NASA TECHNICAL MEMORANDUM

NASA TM X-62,290

NASA TM X-62,290

VARIABLE CONDUCTANCE HEAT PIPES FROM THE LABORATORY TO SPACE

J. P. Kirkpatrick

Ames Research Center
Moffett Field, Calif. 94035

(NASA-TM-X-62290) VARIABLE CONDUCTANCE HEAT PIPES FROM THE LABORATORY TO SPACE (NASA) 16 p HC $3.00 CSCL 20M

N73-28917

Unclas
G3/33 10410

July 1973

16 pp.

J.P.K.

VARIABLE CONDUCTANCE HEAT PIPES FROM THE LABORATORY TO SPACE

J. P. Kirkpatrick
Ames Research Center, NASA
Moffett Field, California, 94035 USA

ABSTRACT

Heat pipes have been developed which can be used as (1) a variable conductance link between a heat source and sink which provides temperature stability; (2) a feedback control mechanism that acts to directly maintain the source at a constant temperature; (3) or as a thermal diode that allows heat to be transferred in one direction only. To establish flight level confidence in these basic control techniques, the Ames Heat Pipe Experiment (AHPE) was launched in August 1972 and the Advanced Thermal Control Flight Experiment (ATFE) is scheduled for launch in May 1973. The major efforts of the technology development, initial flight results of the AHPE, and ground test data of the ATFE are discussed.

INTRODUCTION

Heat pipes allow the thermal designer to regulate the transfer of thermal energy in ways that previously did not exist, at least not in such a convenient form. For example, by the use of various techniques, a heat pipe can be used as (1) a variable conductance link between a heat source and sink, which provides temperature stability; (2) a feedback control mechanism that acts to directly maintain the source at a constant temperature; (3) or as a thermal diode that allows heat to be transferred in one direction only. Many spacecraft applications require close temperature control while internal power dissipations and/or external heat fluxes vary widely, thus making variable conductance capabilities desirable, if not necessary. In 1969, the National Aeronautics and Space Administration (NASA) initiated a technology development program for such techniques at Ames Research Center. This paper discusses the major development efforts of this on-going program.

As progress was made in the laboratory, it became evident that flight level confidence must also be established. Consequently, the Ames Heat Pipe Experiment was developed for the Orbiting Astronomical Observatory (OAO-C), which was placed in earth orbit in August 1972; the Advanced Thermal Control Flight Experiment was developed and qualified for flight aboard the Applications Technology Satellite (ATS-F), which is scheduled for launch in May 1974. This paper reflects the experience gained in moving variable conductance techniques from the laboratory to space. It also presents initial flight results for the Ames Heat Pipe Experiment and ground test data for the Advanced Thermal Control Flight Experiment.

TECHNOLOGY DEVELOPMENT

Several researchers, both in the United States and Europe, have contributed significantly to the development of basic control mechanisms. However, only the efforts of the Ames Research Center and its contractors (Table I) are summarized below.

Variable Conductance

Initial efforts were directed toward identifying various techniques by which a heat pipe could be made to operate as a variable conductance link between a heat source and sink. Three promising techniques were identified and carried to various stages of development: gas control, excess liquid control, and vapor control.

The use of noncondensing gas to vary the effective condenser length was investigated in the greatest detail. Basically, the technique involves the addition of a fixed quantity of gas which does not condense at the lowest temperatures experienced by the heat pipe. The gas, since it cannot be wicked back to the evaporator region, is swept to the end of the condenser and any reservoir volume that has been provided, forming a gas plug (Fig. 1). This gas plug acts as a diffusion barrier to the flowing vapor and effectively "shuts off" that portion of the condenser it fills. Consequently, variation in the length of this gas plug in response to changes in evaporator and/or reservoir temperature represents a variation in active condenser length and hence in heat transfer from the system.

Since the operating temperature of a gas-controlled heat pipe varies with reservoir temperature, the reservoir should be placed in one of two locations where its temperature is most easily determined. In one case (cold reservoir), the reservoir is located at the end of the condenser so that its temperature depends on the effective space temperature (T_S) and fluctuates with variations in thermal environment (Fig. 1(a)). The second case (hot reservoir) thermally couples the reservoir to the evaporator so that its temperature range corresponds to the control range of the heat pipe (Fig. 1(b)).

There is a fundamental difference in these two approaches. The cold external reservoir must be wicked since vapor diffusing through the gas will condense in the reservoir and be lost to the wicking system. The partial pressure of vapor in the reservoir will then be the vapor pressure corresponding to its temperature. On the other hand, the hot internal reservoir must not be wicked since its vapor pressure would then be equal to that in the evaporator (i.e., the total pressure) and it could contain no gas. Without wicking, the partial pressure of vapor in the reservoir is established by diffusion to and from the reservoir entrance (e.g., the end of the condenser) and hence, at steady-state conditions, it corresponds to the temperature at this point (T_S'; Fig. 1(c)).

Ames Research Center was offered an opportunity to fly a variable conductance heat pipe on the OAO-C shortly after the initiation of its study of control techniques. Based on the understanding of the OAO-C application and the state of the art at that time, a hot, nonwicked gas-controlled heat pipe was chosen.[1,2] Consequently, much of the succeeding technology development[3] was focused on this technique. The steady-state and transient performance was characterized for hot reservoir heat pipes[4,5] and, for gas-loaded heat pipes in general, the heat and mass transfer in the vicinity of the vapor-gas front was analyzed[6] and computerized.[7] The use of noncondensing gas to aid start-up from the frozen state and the freeze-out of vapor diffusing into the inactive, cold portion of the condenser was also investigated analytically and experimentally.[5,8]

Using the above technology, a cold, wicked reservoir heat pipe/radiator was developed in response to a potential thermal problem on the Apollo 16 Lunar

Surface Magnetometer (LSM).[9] Although it was eventually determined that the heat pipe/radiator was not required for adequate functioning of the LSM, its design, fabrication, and testing in a period of only 6 weeks demonstrated that technology had been developed for using variable conductance heat pipes in important thermal control applications.

The use of excess liquid to effectively vary the active condenser length by blockage similar to gas control was explored in less detail.[3] Vapor control is achieved by interrupting or throttling the flow of vapor between the evaporator and condenser sections, giving rise to a pressure differential between the two regions and thus a temperature difference. Using this principle of vapor modulation, the overall temperature drop can be varied for any given axial heat-transfer rate (i.e., variable conductance) in a manner that is relatively insensitive to variations in heat sink conditions. The development of scaling laws for accelerated life testing was also considered.[10]

Feedback Control

There are characteristics of a passive gas-controlled heat pipe that limit its flexibility and control capability. For example, the vapor temperature inside the active portion of the pipe is stabilized by the gas control mechanism. Therefore, since an ideal variable conductance heat pipe with a constant temperature reservoir of infinite size can only maintain a constant vapor temperature, the heat source temperature will always vary proportionally to the product of its power dissipation and thermal resistance into the vapor. Secondly, variations in reservoir temperature for any reason was shown in the preceding section to also affect controllability. A third problem might be the generation of gas which would tend to shift the control range upward. Finally, the desired control range or thermal operating environment of the heat pipe may not be fully known at the time the fixed quantity of control gas must be added.

To avoid these limitations or potential problems, the heat source temperature must be controlled directly with a feedback mechanism that moves the position of the vapor/gas front beyond that provided by passive control. Two promising methods of achieving this feedback control were identified by a feasibility study.[11]

The most promising method was the use of a wicked reservoir, electrically heated by a controller that senses the temperature of the heat source directly.[12] Such a system is shown schematically in Fig. 2. Increasing the reservoir temperature increases the vapor pressure in the reservoir, thus reducing the partial pressure of noncondensing gas (the total pressure must remain equal to the evaporator vapor pressure). The gas displaced from the reservoir then causes a shift in the vapor/gas front toward the evaporator. Likewise, a reduction in reservoir temperature allows more gas to recede into the reservoir to replace the mass of working vapor diminished by the lower vapor pressure. The application of this method generally requires a careful transient analysis to obtain satisfactory response times with minimum heater power.[13] Feedback control using the heated reservoir was chosen for the ATFE.[14]

There exists some applications in which electrical power is not available and a second method of feedback control must be used. This concept uses a variable volume reservoir (Fig. 3). An increase in heat source temperature causes the expansion of an auxiliary bellows which, in turn, expands the reservoir. The fluctuation in reservoir volume then allows gas to be removed from or forced into the condenser section and moves the vapor/gas front. Although, identified in the feasibility study, this concept has only recently been verified experimentally.[15,16] The mechanical and operational complexity of the variable volume concept requires that further optimization be conducted before attractive performance is achieved. (This optimization is currently in progress at Ames Research Center.[17])

Thermal Diode

An increasing number of applications in both the ambient and cryogenic temperature ranges requires efficient heat transfer in one direction, but can tolerate very little, if any, heat transfer in the reverse direction. Many concepts have been advanced to achieve this diode effect.[18] Among these are the use of noncondensing gas to block the vapor space, freezing or allowing the working fluid to become supercritical, trapping the liquid to dry out all or part of the wick, the use of excess working fluid to block the vapor space, and mechanical methods such as check valves.

Although designed as a gas-controlled variable conductance heat pipe, the LSM heat pipe/radiator operated as a diode during the lunar day.[9] Storing noncondensing gas, however, generally requires significantly larger reservoirs than for excess working fluid. Volumetric sensitivity of the gas to temperature variations is also much greater. Letting the fluid freeze or go supercritical depends, of course, on a close match between fluid properties and the temperature levels that will actually be experienced by the diode, after accounting for conduction along the pipe, etc. Freezing of the working fluid was considered for the LSM application, but was discarded after some interesting temperature excursions were identified.[9]

The liquid trap is based on the tendency of liquid to accumulate at the coldest portion of the pipe, except as displaced by gravity and surface tension. If a reservoir that is capable of holding liquid against gravity and that does not communicate with the pipe wicking system is placed at the hot end of the heat pipe during normal operation (Fig. 4(a)), the wicking system will remain saturated. However, when this reservoir becomes colder than the pipe, liquid will condense in it and be trapped. The wick system then becomes underfilled and loses its pumping capacity until sufficient liquid has been removed to stop the pumping completely. The liquid trap does not place restrictions on the size of the vapor space and therefore is attractive where large heat-transfer rates are required. If, however, much liquid must be removed from the wick to cause the reverse shutdown, considerable energy and a large trap may be required to achieve reversal.

Blockage by excess working fluid also depends on the tendency of liquid to accumulate at the coldest portion of the pipe. Unlike the trap, however, the liquid reservoir is placed at the cold end during normal operation (Fig. 4(b)). When the reservoir becomes warmer during reversal, the liquid enters the pipe, accumulates in the vapor space of the evaporator-turned-condenser, and effectively blocks the reverse vapor flow. This technique is particularly attractive for applications with small evaporators, but the necessity of the liquid to bridge the vapor space places restrictions on vapor flow area and therefore on the axial heat flux.

Following experimental verification of the liquid trap and liquid blockage techniques, the latter was selected for use in the ATFE.[19] Mechanical methods of achieving diode behavior were not considered in detail because of the additional complexity and possible reduced reliability of moving parts.

Hydrodynamics

A potential priming problem exists in any heat pipe that uses a composite or arterial wicking system. The most universal problem is the trapping of noncondensible gas bubbles in the liquid-sheathed wick (Fig. 5). Impurities and material incompatibility often are sources of sufficient gas to cause this difficulty. In the case of gas-controlled heat pipes, the control gas itself represents the problem.source. There appear to be two alternatives for using composite or arterial wicks in the presence of gas: (1) understand the behavior of gas bubbles in sufficient detail to design the heat pipe (choice of fluid, gas, and wick configuration) so that the bubble can be dissolved quickly enough to achieve satisfactory performance or (2) design a wicking system that will not allow bubbles to become trapped.

The lifetime of an arterial bubble under diverse conditions has been analytically and experimentally determined for stagnant conditions using experimentally determined diffusivity and solubility measurements.[20,21] Efforts to extend this understanding to the dynamic conditions inside an operating heat pipe and to accomplish the second alternative are currently in progress.

An interesting alternative to arterial wicks for dielectric fluids is the axial movement of the liquid by electrohydrodynamic (EHD) forces.[22-26] An example of an EHD flow structure is shown in Fig. 6. The EHD polarization force establishes hydrostatic equilibrium similar to capillary forces, which is unbalanced by the evaporation and condensation. The liquid flows continuously to reestablish this equilibrium. EHD offers some potential advantages such as heat-transfer enhancement by the electric field, reliable voltage priming, bubble ejection from the axial flow path, greatly reduced liquid fraction factor for the returning condensate, and voltage control as a variable conductance technique. EHD may also be useful in simply priming large arterial heat pipes. These potential advantages, however, must be weighed against the greater complexity of an EHD heat pipe and the requirement for a high-voltage power supply. Further, the long-term stability of dielectric fluids in the presence of corona or intermittent arcing must be considered.

SPACE-FLIGHT EXPERIMENTS

Ames Heat Pipe Experiment (AHPE)

The AHPE is providing, for the first time, an opportunity to evaluate the performance of a gas-loaded variable conductance heat pipe in the space environment. In addition, the effectiveness of a variable conductance heat pipe in maintaining temperature stability in a specific engineering application is being demonstrated.

System Description

The AHPE controls the temperature of the spacecraft's On-Board-Processor (OBP) by regulating the flow of heat from the back of the OBP equipment shelf to a space radiator (Fig. 7). As in many spacecraft applications, both the power dissipated by the OBP and the external heat flux incident on the radiator vary significantly. A detailed description of these conditions and their impact on the design of the AHPE has been previously reported.[1] The major design features of the AHPE are summarized below:

Working fluid: methanol
Control gas: helium
Pipe material: stainless steel
Reservoir: Hot, nonwicked
Wick system: filled artery
Maximum heat load: 22 W
Radiator sink temperature (design values): -19°C (max.), -52°C (min.)
Control range: 15.5° to 21.0°C
Radiator: Alzak coated aluminum (α/ε = 0.17/0.75)
Reservoir/condenser volume ratio: 10:1

Orbital Performance

Transient response during a typical orbit is shown in Fig. 8. The end of the radiator varies between -18°C at the end of shadow to 5°C during maximum sun. For a reason not yet determined, the orbital average temperature of -7°C is considerably higher than the value of -28°C used in designing the control range. This higher temperature causes the diffusion of additional methanol vapor into the reservoir where it displaces the helium control gas and forces it into the condenser. The evaporator temperature must then increase to compress the control gas sufficiently to allow the required rejection of heat from the OBP.

Consequently, the evaporator temperatures are 2° to 3°C warmer than anticipated by the original design calculations. As indicated in Fig. 8, the evaporator and OBP platform temperatures fluctuate about 2°C in phase with the end of the radiator throughout the orbit. The temperature at the beginning of the radiator rapidly increases near the start of the shadow, indicating that the gas front has been moved from the adiabatic section into the radiator. As the end of the radiator warms up near maximum sun, the gas front is forced back into the adiabatic section. This behavior illustrates the dominance of the high, fluctuating radiator temperature at the entrance to the gas reservoir on the control range as predicted by established variable conductance theory.

During its first year in orbit, the ATFE has demonstrated the capability to hydrodynamically handle at least 26 W and has stabilized the OBP/AHPE interface temperature between 19° and 21°C for operational fluctuations in OBP power dissipation and a wide range of external heat flux incident on the radiator.

Advanced Thermal Control Flight Experiment (ATFE)

The Advanced Thermal Control Flight Experiment is designed to demonstrate, for the first time, the performance of an active feedback-controlled heat pipe and a passive thermal diode heat pipe in a space environment. In addition, the temperature control aspects of a phase-change material (PCM) will also be evaluated.

While the ATFE is an experiment designed to provide performance data for the components mentioned above, it is also a thermal control system that can be used to provide temperature stability of spacecraft components in future applications. Certainly, variations of this system will be used.

System Description

Basically, the ATFE (Fig. 9) consists of a solar absorber, a thermal diode, a simulated equipment package that contains phase-change material (PCM box), a feedback-controlled variable conductance heat pipe (FCHP), and a space radiator. Supporting hardware not shown in Fig. 9 are a solid-state electronics module, temperature sensors, foil heaters, support structure, and thermal insulation.

The ATFE is mounted in the east wall of the ATS-F earth-viewing module with only the outboard surfaces of the solar absorber and radiator exposed to the external environment. Three-axis stabilization and the geosynchronous orbit result in an incident solar flux that rises and sets over a nominal 12-hr period, followed by 12 hr of darkness, similar to the solar cycle experienced by a fixed point on the earth's surface. The absorbed solar energy is used to simulate power dissipation during an electrical duty cycle and is transported from the absorber to the PCM box by the diode heat pipe.

This energy first melts the PCM, which is octadecane with a melting point of 28°C. When melting has been completed, the energy then passes through the PCM box to the FCHP, which transports it to the space radiator. During the cycle, temperature control of the diode/PCM box interface is provided by the FCHP, which senses the temperature at the interface and correspondingly regulates the heat rejection to space to accommodate the variations in both the thermal load and the thermal boundary conditions at the radiator. As the shadow period is approached, the diode and FCHP decrease their conductance to minimize the heat loss from the PCM box to space. Thermal energy released by freezing the PCM is used to compensate for heat lost during the transient shutdown of the diode and FCHP and to provide temperature stability during part of the shadow period. When all the PCM has frozen, the temperature of the equipment shelf decreases at a rate that depends on the heat capacity of the PCM box and its parasitic heat leaks. The amount of octadecane provided in the PCM box is designed to permit cooling of the PCM box to about 0°C. This allows the evaluation of the PCM melting point stability in zero gravity.

The design of the various ATFE components has been previously discussed in detail.[14] Therefore, only the major design features are summarized below:

Thermal diode heat pipe

Working fluid: ammonia
Pipe material: stainless steel
Reservoir: noncommunicating liquid storage
Wick system: tunnel spiral artery with circumferential grooves
Absorber: aluminum coated with black paint and second surface mirrors

Feedback-controlled heat pipe

Working fluid: methanol
Pipe material: stainless steel
Reservoir: wicked, electrically heated
Controller: solid-state on/off
Wick system: composite slab with circumferential grooves
Control gas: helium

Reservoir/condenser volume ratio: 5:1
Radiator: segmented aluminum coated with second surface mirrors

PCM Box

PCM: practical grade octadecane
Matrix: expanded aluminum honeycomb
Void space: 15% total internal volume
Liquid management: correctly sized holes
Energy storage: 26 W-hr

System Thermal Performance During Acceptance Testing

The ATFE has been qualified and accepted for flight in accordance with the ATS-F environmental test specifications for experiments which required electromagnetic interference, functional, leak, vibration, storage temperature, hot and cold soak, and thermal/vacuum testing.

The performance of the ATFE under simulated orbital conditions for various operational modes was of major interest and therefore comprised a significant portion of the testing program. The ATFE was mounted in a panel representing the east wall of the spacecraft. This panel formed one side of a box that radiatively simulated the internal cavity of the spacecraft. The temperature of this box was then controlled to the desired spacecraft temperature. Foil heaters bonded to the inboard sides of the absorber and radiator were used to simulate absorbed solar energy. Voltage to the heaters was automatically stepped at 20-min intervals to the correct level corresponding to the solar energy cycle. Throughout the entire orbit, the absorber and radiator viewed the cold chamber walls.

Typical Transient Performance with Feedback Control

The ATFE exhibited the characteristic transient performance shown in Fig. 10. As the ATFE moved from the end of the shadowed period into sunlight, the absorber quickly rose from -60°C to a maximum of 32.5°C near maximum solar input. It then decreased in temperature as the sun "went down" until the diode completed its reversal. The absorber remained at a plateau of -39°C until all the PCM had frozen and the PCM box dropped in temperature. Some inconsistency in the temperature level of this plateau was encountered with both the qualification and flight units. On some occasions, temperature levels as high as -19°C have existed after an apparent partial reversal of the diode. Another interesting phenomenon has been a tendency of the absorber to show a slight warming trend just prior to complete freezing of the PCM. It appears that the extreme sensitivity of the fluid inventory remaining in the noncommunicating diode reservoir to temperature profiles along the pipe may be the major factor causing the inconsistent behavior.

The PCM box also increased rapidly in temperature as the diode began transferring energy to it early in the solar cycle. It then became stabilized near 28°C (octadecane melting point), with a sufficient temperature gradient (approximately 2°C) from the diode to FCHP side to assure that all the PCM was melted. It should be recognized that the temperature stability of the system can be no better than the temperature gradients required in the PCM box to assure melting and freezing of the PCM. For the ATFE, this minimum range is approximately 26° to 30°C.

As the absorber temperature drops below that of the PCM box, the freezing PCM provides energy to reverse the diode and to compensate for parasitic heat leaks. The diode side of the PCM box during this period is seen to be stabilized near 27°C. Since the temperature gradients in the box would be expected to be less at this time than during the melting process at peak solar conditions, some subcooling (or shift in the octadecane freezing point) seems evident.

The influx of solar energy to the FCHP reservoir radiator during the initial portions of the cycle supplements the heater power within the reservoir and results in a rapid increase in temperature. When the diode side of the PCM box (controller sensor location) reaches the control set point (28°C), the reservoir heater turns off and the reservoir temperature begins to decrease. The transient response of the reservoir during this period is perhaps the single most important factor in the FCHP's transient performance. If the reservoir temperature drops slowly and to an insufficiently low level, the control gas is not allowed to recede into the reservoir quickly enough to allow the FCHP condenser to open wide enough to reject the required heat load. A temperature overshoot then occurs at the control location. For example, the ATFE design is such that each 3°C increase in reservoir temperature near peak solar input results in approximately a 1°C overshoot on the diode side of the PCM box. A major difficulty with the ATFE was thermally decoupling the FCHP reservoir from the absorber which, by necessity, surrounded it on three sides.

Progressing through the solar cycle, the controller is seen to turn the reservoir heater back on (approx. 0900 suntime) with the resulting increase in FCHP reservoir temperature. This temperature, however, begins to decrease to a quasi-steady-state level during shadow. If the reservoir temperature drops too low while the vapor temperature remains stabilized by the PCM, the FCHP condenser shows a tendency to partially open and allow the remaining energy in the PCM material to be rejected. The temperature control of the FCHP reservoir, therefore, is a careful compromise to achieve as low a temperature as possible during peak solar conditions while maintaining a sufficiently high temperature during shadow. For the ATFE, this resulted in an important tradeoff between heater power, heat-rejection capability, thermal capacitance, and thermal coupling to other portions of the experiment.

Typical Temperature Profiles with Feedback Control

Perhaps the interaction of the various components as a system is better visualized in Fig. 11. During peak solar input, the absorber and diode are nearly isothermal. A temperature drop of a few degrees exists through the PCM box to the feedback pipe, whose profile is nearly linear until the gas-blocked region of the condenser is reached. The reservoir heater is off, allowing the reservoir to approach equilibrium with the external environment and the remainder of the ATFE. On the other hand, during the shadow, the PCM holds the PCM box at its freezing point while the diode allows the absorber to drop to its low temperature. The feedback reservoir heater is on, thereby raising the reservoir temperature and forcing additional amounts of gas into the condenser, which it blocks completely. The large temperature drops from the PCM box to the absorber (62°C) and to the radiator (110°C) demonstrate the effectiveness of these new thermal control tools.

J.P.K.

SUMMARY

Ames Research Center has been engaged in an extensive program of heat pipe development with particular emphasis on basic control mechanisms. Early efforts were focused on gas control and resulted in the Ames Heat Pipe Experiment on the OAO-C spacecraft. Orbital performance of the AHPE has been in accordance with established theory. Additional development is required for other promising variable conductance techniques such as vapor control and condenser blockage by excess fluid.

Two methods of feedback control have been established. The use of a variable volume reservoir requires further optimization, while the use of electrical heaters to vary the reservoir temperature has shown impressive performance. This latter method has been selected for the ATFE scheduled for launch aboard the ATS-F spacecraft in May 1974.

Several concepts for achieving thermal diode behavior have been explored and verified experimentally. One of these — liquid blockage by excess fluid — has also been incorporated into the ATFE. Considerable work remains to be done in developing the various techniques for potential applications, particularly in the cryogenic temperature range.

The reliable priming of arterial wicking systems in the presence of noncondensing gas is a major concern, especially where gas has been intentionally added for control purposes. Therefore, an understanding of the static and dynamic behavior of bubbles in arteries is being developed. An alternative is the development of arterial wicks that do not trap bubbles. Electrohydrodynamic (EHD) pumping appears to be a feasible substitute and/or priming aid for capillary-pumped arteries in special applications. However, EHD heat pipes are still in the early stages of development.

Based on the established fundamental understanding of basic control mechanisms, the orbital performance of the AHPE, and the impressive performance of the ATFE during flight acceptance tests, it can be said with some confidence that variable conductance heat pipes are moving from the laboratory to space.

REFERENCES

[1]J.P. Kirkpatrick and B.D. Marcus: A Variable Conductance Heat Pipe Flight Experiment. AIAA Paper 71-411, April 1971 (also in AIAA Progress in Astronautics and Aeronautics: Fundamentals of Spacecraft Thermal Design, Vol. 29).

[2]B.D. Marcus: Ames Heat Pipe Experiment Document. NASA CR-114413, Jan. 1972.

[3]B.D. Marcus: Theory and Design of Variable Conductance Heat Pipes. NASA CR-2018, April 1971.

[4]B.D. Marcus and G.L. Fleischman: Steady-State and Transient Performance of Hot Reservoir Gas-Controlled Heat Pipes. ASME Paper 70-HT/SpT-11, June 1970.

[5]D.K. Edwards, G.L. Fleischman, and B.D. Marcus: Theory and Design of Variable Conductance Heat Pipes: Steady State and Transient Performance. NASA CR-114530, Dec. 1972.

[6]D.K. Edwards and B.D. Marcus: Heat and Mass Transfer in the Vicinity of the Vapor-Gas Front in Gas Loaded Heat Pipe. ASME Paper 71-WA/Ht-29, Nov. 1971.

[7]D.K. Edwards, G.L. Fleischman, and B.D. Marcus: User's Manual for the TRW Gaspipe Program. NASA CR-114306, April 1971.

[8]B.D. Marcus, G.L. Fleischman, and D.K. Edwards: Diffusion Freezeout in Gas Loaded Heat Pipes. ASME Paper 72-WA/Ht-33, Nov. 1972.

[9]J.P. Kirkpatrick and B.D. Marcus: A Variable Conductance Radiator for the Lunar Surface Magnetometer. AIAA Paper 72-271, April 1972 (also in AIAA Progress in Astronautics and Aeronautics: Thermal Control and Radiation, Vol. 31).

[10]W.T. Anderson, Jr.: Hydrogen Evolution in Nickel-Water Heat Pipes. AIAA Paper 73-726, July 1973.

[11]W.B. Bienert: Study to Evaluate the Feasibility of a Feedback Controlled Variable Conductance Heat Pipe. NASA CR-73475, Sept. 1970.

[12]W.B. Bienert, P.J. Brennan, and J.P. Kirkpatrick: Feedback-Controlled Variable Conductance Heat Pipes. AIAA Paper 71-421, April 1971 (also in AIAA Progress in Astronautics and Aeronautics: Fundamentals of Spacecraft Thermal Design, Vol. 29).

[13]W.B. Bienert and P.J. Brennan: Transient Performance of Electrical Feedback-Controlled Variable Conductance Heat Pipes. ASME Paper 71-AV-27, July 1971.

[14]J.P. Kirkpatrick and P.J. Brennan: The Advanced Thermal Control Flight Experiment. AIAA Paper 73-757, July 1973.

[15]C.A. Depew et al.: Construction and Testing of a Gas-Loaded Passive-Control Variable Conductance Heat Pipe. NASA CR-114597, June 1973.

J.P.K.

[16]C.A. Depew, W.J. Sauerbrey, and B.A. Benson: Construction and Testing of a Gas-Loaded, Passive-Control, Variable-Conductance Heat Pipe. AIAA Paper 73-727, July 1973.

[17]K.R. Schlitt: Design and Testing of a Passive Feedback Controlled Variable Conductance Heat Pipe. Proceedings of the 1st International Heat Pipe Conference, Stuttgart, Germany, Oct. 1973.

[18]B. Swerdling and R. Kosson: Design, Fabrication, and Testing of a Thermal Diode. NASA CR-114526, Dec. 1972.

[19]B. Swerdling et al.: Development of a Thermal Diode for the Advanced Thermal Control Flight Experiment. AIAA Paper 72-260, April 1972 (also in AIAA Progress in Astronautics and Aeronautics: Thermal Control and Radiation, Vol. 31).

[20]E.W. Saaski: Investigation of Bubbles in Arterial Heat Pipes. NASA CR-114531, Dec. 1972.

[21]E.W. Saaski: Gas Occlusions in Arterial Heat Pipes. AIAA Paper 73-724, July 1973.

[22]T.B. Jones: The Feasibility of Electrohydrodynamic Heat Pipes. Research Rept. 1, NASA CR-114392, Oct. 1971.

[23]T.B. Jones and M.P. Perry: Entrainment in Electrohydrodynamic Heat Pipes. NASA CR-114499, Aug. 1972.

[24]T.B. Jones and M.P. Perry: Experiments with an Electrohydrodynamic Heat Pipe. NASA CR-114498, Sept. 1972.

[25]T.B. Jones: An Electrohydrodynamic Heat Pipe. ASME Paper 72-WA/Ht-35, Nov. 1972.

[26]T.B. Jones: Electrohydrodynamic Heat Pipes. Intern. J. Heat Mass Transfer 16, (1973), pp. 1048-1095.

TABLE I

SUMMARY OF HEAT PIPE CONTRACTS

Contract	Contractor	Publications
NAS 2-5503, Variable Conductance Heat Pipes	TRW Systems Group	1-10*
NAS 2-5722, Feasibility of Feedback-Controlled Heat Pipes	Dynatherm Corp.	11,12
NAS 2-6227, Feedback-Controlled Heat Pipes	Dynatherm Corp.	13,14
A-52728A, Passive Feed-back-Controlled Heat Pipe	University of Washington	15,16
NAS 2-6493, Ambient Temperature Diode Heat Pipes	Grumman Aerospace Corp.	18,19
NAS 2-6991, Bubble Behavior	Donald W. Douglas Labs.	20,21
NAS 2-7492, Cryogenic Thermal Diodes	Grumman Aerospace Corp.	New Contract
NAS 2-7596, Arterial Occlusions	Donald W. Douglas Labs.	New Contract
NGR-06-002-127, Electrohydrodynamic Heat Pipes	Colorado State Univ.	22-26

*Refers to references.

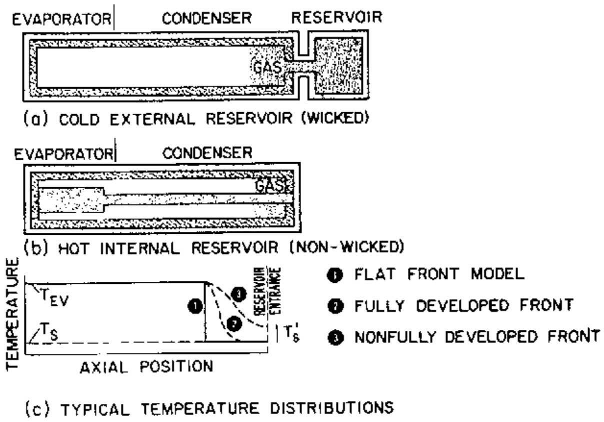

Fig. 1. Cold and hot reservoir heat pipes.

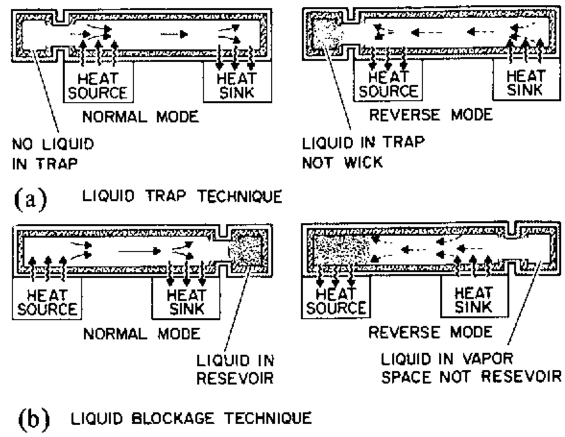

Fig. 4. Liquid blockage and liquid trap thermal diodes.

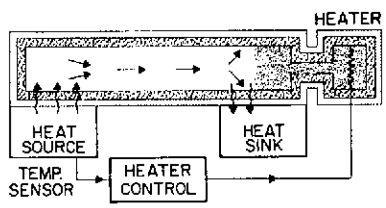

Fig. 2. Feedback-control (electrically heated reservoir).

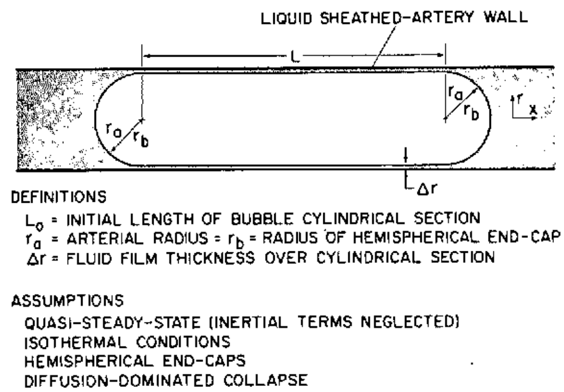

Fig. 5. Arterial bubble.

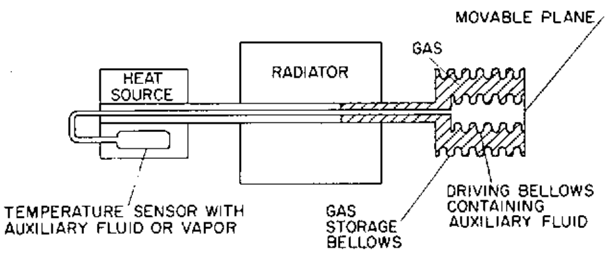

Fig. 3. Feedback-control (variable storage volume).

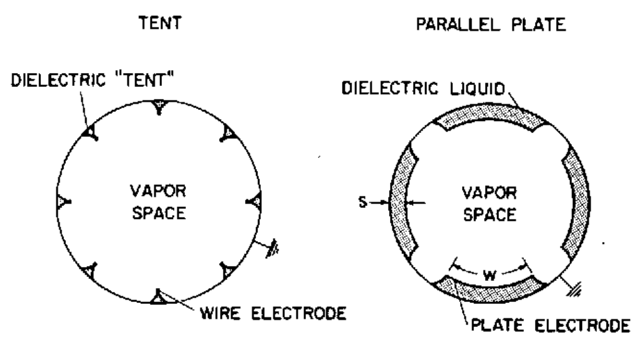

Fig. 6. EHD flow structures.

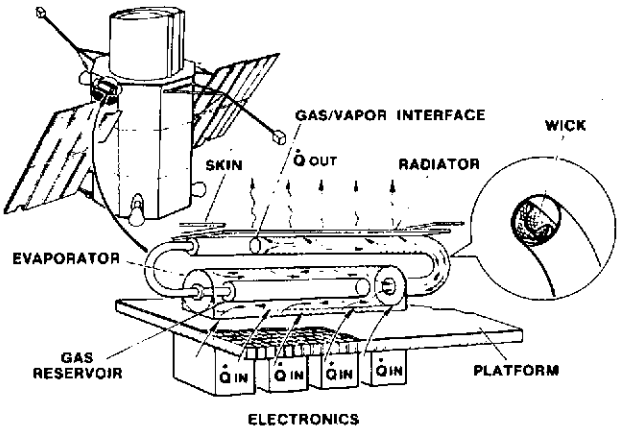

Fig. 7. Ames heat pipe experiment.

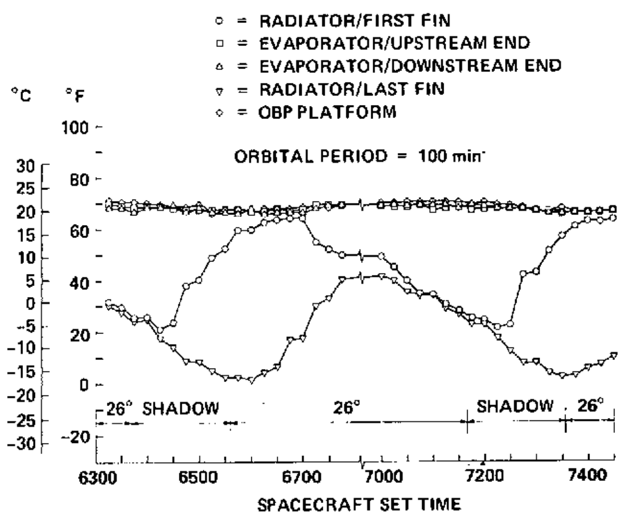

Fig. 8. Typical AHPE orbital data.

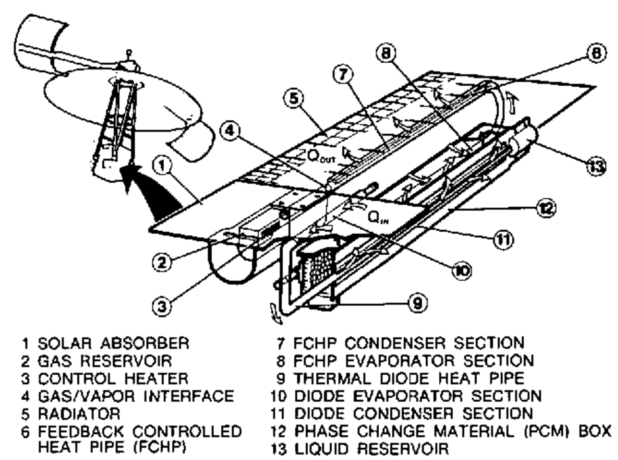

Fig. 9. Advanced thermal control flight experiment.

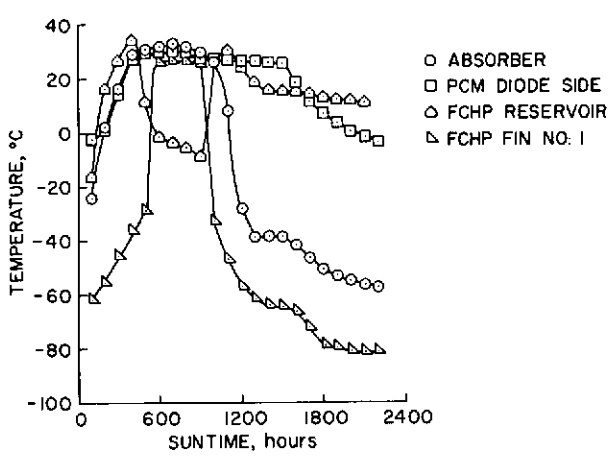

Fig. 10. Typical ATFE transient performance.

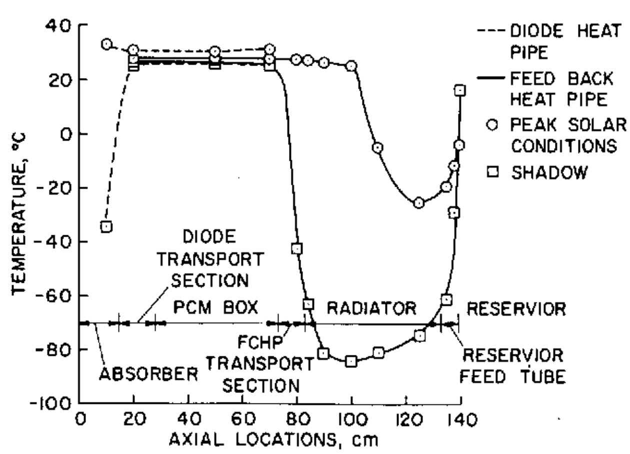

Fig. 11. Typical ATFE temperature profile.