Flow Visualization of Thermal Stratification with Localized Heat Sources

THOMAS M. LOVRICH*
McDonnell Douglas Astronautics Co., Huntington Beach, Calif.
AND
SIDNEY H. SCHWARTZ†
West Virginia University, Morgantown, W.Va.
AND
LEROY A. HOLMES‡
Modesto Junior College, Modesto, Calif.

A flow visualization and thermal stratification study with localized heat sources was performed using Freon 113 and water individually as the test liquids. The experiments were conducted at atmospheric pressure with the liquids in the subcooled state. Flow visualization results were obtained with a schlieren-photographic system using a horizontal cylinder. A vertical cylinder was used for measuring the temperature profiles. The flow patterns and the thermocline development were strongly linked to the heater location. Three internal baffle arrangements were tried in the horizontal cylinder but they did not affect the thermocline location.

I. Introduction

CONSIDERABLE effort has been extended towards solving the problem of thermal stratification of liquids heated in closed and open containers, encompassing both analytical and experimental techniques. However, much of this work has been focused on the uniform heating of the container walls, often associated with the heating of cryogenic propellant storage tanks for space vehicles. With the advent of multilayer insulation blankets, the magnitude of the heat flux associated with the propellant tanks has been reduced to very low levels. However, where attachment points and other irregularities in those propellant tank geometries prevent uniform insulation coverage, local heat flux values at these irregularities can greatly exceed the values through the uninterrupted portion of the insulation blanket. As a result, a large portion of this study qualitatively examines the flow phenomena associated with the heating of a contained liquid from a single line source of heat. The flow visualization portion of this work was accomplished with a schlieren system. Some experiments were also conducted in a second container of liquid where a heat flux was imposed over a relatively large fraction of the container's surface. These experiments were performed to determine whether or not there were any thermal-fluid dynamic similarities in the liquid when comparing the heating from a small localized heat source and uniform heating over a segment of the surface of the container.

A related problem was studied earlier by Schwartz and Holmes[1] who investigated the flow patterns and the resulting temperature profiles for both uniform and local heat sources. In that investigation, a schlieren system was also used to observe the convection currents both in the fluid and on the walls. Thermocouples were used for recording the temperature distributions for uniform and local heating. However, the apparatus was limited in its ability to vary the location and the range of local heat flux values. In addition, Anderson and Kolar,[2] Schwind and Vliet,[3] and Vliet and Brogan[4] performed similar flow visualization studies of liquids in heated containers. In this study, the smaller tank was capable of arbitrarily varying the orientation of a line heat source as well as achieving heat flux values high enough to allow boiling with water and with Freon 113 in a subcooled state.

Most of the experimental program was a simple flow visualization study of the fluid motion resulting from a line source of heat. The orientation of the heat source was varied, as well as the heat flux and liquid level. In addition, several baffle geometries were studied to determine whether or not they had a significant effect on the convection currents. Water and Freon 113 were used individually in the program in both the highly subcooled and nearly saturated states. Results indicated that all of the heated liquid remained above the line source of heat for all but the most vigorous boiling conditions in a saturated liquid.

When this phase of the experiment was completed, an upright cylindrical container was heated over the upper portion of the tank walls and the centerline vertical liquid temperature profile was measured with a thermocouple rake. The results of these experiments corroborated the line heat source study, where again the heated liquid always remained above the bottom edge of the heated part of the wall.

II. Apparatus

A. Flow Visualization Container

The container designed for use in a schlieren system was a short steel cylinder with glass windows on each end. It was $7\frac{1}{2}$ in. in diameter and 3 in. wide and was mounted on a frame with provisions for rotation so that the heater orientation could be changed. The windows were oriented vertically and perpendicular to the light rays in the schlieren system. A copper coil heat exchanger wrapped around the outside surface of the cylinder provided the capability of adding to or removing heat from the container fluid.

Received February 5, 1974; revision received April 23, 1974. This work was performed under McDonnell Douglas Astronautics Company Low Gravity Fluid Mechanics and Heat Transfer 1971–72 IRAD Program.

Index categories: LV/M Fuel and Propellant Systems (Including Storage and Transfer); Fuels and Propellants, Properties of; Thermal Modeling and Experimental Thermal Simulation.

* Engineer Scientist/Specialist, Heat and Mass Transfer Branch, Aero/Thermodynamics and Nuclear Effects. Member AIAA.

† Associate Professor, Mechanical Engineering Department; also consultant to McDonnell Douglas Astronautics Company.

‡ Instructor, Department of Engineering.

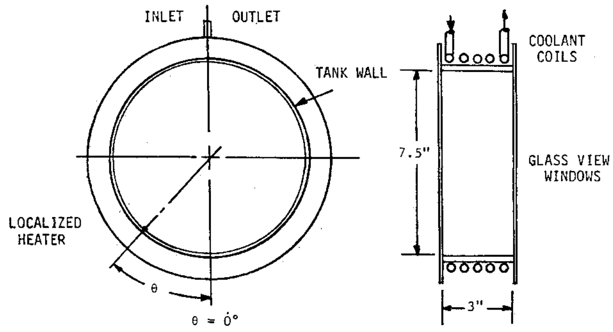

Fig. 1 Schematic of small cylindrical test tank.

Figure 1 is a schematic and Fig. 2 is a photograph of the container. The heater was a nichrome wire 2-in. long and 0.01 in. in diameter. The wire was imbedded in a fiberglass block so that only one-half of its surface was exposed. Electrodes spot welded to each end of the wire were taken through the block to a power source. In addition, two copper-constantan thermocouples making contact with the unexposed surface of the wire were led through the block out of the container (Fig. 2). Thus, the wire, serving as a reistance heater, was essentially a line source of heat with thermocouples attached to record the source temperature.

The schlieren system was built by the Unertl Optical Co. and included two 12-in. mirrors. The photographs were taken with a camera which was part of the schlieren system.

B. Upright Cylindrical Tank

A larger cylindrical tank with spherical ends was used for this phase of the study. The cylinder was 18 in. in diameter and 36-in. long, and was in the upright position. Electrical heating blankets covered the entire tank wall surface and were sectioned into five separate regions, each with its own electrical leads. This was done to allow heating of any portion of the tank separately or together. A polyurethane foam insulation, approximately 8-in. thick, covered the entire tank.

A thermocouple rake ran along the axis of the tank from top to bottom with 37 copper-constantan thermocouples attached to it. These thermocouples were referenced to a 150°F thermocouple reference oven. The output of the thermocouples went to a Hewlett-Packard Model 2411A guarded data amplifier and then to a Hewlett-Packard 2401C integrating digital voltmeter which had a resolution of 1 μv. Figure 3 is a schematic of the tank and the sectioned heater blankets.

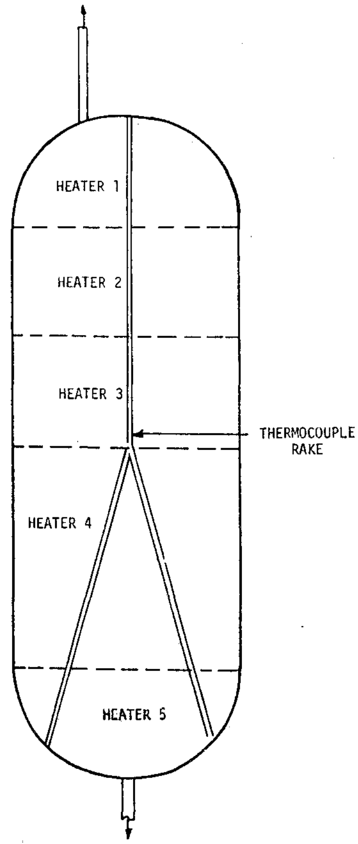

Fig. 3 Schematic of heater locations for vertical cylinder.

III. Experimental results

A. Introduction

The schlieren system showed that the heated liquid remained at and above the level of the line heat source. For all cases, it was observed that the convective flow of the heated liquid was upwards away from the heat source and that the colder liquid which replaced it came from the level of the heater or from above it. Thermometer measurements in the vertical direction showed a gradually decreasing liquid temperature from the

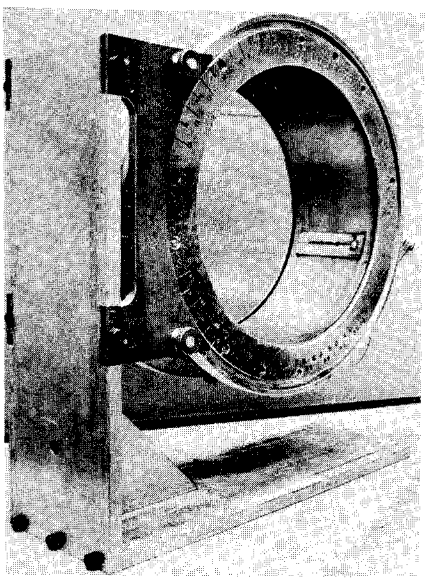

Fig. 2 Small cylindrical test tank.

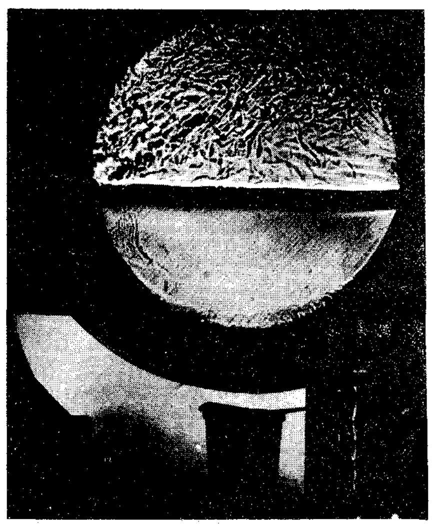

Fig. 4 Line heat source at 90°, Freon 113.

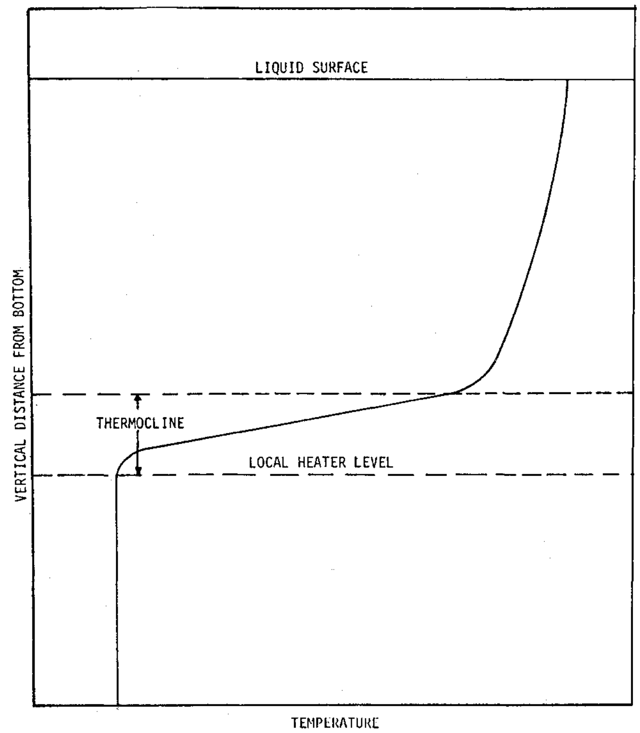

Fig. 5 Typical temperature profile with line heat source.

interface downward and a sharp temperature drop near the heater level. Figure 4, taken with the schlieren system, shows the heated liquid region above the heater (located at 90° from the bottom) as well as the thin dark band at the heater level characterizing the thermocline where the sharp drop in the liquid temperature occurs. The general form of the measured temperature profile is illustrated in Fig. 5 although a parametric study of the temperature profile was not made with this tank. This steep temperature gradient is similar to the thermocline found in large natural bodies of water.

Both Freon 113 and water were used individually in this study over a range of heat flux values from 500 to 100,000 Btu/hr-ft^2 in highly subcooled and near thermally saturated liquid conditions. Experiments were conducted at various heater orientations and liquid levels. In addition, several baffle arrangements were tried in the small horizontal cylindrical test tank to attempt to significantly divert the convective flow pattern, but all variations resulted in the same basic finding, the heated liquid remained in the area above and down to and including the plane of the heater source when the liquid was subcooled.

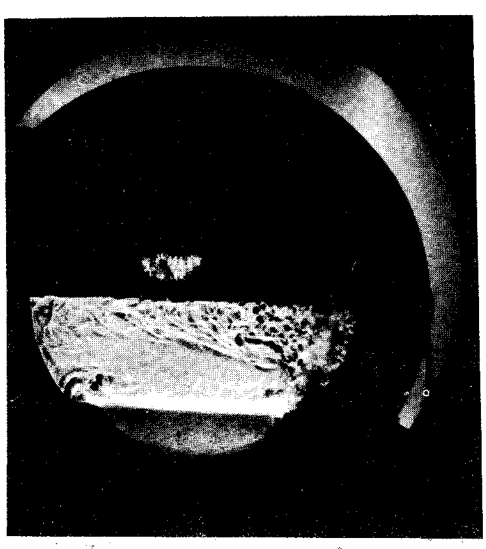

Fig. 6 Line heat source at 45° water, container half full.

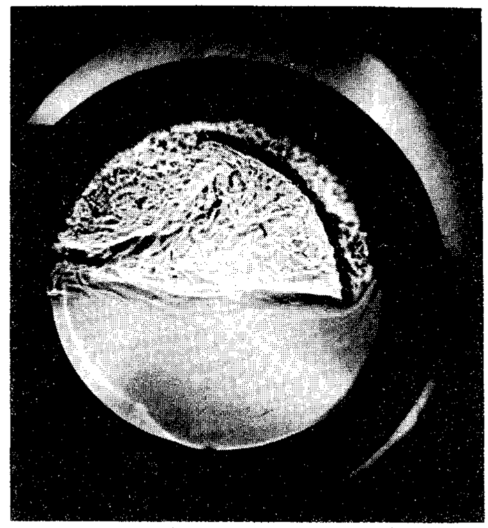

Fig. 7 Line heat source at 90° with baffle near heater, Freon 113.

The upright tank experiments were conducted with Freon 113 initially at the saturated state. The tank was then closed off (sealed) and allowed to pressurize as a portion of the cylinder was heated. The thermocouple measurements in the liquid showed that the heated liquid remained above the heated portion of the tank, with a temperature rise in the liquid extending down to the bottom edge of the heater. The following discussion will consider all of the above cases in detail.

B. Flow Visualization Container

1) Effects of heater location

The heater orientation was varied from 45° to 135° above the small horizontal test tank bottom. This was done both with water and with Freon 113 at a number of heat flux values and liquid temperatures. In all cases the thermocline formed at the heater level and the temperature drop across this narrow band exceeded 30°F in some cases. Figure 4 illustrates the thermocline in Freon 113 with the heater at 90°. Figure 6 illustrates the thermocline with the tank half full of water. This photograph typifies the partially filled case and shows that the thermocline still remains at the heater level which, in this case, is located at 45° from the bottom. It is of interest to note that the flow patterns for both liquids appeared to be the same, although a clear definition of the thermocline occurred sooner with the Freon since its specific heat is less than that of water.

2) Baffle arrangements

Several baffle arrangements were tried in the small horizontal cylindrical test tank to determine whether or not the flow pattern which always began at the heater level and remained above this level without baffles could be induced to flow around the tank to a level below the heater. Such a flow could not be produced with any of the arrangements that were tried. Figure 7 shows the case where a curved baffle was placed parallel to the wall at a distance of approximately 1 in. It was found that the basic flow patterns were quite similar to those without the baffle. This held true regardless of whether the baffle was shifted such that it was entirely above the heater plane or partly below it. The same baffle was then placed on the opposite side of the heater as shown in Fig. 8. As can be seen, the gradient again formed at the plane of the heater although a small secondary flow did develop at the bottom of the baffle.

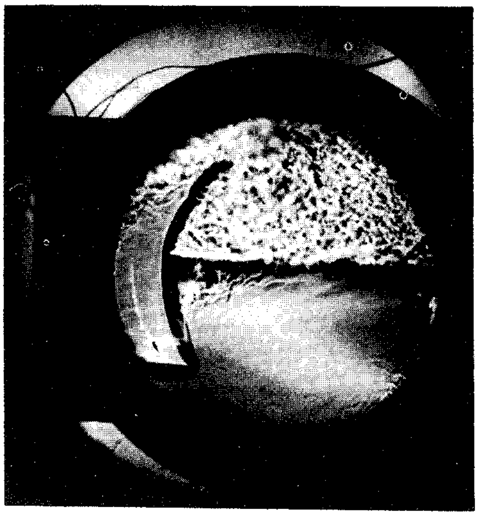

Fig. 8 Line heat source at 90° with baffle across from heater, Freon 113.

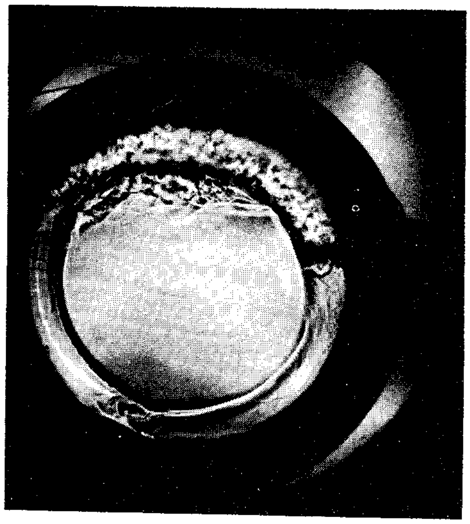

Fig. 9 Line heat source at 90° with circular baffle, Freon 113.

A third baffle configuration forming a complete loop was tried which was intended to see if the heated fluid would remain close to the walls and circle the container. However, it was found that the fluid traveled part way around the tank and then doubled back in the narrow channel and moved towards the heater, again staying above the heater level. Figure 9 illustrates this condition.

3) Discussion of results

The following discussion is intended to interpret the results within the context of the limited number of experiments performed. Several sketches of the flow patterns are presented which are not obvious from the schlieren photographs but were observed by following small particles within the fluid made visible by the schlieren system.

Figure 10a shows the convection currents without the baffle and Fig. 10b with the baffle on the heater side. In both cases the flow deflected as it approached the thermocline on the wall opposite the heater, separating into essentially two streams as it neared the thermocline. One stream deflected upward and away at nearly 45° from the thermocline, gradually fanning out and then flowing back towards the thermocline and feeding into it. The other stream, appearing to be smaller, made a smooth turn and traveled parallel to the thermocline moving toward the heater and merging with the entrained fluid from the stream above it. Qualitatively, it is suggested that this flow results from the inability of the heated fluid to penetrate the thermocline because it was less dense than the stationary cold fluid below the thermocline. This argument is consistent with the baffle experiments on the opposite wall. Figure 10c shows the streamlines for this case and, as can be seen, the hot fluid could not penetrate the space between the opposite wall and the baffle but completely reversed its direction of flow, traveling back towards the wire heater. It is felt that this illustrates that the hot moving fluid cannot pass through the colder fluid between the baffle and the wall and hence, in effect, follows the path of least resistance by reversing direction and moving through the less dense liquid. Again, this flow feeds back toward the heater along the thermocline. A secondary flow did form near the baffle as a small amount of fluid pushed through the baffle space along the wall and rose along the outside of the baffle feeding into the thermocline. This secondary flow may have been caused by cooling of the liquid moving near the relatively cold wall.

A final set of experiments were conducted with a baffle which went entirely around the tank as shown in Fig. 10d. The baffle was shifted off-center closer to the wall with the heater to see whether or not the hot rising fluid could be induced to completely circle the tank. However, as shown in Fig. 10d this did not occur but instead the rising stream again turned around and fed back to the heater through the same narrow gap through which the rising fluid moved.

These results strongly indicate that a thermocline will occur at the plane which encompasses a localized heater regardless of the internal tank geometry. However, it should be noted that this generalization may break down for a fluid which is heated near the saturation temperature. This statement is based on additional experiments with nearly saturated water at the heat flux values which produce vigorous boiling. Here it was found that as the water temperature approached 190°F the thermocline began to expand below the heater level with time until it finally reached the bottom of the tank, at which point the flow then began to circulate completely around the tank resulting in a radial stratification profile with a decreasing temperature towards the center. It is felt that the reason for this result is that once the fluid temperature approached the saturation temperature, the opposing buoyancy force diminished (i.e., the buoyancy forces tended toward zero). Hence, the combination of vigorous boiling and the relatively high velocity of the rising fluid finally results in sufficient momentum for the fluid so that the limited negative buoyancy cannot repel it and hence a stable thermocline

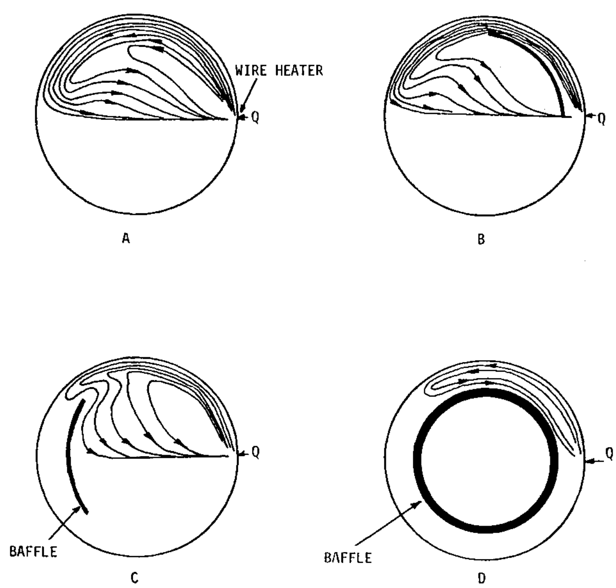

Fig. 10 Streamlines with line heat source.

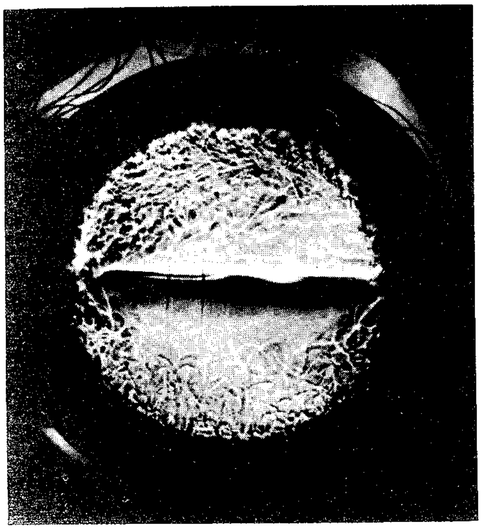

Fig. 11 Line heat source at 90° plus wall heating, water.

cannot occur. Finally, an experiment was conducted to determine whether or not the thermocline would form with uniform wall heating or cooling in addition to the localized heating. Here, the heat exchanger coils were wrapped around the container walls and used both to heat and cool the walls while the wire heater was operating. In each case the thermocline did form and Fig. 11 shows the case with wall heating. However, no conclusions can be drawn as to whether or not there is a lower limit for the ratio of q_{wire}/q_{wall} where a thermocline forms.

C. Cylindrical Tank

Two tests were conducted with this apparatus. One was run with the container half full with the Freon initially at 117.5°F.

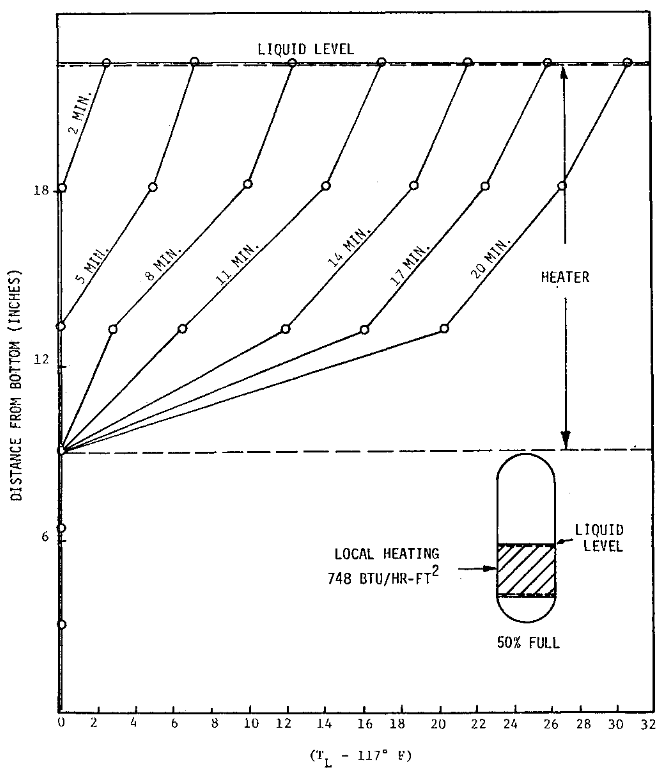

Fig. 12 Thermal stratification in vertical cylinder with local heating, Freon 113. Container 50% full.

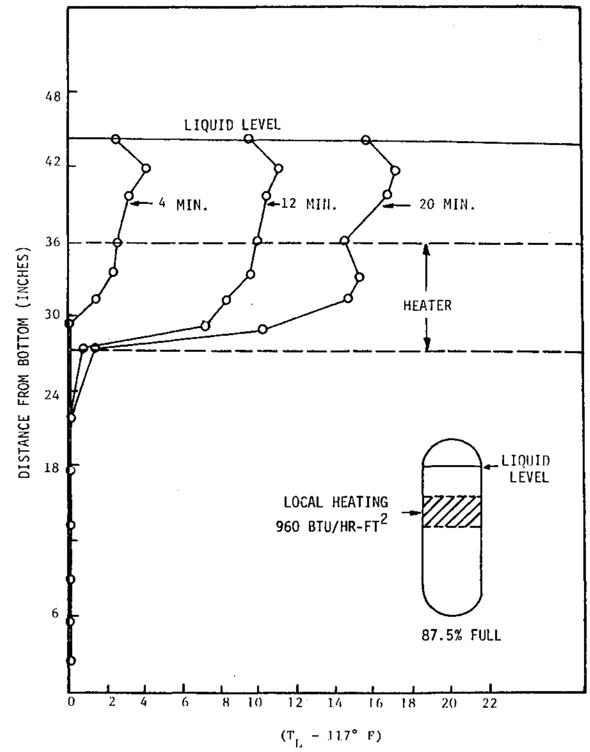

Fig. 13 Thermal stratification in vertical cylinder with local heating, Freon 113. Container 87.5% full.

Heater 4 (Fig. 3) was used at 748 Btu/hr-ft^2 which resulted in the heating of the cylindrical portion of the tank up to the liquid interface with the tank 50% full. Figure 12 shows the temperature profiles at various times during the experiment, illustrating that the liquid below the heated walls remained at the initial temperature throughout the entire period of heating. It should also be noted that there is a relatively sharp temperature drop-off just above the lowest edge of the heater surface. This is somewhat similar to the thermocline found in the local line heat source experiments. The second experiment was conducted with the tank 87.5% full. Heater 3 (Fig. 3) was used here which is 9-in. wide and was located below the surface of the liquid. Figure 13 shows that the temperature profile is quite similar to that found previously. Thus, in both cases, with wall heating of only a portion of the liquid in the container, a sharp temperature drop occurred in the liquid at or near the bottom level of the heaters. The explanation for this phenomenon is most likely the same as that for the local heat source.

IV. Conclusions

The basic conclusion from this study was that a steep temperature gradient or thermocline formed at the level of the line heat source and at the bottom level of the vertical tank heaters. Thus, the heated fluid remained above the level of the heater with the temperature below this level remaining essentially unchanged during the heating period. These experiments were conducted both in a short cylindrical container oriented with the axis of the cylinder perpendicular to the gravity vector and a long cylinder with spherically capped ends in the upright position. The following specific observations were made.

1) The phenomenon occurred both with Freon 113 and with water for all heat flux values in the nonboiling region for the short cylinder as well as in the vertically oriented, long, self-pressurized cylinder starting with saturated Freon 113 and with a wall heat flux.

2) The thermocline appeared for heat flux values in the subcooled boiling regime, but disappeared as the bulk liquid temperature approached saturation with vigorous boiling from

the heater when the small flow visualization horizontal cylindrical tank was used.

3) The thermocline formed with a baffle placed adjacent to the line heat source, directly across from it, and with a baffle which was concentric with the small horizontal cylindrical tank having approximately one inch clearance between it and the wall.

4) The thermocline also formed when uniform wall heating was added to the line heat source heating in the small horizontal cylinder.

5) The thermocline formed with the container at several liquid fill levels.

In summary, these preliminary experiments have shown the likelihood of obtaining a thermocline at the level of a localized heat source both with and without container baffles. Although a parametric study of the liquid temperature-heat flux values was not made, indications were that this thermocline could be destroyed at liquid temperatures near the saturation temperature (without self pressurization) of the liquid with vigorous boiling heat flux values. In addition, the heating of a fraction of long cylindrical tank surface resulted in a similar sharp temperature gradient at the bottom edge of the heated portion of the tank, where self-pressurization resulted in a subcooled liquid below the surface of the liquid.

References

[1] Schwartz, S. H. and Holmes, L. A., "Flow Visualization and Thermal Stratification of Water in a Horizontal Cylinder and a Sphere," Douglas Paper 4131, Oct. 1966, McDonnell Douglas Astronautics Co., Huntington Beach, Calif.

[2] Anderson, B. H. and Kolar, M. J., "Experimental Investigation of the Behavior of a Confined Fluid Subjected to Non-Uniform Source and Wall Heating," TND-2079, Nov. 1963, NASA.

[3] Schwind, R. G. and Vliet, G. C. "Flow Visualization and Interpretive Studies of Natural Convection Phenomenon." *Proceedings of the 1964 Heat Transfer and Fluid Mechanics Institute,* Berkeley, Calif. June 1964.

[4] Vliet, G. C. and Brogan, J. J., "Experimental Investigation of the Effects of Baffles on Natural Convection Flow and on Stratification," presented at the Conference on Propellant Tank Pressurization and Stratification, Jan. 1965, Marshall Space Flight Center, Huntsville, Ala.

SEPTEMBER 1974 J. SPACECRAFT VOL. 11, NO. 9

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure or vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

SERT II Hollow Cathode Multiple Restarts in Space

WILLIAM R. KERSLAKE* AND ROBERT C. FINKE†
NASA Lewis Research Center, Cleveland, Ohio

Introduction

THE SERT II (Space Electric Rocket Test II) spacecraft was reactivated in May 1973 to demonstrate extended thruster cathode restarts in space. The original (1967) design goals of the SERT II thruster[1,2] did not call for the numerous restarts (~2000) required by many currently proposed electric thruster missions. Although the SERT II spacecraft was not programed to perform automatic thruster restarts, it was possible to manually command the thruster cathodes to light and then to turn them off. Constraints of ground base tracking stations schedules and spacecraft orbits limited restarting attempts to 30–40 per month.

In September 1973, a spacecraft ground-control room, necessary to continue restart testing of the SERT II thruster cathodes, was withdrawn from use by this program. The loss of this room prevented additional restarts from being attempted. This program, however, could not have been continued indefinitely due to a gradual loss of solar power. The initial sun-synchronous, polar orbit of the SERT II spacecraft had precessed such that a now oblique sun angle gave only marginal power to operate the cathodes. Wobbling of the spacecraft was already causing a critical time-varying available power in Sept. 1973 and submarginal power was predicted within a few months.

Thus, the test period available to this program was May through Aug. 1973, and 112 restarts of each cathode (two main and two neutralizer cathodes) were made during this test period. These tests showed no deterioration of cathode heaters, nor has any change been required in starting voltages and currents. In addition, restart after long periods (490 days) of space storage has been demonstrated.

This Note presents a summary of the cathode starting data obtained from the SERT II spacecraft during the above four month period and compares it with cathode starting data for the entire mission. For a more complete description of this program, test procedures, and cathode operational history, the reader is referredto the conference preprint[3] and earlier SERT II references.[4,5]

Flight Thruster Cathode Starting

Figure 1 chronologically shows the number of cathode restarts, storage time between, and total hours of operation. The cathodes were ground tested before launch in Dec. 1969, endurance tested in space during 1970, restarted numerous times through early 1972, and then stored (490 days) until May 1973. Restarts during the endurance phase were necessary because lunar eclipses of the sun caused temporary loss of solar cell power on board the spacecraft.

Figure 2 shows the time to start each cathode of flight thruster 1. (The data for thruster 2 are, in general, similar and are presented in Ref. 3.) All of the last 112 restarts are plotted along with representative starting times back to the original ground tests. The time between starts can be determined with the help of Fig. 1. The time to start is a parameter which indicates cathode starting reliability because each restart

Received October 29, 1973; presented as Paper 73-1136 at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nev., October 31–November 2, 1973; revision received May 17, 1974.

Index category: Electric and Advanced Space Propulsion.

* Technical Consultant, Electric Propulsion Branch. Associate Fellow AIAA.

† Chief, Electric Propulsion Branch.