Terrestrial and Micro-gravity Experimental Study of Micro-scale Heat Transport Device Driven by Electrohydrodynamic Conduction Pumping

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Abstract -- **Research on heat transport in micro-scale has been generating much interest in recent years due to the development of state-of-the-art, high-powered electronics used in aerospace and terrestrial applications and the large amount of heat produced during their operation. Micro-scale, two-phase flow heat transport devices are seen as one solution to this problem of high heat-flux removal. Micro-scale devices have extremely high heat fluxes due to the small heat transfer surface area. In addition, the need for robust, non-mechanical, lightweight, low-noise and low-vibration devices in specialized aerospace applications has led researchers to investigate electrically driven flow devices rather than their mechanical counterparts. This paper for the first time presents the results of an experimental study of a unique micro-scale heat transport device that is driven by electrohydrodynamic (EHD) conduction pumping. Results from ground-based single-phase experiments with a micro-scale EHD pump are compared to experiments conducted on board a variable-gravity parabolic flight. Data show that the EHD pump functions well in both environments and can potentially be used in heat transport devices in the absence of gravity.**

Index Terms—**Electrohydrodynamics, Dielectric Liquids, micropumps, microgravity.**

I. Introduction

Heat transport in micro-scale is currently a widely studied area of heat transfer with many fundamental and applied paths of research. Micro-scale, two-phase flow cooling loops are used in heat transfer applications where traditional passive techniques and single-phase loops are incapable of removing the heat being generated in the system. The phase change of the fluid results in higher heat transfer coefficients and higher heat removal than single-phase heat transport due to the latent heat and convective boiling of the fluid. In addition, reduction in size results in a more compact thermal management system that is more efficient and practical than a larger macro-scale system. Micro Heat Pipes (MHPs) are examples of such small-scale two-phase flow devices. MHPs are used in aerospace applications and cooling of microelectronics and consist of an evaporator section for heat absorption, a condenser section for heat removal and an adiabatic section. The working fluid moves between the evaporator and condenser through a wicking structure or a micro-groove. Both use capillary pressure difference to drive the fluid in the loop [1]. While these devices function well and have high heat transport capacity with no external driving mechanism, they are limited by the capillary pressure head. In situations where the pressure drop due to viscous forces can no longer be overcome by this capillary mechanism, heat transport will cease. As there is no way to increase the pressure head generated, the system stalls and goes into a state of evaporator dry-out, which is usually accompanied by rapid increase in temperature and possible damage to equipment [2].

Electrohydrodynamic (EHD) conduction pumping is a technique that can effectively be used to overcome problems with evaporator dry-out. This has already been demonstrated in a macro-scale monogroove heat pipe by Bryan and Seyed-Yagoobi [3] where immediate recovery from evaporator dry-out during startup and transient heat loading was shown. Substantial heat transport with exceedingly low power consumption was also achieved.

The key mechanism behind EHD conduction pumping of a dielectric liquid arises from the interaction of the induced electric field and flow fields via the Coulomb force. It involves the dissociation and recombination of a neutral species, AB, and its positive and negative ions, A+ and B-, respectively

$$AB \xleftarrow[\text{Recombination}]{\text{Disocciation}} A^{+} + B^{-} \quad (1)$$

When the external electric field exceeds a threshold (usually on the order of 1 kV/cm, depending on the fluid characteristics), the rate of dissociation exceeds that of recombination. There is a non-equilibrium layer of charge that forms in the vicinity of the electrode, due to ion motion caused by the Coulomb force. This heterocharge layer (i.e. layer of charges of opposite polarity to that of the adjacent electrode) has a thickness that depends on dielectric liquid properties and the external electric field. The attraction of the heterocharges to the adjacent electrodes causes bulk fluid motion.

There have been some recent research efforts using various EHD techniques in two-phase heat transport systems. Mo et al. [5] demonstrated thermal management of an EHD assisted capillary pumped loop with enhancement in heat transfer coefficient. Jeong and Didion [6] have also shown that an EHD conduction pump can be used for stand-alone system for high heat flux thermal control of laser equipment. In addition, active temperature control of a micro heat pipe array was also explored by Yu et al. [7] with the development of a simulation and experimental model.

While most of these studies are generally in macro-scale, there is an interest to develop EHD conduction pumping in micro-scale. The reason is that there is a significant enhancement of heat transfer that accompanies such a change in scale. For a given flow regime, as geometry of the pump becomes smaller, the convective heat transfer coefficient increases dramatically in order to maintain the balance between conduction and convection heat transfer. Therefore, considerable amounts of heat can be removed per unit surface area. From a practical standpoint, as the spacing between electrodes approaches the order of several hundred microns, the electric field strength becomes intense at lower voltages than those applied in a macro-scale pump. This is advantageous since voltages are reduced from several kilovolts to several hundred volts. In addition to the above, the effect of absence of gravity on conduction driven flows has not been explored at all. The effects of gravity cannot be eliminated under terrestrial (1-g laboratory) testing. To eliminate the effects of gravity, well designed experiments need to be conducted in a microgravity environment. These experiments will enable researchers to develop an understanding of the importance of gravitational acceleration in single- and two-phase heat transfer and mass transport in EHD conduction driven flows.

The micro-pump described in this paper has a unique disc-electrode design which ensures that the electrodes are integrated directly into the pumping channel. This prevents any obstructions which may hinder flow generation and reduce the flow rate. The present work extends the study of two-phase heat transport devices by Pearson and Seyed-Yagoobi [8] by moving from rectangular meso and micro-scale channel flow to circular tube flow and will allow examination of differences in electric field, flow field and heat transfer that result from this change in geometry. It will also pave the way for a full micro-thermal management system driven by EHD conduction as is currently developed in [8]. From an application perspective, the research and development effort and understanding of microgravity environment effects will provide technological advances that will meet the inevitable need for high heat flux thermal control for spacecraft. However, while the primary focus of this research is heat transfer enhancement and the experiment was designed accordingly, the results presented in the paper are purely for single-phase pressure and flow generation. As such, heat transfer results are not included in the paper and are left for future experiments.

II. Electrode Design and Experimental Setup

A. *Electrohydrodynamic Pump Design*

The geometry of the electrodes in the EHD pump can be designed such that a nonsymmetric electric field is created, resulting in a net electric force. The direction of fluid flow can be changed by modifying the electrode design. For the experiments in this paper, the EHD pump is fabricated from disc-electrodes with a central hole of 1 mm diameter, which when stacked together with other electrodes forms a tube of 1 mm inner diameter. Stainless steel discs of differing thicknesses are used to create the asymmetry in the electric field. Fig. 1 shows the electrodes, along with Teflon spacers which make up a single electrode pair and the assembled EHD pump with 20 electrode pairs. It should be noted that this pump has the same specifications as in [9] with the important difference of having twice as many electrode pairs. This improves pump performance significantly with only a slight increase in the input power. This pump was also used in a different loop fabricated with various instrumentation installed for two-phase flow.

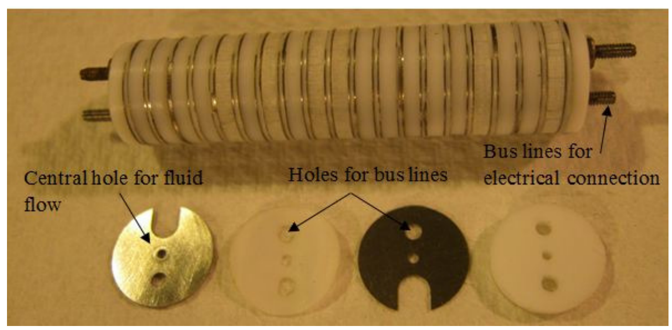

Fig.1. Electrodes and spacers (top) and assembled EHD pump (bottom)

At the top of Fig. 1, from left to right, are the wide electrode, narrow spacer, narrow electrode and wide spacer. The wide spacer is used to isolate adjacent electrode pairs and hence is significantly thicker than all other components. Holes in each electrode disc are used to connect bus lines for high voltage and ground connections. The narrow and wide electrodes are connected to the ground and high voltage lines, respectively. Yazdani and Seyed-Yagoobi [10] have shown numerically that the flow is always generated from the narrow electrode to the wide electrode, regardless of polarity. This has also been shown experimentally [11]. The electrode and spacer arrangements in a single electrode pair are shown in Fig. 2 and dimensions are in Table I. The total length of the EHD pump with 20 electrode pairs is 48 mm.

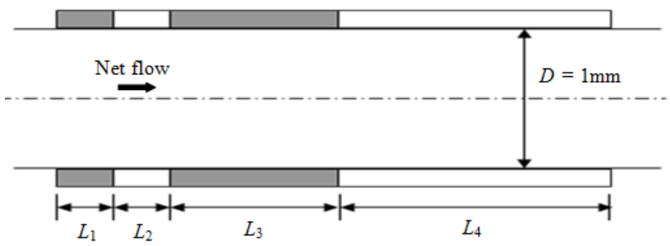

Fig. 2. Single-pair electrode and spacer arrangement

TABLE I
COMPONENT DIMENSIONS FOR FIG. 2

Component	Thickness
Narrow Electrode	L_1: 0.127 mm
Narrow Spacer	L_2: 0.127 mm
Wide Electrode	L_3: 0.381 mm
Wide Spacer	L_4: 1.588 mm

B. *Experimental Setup*

The EHD conduction pump is one component in a heat transfer loop, which also includes a preheater, evaporator, condenser and reservoir. A schematic of the experimental setup is shown in Fig. 3. The preheater, evaporator and condenser were not actively controlled for the present studies. The reservoir houses a wick structure, which – when heat is added to the liquid in the bottom of the reservoir – separates the liquid and generated vapor, allowing the saturation pressure of the liquid in the loop to be controlled based on the temperature set point of the reservoir heater. The wick is required to maintain the vapor-liquid separation during microgravity. The reservoir heater is relay-controlled to 28°C (4-6°C above ambient), which corresponds to a saturation pressure of 102.3 kPa (14.84 psia) for the working fluid HCFC-123 [12]. Fluid properties (at 25°C) are in Table II.

TABLE II
WORKING FLUID PROPERTIES

Property	Value	Ref.
Viscosity (Pa·s)	456E-6	[12]
Liq. density (kg/m^3)	1463	[12]
Latent heat (kJ/kg)	170	[12]

During testing, the saturation pressure ranges from 102.0 to 105.5 kPa. Thus, the fluid in the loop is always sub-cooled because the pressure of the liquid in the loop (set by the reservoir) is greater than the corresponding saturation pressure based on temperature of the fluid in the loop (22-24°C).

The following measurements are recorded during testing: absolute pressure of the fluid at the pump inlet (Druck PDCR 4361, ± 710 Pa), differential pressure across the pump (Honeywell FP2000, ± 6 Pa), liquid flow rate (Sensirion SLQ-HC60, ± 0.35 cm^3/s), acceleration due to gravity (Honeywell MA312, ± 0.02 g), applied EHD pump voltage (Trek 677B, ± 2 Vdc) and pump current (Trek 677B, ± 5 µA). Data is acquired using the Agilent 34970A data acquisition unit, two Agilent 34901A 20-channel multiplexer cards and one Agilent 34903A 20-channel general purpose switch card. A National Instruments (NI) GPIB-USB-HS controller connected to a notebook computer running NI LabVIEW virtual instrument software allows users to control the loop.

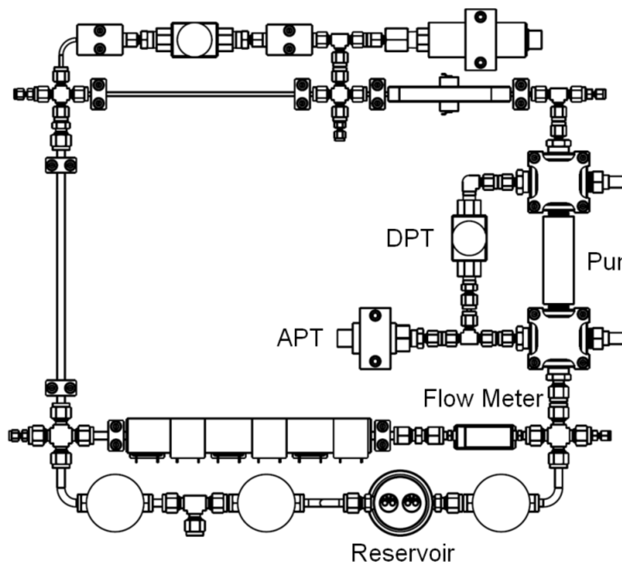

Fig. 3. Schematic of experimental setup

C. *Microgravity Test Environment*

The experiment was flown aboard the Zero Gravity Corporation's modified Boeing 727 aircraft. The experiment was installed in a specially designed rack with all instrumentation and data acquisition systems fixed in place. The rack was then mounted in the aircraft, shown in Fig. 4.

Fig. 4. Experiment rack installed in variable gravity aircraft

As shown in Fig. 4 the experiment is located on the second shelf from the top, with the top shelf reserved for a laptop computer for data acquisition. Power supplies and other data acquisition systems were installed in the shelves below. The aircraft achieves variable gravity by performing parabolic maneuvers. The parabolic maneuvers begin with a 1.8-g pull-in, followed by approximately 20 seconds of 0-g, and terminate with a 1.8-g pull-out, as shown in Fig. 5 [13]. The parabolas were flown in four sets of 10 per flight in general and four flights were flown in total, over a period of four days. The acceleration due to gravity was monitored using an accelerometer (described previously) attached to the experiment base plate where the fluid loop was also located.

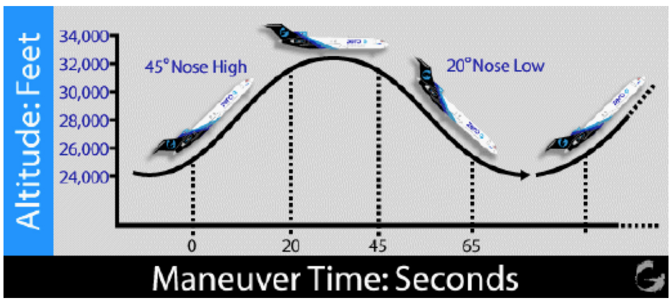

Fig. 5. Variable gravity parabolic maneuver [13]

III. Results and Discussion

Single-phase data were acquired in ground-based tests and in the microgravity environment. All data were continuously acquired by the data acquisition system even during the 1.8-g portions of the flight. The data presented in the graphs that follow are for both the high gravity and microgravity conditions and represent values averaged over the time for which the condition lasted. This information was available from the accelerometer readout. Data from ground based tests were averaged over similar periods of time in order to maintain consistency despite random uncertainties. The ground based tests were conducted immediately after the flight tests. Fig. 5 shows pressure generation of the EHD pump and current as a function of applied EHD voltage in both terrestrial and variable gravity tests.

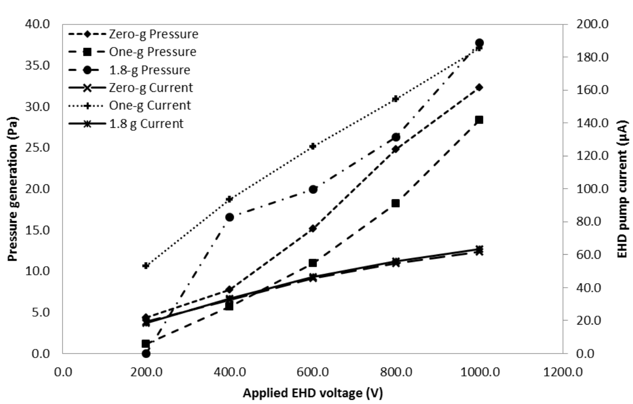

Fig. 5. EHD pump pressure generation and current vs. applied EHD voltage

It should be noted that while the pressure generation is relatively low, the purpose of the experiment was to confirm the functionality of the EHD pump in microgravity, rather than to provide optimum performance. As can be seen, the pressure generation in microgravity is higher than in terrestrial tests. However, the current in terrestrial tests is significantly higher which may be attributed to changes in the saturation temperature and pressure when each test was conducted. Due to temperature control onboard the aircraft, the average temperature during the variable gravity flight was slightly different from the average temperature on the ground during testing. This temperature difference may have affected the relative permittivity and viscosity of the fluid which could result in changes in pressure generation and flow velocity [14]. The flow rate and flow velocity generated by the EHD pump is presented in Fig. 6. The flow velocity is calculated based on the cross-sectional area of the EHD pump through which the fluid flows (i.e. the 1 mm diameter hole). As with the pressure generation, flow rate generation also shows an increase in microgravity.

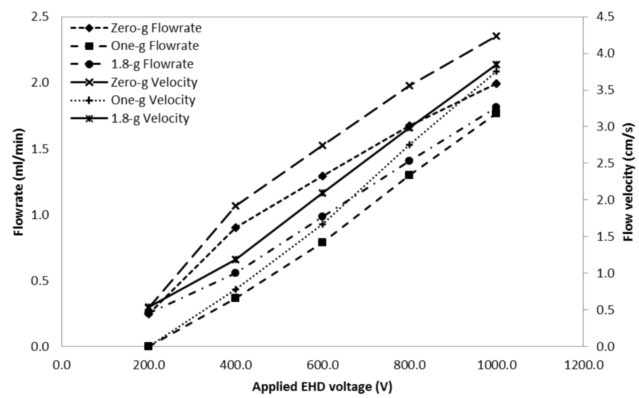

Fig. 6. EHD pump flow rate and flow velocity vs. applied EHD voltage

The EHD power, calculated from the EHD voltage and current is shown in Fig. 7 as a function of the applied EHD voltage.

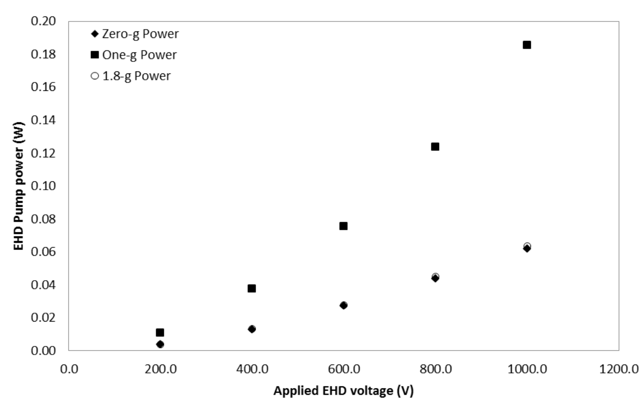

Fig. 7. EHD pump power consumption vs. applied EHD voltage

As can be seen, the power consumption is much higher for terrestrial tests, due to the high current shown in Fig. 5.

However, maximum power consumption is still much below 1W which makes the potential benefit of using EHD conduction pumping for various applications even greater.

IV. Conclusions

The use of EHD conduction pumping in both ground-based and zero-gravity environments has been confirmed. Single-phase pressure and flow data indicate that the device functions well and can be used in subsequent two-phase flow testing. While there are differences in flow and pressure generation, preliminary single-phase data show that the absence of gravity does not affect performance of EHD pumps based on conduction mechanism.

Acknowledgments

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