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Experimental Investigation on Electorhydrodynamically Enhanced Heat Transfer in Partially Open Enclosures

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ABSTRACT

Experimental investigation on heat transfer enhancement by applying electrohydrodynamics (EHD) in partially open multiple fined enclosures with different aperture position has been performed. The enclosure had five thermally and electrically insulated faces; while one face was copper finned plate with an aperture located on its opposite face. In the present study, different parameters including electric current, number of fins, aperture position, and corona polarity were investigated. It was concluded that heat transfer enhancement is proportional to the supplied current. Higher number of fins can lead to further heat transfer enhancement and as the location of aperture is shifted upward, the heat transfer coefficient is improved more significantly by EHD.

Keywords: EHD; Convection; Fin; Corona; Aperture.

NOMENCLATURE

A_b	base fin surface, m^2
A_C	cross surface of fin, m^2
A_t	total surface of fin, m^2
E	electric field intensity, V/m
h	heat transfer coefficient, W/m^2 K
I	current, A
k_a	air thermal conductivity, W/m K
K	thermal conductivity, W/m K
L	fin length, m
N	number of fins
Nu	Nusselt number
P	fin circumference, m
q_t	total heat transfer, W
T_{bulk}	bulk temperature, K
T_{bf}	base fin temperature, K
V	voltage, V
W	fin width, m
η	efficiency
θ	temperature difference, K

Subscripts

a	air
bf	fin base
c	corrected
C	cross surface
f	fin
t	total

1 INTRODUCTION

Electrohydrodynamics (EHD) may be used as an active method of heat transfer enhancement in which a large electric field is used to induce a secondary flow known as ionic wind. This secondary flow may reduce the thickness of the thermal boundary layer which leads to reduction of convective heat transfer resistance. Many investigations have been conducted to study the effects of EHD on heat transfer enhancement. Laohalertdecha, Naphon, and Wongwises (2007) have reviewed the published research works on electrohydrodynamic heat transfer enhancement which can be used as the first guideline for the researcher in using EHD techniques for heat transfer enhancement. Yonggang, Jonping, and Zhongliang (2006) studied the effect of the ionic wind on the heat transfer rate from a heated vertical flat plate and have concluded that the convective heat transfer coefficients increase by several times with the help of the ionic wind. Bhattacharyya and Peterson (2002) examined the influence of the corona wind on the augmentation of natural convection heat transfer from a vertical copper plate. They investigated the effects of varying a series of parameters coupled with a range of electrode voltages and its polarity. They have concluded that electric field strength had a direct and significant influence on the enhancement scale, whereas polarity change of the applied field did not produce much significant influence on the enhancement ratio. Grassi, Testi, and Della Vista (2006) examined the heat transfer enhancement on the upper surface of a horizontal heated plate in a pool by employing an electrohydrodynamically induced impinging liquid flow in a point-plane geometry and managed to augment heat transfer coefficients more than 200% by varying the high voltage and the point-to-plane spacing.

Recently, the application of open and closed cavities in various engineering systems has attracted the attention of many researchers. Some of these systems include but not limited to solar thermal receivers, solar collectors, heating and ventilation of rooms, cooling of radioactive waste containers, fire prevention, and electronics cooling devices, Kasayapanand (2009-a, 2009-b). Few numerical modeling have been developed to study the effect of imposing electric field inside two dimensional cavities in the absence of forced flow, Kasayapanand, and Kiatsiriroat, (2007), Kasayapanand (2007-a, 2007-b). The effect of electrohydrodynamics on heat transfer in the presence of an external forced flow was studied numerically by Kasayapanand (2005, 2006). Grassi, Testi, and Saputelli (2005) conducted an experimental research to investigate the EHD enhanced heat transfer in a vertical annular channel. They managed to obtain local heat transfer improvement by inserting appropriate points on the inner surface of the annulus which generally acted as the positive electrode, while the surrounding pipe was grounded.

Fins are used to enhance heat transfer passively. Several numerical researches are reported by Kasayapanand (2007-c, 2008, 2009-a) on the effect of imposing electric field on the partially open or closed finned enclosures. One of the shortcomings of the numerical methods is that they cannot predict the breakdown or spark over voltage correctly. A corona discharge is an electrical discharge brought on by the ionization of a fluid surrounding a conductor that is electrically energized. The discharge will occur when the strength (potential gradient) of the electric field around the conductor is high enough to form a conductive region, but not high enough to cause electrical break-down or arcing to nearby objects. Breakdown voltage or spark over voltage is the voltage at which an insulator, e.g. air, "breaks down" and begins to pass current. The spark over voltage in the air depends on many experimental conditions such as electrodes geometry, their distance, and humidity of the air. Coronas may be positive or negative. This is determined by the polarity of the voltage on the highly curved electrode. If the curved electrode is positive with respect to the flat electrode, it has a positive corona, if it is negative, it has a negative corona.

In the present study, an experimental procedure has been devised to investigate the effects of electrohydrodynamics on heat transfer enhancement in partially open and finned enclosures. Three different finned enclosures including single fin and multiple fins (3 and 7 fins) were used. Both the positive and negative polarity coronas were investigated.

2 EXPERIMENTAL SETUP AND PROCEDURE

In the present study the effects of DC electric field on heat transfer enhancement inside partially open and finned enclosures is investigated experimentally. The experimental setup is schematically shown in Fig. 1.

The high voltage power supply (Heinzinger, PNC series, 0-40kV and 0-5mA, reversible polarity) was used for applying an electric field between the wire electrode and the finned plate which forms one face of the cavity. The finned copper plate which was grounded, was heated by a flat heater ($5.95\,\Omega$) attached to its back. Thermal grease was applied between the heater and the copper plate to reduce contact resistance between them. The heater was powered by a standard power supply (Philips, PE 1646 series, 0-75V and 0-6A). The outside face of the heater was insulated by layers of yonolit (k=0.037 W/m.K) and glass wool (k=0.09 W/m.K). The connections between the high voltage power supply, electrodes, and finned plate are shown in Fig. 1.

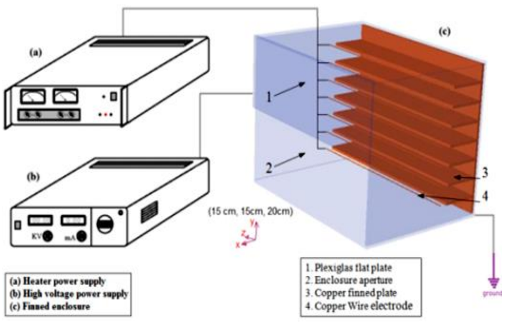

Fig. 1. Schematic diagram of the experimental setup.

The dimensions of the enclosure are $15cm \times 15cm$ in the x-y plane and $20cm$ in the z direction (cavity length). The finned plate is made of commercial pure copper with thickness of $3mm$ and the length of the fins is one quarter of the cavity width. Three enclosures were used in this study one being single finned, whereas the other two were three and seven finned. An identical fin thickness was used in all enclosures. Other walls of the enclosure are made of $3.2mm$ thick Plexiglas flat plate which is electrically non-conducting material, and were thermally insulated. The Plexiglas plates were coated with layers of the glass wool and nylon to eliminate heat losses.

The face opposing the finned plate has an aperture with height of $7.5cm$ in the y direction. The working fluid used in this research was atmospheric air. The aperture allows the cavity to exchange heat and mass with the ambient. The aperture could be at one of the three different locations on the wall, i.e. it can take the upper, middle, or the lower position. Figure 2-a schematically illustrates the aperture positions. The wire electrodes used for applying electric field were installed in front of the fins. The electrode was installed parallel to the fin and at a distance of 4.7*cm* from the base of the fin, Fig. 2-b. In order to study the effect of electric field on heat transfer enhancement, voltages ranging from zero to the spark over voltage were examined. The numerical previous researches Kasayapanand (2007-c, 2008, 2009-a) were not limited to the mentioned fact.

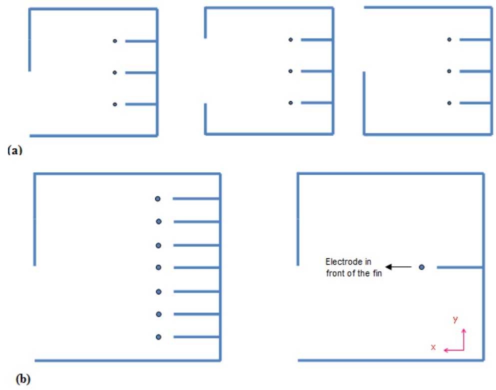

Fig. 2. The schematic diagram of, a) aperture position for 3-fins models, and b) electrodes position for single &7-fins models.

To calculate the convective heat transfer coefficient, temperature of the plate and air bulk temperature should be measured. For this purpose, three narrow bores, 5*cm* apart from each other were drilled on each fin from the back side for placing thermocouples. The depth of the bores was equal to the plate thickness. Sheathed thermocouples (type K) were used to prevent any interference between the thermocouple and electrical field. Temperatures were recorded when steady state condition was reached. The bulk temperature of air in the enclosure was obtained by averaging the measured temperature at the top and bottom of the aperture. The temperature indicator (STANDARD ST-612 series) was calibrated prior to installation. The resolution of the thermometer was $0.1\,^{\circ}C$. The laboratory was air conditioned and its temperature was kept constant at $24\,^{\circ}C \pm 0.5\,^{\circ}C$.

The full factorial method was used for experiments design in this study and experiments were performed randomly and repeated twice. Repeating the experiments reduces personal and instrumental errors, and randomization diminishes the surrounding effects.

3 Calculation of Convective Heat Transfer Coefficient

The variables of this study included the number of fins, aperture position, electrical voltage and current, and the corona polarity. To obtain the heat transfer enhancement, one may use equations 1-4 below, Incropra and Dewit (2006) via trial and error process. To do this, base temperature of the fin(s), bulk temperature of air in the enclosure, and the power supplied to the heater (q_t) should be measured.

$$q_t = hA_t\left[1-\frac{NA_f}{A_t}(1-\eta)\right]\theta \tag{1}$$

$$A_t = NA_f + A_b \tag{2}$$

$$\eta_f = \frac{\tanh mL_c}{mL_c} \tag{3}$$

$$m = \sqrt{\frac{hP}{K_{copper}A_C}} \tag{4}$$

where θ is defined as the difference between the air bulk temperature and the base temperature of the fin(s); $\theta = T_{bulk} - T_{bf}$. Power was supplied to the heater at a fixed net rate of 19.5 *W*.

Having known the heat transfer coefficient, the Nusselt number is obtained from Eq. (5).

$$Nu = \frac{hW}{k_a} \tag{5}$$

To present the results more concisely, a non-dimensional enhancement ratio is defined as following:

$$ER = \frac{Nu_{EHD}}{Nu_{NC}} \tag{6}$$

where Nu_{EHD} is the Nusselt number acquired using EHD technique, and Nu_{NC} represents the Nusselt number corresponding to a pure natural convection without applying electric field in the enclosure.

4 Result and Discussion

4.1 Applied Voltage and Current

Variation of the EHD voltage versus EHD current is illustrated in Figs. 3-5 as a function of aperture position and corona polarity for different fin numbers. From these figures it is evident that for any given geometry and electrical current, a higher voltage must be applied for positive corona relative to negative corona. Comparison of these figures also reveals that as the number of fins increases and so does the number of electrodes and the effective distance between them, the difference between the positive and negative corona V-I curves diminishes.

4.2 Enhancement Ratio

In the absence of EHD, fluid tends to moves upward due to buoyancy effect as a result of heating on the finned wall. On the other hand, fins obstruct the movement of fluid. When EHD is applied, a secondary flow is induced by the ionic wind at the wire electrodes which causes cellular rotating motion. The thermal boundary layer is perturbed by the electric field when it extends over the recirculation region. Kasayapanand, N. (2009-a) used a computational fluid dynamics technique to analyze the interactions between electric, flow, and temperature fields. His results indicated the presence of a single rotating cellular motion for non-EHD, and two rotating cellular motions when EHD is applied.

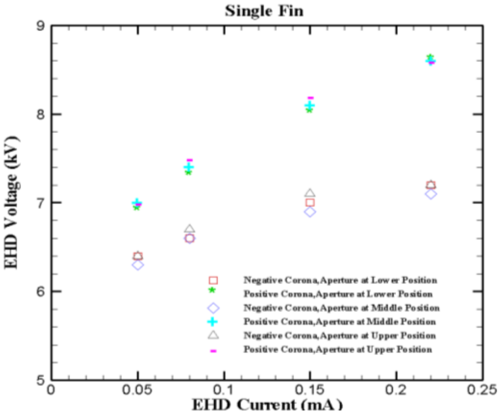

Fig. 3. Effect of aperture position and corona polarity on *V-I* curve for single fin enclosure.

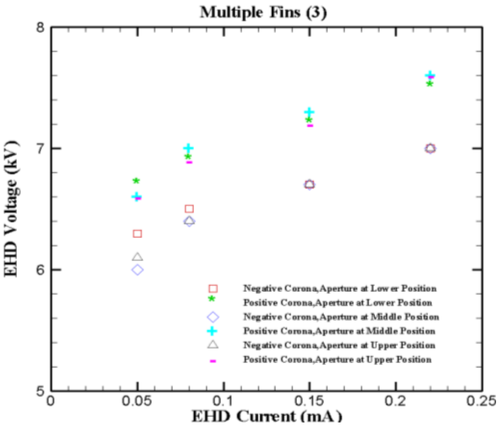

Fig. 4. Effect of aperture position and corona polarity on *V-I* curve for multiple fins (3) enclosure.

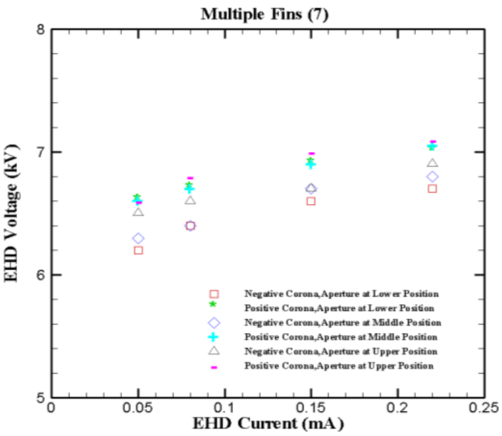

Fig. 5. Effect of aperture position and corona polarity on *V-I* curve for multiple fins (7) enclosure.

In Figs. 6-11 heat transfer enhancement ratio is depicted as a function of corona current, while fin number and aperture position are varied. In all of cases enhancement ratio has increased as corona current has increased. Increase in fin number or electrode number has a similar effect.

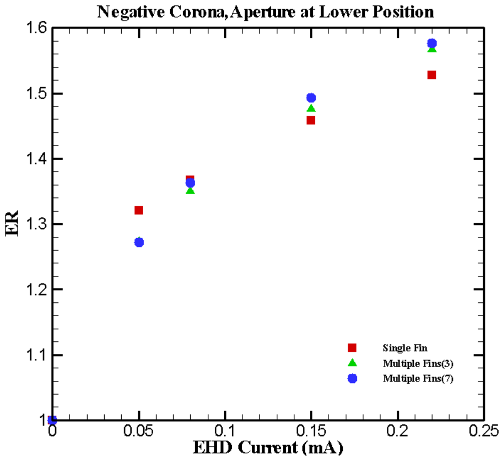

Fig. 6. Enhancement ratio vs. current and fin number for lower aperture position (negative polarity).

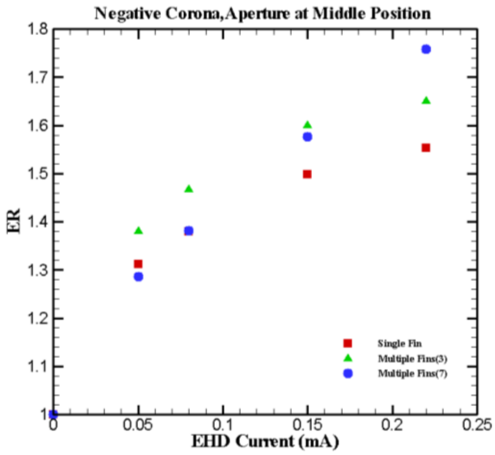

Fig. 7. Enhancement ratio vs. current and fin number for middle aperture position (negative polarity).

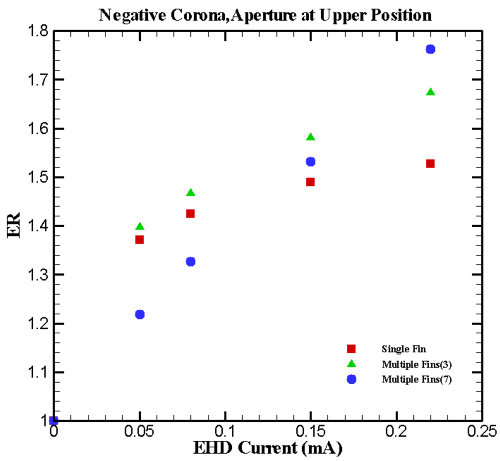

Fig. 8. Enhancement ratio vs. current and fin number for higher aperture position (negative polarity).

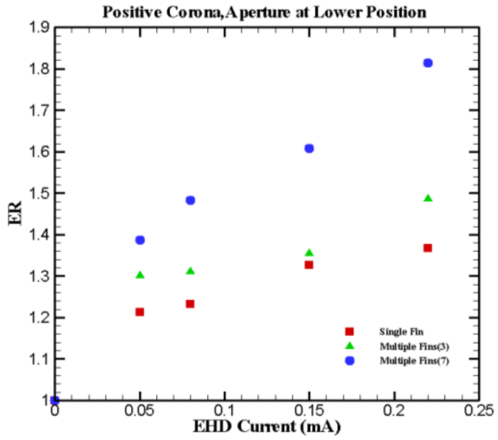

Fig. 9. Enhancement ratio vs. current and fin number for lower aperture position (positive polarity).

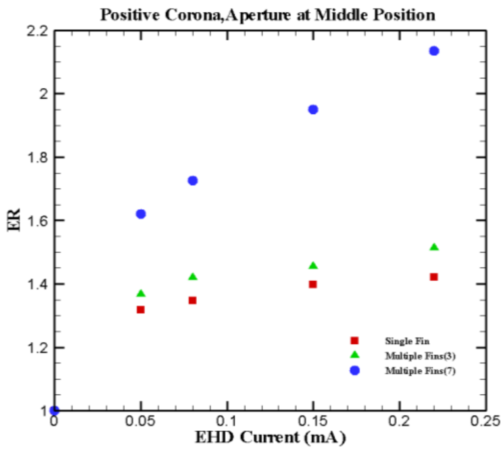

Fig. 10. Enhancement ratio vs. current and fin number for middle aperture position (positive polarity).

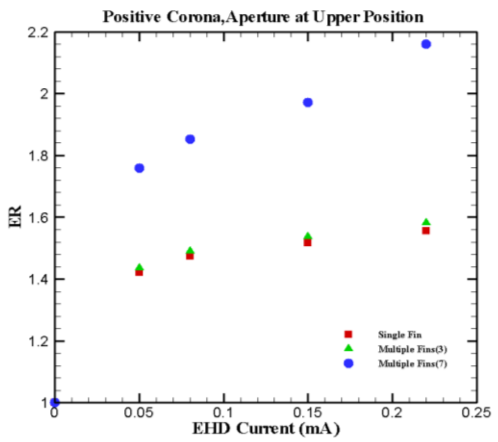

Fig. 11. Enhancement ratio vs. current and fin number for higher aperture position (positive polarity).

When the aperture was at the lower position, natural convective heat transfer was the most effective. Intuitively, the higher aperture position induces the weakest free convection. Therefore, the electric field influence would be expected to be pronounced the most for the higher aperture position case as opposed to the lower aperture position. This is more clearly observed for the positive corona case.

Air enters the cavity at the lower part of aperture, gets heated up on the hot wall while moves upward. Then conveys along the cavity width and finally exits from the upper part of the opening.

The 7-fin model has the highest enhancement ratio compared with other models. As the number of fin increases, and so does the number of electrodes, the secondary flow due to ionic wind becomes more effective, hence enhancement. This is observed for all cases except for the lowest electric current of negative polarity.

One may conclude from Figs. 6-11 that the positive corona is more effective in enhancing heat transfer as the number of fins is increased from one to seven. To justify this one can say that the electrons are lighter than positive ions and their speed is 100 times the positive ions. Hence, the negative corona (for non-electronegative gases) occurs at lower voltages compared with the positive corona.

The positive corona has high intensity and exerts more body force to fluid. In single fin model, resistance to fluid flow is smaller compared with the 7-fin model; therefore negative corona can easily overcome it at low voltages, hence better enhancement. But, for multiple fin models where the blocking effect of the fins is significant, the positive corona has better performance.

4.3 Uncertainty Analysis

It is conceded that there is potential for inaccuracies because of the nature of empirical correlation so deeply entrenched in the analysis of the results. The independent variables in the present experiment are the temperature at the base of the fin(s), the bulk temperature of air, the input voltage and current to the heater, and the specific length (the width of the enclosure). The highest error was observed for the applied voltage. The uncertainties corresponding to the measured parameters are evaluated as followings. For the base fin temperature: 1% of the reading, for the air bulk temperature: $0.5\,^{\circ}C$, for the specific length: 1% of the reading, and for the input voltage and current: 10% of the reading and $0.1A$, respectively. The uncertainty analysis was performed using Kline and McClintock (1953) method.

The uncertainty bands corresponding to the above parameters are presented in Fig. 12, with a maximum uncertainty of 10% for single fin model, 4-6% for 3-fin model, and 3-5% for 7-fin model.

By use of reproducibility method, the experiments were repeated two times to ensure that the data presented in this study are not affected by the experimental uncertainty. For this purpose, absolute deviation is defined as following and presented in Fig. 13.

$$Absolute\,Deviation = \left| \frac{Nu_{The\ first\ experiment} - Nu_{The\ second\ experiment}}{Nu_{The\ first\ experiment}} \right| \tag{7}$$

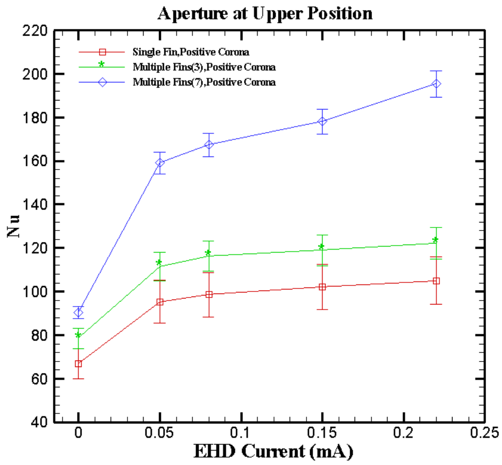

Fig. 12. Uncertainty graph for Nusselt number as a function of EHD current.

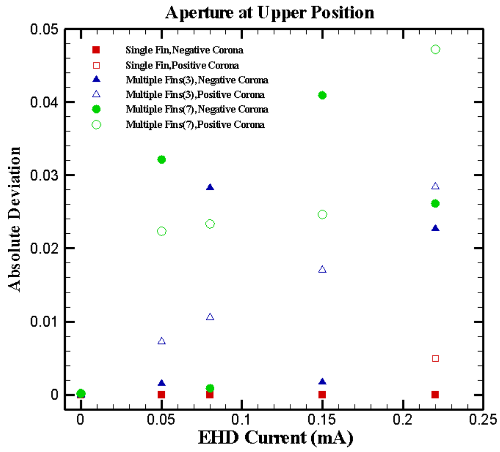

Fig. 13. Reproducibility graph for absolute deviation as function of EHD current by negative & positive corona.

As is seen in Fig. 13, all data placed well within the uncertainty bands. It is observed that the data scattered as the supplied current increases. This should be attributed to the unsteady behavior of corona discharge at high voltages, especially near the breakdown voltage.

5 CONCLUSION

The effects of applying a high electric field or electrohydrodynamics (EHD) on heat transfer enhancement in an enclosure with a partially open face were investigated experimentally. The results may be summarized as followings.

1. When EHD is applied, the maximum enhancement occurs when the aperture is at the upper position.
2. The positive corona is more effective on enhancing heat transfer when the number of fins is increased from one to seven.
3. Generally, heat transfer enhancement increases while the applied EHD current increases.
4. The maximum heat transfer enhancement occurs at the medium supplied power.

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