Characterization of electrohydrodynamic heat transport components in a space-type nuclear reactor

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Abstract

The paper characterizes and describes the design of a capillary pumped loop with an EHD enhanced evaporator for use in a space reactor. The evaporator uses a wick to transfer the vapour and heat to a vapour section where the vapour is pumped using a EHD gas pump. The vapour is then transferred to a condenser where it is condensed into a liquid and recirculated after the heat has been removed. The design is shown in concept to be an effective method of heat transport in zero and microgravity environments.

1.0 Introduction

The investigation and exploration of outer space has been of interest to science and engineering since ancient Greece and Aristotle. In recent decades, humanity has ventured out into space itself on missions of exploration and science. Satellites and spaceships have been sent into orbit and deep space to further our understanding of the solar system and the universe. These satellites and spaceships require power and propulsion. Research has shown nuclear space reactors are an excellent choice to provide power generation and propulsion in missions to both near Earth orbit and deep space missions and applications. Especially for deep space missions as the decrease solar intensity due to the increasing distance between the spaceship and the sun makes solar power impracticable [22]. Nuclear space reactors have been studied for over 4 decades beginning in Russia in the 1960s where the Russians eventually developed a reactor to power satellites. Between 1970 and 1988 Russia launched several nuclear powered satellites into orbit. Since then several satellites using nuclear power were launched and nuclear power have also been used in recent exploratory unmanned missions to Saturn and Pluto [36]. As applications in space increase and exploration ventures further out into the solar system the demand for nuclear reactors in space applications will only increase.

Space type nuclear reactors differ in design and design requirements to traditional reactors on Earth used in power plants or even those on submarines due to the differences the environment on Earth and in space, mainly the significant reduction in gravity. Once in space, the reactors will be difficult to repair so reliability and operation life increase even further an importance to ensure a mission's successful completion. If power cannot be provided to the ship or outpost it could leave people stranded without the power in the middle of space, so ensuring operation life and removing any single point failures is a key aspect of space reactor design [33]. Currently, new designs for space reactors for both power generation and propulsion are being studied and developed around the world including NASA and other space agencies [22]. These studies are focusing on advanced reactor designs such as pebble bed and fast energy spectra reactors [22]. However, heat transport and its related systems still need to be studied and redeveloped so that they are suitable for a space environment. Studies involving heat transfer [22] have shown that these reactors will require new methods of transporting heat more suitable to space environments as opposed to the traditional methods used in land-based reactor designs. The difficulty in repairing and maintaining components in space, limited resources and the micro gravity environment require heat transport systems to have minimal moving components, minimal power consumption and be able to operate efficiently in a zero or micro gravity environment.

One design that appears promising to provide heat transfer and cooling to a nuclear space reactor is an Electrohydrodynamically (EHD) enhanced capillary pumped loop. The purpose of this paper is to characterize an EHD enhanced capillary pumped loop designed to provide heat transport to a space reactor [1-21]. Figure 1 displays a schematic of such a design.

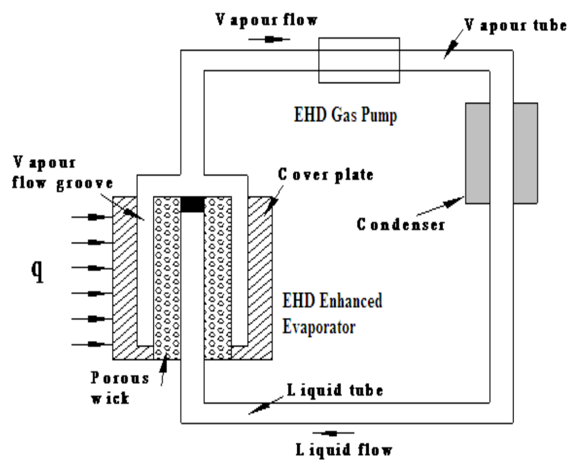


Figure 1: Schematic of an EHD Enhanced Capillary Pumped Loop

The loop consists of an evaporator section; a condenser, and connected piping. The transport fluid is Freon 134a. Heaters are applied to the evaporator section, as shown in Figure 2.

Figure 2: Picture of an EHD Evaporator

The outer channel of the evaporator boils the Freon. Between the outer channel and the inner channel is a porous polyethylene wick of pore size 20 microns. As the fluid in the outer channel evaporates, Freon passes through the wick via capillary action.

The evaporated Freon transports to the condenser where it is condensed back to a liquid state. Research has shown [16] that natural circulation occurs in this configuration, but is limited by the performance of the capillary action. Dryout of the wick can occur causing the impairment of the fluid transport.

Additional research [3] has demonstrated that the application of an EHD electrode in the evaporator can enhance fluid transport across the wick.

Figure 3: Cross Section of an EHD Evaporator

An electrode is included in the wicked evaporator of diameter 3.1mm to enhance fluid transport. To further enhance the fluid transport, an EHD gas pump is considered in the vapour leg of the loop. The presence of a gas pump is believed to help the vapour reach the condenser and enhance the flow from the evaporator by creating backpressure in the system. The pump then allows the vapour leg to act as a push-pull system between the evaporator and the condenser. More information on the loop and its components is provided in Sections 3 and 4. EHD and its accompanying force is explained in Section 2.

2.0 Electrohydrodynamics

EHD refers to the motion of a fluid generated by forces induced by an electric field. The accelerated ionized molecules collide with neutral particles, exchanging momentum inducing a gas flow away from the electrical source [2].

The electrical field is usually created by applying high voltage to an electrode. Under sufficient applied voltage, a corona type discharge can occur. The current created by a corona discharge then moves towards a ground electrode, due to Coulomb's forces, inciting the fluid motion in a gas. The force acting on the fluid causing motion is called the electrophoretic force [1-7]. The evaporator . When multiple phases are present in the flow, the dielectric constant for each phase is different, adding additional force to the system known as the dielectrophoretic force..

As EHD motion is generated using high voltages and a low current, the electric field equation can be simplified for EHD motion and is represented by the following equation:

$$\vec{F}_{EB} = \rho_{ie}\vec{E} - \frac{1}{2}E^2\nabla\varepsilon + \nabla\left[\frac{1}{2}\rho E^2\left(\frac{\delta\varepsilon}{\delta\rho}\right)_T\right] \quad (1)$$

Each term in Equation 1 represents a component of the force. The first term is the electrophoretic force, the second is the dielectrophoretic force and the last term is the electrostrictive force. The electrostrictive force is the force generated from the changing temperature of the system on the dielectric fluid. At any time in a system the three forces could be acting on the fluid causing motion, however often one force is more dominant at a specific point or region than the other forces [1]. To determine the effect each force has on a particular system, dimensionless numbers have been generated to calculate each term's influence on the system.

The Ehd number is a ratio that represents the relative strength of the electrophoretic forces compared to the viscous forces in the system. The Ehd number has the following equation:

$$Ehd = \frac{I_s L^3}{A \rho_f \upsilon_f^2 \mu_i} \qquad (2)$$

Where I_s is the discharge current, L is the characteristic length, A is the cross-sectional area, ρ_f is the fluid density, ν_f is the kinematic viscosity of the fluid and μ_i is the ion mobility of the fluid. For this work, the Ehd number has a value of 0 and 2.5 x 10^5 in the evaporator and gas pump respectively [3].

The ratio of the dielectrophoretic force to the viscous force is called the Masuda number and is represented by the following equation:

$$Md = \frac{\varepsilon_o E_s^2 L^2}{\rho_f \upsilon_f^2} \qquad (3)$$

Where ε_o is the permittivity of free space and E_s is the reference electric field. For this work, the Masuda number has a value of 41.3 and 1.1 x 10^5 in the evaporator and gas pump respectively [3].

The last dimensionless number is the electrostriction number and is the ratio between the temperature dependence of the dielectrophoretic force and the viscous force:

$$Es_E = \frac{\varepsilon_o E_s^2 L^2}{\beta \Delta T_s \rho_f \upsilon_f^2} \qquad (4)$$

Where ΔT_0 is the temperature gradient and β is the thermal expansion coefficient. For this work, the electrostriction number has a value of 65.8 and 1.2 x 10^7 in the evaporator and gas pumps respectively.

Often to determine how the forces are affecting the flow, the force components are compared to the Reynolds number, which is a ratio between the inertial forces and the viscous forces and is defined as follows:

$$Re_f = \frac{\rho_f U D_h}{\mu_f} \qquad (5)$$

Where U is the velocity of the fluid and D_h is the hydraulic diameter.

The dimensionless numbers are usually compared as a ratio of the force component to the inertial forces. Using the Ehd number as an example, the ratio is usually expressed as $\frac{Ehd}{Re}$ or $\frac{Ehd}{Re^2}$. The ratio for this system using this example is 0, while the ratio between the Masuda Number and the Reynolds number squared is 8.7 x 10^8. The ratio is then able to demonstrate that the dielectrophoretic force is acting as the dominant force, while the electrophoretic force is unable to overcome the thermal buoyancy forces in the evaporator [3].

3.0 Capillary Pumped Loop with a Electrohydrodynamic Evaporator

Capillary pumped loops are limited in their ability to transport heat by two key factors. CPLs are constricted by their flow limits. However, previous studies have demonstrated that the addition of EHD forces to the evaporator section can enhance the efficiency of heat transport in CPLs by improving their flow rates by a factor of 3 to 4 times without any significant increase in pressure drop [3]. However, the CPLs flow is still limited in the vapour leg as the flow is controlled by the backpressure generated by the condenser. Improving the flow rates from the evaporator section to the condenser would help improve the flow limits of the loop and increase its ability to transport heat efficiently. A diagram of CPL with an EHD enhancement is displayed in Figure 4.

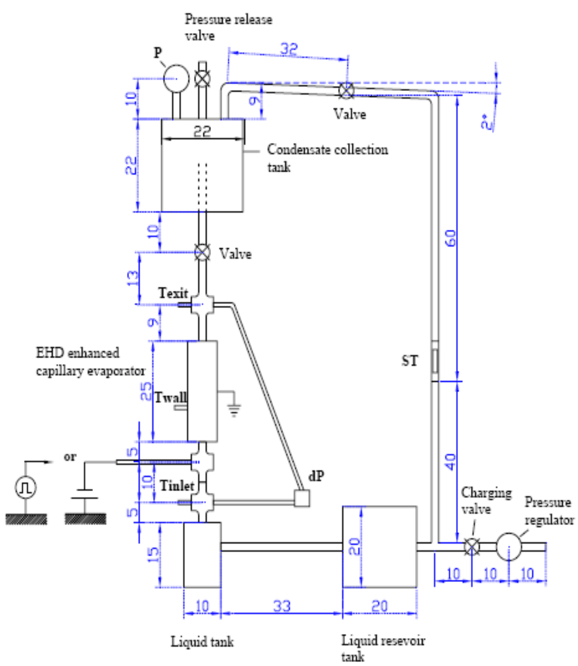


Figure 4: Diagram of CPL with EHD enhancement[1]

The addition of a gas pump such as an EHD gas pump is one proposed solution to further mitigate this issue.

The other issue that causes limitations when using CPLs is wick dry out. The heat and pressure of the loop can cause the wick to dry out quickly and become damaged reducing the efficiency of the loop and its heat transport capabilities. The addition of EHD forces to the loop has experimentally shown to increase the time before dry out [1,3]. However, these results still require further study in this regard. The wick also once its damaged from dry out can lose its shape and become warped. The wick can then shift its position in evaporator causing further decrease in efficiency. A damage wick is displayed in Figure 5.

(a) (b)

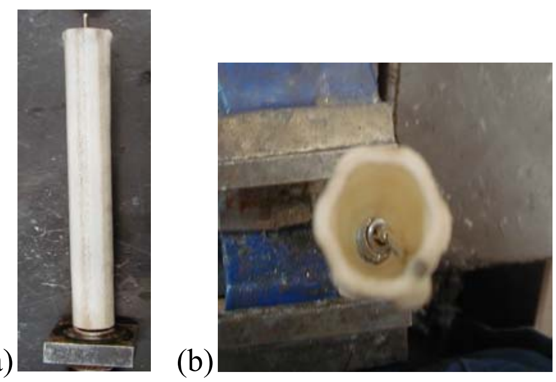
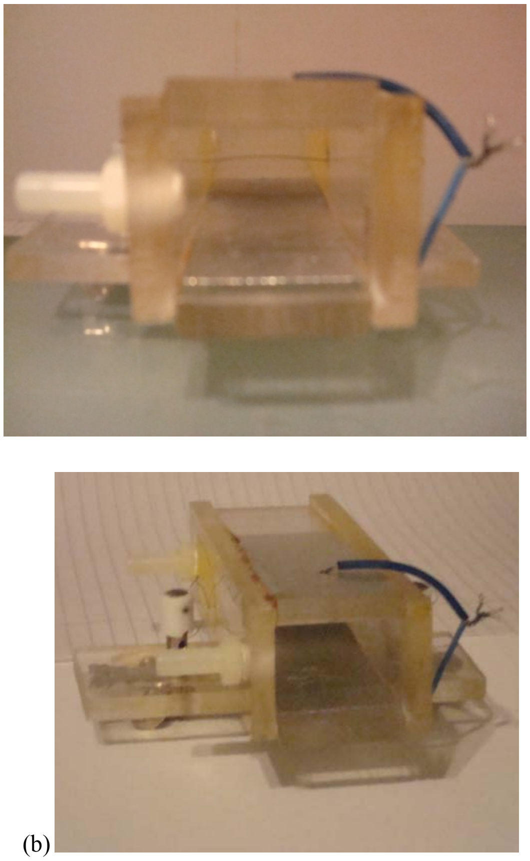


Figure 5: Damaged Wick (a) side view (b) top view

Currently, there are several proposed solutions to alleviate dry out including increasing the surface area of the vapour channels to adding lubricants to prevent dry out. However, further research and study is required to increase the time before dry out occurs in order to improve the heat transport efficiency of CPLs.

4.0 Electrohydrodynamic Gas Pumps

In the EHD enhanced CPL for a space reactor the pump is to be placed in the hot leg or vapour section of the loop to transfer the vapour from the evaporator to the condenser. Figure 6 displays a picture of a typical EHD gas pump.



(a) (b)

Figure 6: Picture of an EHD gas pump (a) side view,(b) end view

EHD gas pumps consist of a corona electrode placed perpendicular to flow inside a flow chamber. Also in the chamber is a ground or a set of ground electrodes. A diagram of a wire-plate type gas pump can be seen in Figure 6.

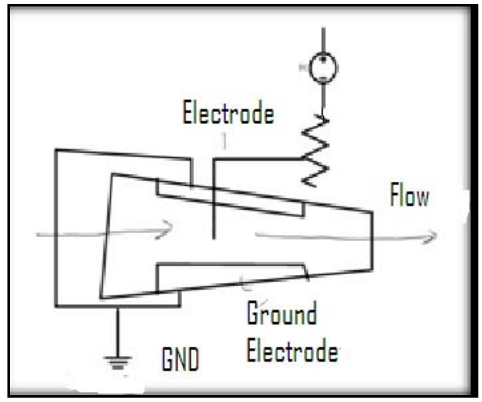


Figure 7: Diagram of a wire-plate type EHD gas pump

The corona discharge then creates an EHD effect causing fluid motion in the direction of flow. Generally, the fluid is single phase for EHD gas pump applications; however the pump can operate using two-phase flow. The conditions within the pump usually are not conducive to generating a phase change, so the flow would already have to be two-phase when entering the chamber. In the CPL the EHD gas pump may incur two-phase flow conditions, but single phase flow is expected.

4.1 EHD Gas Pump Experiments

. The experiments were performed with the pump on a Plexi-glass platform inside a Faraday cage. The working fluid in the experiment is air at room temperature. The experiment used a hot-wire anemometer to record velocity and temperature at the outlet. A T-type thermocouple was also used to measure the outlet temperature. The experiment was performed with the gas pump orientated in both a vertical and horizontal direction. The experiment was also performed on several days over a period between October and January.

The results of the experiment are presented as follows. Figures 8 and 9 present the results of the gas pump experiments measuring voltage and temperature change across the gas pump. TC stands for temperature measurements taken with a thermocouple, while A stands for temperature measurement taken with an anemometer. The data has a consistent profile except for the experiment performed on December 21st.. During this experiment the chamber retain its heat better compared to experiments performed on the other dates. The differences in values may be due to humidity and temperature of the chamber being higher during this experiment compared to the other experimental runs, which share similar humidity and temperature conditions. The next step of the experiment is to verify any humidity effects. Figure 10 displays the velocity measurement at the outlet of the gas pump for the vertical and horizontal orientations, where V stands for vertical and H for horizontal.

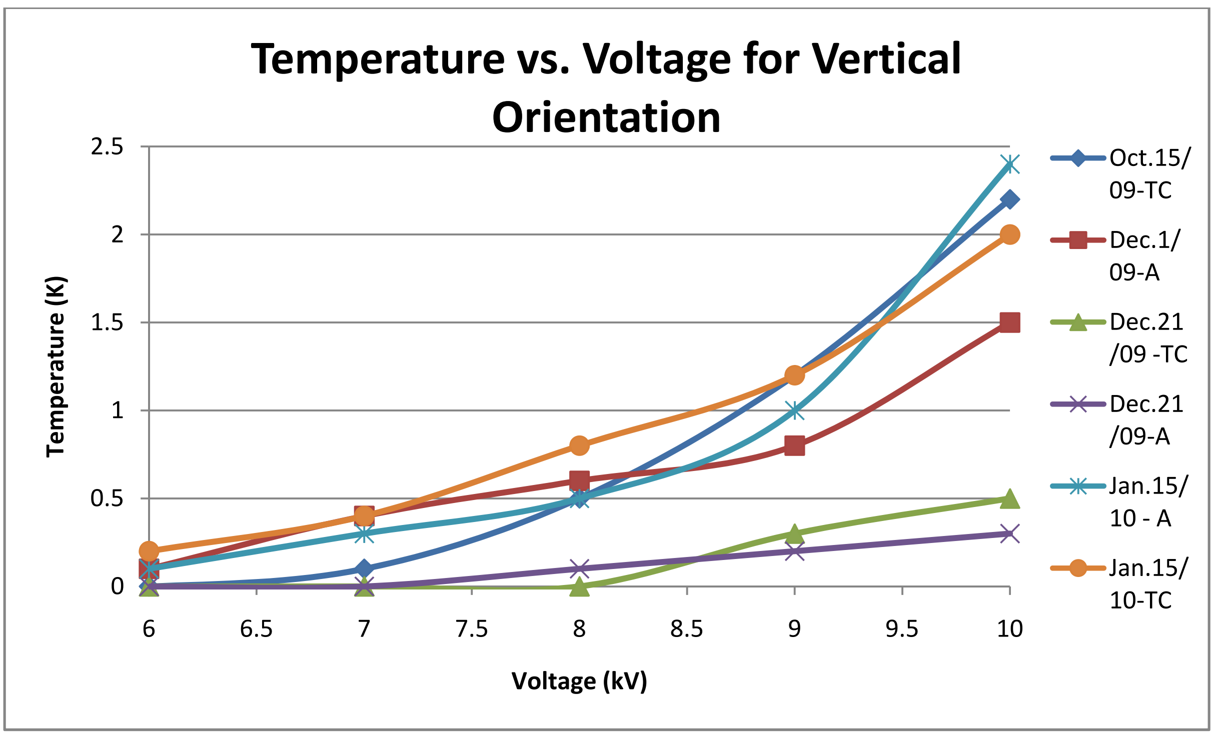


Figure 8: Graph of Temperature vs. Voltage for an EHD Gas Pump in a vertical orientation

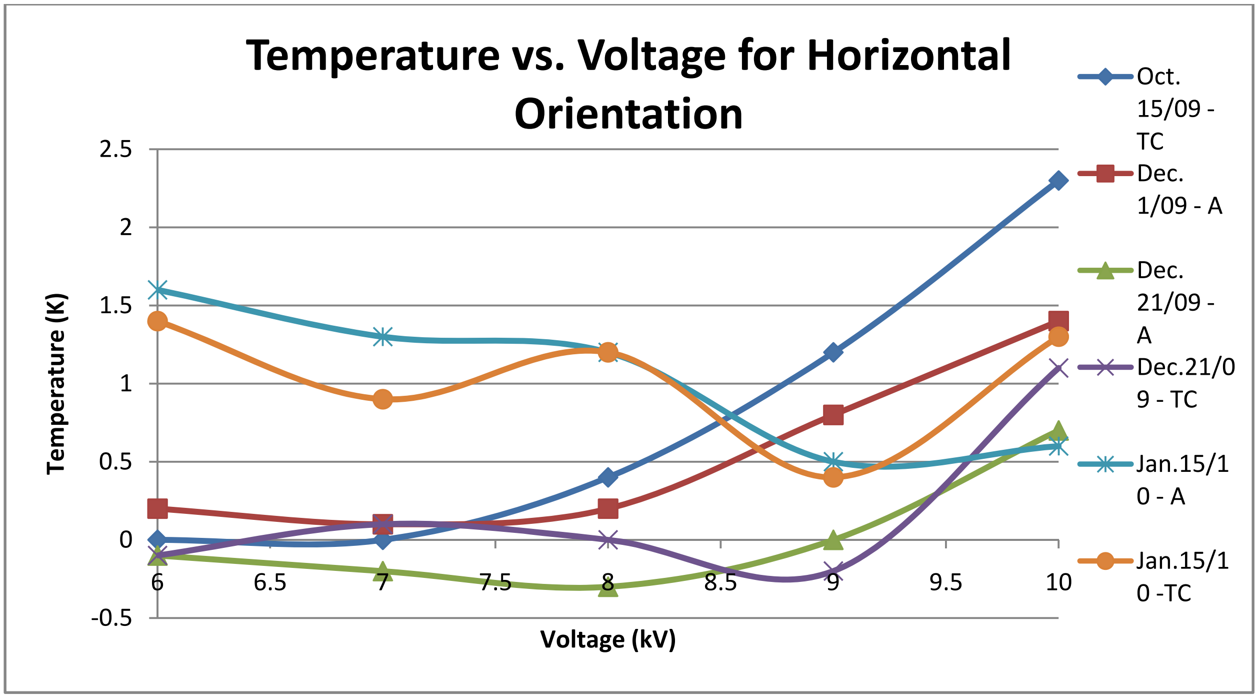


Figure 9: Experimental data for Temperature vs. Voltage for an EHD Gas Pump in Horizontal Orientation

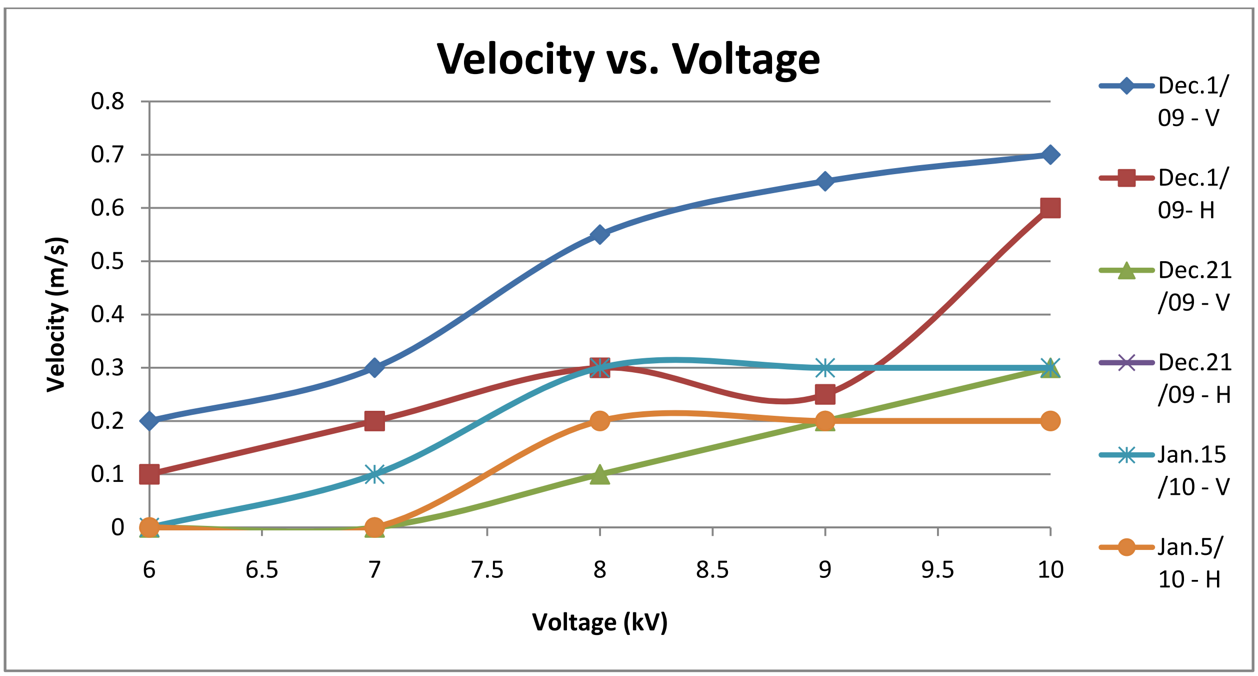


Figure 10: Experimental data of Velocity vs. Voltage for an EHD Gas Pump

The temperature graphs clearly display an increase in the temperature gradient with applied voltage. This trend is expected to be present until spark discharged is reached.

There is not a significant difference between the temperature gradient with respect to orientation suggesting the dominant forces at play are EHD forces and not buoyancy forces. In the velocity graph the velocity tends to peak at a maximum velocity before spark discharge. There seems to be a velocity benefit due to buoyancy when the pump is a vertical orientation. In outer space due to the lack of gravity this effect should not be present.

5.0 Conclusions

An EHD enhanced CPL with an EHD evaporator and an EHD gas pump is considered to be a viable option for heat transport in a nuclear space reactor. The design of the loop is to be effective in the conditions expected in outer space. During the characterization of the design the following conclusions were ascertained.

(1) Nuclear reactors are currently being designed for space applications. A more cost effective and reliable heat transport system for these reactors needs to be developed.

(2) Capillary Pumped Loops have shown to effectively move heat and fluids without the use of moving parts. The addition of an EHD enhanced evaporator to a CPL allows for a CPL to improve its efficiency in a zero gravity and microgravity environments

(3) EHD enhanced evaporators improve the heat transport of CPLs. An optimized design for a EHD enhanced evaporator needs to be developed.

(4) The inclusion of EHD gas pumps in a CPL increase the efficiency of the loop and its ability to transport fluid in the vapour section of the loop.

6.0 References

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