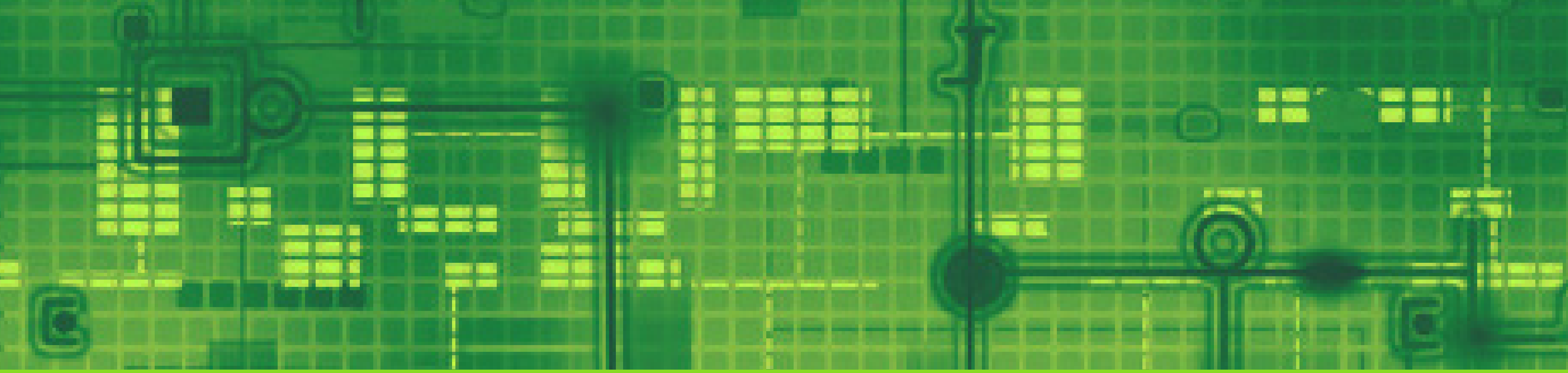

Enhancing Heat Sink Performance

in Natural Convection Using EHD

Introduction

Electrohydrodynamics (EHD) is the study of the dynamics of electrically charged fluids [1]. More specifically, it is the study of the motions of ionized particles or molecules and how their interactions with electric fields affect the surrounding fluid. With more research, EHD has the potential to start entering the thermal management scene of the electronics industry because of its ability to cool heat sinks that do not have a system flow available, while staying completely quiet. There are various ways to apply EHD to enhance heat transfer. Utilizing electrostatic force is one of the most promising methods among various active techniques because of its several advantages [2].

It is understood that natural convection in vertical channels is encountered in many engineering applications which include, heat exchangers and the cooling of electronics equipment, that incorporate heatsinks. One look at applying EHD to natural convection can be found in Kasayapanand et al. [2] research in Numerical modeling of the electrohydrodynamic effect on natural convection in vertical channels. Conclusive evidence from this study has proven that EHD can be used to increase the heat transfer of a heat sink in natural convection.

The setup of Kasayapanand et al. research consisted of two vertical plates with electrodes spanning through the channel. Various electrode configurations were explored. The electrode configuration, where the electrodes are densest at the ends of the channel, was found to be the most conducive to an increase in heat transfer. When the electrodes are most dense at the ends, a maximum heat transfer enhancement is reached due to a high temperature gradient along the vertical plates.

As stated earlier, EHD corresponds to the motion of ionized particles or molecules. When a discharged particle and grounded particle are present in the surrounding air, the result is an air motion called a corona wind, or ionic wind. In a study done by O'Brien et al. [3], this ionic wind has been shown to reach a maximum heat transfer enhancement of 8.5 times when compared to natural convection alone. Their study was done to observe the effect of ambient pressure on heat transfer performance of a vertical plate in an electric field.

Forced convection using corona winds, have been around for more than a century however, corona winds and thermal management have just been recently combined in the 1960's. As stated by Li et al. [3], previous researches focused mainly on the fundamental study of corona winds on a plate or in a tube. The following study by Li et al. makes strides towards developing an EHD integrated passive thermal solution that can be applied to high power generation applications.

Experimental Setup

The experiments for this study are performed in an environmental chamber with a volume of

0.5 x 0.5 x 0.65m (LxWxH). This allowed the test setup to have a fixed ambient temperature of 25°C and no external airflow. Besides the environmental chamber the test consists of a plate fin heat sink, kapton heater, an insulation box, and an electrode framework that sits above the heat sink. A picture of the experimental setup can be seen in Figure 1.

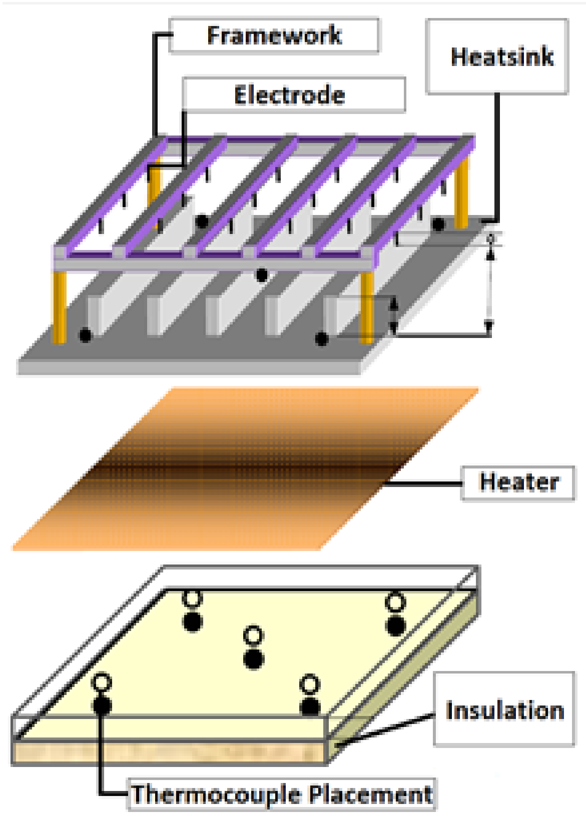

Figure 1. Experimental Setup

The heater, which is the same size as the heat sink (in order to minimize spreading resistance), is adhered to the bottom of the heat sink with thermal grease. Insulation is placed beneath the heater in order to minimize heat loss. There are five thermocouples in the heat sink base. These thermocouples obtain the mean temperature of the heat sink base. Also, ten thermocouples are placed in the insulation at two cross positions to calculate the heat loss from the heater.

With the heat sink grounded, the electrode framework is connected to a high voltage generator. A voltmeter is set in series between the voltage generator and heat sink, while a microammeter is set in series between the heat sink and the voltage generator. With these instruments, the applied voltage and corona current are monitored. A figure depicting the aforementioned setup can be seen in Figure 2. The electrode arrays that are observed in this study can be seen in Figure 3.

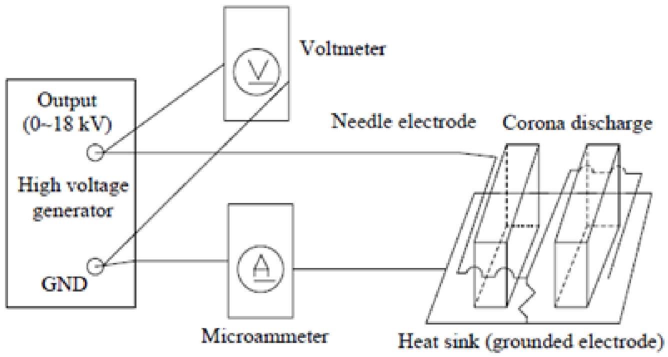

Figure 2. Arrangement of Voltmeter and Microammeter

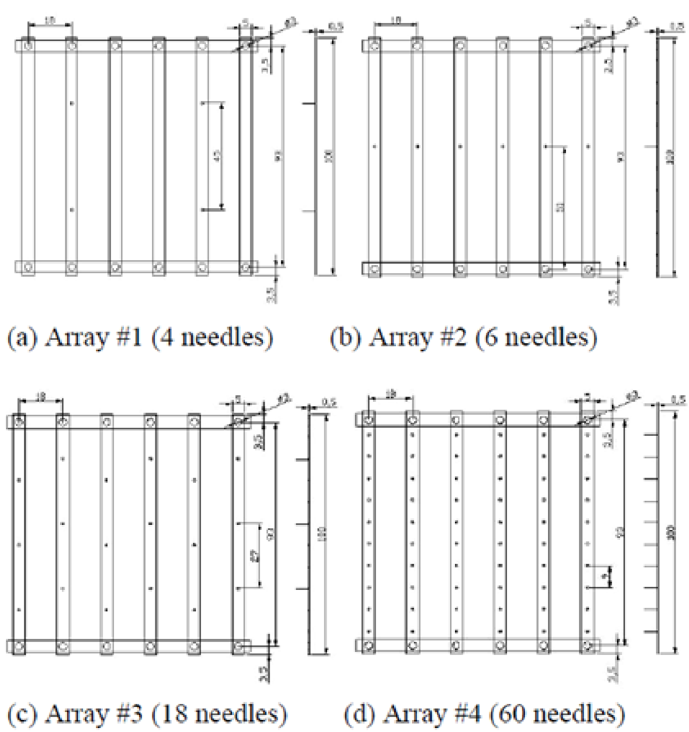

Figure 3. Orientation of the Four Different Electrode Arrays

Data Reduction

To get to the EHD performance, a series of heat transfer equations must be solved with the resulting experimental data. The total heat input to the heat sink can be calculated by Equation 1.

$$Q_t = \frac{V^2}{R} \quad (1)$$

Where V is the applied voltage and R is the resistance of the heater.

The heat loss through the bottom of the heater, or insulation, can be calculated by the conduction equation. The conduction equation is denoted as Equation 2.

$$Q_l = kA\frac{dT}{dx} = kA\frac{T_{ins,1} - T_{ins,2}}{t} \quad (2)$$

Where k is the conductivity of the insulation, A is the cross-sectional area of the insulation, $T_{ins,1}$ is the temperature of the insulation at a given thermocouple, $T_{ins,2}$ is the temperature of the insulation at the spot above the previous given thermocouple, and t is the thickness of the insulation.

The total heat transferred to the heat sink can be represented by Equation 3.

$$Q_f = Q_t - Q_l \quad (3)$$

The total heat transfer consists of heat transfer by convection and radiation. Equation 4 represents heat transfer by radiation and Equation's 5 and 6 represent heat transfer by convection.

$$Q_r = \varepsilon\sigma A(T_b^4 - T_\infty^4) \quad (4)$$

Where ε is the surface emissivity, σ is the Stefan-Boltzmann Constant, A radiating surface area, Tb is the base surface temperature, and T∞ is the ambient temperature.

$$Q_c = Q_f - Q_r \quad (5)$$

$$Q_r = \bar{h}A\eta_0(T_b - T_\infty) \quad (6)$$

Where $\bar{h}$ is the average heat transfer coefficient, At is the convective heat transfer surface area, η_0 is the overall fin efficiency, T_b is the base temperature, and T_∞ is the ambient temperature. The overall fin efficiency can be assumed as 1, since for this heat sink configuration it is 0.99 for natural convection and 0.97 for corona wind convection (the efficiencies were obtained by solving Equation 6 with an iteration process).

To characterize EHD performance, Equation 7 can be used. It is a non-dimensional number that is used as an index for performance.

$$\xi = \frac{\bar{h}_{EHD}}{\bar{h}_{NC}} \quad (7)$$

Where $\bar{h}_{EHD}$ is the average convection coefficient when using EHD and h_{NC} is the average convection coefficient in natural convection.

Testing of Different Parameters

When using EHD there are several factors, or variables, that affect the enhancement ratio. The polarity of the electrodes is important because it dictates how much current is emitted from corona discharge. For a negative polarity, the metal surface barrier energy is lower than the gas ionization energy. This causes generation of extra emitting current at the beginning of corona discharge and from thereon thus, producing a higher EHD performance ratio than using electrodes with a positive polarity.

Figure 4 shows that a negative polarity needs less voltage to provide a similar EHD ratio. It can also be seen that, when the voltages of a corresponding negative and positive polarity are equal, the EHD ratio is larger when a negative polarity is used. The variable "H" is defined as the distance between electrodes.

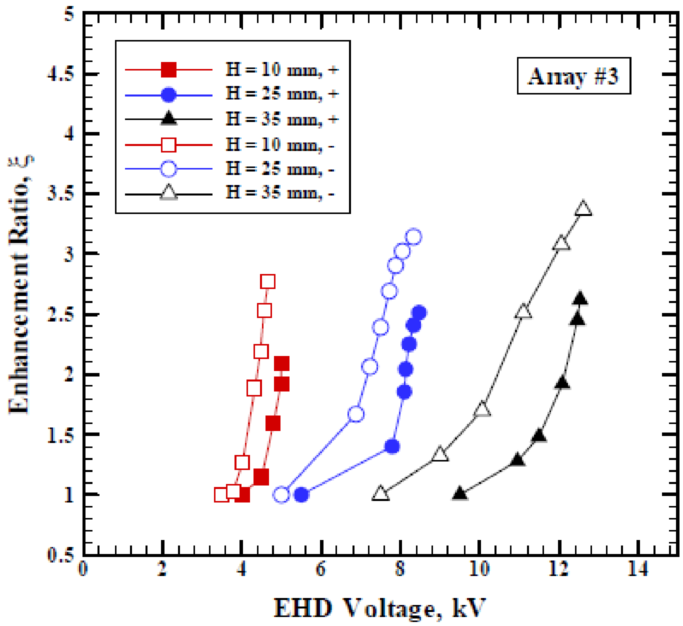

Figure 4. EHD Voltage vs. EHD Ratio for Array #3 at Specified Electrode Distances with Different Polarities [3]

Figure 5 shows that a negative corona, at a lower voltage, not only produces a corona current earlier than a positive corona but also produces a stronger corona current overall. It is apparent that a negative polarity is essentially more efficient than a positive one.

The distance between electrodes affects the enhancement ratio. The larger the distance between electrodes, the smaller the electric field and free electron energy is. Figure 6 shows this trend. Regardless of applied voltage and polarity, the enhancement ratio decreases as electrode distance increases. At the limit where the distance between electrodes gets so large, the enhancement ratio approaches 1, meaning that the electrodes are ineffective.

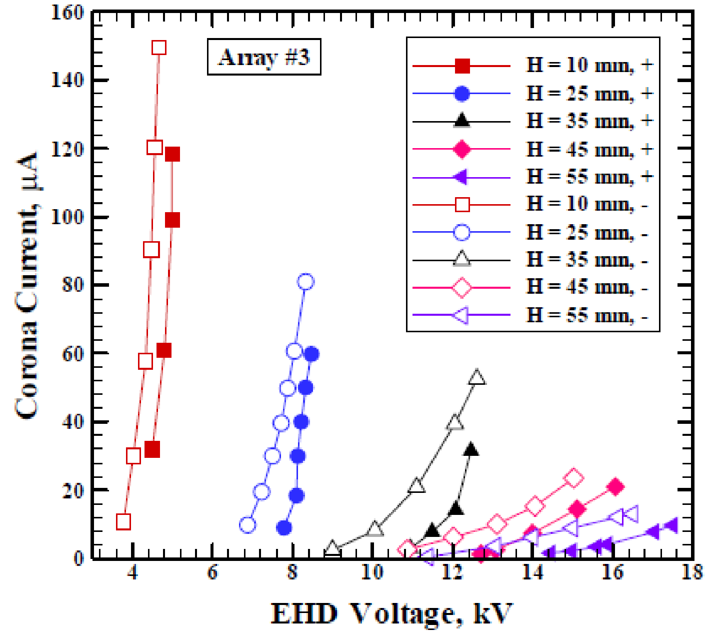

Figure 5. EHD Voltage vs. Corona Current [3]

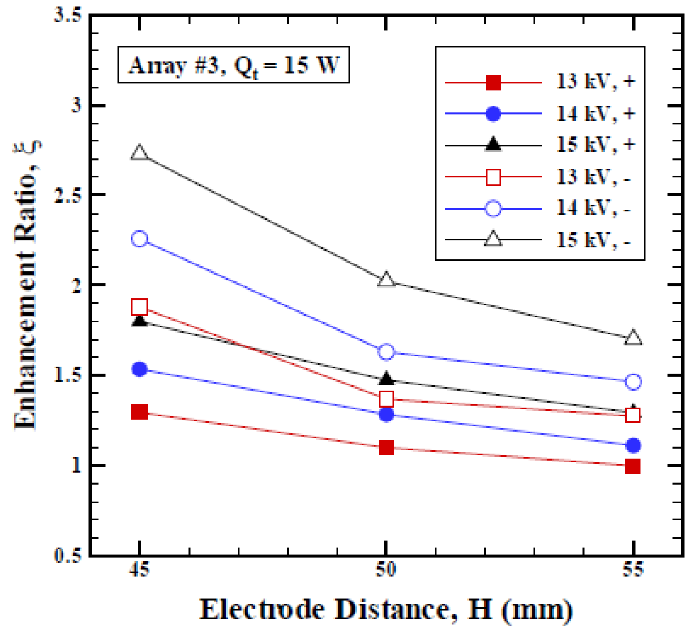

Figure 6. Electrode Distance vs. Enhancement Ratio for Array #3 at 15W [3]

Heat dissipation is inversely proportional to the EHD ratio so, as heat dissipation from the heat sink increases, the EHD ratio decreases (never less than 1). This is due to the fact that, in this given test setup when the heat dissipation gets so large, the

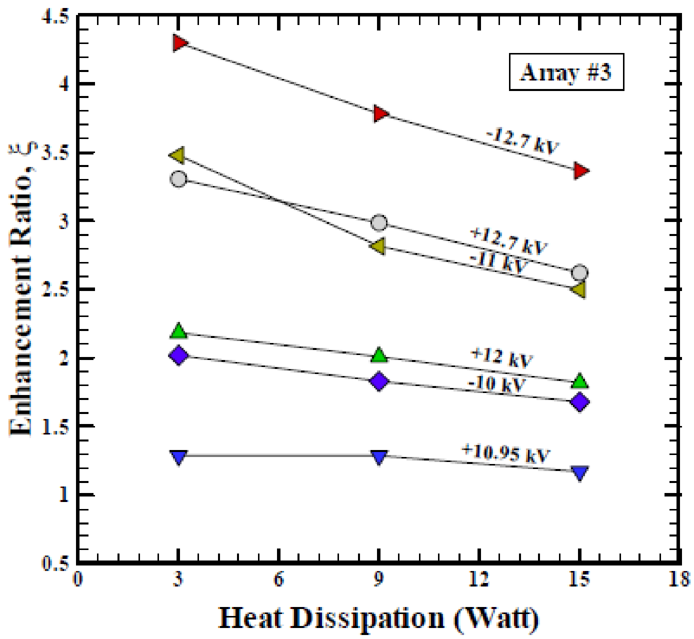

Figure 7. Heat Dissipation vs. EHD Ratio in Array #3 [3]

direction of the natural convection flow conflicts with the corona wind. These conflicting flows cause the overall convection to decrease and thus the enhancement ratio decreases. In other words, with convection from the corona winds staying constant, as natural convection increases the total percentage increase of enhancement decreases. This phenomenon can be quantified in Figure 7. Also note in Figure 7 that the negative polarity voltages produce a higher enhancement ratio.

This phenomenon has also been confirmed, in terms of the Rayleigh number [2]. The larger the Rayleigh number, the more heat transfer by natural convection takes place. As stated in Kasayapanand et al. research, flow patterns and temperature distributions closely resemble convection with non-EHD at high Rayleigh numbers. This indicates that EHD does not signify a change in heat transfer the larger the Rayleigh number gets [2].

The last factor that has been noted in this study to affect the EHD enhancement ratio is the electrode arrangement. Results of these last tests prove that the optimal electrode density depends on electrode distance. For an electrode distance of 10mm, the enhancement ratio increases with electrode density since there is a greater impinging area and corona current. As seen in Figure 8, array #4 (the most dense array) provides the highest enhancement ratio.

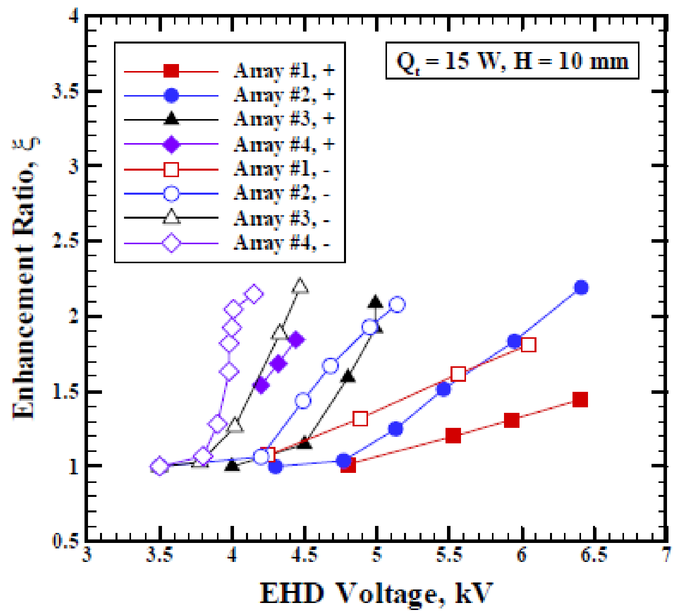

Figure 8. EHD Voltage vs. Enhancement Ratio at Electrode Distance of 10mm for Certain Arrays [3]

With an electrode distance of 35mm, the optimal electrode arrangement is completely different than at a distance of 10mm. This can be attributed to the occurrence of corona wind interference for a dense array since the electrodes are further away from each other. Essentially, the resulting flow from an individual electrode interferes with the adjacent electrode. These trends can be seen in Figure 9.

At an electrode distance of 55mm, the optimal electrode arrangement changes again but is similar to a distance of 35mm. Since array #1 has nearly no effect on EHD, it can be assumed that the fewer electrodes there are, the more incapable the arrangement becomes at generating sufficient corona current. A large gap between electrodes negatively impacts the discharging and collecting of electrodes. Figure 10 shows such trends.

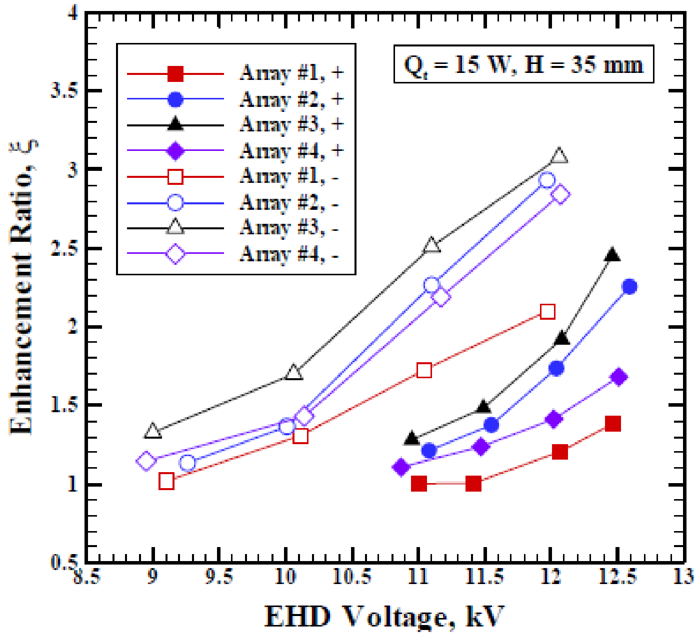

Figure 9. EHD Voltage vs. Enhancement Ratio at Electrode Distance of 35mm for Certain Arrays [3]

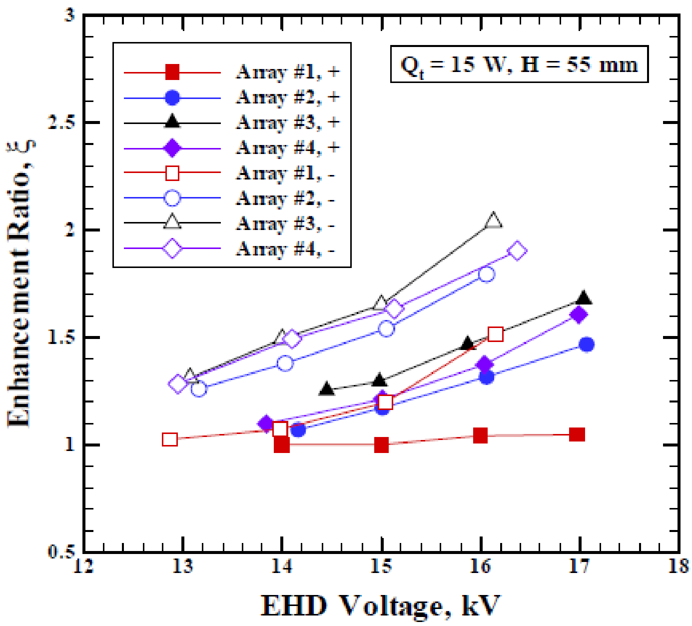

Figure 10. EHD Voltage vs. Enhancement Ratio at Electrode Distance of 55mm for All Arrays [3]

Conclusion

The previous parameters discussed, provide a good starting point when developing heat sinks with EHD for natural convection cases. There are other parameters that need to be analyzed in order to develop the full range of design criteria needed to successfully deploy an EHD integrated heat sink. Even though a full set of design criteria is unknown, there is conclusive evidence for the parameters that were studied. A negative polarity induces a stronger corona current and therefore provides a higher enhancement ratio. The larger the distance is between the electrodes the lower the enhancement ratio. The more heat dissipated the lower the enhancement ratio is. If one wants to develop an EHD integrated heatsink, the electric field strength, the electrode arrangement, the electrode distance, the fin structure, and the fluid characteristics need to be taken into account.

References:

1. **Castellanos, Antonio, ed."Electrohydrodynamics." Italy: SpringerWienNewYork, 1998. Print.**

2. **Kasayapanand, N., and T. Kiatsiriroat. "Numerical Modeling of the Electrohydrodynamic Effect to Natural Convection in Vertical Channels." Thaiscience.info. ThaiScience, 20 Dec. 2006. Web. 23 Sept. 2014.**

3. **Li, H. Y., et al. "EHD Enhanced Heat Transfer with Needle-Arrayed Electrodes." 23rd IEEE SEMI-THERM Symposium, 2007.**

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