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Orbital Heat Pipe Experiment

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ORBITAL HEAT PIPE EXPERIMENT

by

J. E. Deverall, E. W. Salmi, and R. J. Knapp

with an Appendix by G. F. Erickson

ABSTRACT

The "Grover Heat Pipe" is a self-contained, thermal conductance device which has no moving parts, utilizes the heat being transferred for its operation, has a thermal conductance higher than any known material, and conducts heat with essentially no temperature difference. Heat is transferred by means of mass flow of a fluid utilizing the latent heat of a two-phase system.

The object of this experiment was to demonstrate that a heat pipe will function properly in a zero gravity field.

A water heat pipe, 12-in. long and 3/4-in. o.d., was operated in an earth orbit and its performance monitored by telemetry at several tracking stations during 14 revolutions. The satellite module in which the heat pipe was mounted was supplied by the Lockheed Missiles and Space Company, Sunnyvale, California, under an Air Force Contract and launched into orbit from Cape Kennedy by an Atlas-Agena launch vehicle.

Results indicate that there was no degradation of heat pipe performance in a zero gravity field as compared to the performance in laboratory tests.

I. Introduction

In the present day space program there is an increasing number of problems involving the transfer of heat. One such problem is the thermal control of electronic components and batteries which must operate between certain temperature limits to function efficiently. Another problem is the transfer of heat with a minimum temperature drop, as to a radiation-type, heat-rejection system where heat rejection at the highest possible temperature is desired to reduce radiator area. In many cases, dimensional and weight limitations in satellites make it difficult to provide large enough conduction paths to meet the heat transfer requirements regardless of the material's thermal conductivity.

The "Grover Heat Pipe,"¹ which has a fraction of the weight of a solid conductor and orders of

magnitude greater heat transfer characteristics, appears to have great potential for the solution of heat transfer problems in satellites.² By replacing the heat flow mechanism of conduction with a fluid flow system utilizing latent heat of vaporization, heat transfer devices can be constructed which have several hundred times the thermal conductance per unit weight of any solid conductor. By proper choice of fluids, heat pipes can be constructed for operating temperatures from below 0° to over 2000°C.³

A heat pipe is a sealed container in which a fluid continuously evaporates and condenses thereby establishing a two-phase system and an essentially constant temperature throughout the length of the container.⁴ Heat addition into the evaporator section of the heat pipe is distributed throughout the

condenser section by flow and condensation of vapor. The cycle is completed with the return of the condensate to the evaporator by capillary action through a wick structure lining the container wall. The driving force for the vapor is created by a higher vapor pressure in the evaporator section which is caused by the slightly higher liquid temperature at the heat input area, see Fig. 1.

In a two-phase system, the vapor pressure is a function of temperature. If a heat pipe is operated at a pressure that corresponds to a section of

Fig. 1. Grover Heat Pipe

the vapor pressure curve having a steep slope, the pressure difference necessary for the vapor driving force produces a very small temperature drop along the length of the pipe, see Fig. 2. Therefore, except for extremely high input heat fluxes, the pipe operation is essentially isothermal.

In a gravitational field, the vertical wicking height is a function of the liquid density; however, in free space, capillary action should be independent of heat pipe orientation.

The object of this experiment was to demonstrate that a heat pipe will operate normally in the absence of gravitational forces. The necessary evidence to substantiate this fact was considered to be the isothermal operation of a heat pipe while in an earth orbit.

II. Heat Pipe Assembly

The heat pipe, developed and constructed by the Los Alamos Scientific Laboratory, consisted of a No. 347 stainless steel tube lined its full length with a stainless steel wick structure. The

Fig. 2. Vapor Pressure Curve

tube was 12-in. long and 3/4-in. o.d. with a 0.035-in. wall. The wick structure was formed by rolling 100 mesh screen into a hollow cylinder of three layers and inserting it into the tube. A steel ball was then pushed through the hollow screen cylinder to press it against the wall. To ensure continued contact of the wick with the wall under operating conditions, a stainless steel helical spring was pulled through the full length of the wick structure under tension and then released to provide additional radial pressure. Closure of the heat pipe was made by welding a machined end-cap into each end. An annealed nickel capillary tube welded into one end-cap provided a means for sealing the fluid under vacuum after loading. All parts of the heat pipe were carefully cleaned and outgassed according to the procedure outlined in The Appendix.

Heat was supplied to the heat pipe by a 10-watt electric heater operating at 25 volts. The heater element was 30-gauge nichrome wire wound in a 1/16-in.-diam helix. Insulation was provided by ceramic beads threaded on the helix, and the complete winding was then inserted into a length of 3/16-in. o.d. copper tubing. The copper tubing was wound around the heat pipe and soldered in place with pure tin to provide a good mechanical and thermal bond. Leads to the heater were formed by inserting a 24-gauge copper wire into the end of the nichrome helix, silver-soldering them together, and setting the solder joint in epoxy cement.

After the heat pipe was assembled and helium leak-tested, it was loaded with the proper amount of distilled water. The pipe was first evacuated for several hours until the pressure was 10^{-7} mm of Hg. The vacuum line was then sealed off, and the valve to a pipette containing distilled water was opened. When the desired amount of water was metered into the heat pipe, the pipette valve was closed. The vacuum line was again opened to the heat pipe, and the pipe was flamed slightly to remove any gases which might have been in the water. A seal valve on the heat pipe was then closed, and the pipe was disconnected from the vacuum system. Several thermocouples were then attached along the length of the pipe, and the pipe was operated to check for excess liquid. With the heater end of the pipe slightly elevated and the thermocouples facing down-

ward, excess liquid was indicated by a temperature gradient at the end of the pipe. Excess liquid was removed by quickly opening and closing the seal valve, when the heat pipe was operating above 100°C, until the temperature gradient disappeared. The valve was then removed from the heat pipe by cutting the annealed nickel capillary tube with a pinch-off tool which sealed the tube. Protection of the pinch seal was provided by a 3/8-in.-diam sleeve placed over the capillary tube and filled with an epoxy cement. By weighing, it was determined that the proper amount of water needed to saturate the wick, with no excess, was 7.5 grams.

The heat pipe was supported by two brackets clamped to its ends. The brackets were attached to an aluminum baseplate by six countersunk machine screws to form the complete assembly, see Fig. 3. The heater leads were supported by clamping them to the bracket at the heater end.

III. Instrumentation

Resistance thermometers were used to measure the temperatures along the axis of the heat pipe. The thermometers were coupled to a voltage divider network which provided a 0- to 5-volt output as a function of thermometer temperature. To provide more sensitivity over a wider temperature range, two sets of thermometers with different temperature spans were used for the 0- to 5-volt output range. The low temperature band (thermometers 1 to 6) was set for -7° to 80°C, and the high temperature band (thermometers 7 to 12), for 70° to 140°C. The same type of thermometer was used for each band, with the temperature span being fixed by resistors in the voltage divider network. Six thermometers for each band were spaced along the axis of the heat pipe with one low band and one high band thermometer at each temperature station as shown in Fig. 4. The thermometers were fastened to the pipe with epoxy cement with the leads attached to connectors mounted on a baseplate rail as shown in Fig. 5. A thermometer was also attached at each end of the baseplate to indicate baseplate temperature. As heat pipe operation is essentially isothermal, an end-to-end calibration of the thermometers was made by operating the heat pipe, in vacuum, at several different temperatures and plotting telemetry output voltage vs temperature as measured by iron-

SECTION A-A (ROTATED 90° CCW)

Fig. 4. Thermometer Spacing

Fig. 5. Heat Pipe Assembly

constantan thermocouples attached at each end of the heat pipe. Calibration curves for thermometers No. 1 and No. 7 are shown in Fig. 6. The accuracy of the end-to-end system was estimated to be $\pm 2^{\circ}\text{C}$.

IV. Vibration and Shock Tests

A qualifying model was subjected to vibration and shock tests according to the specifications applying to the section of the Agena in which the heat pipe was mounted. This model was a duplicate of the flight model, complete with resistance ther-

mometers, connectors, and connector mounting rail. All phases of the vibration and shock tests were conducted with test forces applied through the normal mounting points of the baseplate. These tests subjected the model to the vibration and shock that the flight model would experience during launch, including the Atlas boost phase and the Agena boost phase. Tests were conducted along each of the three mutually perpendicular axes.

Before and after the vibration and shock tests, the resistances of each thermometer and the

Fig. 6. Thermometer Calibration Curves

heater were measured. The heat pipe was then fitted with six thermocouples along its axis, and the pipe was operated at temperature to establish that it was leak-tight by operating isothermally. Any in-leakage of air creates a large temperature gradient along the length of a heat pipe.

The results of the vibration and shock tests indicated that sinusoidal and random vibrations and shock conditions experienced during the Atlas-Agena launch would not affect the operational characteristics or the structural integrity of the heat pipe assembly.

V. Preflight Thermal Tests

As the experiment was not programmed to turn on until approximately three hours after launch, there was a possibility that the satellite module would become very cold and freeze the water in the heat pipe. To determine the start-up characteristics of the pipe when all the water was frozen, a start-up test was conducted with a qualifying model

at -60°C . Seven thermocouples were attached along the length of the heat pipe with six on the condenser section and one in the heater area to measure the temperature gradient. With the pipe temperature below -60°C , 10 watts were applied to the heater, and temperatures were recorded at various time intervals. A plot of the resulting temperature gradients is shown in Fig. 7. Even when all the water was frozen, heat was transferred the full length of the pipe by vapor flow formed by sublimation. As the wick contained ice, however, there was no fluid return to the evaporator to replace the sublimed working fluid. This was apparent from the rapid rise in heater temperature until temperature stations 1, 2, and 3 rose above the ice melting point. Water was then wicked into the heater area, and the temperature rise was arrested. This water was rapidly evaporated, and the vapor formed flowed to the end of the condenser where it again became ice. As a considerable portion of the total fluid was still ice, there was insufficient liquid flow into the heater area to prevent it from drying

Fig. 7. Sub-Zero Start-Up Test

out, and the temperature of this section again rose rapidly to 104°C. When the full length of the pipe was above the melting point, water could again wick into the heater area, and the temperature dropped suddenly to 44°C. The heat pipe then started to operate normally and gradually became isothermal, indicating that it would start up with all the fluid frozen.

These curves also show that the heat pipe came up to temperature with a temperature front moving along the pipe creating a transient temperature gradient. This effect was due to a trace of non-condensable gas in the pipe which was gradually compressed by the vapor toward the condenser end as the temperature increased. At equilibrium temperature, the vapor pressure was high enough to compress the gas into a very small volume so that no temperature gradient was apparent. When heat pipes are loaded it is difficult to completely evacuate all noncondensable gases from the system, so this frontal type of startup has often been observed in the laboratory with heat pipes using liquid metals and various other fluids.

Another test was conducted to determine the equilibrium condition the heat pipe would attain if all the water leaked out while the 10-watt input to the heater was maintained. The water was drained out of one of the qualifying models, and it was heated in a vacuum chamber to equilibrium temperature with an input of 10 watts. The temperature distribution along the pipe, shown in Fig. 8, was due to thermal conduction through the heat pipe structure. The highest temperature attained was 200°C at the heater which was not considered excessive from the standpoint of safety. A curve is also shown for normal heat pipe operation, for comparison, which demonstrates that normal heat pipe operation can be determined by measuring the temperature gradient.

VI. Satellite Module

The satellite module consisted of two batteries, transmitter, voltage control oscillator, commutator, dc/dc converter, timer, antenna, and associated circuitry. The configuration of the components is shown in Fig. 9 with the two batteries in the foreground, the transmitter in the center, and the heat pipe and thermometer circuitry at the far end.

Fig. 8. Heat Pipe Test without Water

The two batteries supplied power for the heat pipe heater and all the module components. The total capacity was 3500 watt-hours which was expected to provide an experiment life of 1.3 days.

The transmitter had an output of 10 watts and transmitted on a frequency of 228 megacycles. Signals from each of the data outputs were switched to the telemetry system by means of a 60-point, 1/2-rps, electronic commutator. Every other point on the commutator was used for a data point, with a calibrated 2.5-volt output on the intermediate points to simplify the interpretation of the wave train. A typical cycle from a wave train is shown in Fig. 10, demonstrating the type of wave form and the information received by telemetry.

The complete satellite module was 40-in. long, 16-in. wide and 7-in. high. It was attached to the aft rack of the Agena, as shown in Fig. 11, and remained with the Agena during the entire flight. There was no electrical interface with the Agena or primary payload as the heat pipe experiment was completely self-contained, including its own trans-

Fig. 9. Satellite Module (Photo: Lockheed)

mitting system and frequency. Figure 12 shows the complete Agena vehicle, with the heat pipe module attached, being hoisted up into position for mating with the Atlas.

VII. Flight Program

The heat pipe module was launched April, 5, 1967, at 10:23 P.M. on an Atlas-Agena vehicle as a piggy-back experiment with the NASA satellite, ATS-A. Upon separation of the Agena from the Atlas, a separation switch started a timer which turned on the heat pipe experiment 11,760 seconds later. By this time, the ATS-A satellite had been placed in its orbit, and the Agena had been deboosted by retro-rockets to establish an orbit which would not coincide with that of the primary payload. The Agena then became completely inoperative with no stabilization or maneuvering ability and contained only the heat pipe experiment. This procedure was followed so that there would be no possibility of any interference of the heat pipe experiment with the telemetry commands necessary to place the ATS-A satellite in its orbit. The resulting orbit for the Agena was elliptical, with an apogee of 6000 nautical miles and a perigee of 85 nautical miles, and had a period of 220 minutes.

Telemetry data were received at five different tracking stations: Indian Ocean, Guam, Hawaii, Vandenberg, and East Boston, whenever their facilities were available during a pass. Thirty-five

Fig. 10. Sample Wave Train

Fig. 11. Satellite Module on Agena Aft Rack (Photo: NASA)

Fig. 12. Hoisting Agena to Top of Atlas
(Photo: NASA)

data acquisitions were obtained during 14 orbits before battery voltage dropped too low for signal transmission. All information received was recorded on magnetic tapes which were sent to Lockheed Missiles and Space Company (LMSC), Sunnyvale, California, for data reduction and wave-train printout.

VIII. Results

The experiment started within range of the tracking station at Hawaii, and data were taken continuously for 22 minutes before the satellite passed over the horizon. The heat pipe temperature was slightly above 0°C when the heater turned on, and a normal start-up operation was recorded as shown in Fig. 13. An equilibrium curve is also plotted from data taken by the Indian Ocean station 1.5 hours after startup. These curves show that the heat pipe came up to temperature with a frontal-type startup similar to that observed in the laboratory test and that, at equilibrium, the heat pipe was isothermal within the estimated temperature measurement error of $\pm 2^{\circ}\text{C}$. Temperatures measured by the low band thermometers were used for the

Fig. 13. Flight Start-up Data

start-up data. At equilibrium conditions, voltage outputs from the low band thermometers were well above the 5-volt upper limit and were considered out of band, see Fig. 10, so the high band measurements were used. The isothermal operation was verified by all stations during subsequent passes for the duration of the experiment. The average heat pipe temperature varied between 80° and 95°C as exposure of the module to the sun varied. This depended upon orbital position and changing attitude of the Agena which was no longer stabilized. The heat pipe continued to operate isothermally, however, and ambient temperature changes affected only its operating temperature level. A data sample from each of the tracking stations, for various time intervals during the flight, is shown in Fig. 14. These plots of temperature vs length show that the heat pipe operated isothermally during the life of the experiment and that data from all stations were in good agreement.

IX. Conclusions

The results of this experiment indicate that the absence of gravitational forces does not affect the performance of a heat pipe. The start-up and equilibrium operation were similar to laboratory tests in a gravity field. As closed-cycle operation of a heat pipe is provided by capillary action in the wick structure and depends only upon the surface tension of the fluid, these were the expected results. There is no evidence to indicate that heat pipes using other fluids would not function in a similar manner. With this fact established, the heat pipe principle can be used in various ways to solve many of the numerous heat transfer problems in space systems.

Fig. 14. Data Samples from Each Tracking Station

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APPENDIX

CLEANING PROCEDURE USED WITH THE 300 SERIES STAINLESS STEEL SCREEN, SPRING, AND TUBE PARTS FOR ATLAS-AGENA WATER HEAT PIPES

G. F. Erickson

The screen used in these heat pipes is first cut to size and then cleaned and passivated by the following procedure.

1. Rinse twice in cp trichlorethylene.
2. Shake for 5 minutes in the ultrasonic cleaner in fresh cp trichlorethylene.
3. Rinse twice more in cp trichlorethylene.
4. Shake again for 5 minutes in the ultrasonic cleaner in fresh cp trichlorethylene.
5. Rinse twice more in cp trichlorethylene and drain well.
6. Rinse three times in 190 proof ethyl alcohol with short shakes.
7. Rinse three times in distilled water with short shakes.
8. Clean in a mixture of 800 cc warm distilled water, 200 cc 190 proof ethyl alcohol, 50 cc 30% hydrogen peroxide, and 100 grams sodium hydroxide pellets! This mixture will boil and foam and develop a yellow color upon contact with the stainless steel screen. After foam subsides somewhat, shake 5 minutes in the ultrasonic cleaner.
9. Rinse three times in distilled water with short shakes in the ultrasonic cleaner.
10. Repeat step 8 with fresh solution.
11. Rinse three times more in distilled water with short shakes in the ultrasonic cleaner.
12. Clean in 10:1 dilution of hydrochloric acid in distilled water with a short shake in the ultrasonic cleaner. Do not allow material to stand in this solution, but rinse promptly.
13. Rinse five times in distilled water with short shakes in the ultrasonic cleaner.
14. Wash in 800 cc distilled water and 400 cc concentrated nitric acid heated to approximately 70°C. Shake 5 minutes in the ultrasonic cleaner. This step is to passivate the stainless steel.
15. Rinse five times in distilled water with short shakes in the ultrasonic cleaner and dry in a clean dust- and grease-free environment. Do not touch cleaned parts except with clean tools or white gloves.
16. After inserting screen and holding spring into tube, reclean complete assembly using steps 1-3, 6-8, and 13-15; then insert cleaned end-caps prior to welding. Vacuum outgas the complete heat pipe on a Vac-ion system in a tube furnace at 400°C overnight. Do not exceed 500°C or the stainless steel may be re-activated and react again with hot water to release hydrogen gas.

The pipes are then ready to be filled with high purity distilled water and tipped off. Do not weld, braze, or otherwise heat the tip-off cold weld. Protect the cold weld with a metal sleeve and epoxy or silastic potting compound. High temperatures on the tip-off will generate internal gas by the metal-water reaction.