid. These tests were recorded using motion picture coverage at 64 frames/sec. Typical results from the visualization study are shown in Fig. 2. This photographic sequence shows the high temperature liquid (dyed) in the stratified layer mixing with the cold bulk liquid for a test where the liquid was sloshing in the stable nonplanar mode. Only the first 4.5 sec of the test are shown since the destratification was essentially complete at this time and very little mixing took place over the remainder of the 240 sec test period.

Visual observations of the sloshing tests together with a frame-by-frame analysis of the motion pictures revealed that the stable nonplanar mode set up a strong rotational motion in the sloshing portion of the liquid. As time progressed, the viscous forces caused by the rotating sloshing masses transferred angular momentum to the lower portions of the liquid. Since the rotation was greatest at the free surface and decreased with increasing depth, a vertical pressure gradient was established along the tank wall; that is, the centripetal forces exerted on the fluid particles near the wall were greater near the free surface than near the tank bottom. This pressure gradient caused a flow of hot liquid from the stratified layer down the tank walls. This downward flow of hot liquid in turn caused a flow of cold liquid up the center of the tank to maintain continuity. These flows down the walls and up the center of the tank together formed a rotating toroidal flow pattern which was responsible for the high degree of mixing observed in this mode. The unstable nonplanar mode did not appear to cause as much mixing as the stable nonplanar mode. This is expected since the constantly changing direction of rotation did not allow the establishment of the rotating toroidal flow pattern discussed above. The stable planar mode provided only vertical motions of the liquid and, hence, caused minimal amounts of mixing.

References

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