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EXPERIMENTS WITH AN ELECTROHYDRODYNAMIC HEAT PIPE

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Research Report #3

September 1972

by T. B. Jones and M. P. Perry

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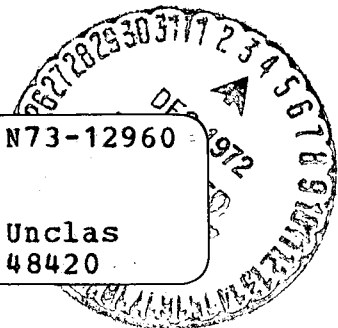
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I. Introduction

The feasibility of an electrohydrodynamic (EHD) heat pipe has been considered in the first research report of this series[1] and elsewhere.[2] A simple analytical model for these devices has been developed. Calculations based upon this model have led to the recognition of some of the performance limits on EHD heat pipes. The principal result of this feasibility study is the indication that EHD concepts can profitably be used in dielectric liquid heat pipes. Also, some possibly very useful special features of EHD heat pipes (not common with capillary devices) have been recognized.

Recently, an experimental program has been undertaken to verify the results of the feasibility study. This present research report details the experimental findings obtained to date.

The experimental program was initiated with several goals in mind. The first goal of the experiments is to build a working model which conclusively demonstrates the concept of the electrohydrodynamic heat pipe. The experiment reported here achieves this goal. A second goal is to observe and record any problems encountered which are likely to provide important characteristic limitations on EHD heat pipes. Several such problems have been identified and are discussed, though complete coverage of this aspect of the program must await more elaborate quantitative experimental activity. A final goal, that of indicating tentatively the ultimate capabilities of EHD heat pipes, is not yet in reach. The experience gained with the first experimental device indicates that greater attention must be placed upon design optimization before a high-performance EHD heat pipe will be realized. More knowledge concerning the compatibility of EHD axial flow structures and circumferential capillary structures will be required initially. These next experiments should lead the way to an optimally designed EHD heat pipe; based upon this optimization a fair assessment of these devices will be forthcoming.

II. Experimental Device

The purpose of this section is to describe the experimental device used for these tests and to explain its operation.

A. Physical Configuration

To achieve flexibility, the first experimental heat pipe was designed to allow for accessibility to the inside. This resulted in a structure with a diameter somewhat larger than most common capillary devices and with removeable ports at both ends. The vessel itself is made from a one foot length of 1-1/4 inch OD oxygen-free (OFHC) copper pipe, with .065 inch wall thickness.* Flanges are silver-soldered to the ends of the pipe. Clear plexiglas ports are bolted to these flanges and "0" rings provide a vacuum and pressure tight seal. Refer to Figures 1a, b, c.

The plexiglas end ports allow observation of the operation of the heat pipe, but also, they provide a means of mounting the high-voltage electrode structure which runs axially the full length of the pipe. This electrode is operated at very high voltages (up to 15 kV) with respect to the vessel walls and so must be well-insulated. Because it is an excellent insulating material, and because it is easily machined, clear plexiglas is used. The electrode structure selected for the first EHD heat pipe is a single wire spaced approximately 1/8 inch from the bottom of the inside wall of the vessel. The wire is stretched taut and tightly fastened with small screws on the outside of the plexiglas ports. The holes where the wires pass through the ports are sealed from the outside with a special low vapor pressure epoxy. Care must be taken to avoid even minor surface

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* The compatibility of OFHC copper with Freon-113, the chosen working fluid, is thought to be good.[3]
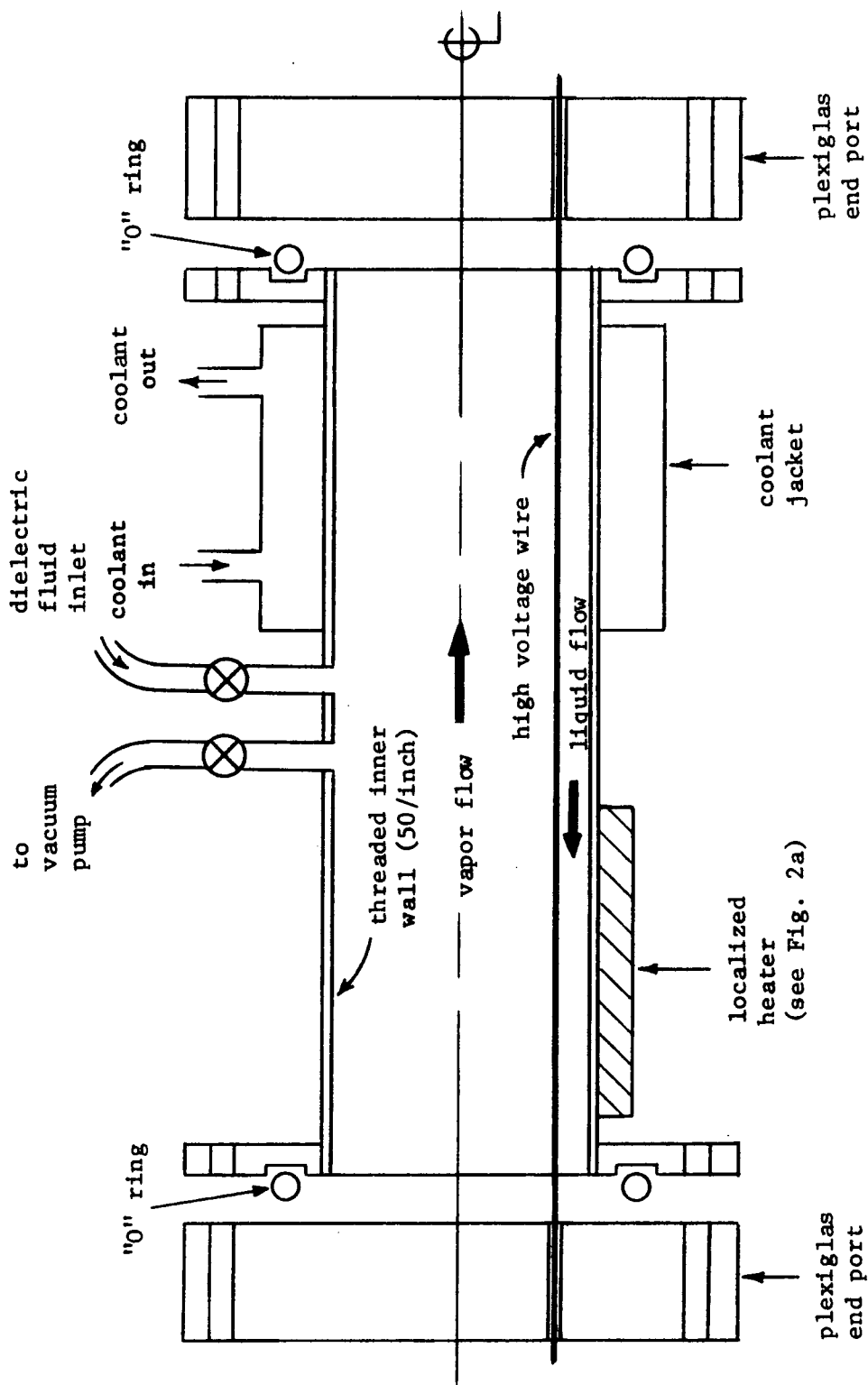
(a.) Half-sectional drawing (not to scale)

Figure 1. The electrohydrodynamic heat pipe
experimental apparatus.
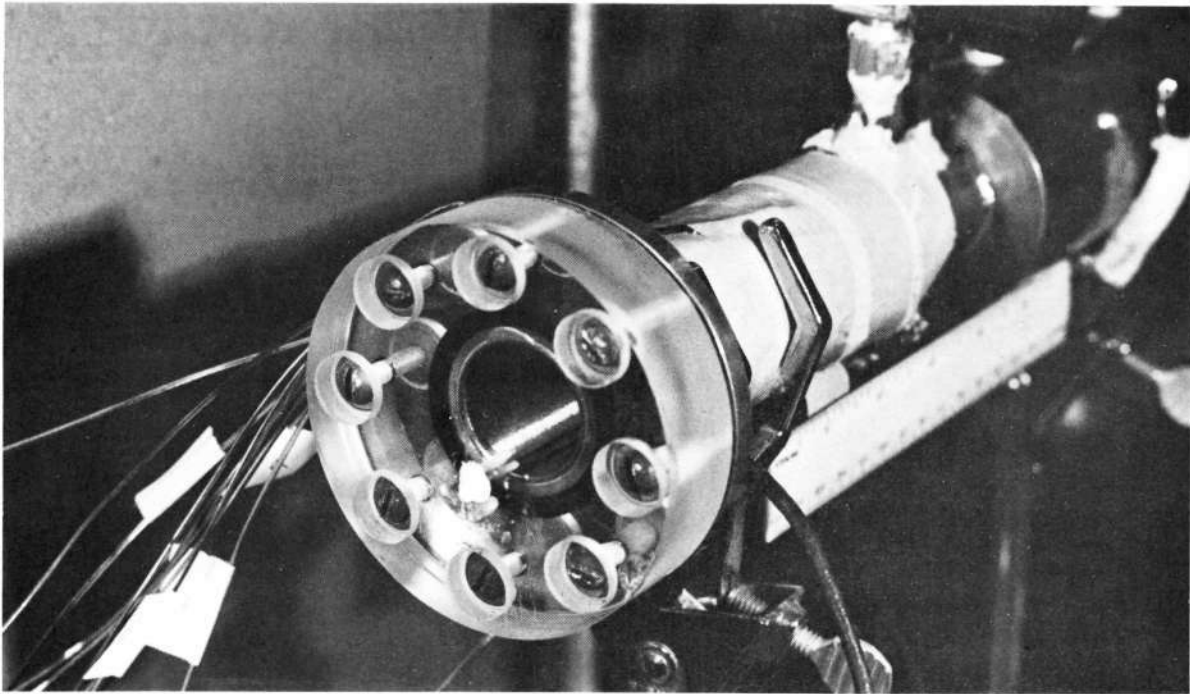
(b.) End view showing plexiglas end port and axial electrode
wire structure. (The circumferential grooves are visible
through port.)

(c.) Side view showing heater (left) and cooling
jacket (right).

Figure 1. The electrohydrodynamic heat pipe experimental apparatus.

scratches on or kinks in the copper wire. Two different diameter wires were tried (1/32 and 1/16 inch diameter). The electrohydrodynamic flow structure which the wire achieves is called the dielectric tent because, as Figure 2a illustrates, the non-uniform electric field between the wire and the vessel wall orients the insulating dielectric fluid in a tent or prism-shaped equilibrium configuration.
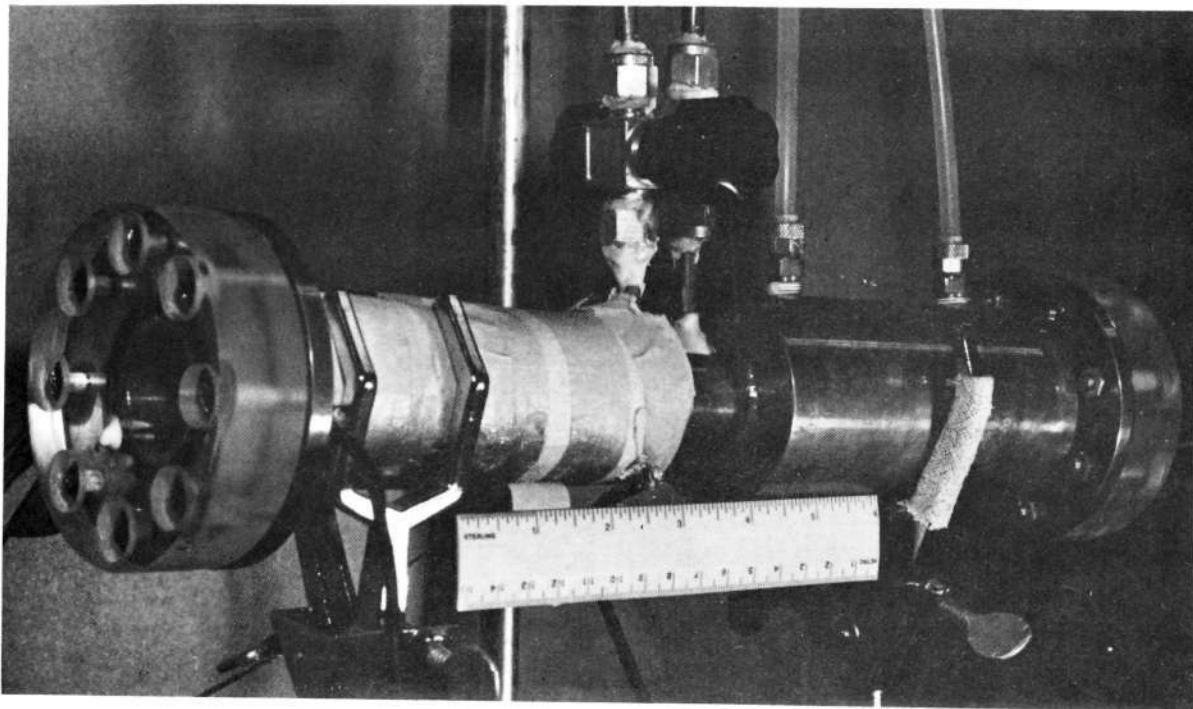
The evaporator and condenser walls are threaded internally with circumferential grooves to enhance evaporation and condensation heat transfer (See Figure 2b). Unfortunately, the ~50 threads per inch achieved are not adequate, either with respect to groove width or depth; the static pumping height for Freon-113 is found to be only ~3/8 inch. Refer to the Appendix where the groove problem is discussed further.

Because of the limited pumping ability of the grooves, the top half of the evaporator remains dry during all tests. Thus, to avoid burn-out, a sectional electrical heater, shown in Figure 2a is used. This localized heating amounts to a significant improvement over a wrap-on heater (used initially), and thus it is used exclusively for all the experiments reported in § III. The total electrical input power is measured continuously with a wattmeter.

A water jacket is used for condenser cooling. The water temperature is maintained and controlled by a temperature bath with $\pm 1°$ F accuracy.

The heat pipe's performance is monitored with a number of copper-constantan thermocouples. Eight thermocouples measure the outside wall temperature of the evaporator; their placement is summarized in Figure 2a. Another thermocouple monitors the temperature of the cooling water in the water jacket. This temperature is assumed to be the same as that of the outside condenser wall. Other thermocouples are used to monitor temperature drops related to losses.
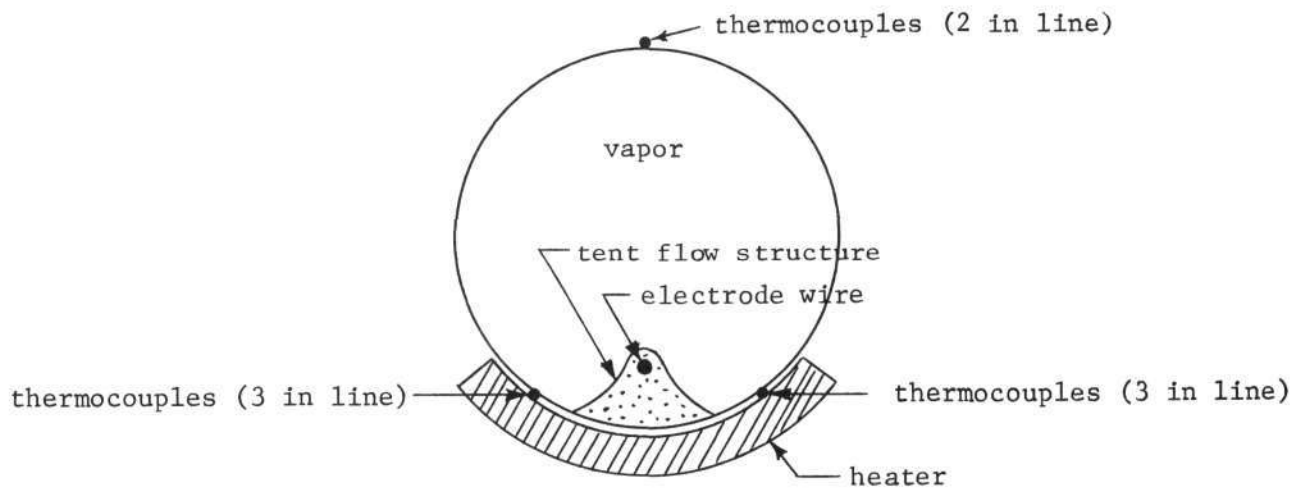
(a.) Drawing showing dielectric tent cross-section,
heater placement, and thermocouple placement.
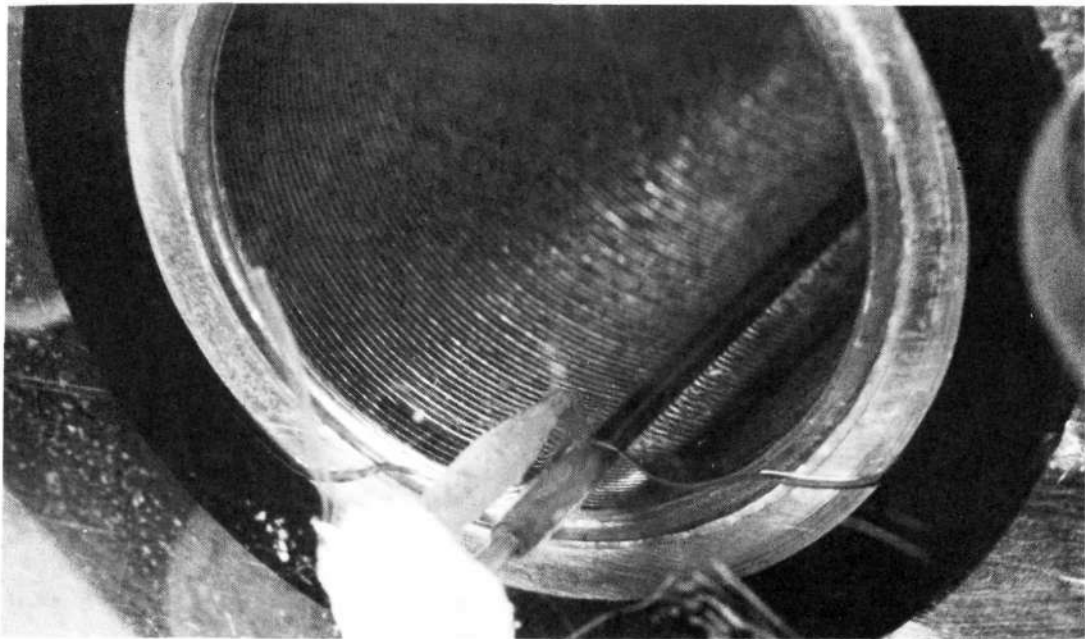
(b.) Photograph of dielectric tent flow structure.

Figure 2. The dielectric tent flow structure.

Figure 3 shows the entire experiment in situ.

B. Basic Operation

The basic concept which this experiment was undertaken to demonstrate is the use of an EHD axial flow structure to guide and pump fluid from the condenser to the evaporator. The grooves in the evaporator serve the primary function of pumping the liquid up around the walls from the EHD flow structure, but they also promote the two-phase heat transfer processes at both ends of the heat pipe. The net result is a new class of *hybrid* flow structures which utilize both electrohydrodynamic and capillary forces to guide and pump liquids. Such structures show great promise in EHD heat pipe technology: the EHD flow structure should provide essentially inviscid axial flow from condenser to evaporator and the capillary structure should provide efficient circumferential pumping to heated evaporator surfaces. The resulting device is similar in some respects to a tunnel artery heat pipe.
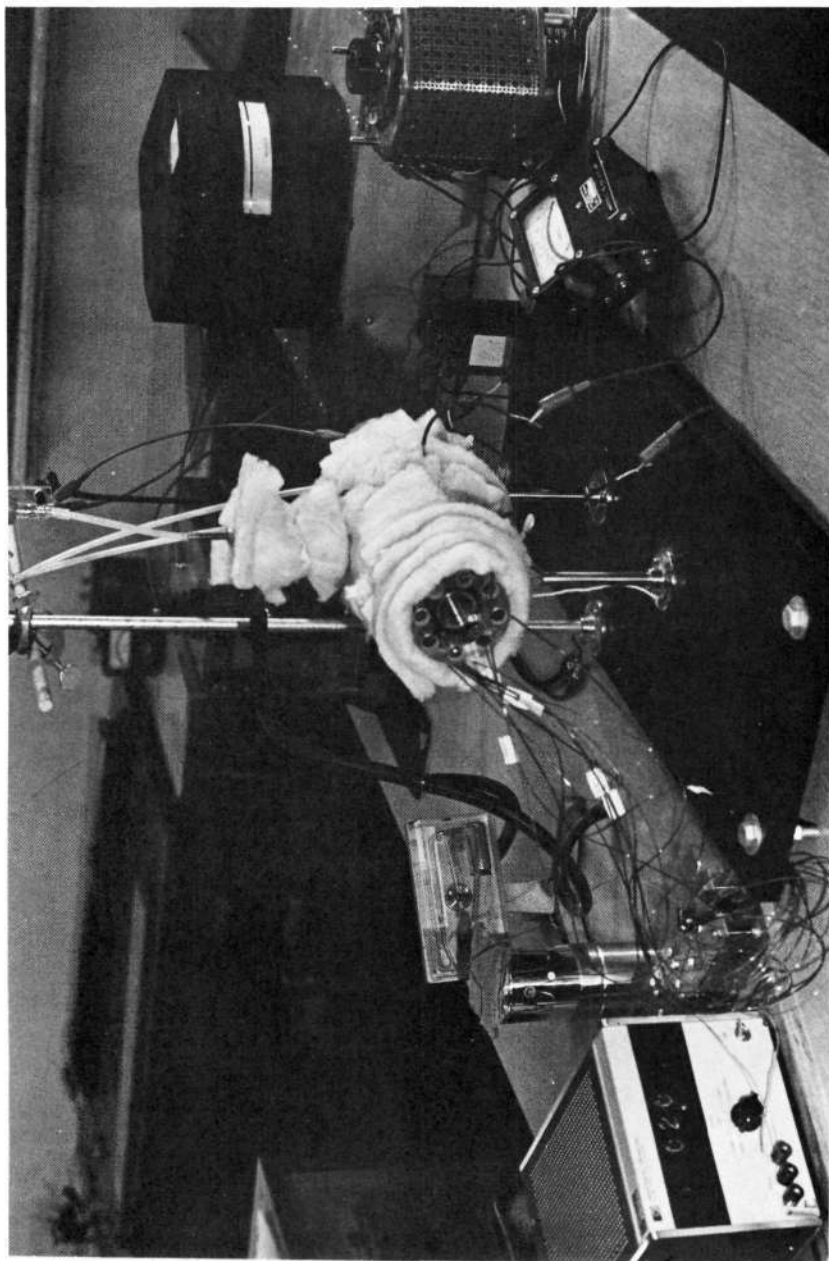
Figure 3. The electrohydrodynamic heat pipe experimental setup.

III. Experimental Results

Early experiments were attempted with wrap-on electrical heaters and with very cold condenser temperatures. The inadequacy of the capillary grooves in pumping the Freon-113 around the circumference of the evaporator was confirmed by the very high temperature readings at the top compared with those at the bottom.

The condenser temperature of ~70°F resulted in internal vapor pressures of ~5 psi, too low for adequate electrical insulation in the vapor.

A. Primary Data Experiments

With sectional heaters, shown in Figure 2a, and elevated internal operating pressures, achieved by circulating water from a constant temperature bath through the cooling jacket, the deficiencies of the early experiments were rectified and successful EHD heat pipe operation was achieved.

The experimental data is presented in two forms to facilitate discussion.

Voltage-Tilt Data

Figures 4a, b plot the average evaporator to condenser temperature drop versus tilt for several values of applied voltage, with the input power to the electrical heaters held constant. For the case of no applied voltage ΔT goes up almost linearly with the tilt until at approximately 0.3" of tilt the value of ΔT levels off. The simple explanation for this behavior with no EHD effects present is that tilting the heat pipe drains liquid out of the evaporator until, with the evaporator about 0.3" above the condenser, the entire evaporator dries out (confirmed by observation) leaving thermal conduction through the relatively thick-walled copper tubing as the only significant heat transfer mechanism from the heater to the water jacket.
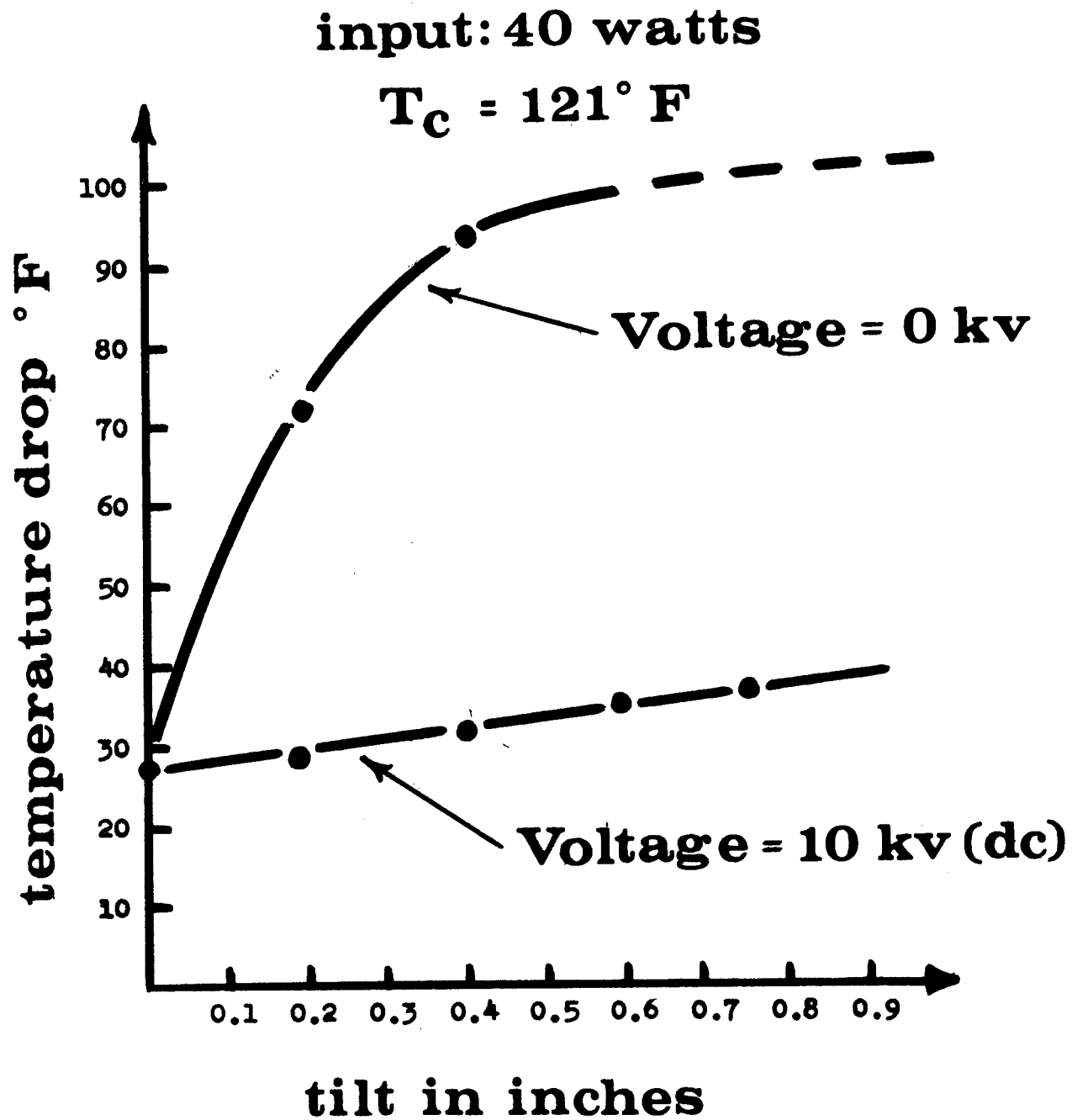
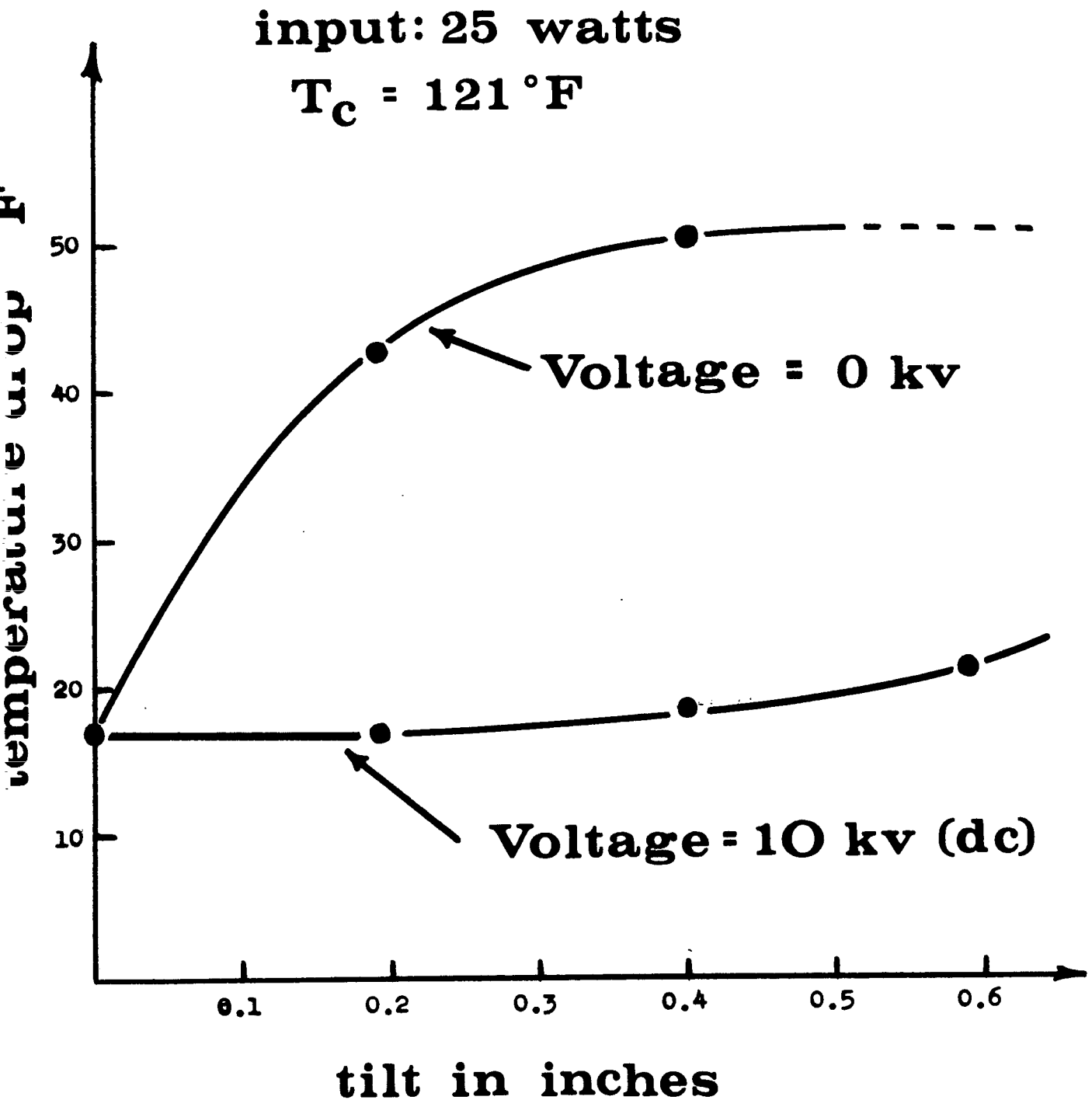Figure 4a. EHD heat pipe data. Temperature drop from evaporator to condenser (ΔT) versus tilt.

Figure 4b.   EHD heat pipe data. Temperature drop
            from evaporator to condenser (ΔT)
            versus tilt.

With 10 kilovolts (dc) applied to the wire electrode, however, liquid is oriented in the tent-shaped configuration which runs the entire length of the heat pipe. The evaporator remains wetted and the temperature drop does not increase rapidly with tilt. As one expects, ΔT does increase slowly as the evaporator is raised, reflecting the increasing adverse gravitational head which the evaporator grooves must pump against.

It is possible to cycle the device by the following procedure.

(i)   Establish stable conditions of constant ΔT for some constant tilt, input power and voltage. (The voltage chosen must be sufficient to wet the entire evaporator.) Note the value of ΔT.

(ii)   Turn off the high voltage, so that liquid is no longer oriented in the evaporator. The evaporator temperature and thus ΔT will rise rapidly from some point on the lower curve to the corresponding point on the upper curve of Figure 4 (a or b).

(iii)   Now turn the voltage on again, slowly bringing it up until the entire evaporator is wetted again. The temperature will immediately start to drop, and after approximately 10 minutes will settle down to the previous value.

It is very interesting to watch the leading edge of the dielectric liquid as it slowly moves up the axial electrode structure into the evaporator. The evaporator wall beneath the liquid is initially quite hot and the superheat is sufficient to initiate violent nucleate boiling. But in a short time, the excess heat is removed and the boiling subsides.

These data and observations verify the point previously made that the present device is severely groove limited. The EHD flow structure imposes no limit on performance other than the requirement of a voltage

(electric field strength) sufficient to orient dielectric liquid hydrostatically in the tent-shaped configuration from the condenser to the elevated evaporator. The use of optimally designed grooves in future designs should impose an increased pumping requirement on the electrohydrodynamic flow structure not encountered in the present device.

Overall Thermal Conductance Data

In an attempt to provide a basis of comparison for the performance of the heat pipe as various experimental parameters are varied, an overall thermal conductance G_{hp} is defined. This quantity is defined as follows:

$$G_{hp} = \frac{Q_{total} - Q_k - Q_{loss}}{\Delta T} \quad ,$$

where:

Q_{total} = measured power input to electrical heaters in watts,

Q_k = calculated and experimentally verified copper conduction thermal power in watts,

Q_{loss} = thermal losses through fiberglass insulation in watts,

and the units of G_{hp} are watts/degree F. Under typical operating conditions with Q_{total} = 40 watts, the copper conduction loss $Q_k \simeq 10$ watts, and the other thermal losses $Q_{loss} \simeq 2$ watts.

Figure 5a shows the overall thermal conductance plotted as a function of tilt for various values of electrical heater input power. Note that G_{hp} is a relatively weak inverse function of input power, as expected for groove-limited operation.

Figure 5b shows more plots of G_{hp} versus tilt for various condenser temperature values. Note that the highest condenser temperature value gives the best overall thermal conductance. This is because of the enhanced vaporization and condensation heat transfer at higher vapor pressures.
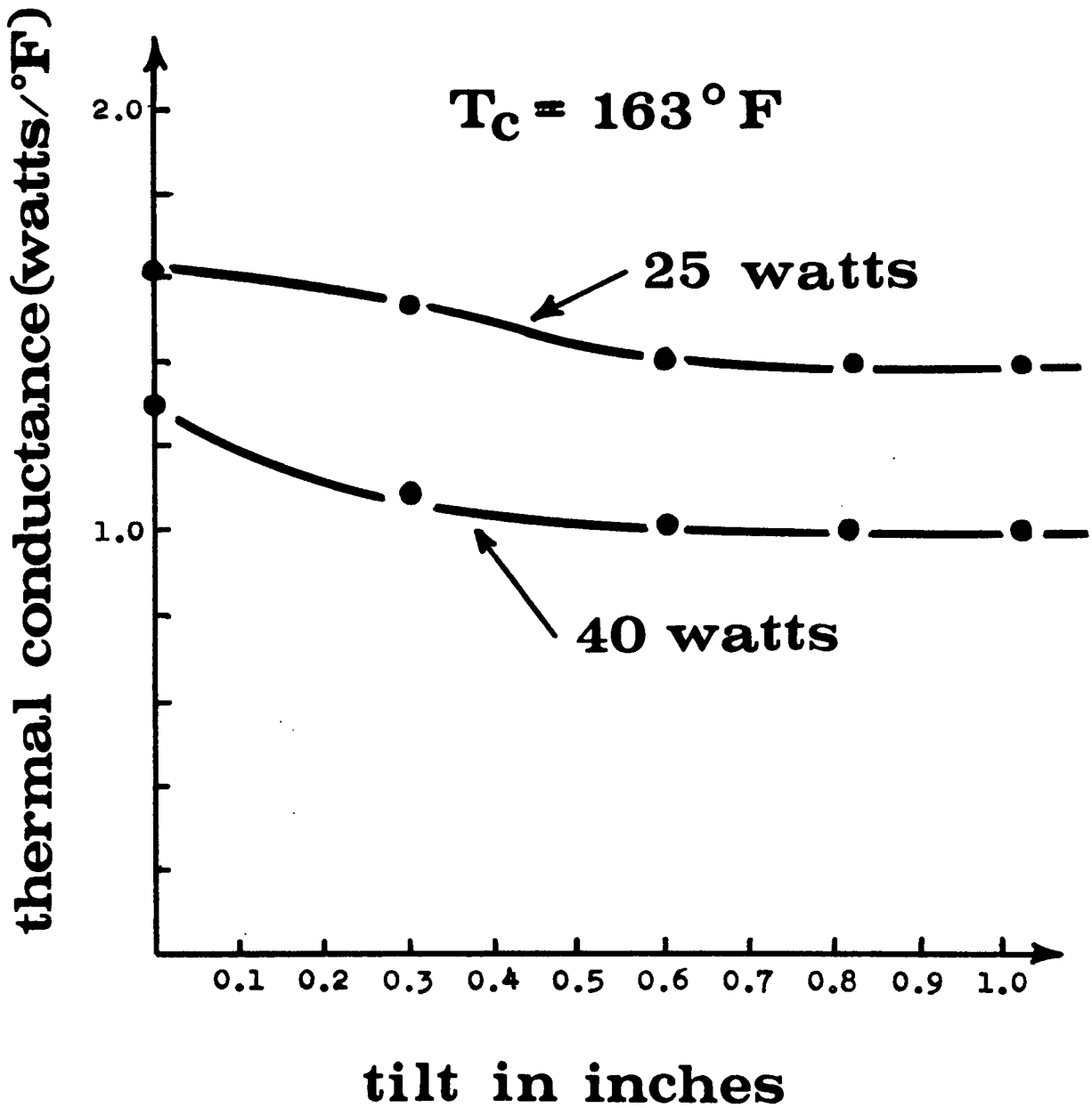
Figure 5a. EHD heat pipe data. Overall heat pipe
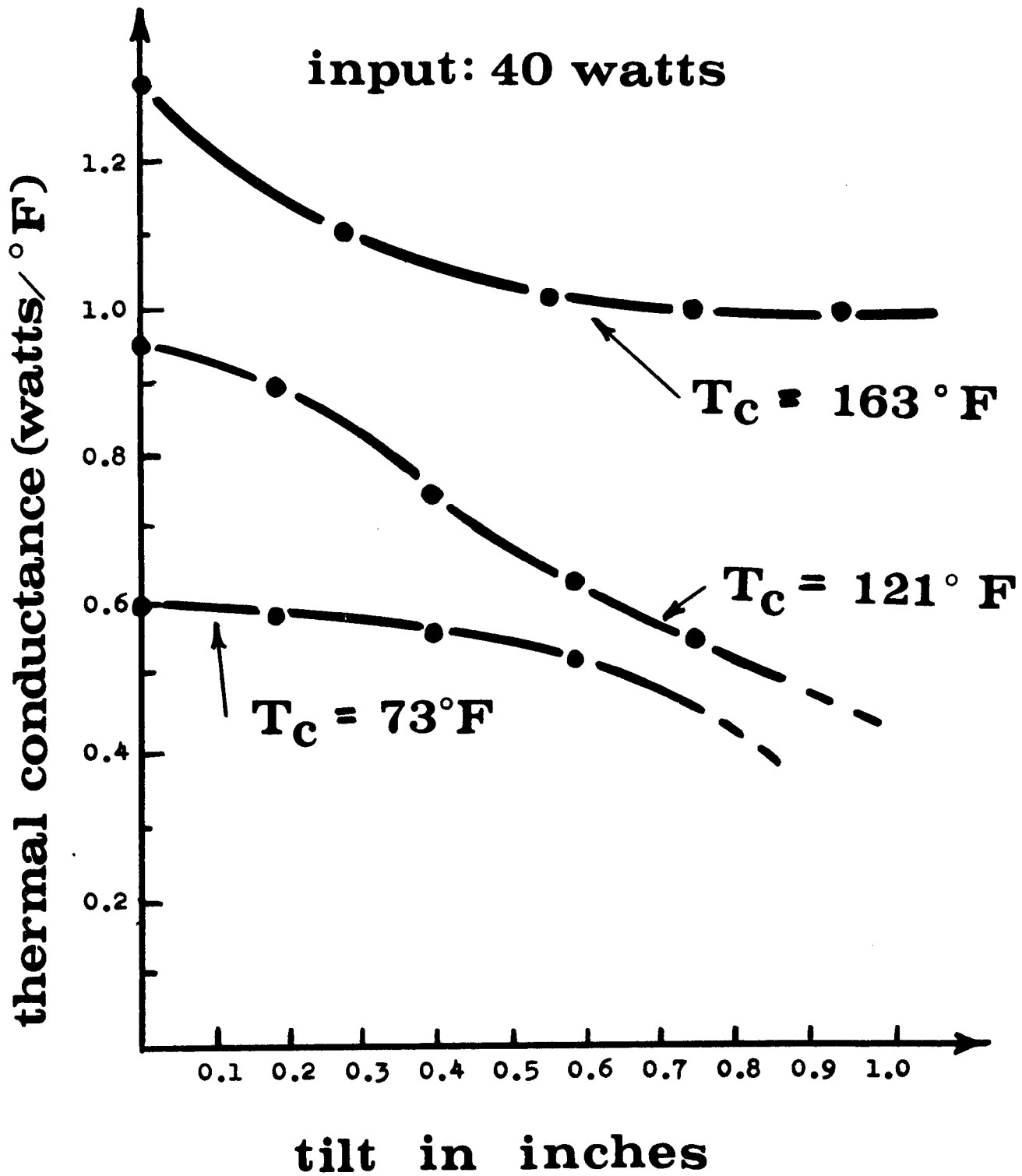thermal conductance G_{hp} versus tilt.

Figure 5b. EHD heat pipe data. Overall heat pipe
thermal conductance G_{hp} versus tilt.

The higher pressure operating point provides an added advantage in increased vapor electrical breakdown strength.

B. Other Experiments and Observations

Screen Wick Experiment

Some effort was devoted to the utilization of a 100 mesh copper screen wick placed over the grooves in the evaporator to enhance the circumferential capillary pumping. Unfortunately it was not possible to hold the screen firmly to the walls; the use of a mandril would have permanently damaged the grooves. Thus these experiments were deemed to be inconclusive. Nucleate boiling appeared to dominate at all power levels.

DC Behavior

Of principal concern to this program is the question of whether or not the use of dc high voltage is possible. The issue revolves around the relative importance of several dc surface instability mechanisms[4,5] in the EHD flow structures. Under certain conditions (particularly when the liquid is not flowing) these instabilities disrupt the hydrostatic equilibrium of EHD flow structures significantly. However, as previously observed by the author, dielectric liquid flow in EHD flow structures apparently sweeps away the accumulating surface charge and suppresses the dc instabilities. The most common mode of operation in the device is the *quiescent mode*. The dielectric liquid surface is observed to be glassy smooth under this condition.

Occasionally, a *spitting mode* is observed. In this mode, thousands of very tiny jets of liquid shoot up from the liquid surface just off the high voltage wire, and emit tiny droplets of liquid which form a visible

cloud in the evaporator. The droplets impact on the evaporator wall surface and then evaporate, the surprising result being a very efficient new heat transfer mode. A third related condition is the *nucleate boiling mode*. In this case vapor bubbles appear to form at the base of the tent liquid structure on either side and grow to a size of approximately 1/4 inch before bursting. These bubbles do not in themselves disturb the EHD flow structure significantly.

When the high voltage is first turned on during a test, some minor surface disruptions are usually observable in the evaporator, occasionally accompanied by nucleate boiling. Within a few minutes this activity usually subsides and the quiescent mode dominates. Occasionally during testing however, vigorous spitting occurs when the high voltage is applied. Once vigorous spitting starts, it almost always remains. In this case, tests are terminated and the heat pipe is disassembled and cleaned. The condition of the high voltage wire electrode appears to influence this phenomenon quite heavily. Clean, highly polished electrodes with a minimum of surface scratches seem to allow attainment of the quiescent mode, but if the electrode is scratched or if an arc occurs, the spitting mode returns. The relation-ship of nucleate boiling to the condition of the electrode is not known, except that nucleate boiling is seen more often when spitting is present. The relationship of spitting to chemical degradation of Freon-113 is unknown at this time.

As expected the use of ac high voltage (> 300 Hz) minimizes the presence of spitting on even badly damaged electrodes, confirming the suspicion that the spitting phenomenon is intimately related to charge relaxation in the dielectric liquid.

Electrical Breakdown

Electrical breakdown of the vapor in the EHD heat pipe has not been a significant problem in experiments to date. Breakdown only occurs when the spitting mode is present or when nucleate boiling is unusually severe, and as stated before, these problems can be avoided by proper care in electrode preparation.

Flow Structure Failure

EHD flow structure failure is related to the voltage required to maintain a completely filled structure in hydrostatic equilibrium under adverse gravity (evaporator above condenser). Under normal conditions, with a uniform electrode structure running axially the length of the heat pipe, an insufficient voltage will result in liquid not quite reaching the far end of the evaporator. Thus failure occurs at the highest point of the structure. But if the structure is sufficiently non-uniform, specifically if the electrode spacing is smaller at the evaporator than at the condenser, then, as the voltage is decreased, or if the tilt is increased, failure can occur first at an intermediate point along the structure. This situation has been observed with the EHD heat pipe. Because the design option of spatially-varying flow structures offers some apparent advantages, further study of this problem is necessary.

IV. Discussion

A. Summary and Conclusions

Based upon the experimental data and observations, a number of conclusions have been reached. These are included in the summary of the present state of the research program below.

Proof of Concept

1. EHD flow structures can be used to provide liquid communication between the condenser and evaporator of a heat pipe. In this capacity they serve an artery-like function quite similar to the tunnel artery of high performance heat pipes.

2. The voltage provides a remote electrical servo linkage of possible use in certain thermal control applications.

3. At least one *hybrid* flow structure, utilizing capillary and electrohydrodynamic forces, has been found functional. The dielectric tent flow structure has been found to be compatible with circumferential grooves.

Concept Evaluation

The experiments reported are with a heat pipe which fares poorly when compared to conventional capillary devices. The grossly sub-optimal size and configuration of the grooves appear to be at fault. Thus, it is felt that the final engineering evaluation of the EHD heat pipe concept must await further tests with an optimally designed device.

Use of DC High Voltage

The use of dc high voltage is possible if special care is used in cleaning and polishing the electrode. These precautions also appear to decrease the occurrence of nucleate boiling. A 1/16 inch diameter wire electrode works better than a 1/32 inch diameter wire in the suppression of

spitting, because of the lower electric field strength for the same voltage drop at the surface of the larger diameter wire. The use of alternating high voltage at ~300 Hz also suppresses spitting.

## B. Proposed Further Experiments

EHD Heat Pipe Performance Evaluation

The primary goal of future experimental effort with EHD heat pipes must be the evaluation of the performance capabilities of such devices. The design, construction, and testing of an optimized EHD heat pipe is thus central to the continuation of the program. In this way questions regarding the practical value of EHD heat pipe technology will become answerable.

The novel nature of the electrohydrodynamic heat pipe presents us with a dilemma regarding the design ultimately to be decided upon. Several possible designs are summarized here.

First, starting with the basic configuration of Figure 2a, either grooves, sintered powder, or a screen wick may be used for circumferential flow of dielectric liquid. Further, additional EHD flow structures may be implemented to help distribute the liquid to the heated evaporator surface. Another possible design, shown in Figure 6a, would employ an electrode structure (not necessarily the dielectric tent) supported by an insulating capillary structure in the center of the heat pipe. This device, quite similar to artery heat pipes, would not suffer the disadvantage of Figure 2a, where the liquid insulates a portion of the wall from the vapor core.

It is concluded here that each of these ideas must receive at least some consideration in any evaluation program of EHD heat pipe concepts. A more flexible experimental apparatus which will allow study of these various schemes is presently in the conceptual design stage. Based upon these experiments, the design of a truly optimized EHD heat pipe will be possible.
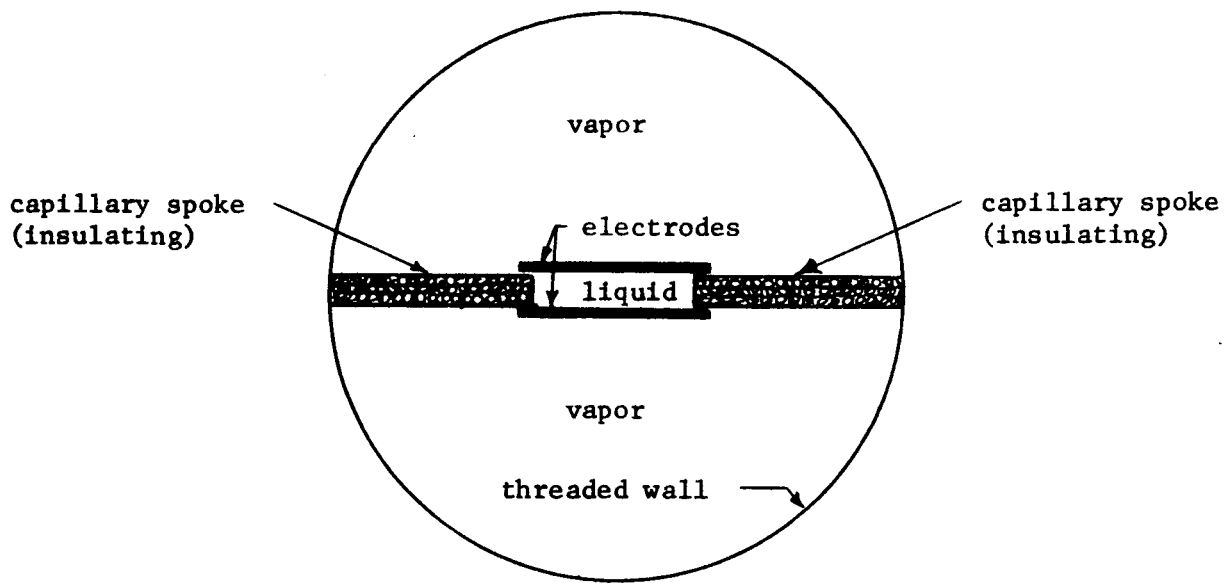
(a.) Conceptualization of heat pipe with EHD arterial flow structure in center of device cross-section. Dielectric capillary wick structure provides radial flow for circumferential distribution in evaporator and collection in condenser.
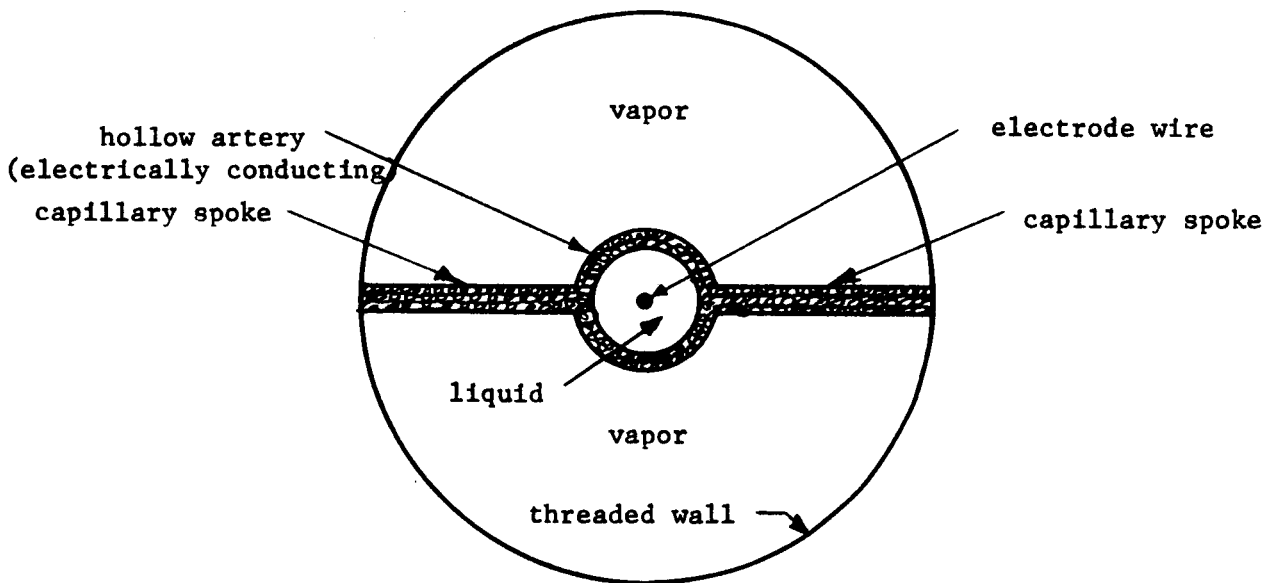
(b.) Cross-section of hollow artery heat pipe with EHD priming structure. Voltage is only applied during priming.

Figure 6. New EHD heat pipe concepts.

Though the next stage of the experimentation will continue to rely upon Freon-113 as a convenient working fluid, the use of other far better dielectric fluids[1] should not be neglected. This may mean going to higher or lower temperature fluids.

EHD Hollow Artery Priming Concept

Figure 6b shows a concept of possible value in the priming of hollow arteries in high performance heat pipes. The artery is equipped with a single electrode wire which is insulated from the wick structure. The capillary itself is made of electrically conductive wicking material such as screen mesh or feltmetal. The high voltage is applied to the electrode wire only during initial priming and re-priming. Such a system shows initial promise in providing reliable priming of high performance devices.

APPENDIX

GROOVE DIMENSIONS AND THE CAPILLARY PUMPING LIMIT

The circumferential grooves in the copper tubing were found to be
inadequate for the effective distribution of dielectric liquid in the
evaporator. This inadequacy was due in part to the use of an apparently
blunted tool in the groove cutting. Further, though 80 grooves per inch
had been originally specified, only ~ 50 grooves per inch were finally
obtained. When this problem became suspect, a section of sample grooved
copper tubing was cut off and etched with acid, in order to measure the
average groove size, spacing, and cross-sectional configuration. The
results are summarized in Figure A1 below.

<u>average measurements</u>

$h \ \simeq$ .0046" (.12 mm)

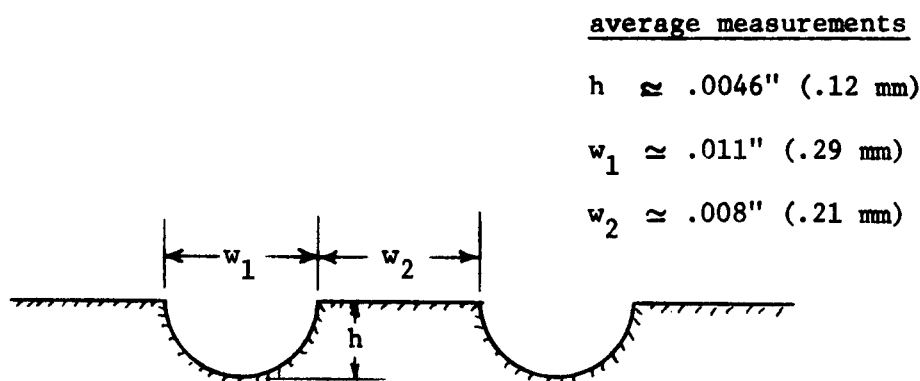$w_1 \simeq$ .011" (.29 mm)

$w_2 \simeq$ .008" (.21 mm)

Figure A1.   Sketch of Groove Cross-section
with Average Dimensions.

Note the evidence of a blunted cutting tool: the grooves are wider
than they are deep. Also, the grooves are spaced too far apart to make
really effective use of the enhanced evaporative heat transfer mechanism
desired.

The static capillary pumping height of these grooves in the EHD heat pipe is observed to be approximately 3/8" (~ 1 cm). This value checks reasonably well with calculations.

$$h = \frac{\gamma \cos \theta}{\rho gr} \quad , \tag{A1}$$

where h is the static pumping height, γ is the surface tension, θ is the contact angle, ρ is the liquid density, g is gravitational acceleration, and r is the radius of curvature. Because Freon-113 is a good solvent, we let the contact angle $\theta = 0$.[6] The radius of curvature r is set equal to $w_1/2$. Using these numbers in Eq. (A1), we obtain

$$h \simeq 1 \text{ cm} \quad , \tag{A2}$$

which checks closely with observation.

These grooves are clearly inadequate on several counts. Deeper finer grooves, more closely spaced, should greatly improve operation. Further, the heat pipe diameter of 1 1/4" is far too large, because the capillary forces must be able to pump against gravity to a height of one diameter, even when the heat pipe is horizontal.

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