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MIXING-INDUCED FLUID DESTRATIFICATION AND ULLAGE CONDENSATION

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In many applications, on-orbit storage and transfer of cryogenics will require forced mixing to control tank pressure without direct venting to space. During a no-vent transfer or during operation of a thermodynamic vent system in a cryogen storage tank, pressure control is achieved by circulating cool liquid to the liquid-vapor interface to condense some of the ullage vapor.

To measure the pressure and temperature response rates in mixing-induced condensation, researchers at Boeing developed an experiment that uses Freon 11 to simulate the two-phase behavior of a cryogen. This is a normal-gravity experiment designed to provide thermal data to correlate with previous dye-mixing experiments. A thin layer at the liquid surface is heated to raise the tank pressure, and then a jet mixer is turned on to circulate the liquid, cool the surface, and reduce the pressure. Many nozzle configurations and flow rates are being used. Tank pressure and the temperature profiles in the ullage and the liquid are measured.

Initial data from this ground test are shown correlated with normal-gravity and drop-tower dye-mixing data. Pressure collapse times are comparable to the dye-mixing times, whereas the times needed for complete thermal mixing are much longer than the dye-mixing times. Results and experience from this experiment are being applied to the design of a microgravity experiment to be flown on the Space Shuttle.

INTRODUCTION

On-orbit storage and transfer of cryogenic fluids will be an increasingly important part of space operations. For example, the projected growth version of NASA's Space Station will require the storage and resupply of liquid nitrogen, oxygen, and hydrogen. The Orbital Transfer Vehicle will use liquid oxygen and liquid hydrogen propellants and will be refueled from storage tanks at the Space Station. Satellites and space platforms will be resupplied by tankers operating from the Space Station and orbiting fuel depots.

An understanding of mixing phenomena in low gravity is essential to the successful design of cryogenic storage and resupply systems. Forced mixing will be required during a no-vent fill to enhance condensation and reduce fill times. It may also be required in cryogen storage tanks to chill hot spots in the liquid, thereby reducing the vapor pressure.

Low-G Mixing

- On-orbit cryogen storage
 - Tank pressure depends on temperature of warmest liquid in tank
 - Compact heat exchanger/thermal vent system requires active mixing to distribute cooling evenly throughout tank
- On-orbit transfer of storable and cryogenic liquids
 - For many low-g applications, no-vent fill is attractive option
 - Active mixing in receiver tank collapses ullage, leading to much shorter transfer times

Figure 1

PREVIOUS TESTING

There have been several investigations of mixing phenomena over the past twenty years. These tests have been performed in normal-gravity and low-gravity conditions with a variety of fluids. Several different mixing criteria have been used, including dye observation, thermal measurements, and acid-base indicators. The following is a summary of these mixing tests.

- . Lewis Research Center (LeRC) - J. C. Aydelott (ref. 1)
 - . Drop tower and 1-g data
 - . Visual observation of dye mixing in water
- . Martin Marietta - S. M. Dominick (ref. 2)
 - . 1-g tests
 - . Freon 113 and Freon 11
 - . Thermal data
- . General Dynamics Fort Worth - L. J. Poth (ref. 3)
 - . 1-g tests
 - . Temperature measurements in water
 - . Open and closed test tanks
- . General Dynamics Convair - M. A. Wollen (ref. 4)
 - . 1-g tests
 - . Dye disappearance tests in water (neutralization of acid with base)
- . Lockheed - B. R. Bullard (ref. 5)
 - . 1-g tests
 - . Condensation rates in closed tanks
 - . Freon 12, Methane, LN₂, LH₂

CURRENT RESEARCH AT BOEING

Data on low-gravity fluid mixing are limited. The drop-tower data obtained by Aydelott are the most useful, although the scale of his experiments was necessarily small and the dispersion of dye in water needs to be related to thermal mixing in cryogenics. Ground-test data on thermal mixing help in determining that relationship. However, buoyancy effects that are absent in low gravity are readily apparent in these data.

We have begun a two-part effort at the Boeing Aerospace Company to obtain additional data. The first part is a series of normal-gravity experiments using Freon 11 and a jet mixer. The second part is to be a Get-Away Special experiment on the Space Shuttle. Our principal objectives are to obtain design data for low-gravity fluid management systems and to help verify the NASA-ECLIPSE fluid motion and thermodynamics simulation code.

Cryogen Tank Pressure Control in Low Gravity

Boeing Aerospace Company IR&D

- Objective:
- Determine mixing requirements for efficient pressure control in cryogen tanks
 - Verify BAC and LeRC models of fluid destratification and ullage condensation
- Rationale:
- Pressure control during thermodynamic vent system operation or during tank fill may require active mixing
 - Low-gravity mixing data is lacking
- Approach:
- Test a variety of mixer configurations on the ground, using saturated Freon to simulate cryogenics, to provide detailed thermal profiles for validation of numerical model
 - Perform low-gravity tests in STS Get-Away Special payload carrier

Figure 2

GROUND TEST OBJECTIVES

The objectives for our laboratory experiment are summarized in Figure 3 below. Our emphasis is on establishing a correlation between thermal-mixing and dye-mixing data. When computer models are verified with data from space experiments, it may be possible to extrapolate the more readily obtained normal-gravity data to low-gravity conditions.

Test Objectives

- Correlate thermal data to dye mixing data in order to extend usefulness of previous results
- Verify computer models of mixing, heat transfer, condensation
- Acquire data to support design of GAS mixing experiment
- Increase knowledge of mixing, condensation, and heat transfer in l-g

Figure 3

TEST APPARATUS AND PROCEDURE

The test apparatus is a closed cylindrical tank with glass sides and stainless steel domes. The tank is insulated to minimize heat conduction through the tank walls. Within the tank is liquid and vapor Freon 11. This fluid was chosen because its boiling point at one atmosphere vapor pressure differs only slightly from room temperature. The tank is instrumented with thermocouples and pressure transducers. The mixer jet consists of a moveable tube that is fed by a positive displacement pump. The pump draws Freon from the bottom of the tank and circulates it through a heat exchanger to the mixer jet. In future experiments, the heat exchanger will be used to simulate a thermodynamic vent system heat exchanger. A circular heater coil is suspended just beneath the liquid surface.

Pressure Control Ground Experiment

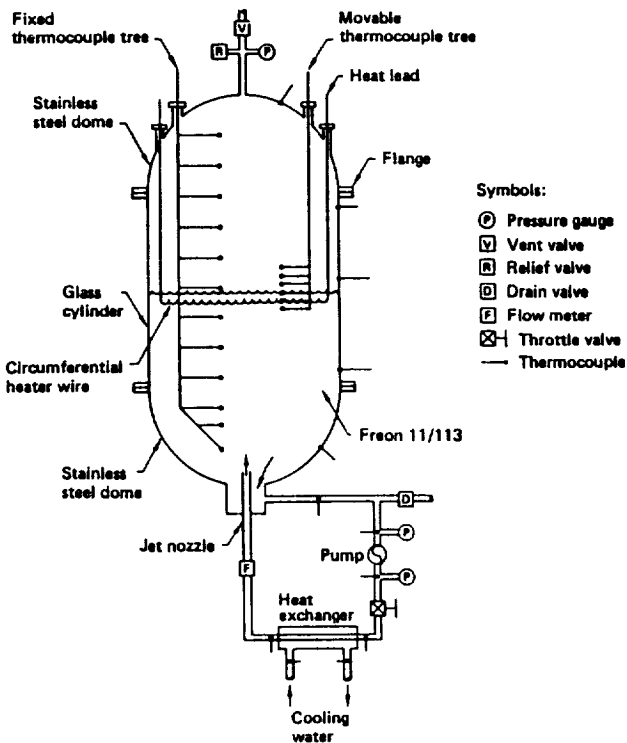
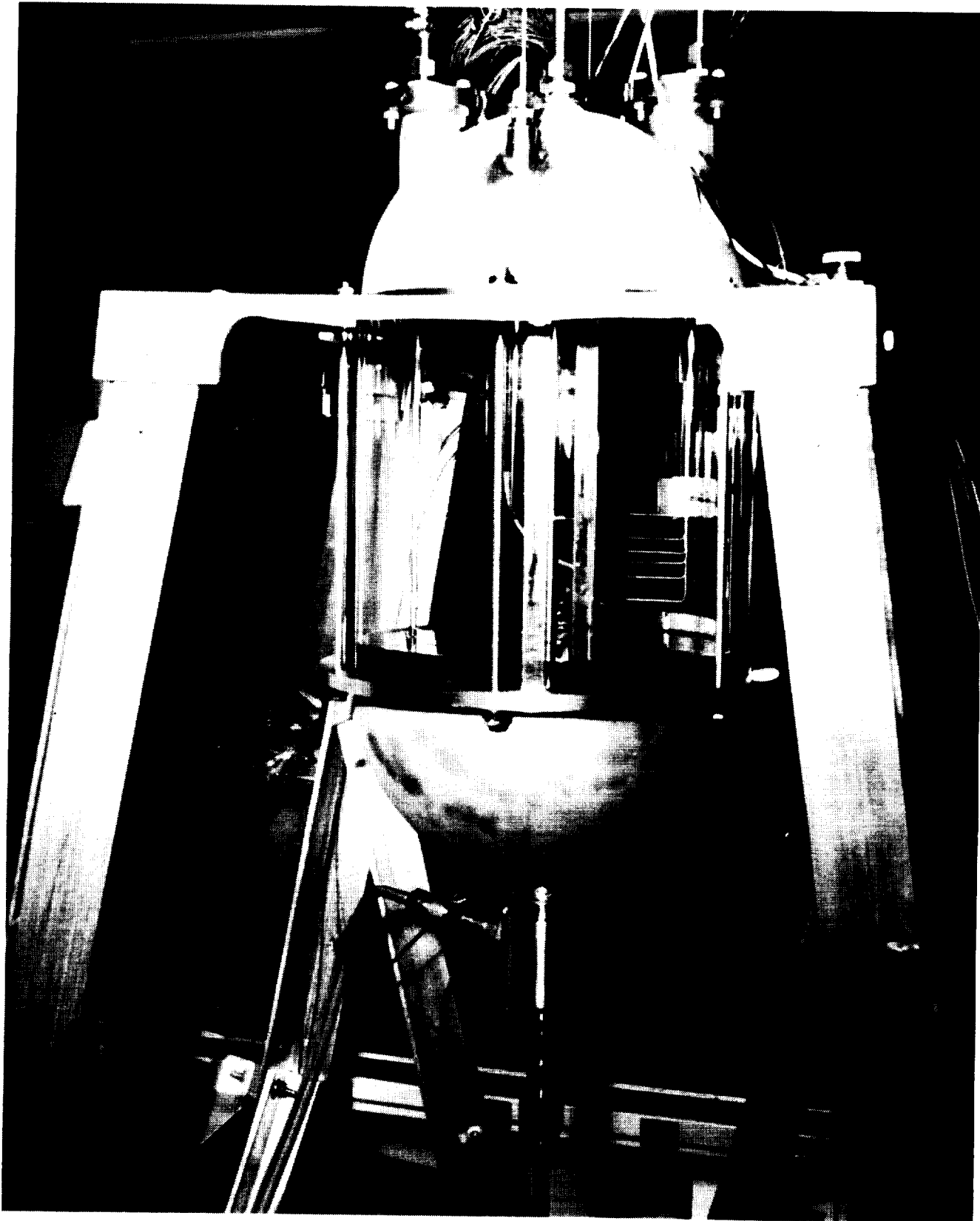


Figure 4

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The test was designed to be flexible, allowing us to gain as much information as possible from one apparatus. In the initial series of tests, however, we maintained many of the design variables constant. So that the results would more directly relate to changes in the mixer configurations, we kept the ullage fraction, heating rate, and total integrated heat input constant. The nozzle diameter, the flow rate, and the distance between the nozzle and the surface were varied.

The measured quantities are the ullage pressure and the vertical temperature profile in the tank. From this data, mixing times were calculated. The reference temperatures and pressures for these calculations were those that would correspond to the fluid in complete equilibrium (after heat has been added). The condensation rates were computed from the temperature and pressure data.

Test Parameters and Outputs

- **Controlled variables**
 - Heat input
 - Flow rate
 - Nozzle height (distance from nozzle to liquid-vapor interface)
 - Nozzle diameter
 - Ullage volume

- **Measured variables**
 - Ullage pressure
 - Temperatures in liquid and ullage

- **Calculated quantities**
 - Mixing time
 - Condensation rate

Figure 6

PROCEDURE

The Freon 11 is stratified by heating it just below the liquid surface. As the surface temperature rises, evaporation from the surface raises the pressure of the vapor. When a predetermined amount of energy has been added by the heater, the heater is shut off and the jet mixer turned on. The jet mixes the fluid, which lowers the surface temperature and causes the vapor to condense.

Test Sequence

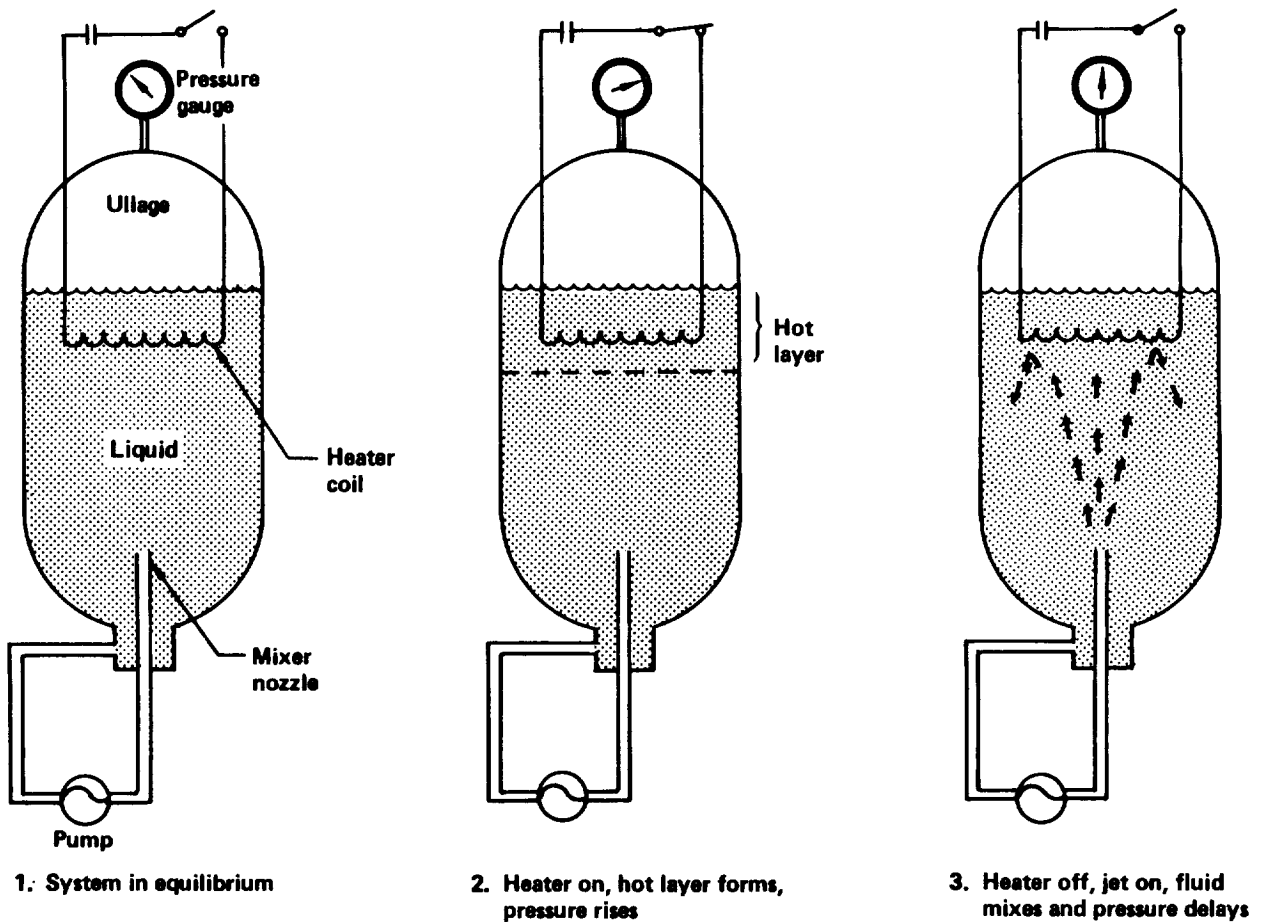


Figure 7

RESULTS

Figure 8 shows a comparison of two experimental test runs and computer simulations of those runs. Both test cases had the nozzle near the bottom of the tank, but one was at a relatively low flow rate (.2 GPM), while the other was at a relatively high flow rate. The time is nondimensional with respect to the jet velocity and diameter at the nozzle and with respect to the tank diameter. The vertical axis is the ratio of the ullage pressure to the pressure corresponding to complete mixing.

While the two computer simulations and the high-flow-rate test case nearly collapse onto a single line, the low-flow-rate test data is markedly different. This is due to buoyancy effects, which were not included in the computer simulations and which become more apparent at low flow rates. At low-flow-rates, the jet does not have sufficient energy to overcome the buoyancy of the warm layer, so the surface temperature and hence the ullage pressure remain fairly constant. Notice that when the jet does break through the hot layer at time = 16, the pressure collapse rate is very nearly the same as in the other cases.

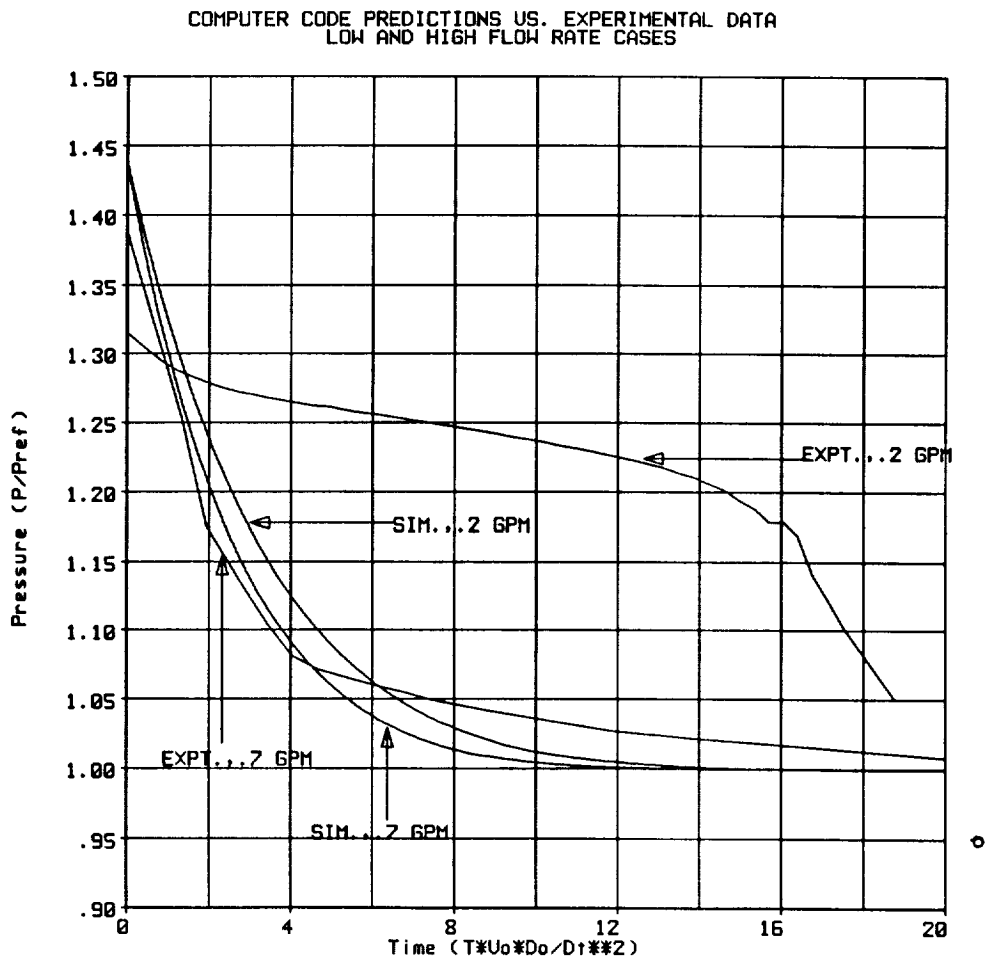


Figure 8

Figure 9 shows the correlation of the test data with a buoyancy parameter. The mixing time (surface temperature within 5% of the bulk temperature) is proportional to the Grashoff number, which is a measure of the strength of the buoyancy forces, and inversely proportional to the square of the jet Reynolds's number, which is related to the energy of the mixer jet. For a low-gravity case, this parameter is small, and the mixing times would be shorter than our 1-g data indicates.

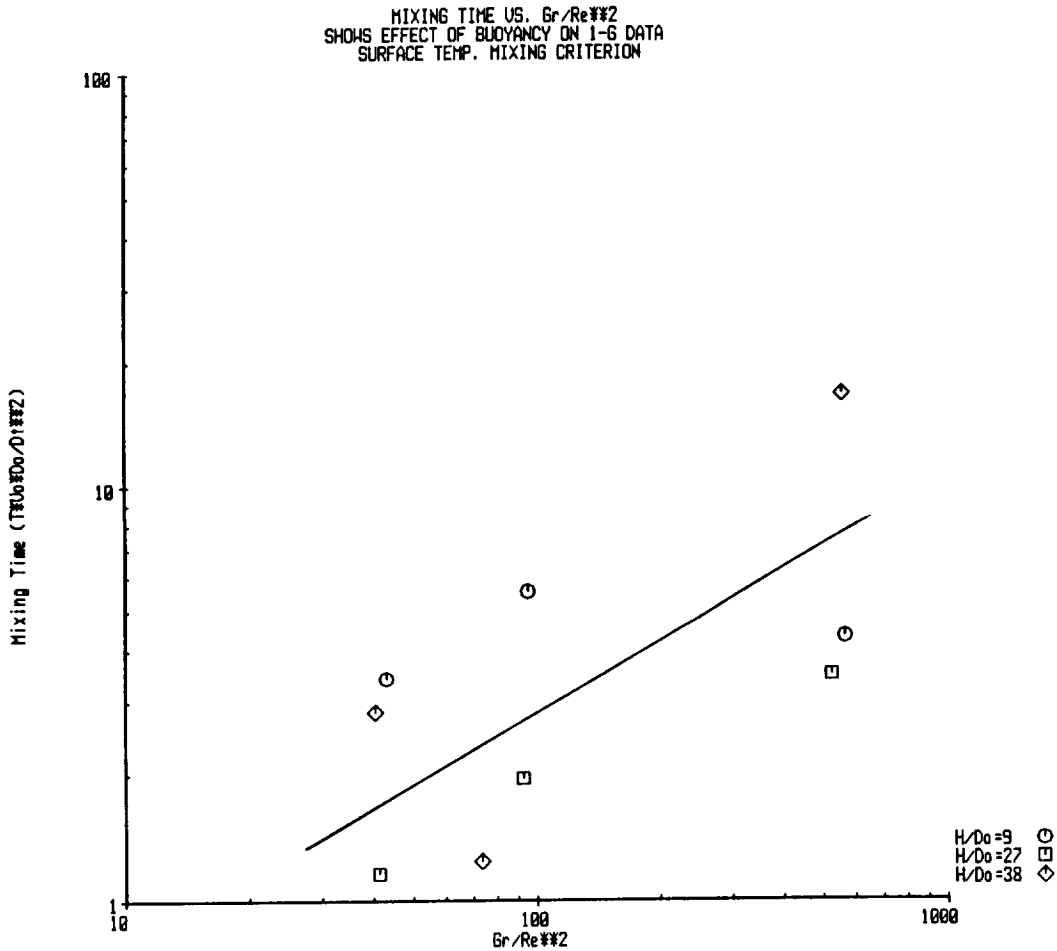


Figure 9

The thermal data in Figure 11 were derived using another definition of mixing time. In this case, it is defined as the time for all liquid temperatures to be within 1% of each other. This is a measure of the time required for complete mixing of the entire fluid. These data indicate mixing times an order of magnitude larger than those obtained in the dye and acid-base mixing experiments.

A possible explanation for the discrepancy is as follows. When the nozzle is close to the surface, circulation patterns may be established that prevent the liquid near the bottom of the tank from mixing with the hot top layer. When the nozzle is near the bottom of the tank ($H/D = 27$), and the jet Reynold's number is large, the mixing times begin to approach the LeRC and Centaur results. With a high enough flow rate, it is conceivable that buoyancy effects would be overwhelmed, and the thermal data would correlate with the dye dispersion data, which is not affected by buoyancy.

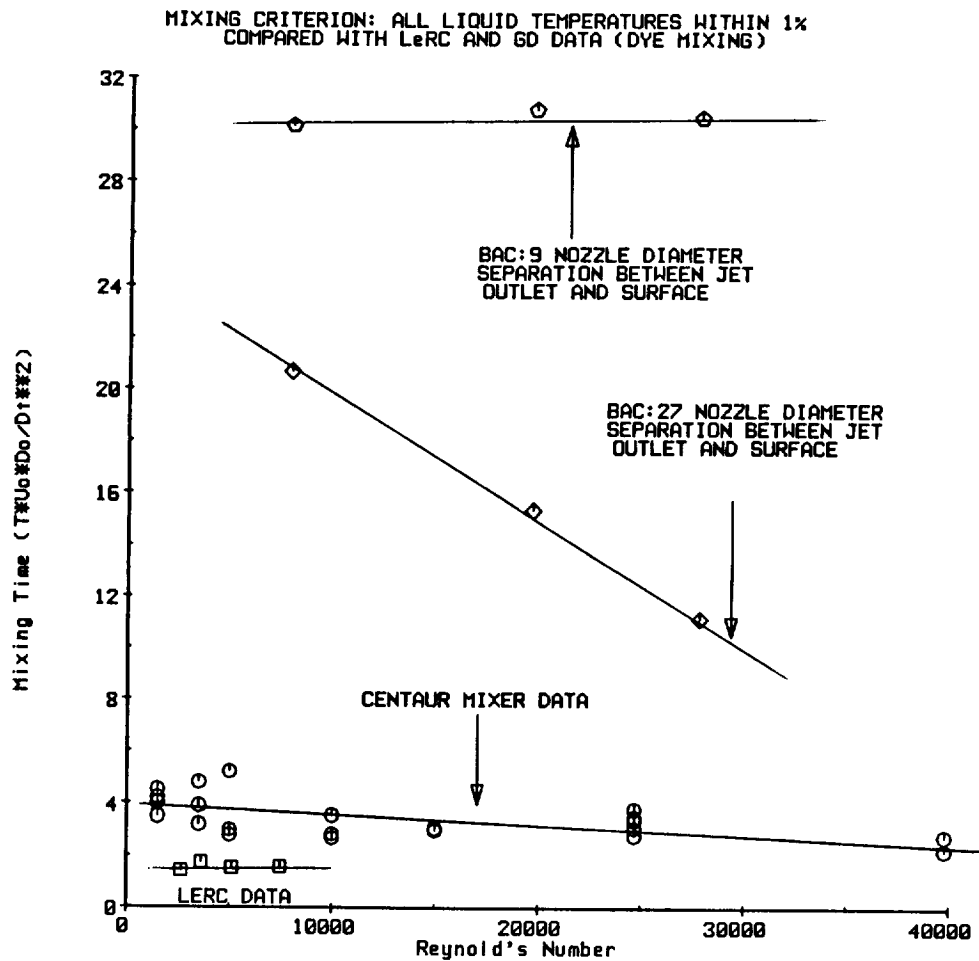


Figure 11

Figure 12 is another comparison between the thermal data and the data based on visual observation of dyed liquid. Both injected dye on top of the water and then plotted the downward motion of the dye as a function of time after the mixer was turned on. Z_{hot} is the height of the bottom of the dye layer, and Z_{noz} is the height of the jet nozzle (both referenced to the bottom of the tank).

For the thermal experiments, we defined Z_{hot} and Z_{noz} in a similar fashion, but with Z_{hot} as the height of the bottom of the stratified layer of fluid. When the layer was displaced downward by the mixer, its progress was revealed by the sudden increase in temperature at successive thermocouples.

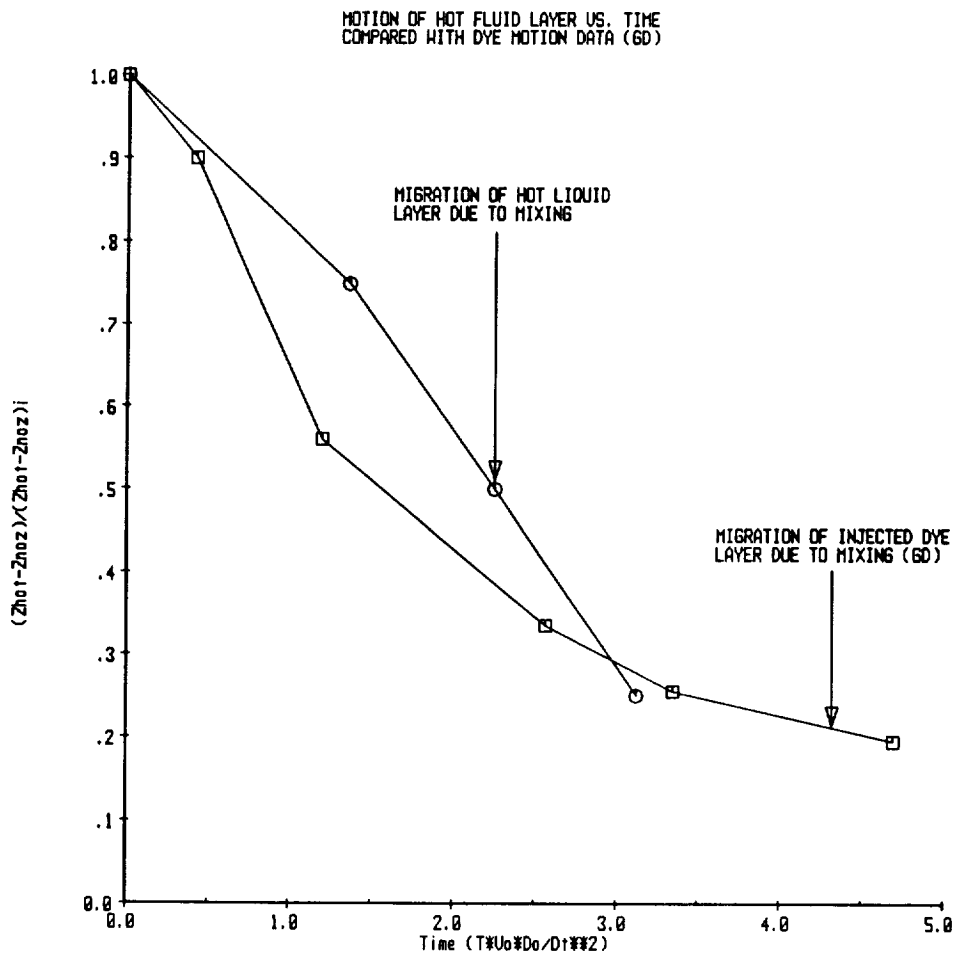


Figure 12

PLANNED SPACE EXPERIMENT

The space experiment depicted in Figure 13 would operate similarly to the previously described ground experiment. The fluid will be Freon 113 rather than Freon 11, which would be chemically incompatible with the plexiglass tank. Electric heaters will locally heat the Freon to raise the tank pressure at the beginning of each test. A jet mixer will cool the heated zone while a digital data system records the tank temperature profile and the pressure collapse rate. A screened-channel liquid acquisition device will ensure that the pump draws liquid-free vapor.

The design for this experiment is nearly complete. Funding is being pursued, and our intent is to fly the experiment on the Space Shuttle as a Get-Away Special payload in two to three years.

Get-Away Special Space Experiment

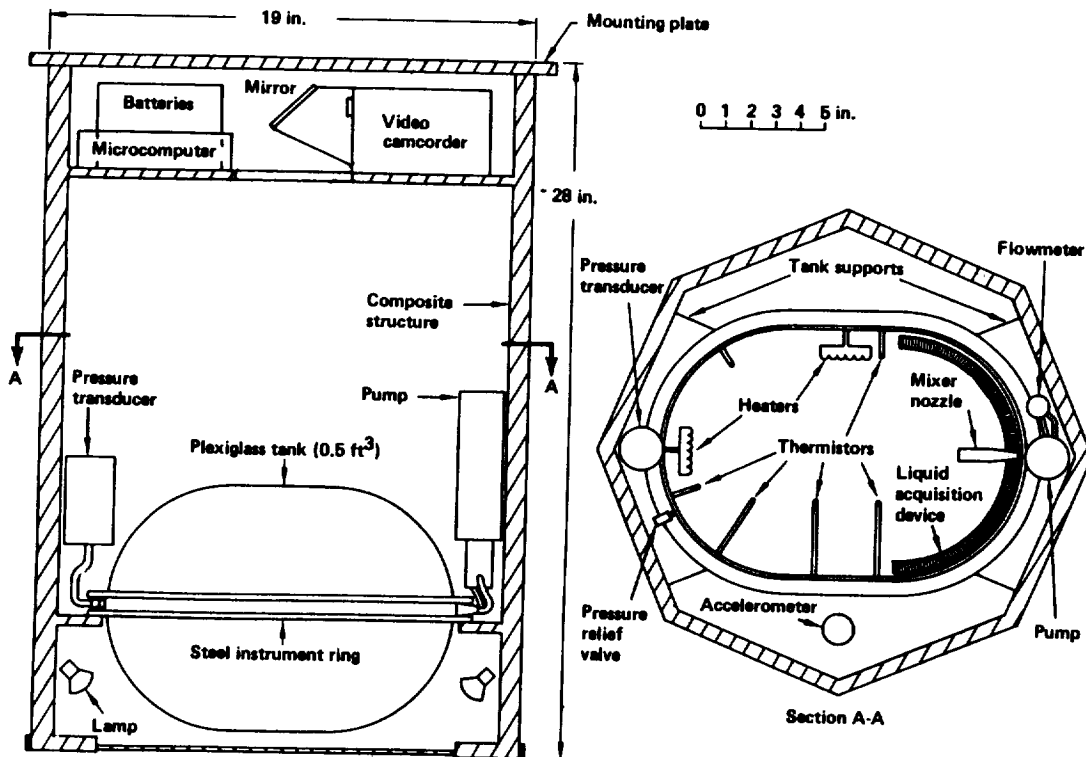


Figure 13

CONCLUSIONS

A few conclusions can be drawn from these initial results. Most notably, nondimensional pressure collapse times in our thermal mixing experiment are similar to the nondimensional mixing times obtained in 1-g and low-g dye mixing experiments. The time required to achieve complete thermal equilibrium in the liquid, however, is an order of magnitude longer.

A simple computer program shows good agreement with experiment data when buoyancy effects are small (that is, when the mixer flow rates are high).

With low flow rates, however, buoyancy effects significantly reduce the thermal mixing rates. Experiments in microgravity are necessary to obtain data spanning the full range of potential mixer operating conditions.

Conclusions

- Simple computer program can predict pressure collapse rates well, except when buoyancy is dominant (high Gr/Re^2)
- Dimensionless mixing times based on thermal equilibrium throughout liquid are much larger than those from previous studies based on the dispersion of dyes
- Dimensionless mixing times based on surface temperature (destratification) are similar to dye and acid-base data
- In 1-g tests, strong buoyancy effect makes measured mixing times conservative (higher) compared to expected low-g values
- Although 1-g data is useful for determining general trends, low-g thermal data is still necessary

Figure 14

References

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