EXPERIMENTAL INVESTIGATION ON FLOW AND HEAT TRANSFER FOR COOLING FLUSH-MOUNTED RIBBONS IN A CHANNEL Application of an Electrohydrodinamics Active Enhancement Method

by

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In the present study, the heat transfer enhancement of a bundle of flush-mounted ribbons placed on the floor of a rectangular duct was investigated experimentally. The flush-mounted ribbons act as heat sources and the cooling happens with air. The air flow was 2-D, steady, viscous, and incompressible under either laminar ($500 \le Re_{Dh} \le 2000$) and turbulent ($2000 \le Re_{Dh} 4500$) conditions. The hydrodynamics and heat transfer behavior of the air flow was studied by means of an active method with application of corona wind. The state-of-the-art of this work revolves around an experimental investigation of an electrohydrodynamics active method and heat transfer enhancement from the surfaces of the flush-mounted ribbons. Due to the intricacies of the required experiment, a special apparatus needed to be designed and constructed.

Key words: convective heat transfer, duct flow, flush-mounted ribbons, heat transfer enhancement, electrohydrodynamics, corona wind

Introduction

The majority of electronic boards are constructed with small elements that generate considerable amount of heat. Cooling of these electronic boards constitutes an essential part for their reliable operation and the main cooling systems deal with a flow of air through channels. Nowadays, because of size reduction (*i. e.*, board compaction), the cooling medium has become a vital part of the system. Optimum active cooling systems are preferred approaches for performance evaluation criteria (PEC) of the electronic boards [1, 2]. The active method with application of corona wind is well known owing to its ability to work with any external sources of energy. Corona is a visible luminous emission caused by the creation of photon and occurs in the vicinity of sharp edges where the intensity of the electric field is high. An important aspect of corona discharge is the generation of corona wind, which is a gas flow induced by corona discharge. This phenomenon is caused by the ionization of gas molecules and formation of electrons that accelerate in strong electric fields and collide with neutral molecules, resulting in more ionization. Because the ions are heavier than electrons, they accelerate and drag the neighboring gas molecules. This action generates a secondary flow, known as corona wind.

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The present work examines an active electrohydrodynamics (EHD) method with application of positive corona wind for the cooling of heat generating flus-mounted ribbons placed at the base of channel. This is a novel cooling approach, and to the authors' knowledge, has not been examined earlier.

In recent work [3], experimental investigation on the heat transfer enhancement of rectangular ribs with constant heat flux located in the floor of a rectangular channel has been achieved. In this study, the behavior of air flow was studied by passive, active, and compound methods. The comparison of the results for various boundary conditions of problem was fairly agreement. In previous works [4, 5], numerical study on the heat transfer enhancement of rectangular ribs with constant heat flux located in the floor of a 3-D duct flow has been achieved. In this study, the effects of the arranged holes between the rectangular ribs in channels have been reported.

Fujishima *et al.* [6] provided analyzed the flow interaction between the primary flow and the secondary flow in the wire-duct electrostatic precipitator. They extended to incorporate the alternately oriented point corona on the wire-plate type electrodes.

Ohadi *et al.* [7] used the wire-plate electrodes for forced convection enhancement in pipe flow. They showed that the two-wire electrode design provided a modest higher enhancement compared to the single wire electrode design. With two electrodes, they showed that for Reynolds numbers up to 10000, it is possible to use this technique for enhancement.

Kasayapanand and Kiatsiririot [8, 9] investigated the heat transfer enhancement with the EHD technique in laminar forced convection inside a wavy channel with different wire electrode arrangements. The electric field is generated by the wire electrodes charged with DC high voltage. The mathematical modeling includes the interactions among the electric flow and temperature fields. The numerical simulation was firstly applied to the rectangular flat channel and later to wavy channel.

Kasayapanand *et al.* [10] investigated the effect of the electrode arrangements in a tube bank with regards to the characteristic of EHD heat transfer enhancement for low Reynolds numbers. The numerical modeling of the laminar forced convection includes the interactions among the electric field, the flow field, and the temperature field. From the numerical results, they showed that the heat transfer was enhanced by the EHD at a low Reynolds number and the short distance between the wire electrodes and the tube surface.

Often times in thermal systems, invigorating the heat transfer rate cause deterioration in the momentum transfer. This phenomenon is called dissimilarity. At first by placing flush mounted ribbons in the floor channel, local pressure, and momentum both drop. Therefore, for a specified inlet velocity situation, more pumping power is needed. On the other hand, due to the local effects such as disturbance and the extending of contact surface, the heat transfer increases. So it is necessary to articulate a convenient similarity between these two opposing phenomena. By using a suitable active method, secondary flow of corona wind creates in space between flush mounted ribbons and causes disturbances. In the present work, to avoid immoderate changes in the physical properties of fluid, the temperature differences between the fluid and flush mounted ribbons are constrained by applying a convenient heat flux on the flush mounted ribbons.

Experimental investigation

In order to generate data of the air flow patterns around the flush-mounted ribbons, a special apparatus was necessary. In designing the test section, the following conditions were taken into consideration:

A fully developed air flow should be supplied before the flow enters into the test section. With regards to the dimensions of the channel, the depth to height ratio is high. Because the depth effects have been ignored the channel is 2-D. The apparatus is designed to accommodate flow with low and large values of Reynolds numbers under laminar $(500 \le \text{Re}_{Dh} \le 2000)$ and turbulent $(2000 \le \text{Re}_{Dh} 4500)$ conditions. The flow is incompressible with very small Mach numbers, $M \ll 0.3$, thus any interaction effects of high voltage electric fields on the measurement of temperature are due to the eliminating side effects of applied high voltage and the accuracy of thermocouples.

Figures 1 and 2 show the layout and the photograph of the main experimental apparatus, respectively. By considering the aforementioned conditions for the main experimental section, a special experimental apparatus was designed for the investigation of heat transfer enhancements involving flush mounted ribbons to fluid. For this purpose, a broad rectangular channel was used. To measure the volume rate of air flow, the orifice meter was used. The ratio in diameter (orifice to pipe) was adjusted to be $\beta = d/D = 0.25$. A special centrifugal fan was used to produce the air flow. To eliminate disturbances, the test section was located on the suction side of the fan.



Figure 1. The schematic of main apparatus



Figure 2. Photographs of the main set-up



Figure 3. Photograph and geometry of the test section

The test section was designed to be a channel with 40 cm length, 4 cm height, and 30 cm width as shown in fig. 3. Before entering the test section flows from a rectangular channel with 2 m length, the fluid proceeds with a rectangular flow-straightened screen with unit dimension of 8 mm to 20 mm.

The velocity domain in the test section was $0.11 \le u \le 1$ m/s. The hydraulic diameter of the main channel (especially the test section) was 7.06 cm.

The fan was adjusted to operate with constant rotation. The flow rate was measured by the orifice meter under the France standard NF X 10-102. The pressure measurements should be determined with high accuracy in the two sides of the orifice. To comply with this, a U-type manometer with kerosene (S. G = 0.865) was used.

In the test section, the ribs were electrically heated with constant heat flux. To isolate the part attached to the floor of the channel, a fire proof fiber was used. The fire proof fiber is an adequate insulator of heat and electricity. The flush mounted ribbons were produced using silicon iron foil. Three flush mounted ribbons were attached on the floor of the channel. The series were connected as resistance to provide a constant heat flux of $q''_w = 4500 \text{ W/m}^2$ by means of a differential voltage transformer. The flush mounted ribbons had 3 cm in width, 30 cm in length, and 3 cm in axial spacing between them. Nine thermocouples were used for measuring the temperature of the bottom channel wall and the ribbons surface in central direction of flow. The type of thermocouples is T-type with Cu-Constantan (C/C_T). The geometric layout of thermocouples in the test section is shown in fig. 4 and tab. 1, where x denotes the streamwise direction from the position of the first thermocouple in the test section. The x location of the thermocouples is determined in the best location for measuring the temperature. The position starts from the first flush mounted to thermocouple number 9. The thermocouple number 1 is used for measuring the ambient air temperature.



Table 1. Position of the insertedthermocouples

No.	2	3	4	5	6	7	8	9
X[cm]	1.2	1.8	2.4	6.6	7.8	8.4	13.2	13.8

For temperature processing, the ADAM digital system was used. This system contains four boards for temperature measurement and a transformation board. Each measuring board receives the information of thermocouples and then transfers them to the PC for processing. High

voltage is applied using a high voltage supplier for the EHD wire-plate active method. Various arrangements of wire and plates were made as ground electrodes were designed between the spacing of the flush mounted ribbons. The high voltage supplier generated voltages up to

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40 kV between the wire and ground electrodes. The corona phenomenon was generated between electrodes with very weak current intensity. The micro-ammeter is used for current intensity measurements with a domain of 0-500 μ A and accuracy of 10 μ A. In all experimental tests, the polarity of wire electrodes is positive. The diameter of wire electrodes is 0.6 mm. The wire and ground electrodes are made from copper and aluminum, respectively. The primary objective of the present work is the comparison of plain case 1 with EHD active heat transfer enhancement method. The geometry of the two cases is shown in figs. 5(a) and (b).



Figure 5. The geometry of two cases, (a) and (b)

The arrangement of electrodes with their geometric coding values is illustrated in fig. 6. The arrangements of electrodes for active method are displayed in the case 2. The wire and ground electrodes were inserted between flush mounted ribbons to enhancement of heat transfer by means of the secondary flow produced from corona wind of EHD wire-plate actuator.



Figure 6. Arrangements of wire electrodes

According to experimental results in active enhancement method, the suitable arrangements of wire electrodes to the ground are arrangements 1 and 3. In active method, the secondary flow of corona wind is from the cold main flow to the hot zone. In conclusion, two kinds of enhancement methods could be beneficial for enhancing of heat transfer from flush mounted ribbons.

The aim of this study is to investigate the heat transfer enhancement of 2-D traverse flush-mounted ribbons placed at the base of the channel.

Three parameters characterize the laminar air flow with heat transfer:

- Rate of heat transfer enhancement, E_t

$$E_{\rm t} = \frac{h}{h_{\rm s}} = \frac{(T_{\rm W} - T_{\rm ref})_{\rm s}}{(T_{\rm W} - T_{\rm ref})}$$
(1)

with $h = q_{rib}''/T_W - T_{ref}$. - Consumed power ratio, E_{lost}

$$E_{\text{lost}} = \frac{\Delta P}{\Delta P_s} \tag{2}$$

and - PEC, η_e

$$\eta_e(\text{PEC}) = \frac{E_t}{E_{\text{lost}}}$$
(3)

In the sequence of eqs. (1)-(3), q_{rib}'' is the constant heat flux from flush mounted ribbons to fluid flow, h – the local heat transfer coefficient, T_{ref} – the reference temperature (inlet temperature to the test section), T_W – the wall temperature in floor of test section, including surface of flush mounted ribbons and spacing of them, ΔP – the pressure loss, and subscript *s* denotes the plain case without enhancement intervention. The Re_{D_h} is Reynolds number based on the hydraulic diameter of the channel, N_{EHD} – the EHD number and it is defined:

$$N_{\rm EHD} = \frac{\rho_{\rm e} E_0^2 L^2}{\rho_{\rm f} v_{\rm f}^2} = \frac{b E_0 L}{v_{\rm f}} = \frac{u_{\rm i} L}{v_{\rm f}}$$
(4)

This parameter is similar to the Re_{D_h} based on velocity of electric ions u_i and with the assumption of similar density for ions and neutral fluid particles. In eq. (4), ρ_e is the density of electric charge, ρ_f – the density of fluid, E_0 – the electric field, b – the mobility of ions, and v_f – the kinematics viscosity of fluid and then u_i is defined:

$$u_{\rm i} = \frac{I_0}{q_{\rm e0}}$$
(5)

In this equation, I_0 is the electric current of corona wind, q_{e0} – the electric charge of one electron, which is $1.602 \cdot 10^{-19}$ C. The L is the characteristic length and defined [11]:

$$L = D_{\rm h} \ \alpha \ \frac{C}{H} \ln\left(\frac{r_{\rm eff}}{r}\right) \tag{6}$$

where α is the view angle between wire and ground electrodes ($\alpha = 1$ for the case of one wire electrode between two ground electrodes and $\alpha = 0.5$ for the case of one wire and one ground

electrode). The C/H is the ratio of space of wire and ground electrodes to channel height. The r_{eff}/r is the ratio of effective radius of wire and ground electrodes to the radius of wire electrode and r_{eff} is defined as $r_{\text{eff}} = 4C/\pi$ where C is the distance between wire and ground electrodes.

By using the active method of EHD wire-plate actuator, the corona wind as a secondary flow between flush mounted ribbons is created. For analyzing this phenomenon, the new parameter of interaction of secondary flow to the main flow (strength of EHD), I_{EHD} is introduced:

$$I_{\rm EHD} = \frac{N_{\rm EHD}}{{\rm Re}^2} \tag{7}$$

Note that I_{EHD} is an important parameter for the kind of active enhancement method under study here.

Results and discussion

The geometry of flush-mounted ribbons arrangements as illustrated in fig. 5 are: $L_1 = L_2 = 110$ mm, L = 30 mm, S = 30 mm, H = 40 mm.

As it is seen in fig. 7, the distribution of wall temperature for the two cases of plain (without EHD, $\text{Re}_{D_h} = 500$) and active cases (arrangement 1; 20 kV) is shown.

The flush-mounted ribbons are heated with constant heat flux and therefore for comparison of EHD active method, the plain case (without EHD, $\text{Re}_{D_h} = 500$) for confined case is base. In this figure, the effects of EHD active method on heat transfer enhancement and the temperature reduction are shown in test section. In the space between the flush-mounted ribbons, the insulator (incombustible fiber) has been applied and adiabatic boundary condition brings a temperature reduction. With regards to the temperature differences in fig. 7, the percent of heat transfer enhancement is of the order of 113%.

In fig. 8, the rate of heat transfer enhancement for laminar forced convection ($\text{Re}_{D_h} = 500$) in arrangements 1 and 2 with voltages of 20 kV and 25 kV is shown. The effect of voltage on heat transfer enhancement depending on the wire arrangement was shown in the figure. In reference to this fig-



Figure 7. Wall temperature distribution in direction of ribbon's surface for forced convection and arrangement 1 (20 kV, $\text{Re}_{D_{c}} = 500$)



Figure 8. Comparison of rate of heat transfer enhancement in direction of ribbon's surface for forced convection and arrangements 1 and 2 (20 and 25 kV, $\text{Re}_{D_{k}} = 500$)

ure, the local and average heat transfer enhancement has been increased as a consequence of increments in voltage. The density of electric charge around of wire electrode in arrangement 1 is higher than that in arrangement 2. Therefore, arrangement 1 is better than arrangement 2.



Figure 9. Comparison of rate of heat transfer enhancement in direction of ribbon's surface for forced convection and arrangements 3 and 4 (20 and 25 kV, $\text{Re}_{D_k} = 4500$)



Figure 10. The rate of heat transfer enhancement in direction of ribbon's surface for forced convection and arrangements 1 and 2 (20 kV, $\text{Re}_{D_h} = 500$ and 3000)



Figure 11. The average rate of heat transfer enhancement in various Reynolds numbers with arrangement 1 for 20, 25, and 30 kV

Figure 9 displays the rate of heat transfer enhancement for laminar forced convection ($\text{Re}_{D_h} = 4500$) in arrangements 3 and 4 with voltages of 20 kV and 25 kV. The effect of voltage on heat transfer enhancement depends on the wire arrangement as shown in the figure. It is clear from the figure, that the local and average heat transfer enhancement was increased with increments in voltage. Therefore, the arrangement 3 is better than arrangement 4.

As it is seen in fig. 10, the rate of heat transfer enhancement for laminar-to-turbulent forced convection in arrangements 1 and 2 with Re = 500 and 3000 is depicted in 20 kV. The impact of Reynolds number on the heat transfer enhancement was seen in the figure. Herein, the local and average heat transfer enhancement for Re_{D_h} = 500 is higher than their counterparts for Re_{D_h} = 3000. For high Reynolds numbers, the main flow power is higher than the power of corona wind (secondary flow) in the main flow eliminating the effects of corona wind.

Figure 11 contains the average rate of heat transfer enhancement for forced convection in various Reynolds numbers with arrangement 1 for 20, 25 kV, and 30 kV. The effect of Reynolds number on average heat transfer enhancement was palpable in the figure. In numbers, the heat transfer enhancement average in $\text{Re}_{D_{1}} = 500$ is higher than those for other Reynolds numbers. The power of corona wind in the case of low Reynolds numbers is higher than in the case of high Reynolds numbers. Consequently, the corona wind in low Reynolds numbers affects the main flow better than in situations of high Reynolds numbers. Inspection of the figure reveals that the average heat transfer enhancement has been increased with elevations in voltage. At high voltages, the density of electric charge and the electric field around of wire electrodes is high. This is interpreted in terms of the corona wind, which at high voltages has a direct influence on the main flow better than those situations of low voltages.

In figs. 12 and 13, the variations of $\overline{\eta}_{e}$ with I_{EHD} number for active method of heat transfer enhancement in $\operatorname{Re}_{D_{h}} = 500$, 2000, and 3000 are presented. As seen in figures, the effect of Reynolds number on heat transfer enhancement for active method demonstrates the

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Figure 12. The PEC in direction of ribbon's surface for active case in $\operatorname{Re}_{D_h} = 500$ with arrangements 1 and 2



Figure 13. The PEC in direction of ribbon's surface for active case in $\operatorname{Re}_{D_h} = 2000$ and 3000 with arrangements 1 and 2

opposite behavior for both low and high values. For the active method, the secondary flow can move further to the spacing between flush-mounted ribbons. The pair of figs. 12 and 13, attests that the density of electric charge around of wire electrode in arrangement 1 is higher



than that in arrangement 2. As a consequence, arrangement 1 is better than arrangement 2. Switching attention to fig. 13 related to $Re_D = 3000$, it is detected that for positive interaction of the average heat transfer enhancement and consumed power ratio (ratio of pressure loss) seems to be better than when $\operatorname{Re}_{D_{h}} = 2000$. This means that the average PEC in $\operatorname{Re}_{D_{h}} = 3000$ is higher than that for $\operatorname{Re}_{D_{h}} = 2000$.

Figure 14. Uncertainty analysis in various temperature points obtained from one sample of iterative tests

The uncertainty analysis for E_t , η_e , E_t , and $\bar{\eta}_{\rm e}$ has been carried out too. The uncertainty for local quantities of E_t and η_e is smaller than 8% and for average quantities of E_t and $\overline{\eta}_e$

is 4-5% [12]. In fig. 14, the uncertainty analysis for various temperature points obtained from one sample of iterative tests is presented.

For the case of active method, the following correlations of various Reynolds numbers have been constructed:

(1) $\operatorname{Re}_{D_{h}} = 500$:

Arrangement 1:

$$\overline{\eta}_{\rm e} = 10^{-42} I_{\rm EHD}^3 - 2 \cdot 10^{-28} I_{\rm EHD}^2 + 8 \cdot 10^{-15} I_{\rm EHD} + 0.6003 \tag{8}$$

Arrangement 2:

$$\overline{\eta}_{\rm e} = 3 \cdot 10^{-41} I_{\rm EHD}^3 - 10^{-27} I_{\rm EHD}^2 + 10^{-14} I_{\rm EHD} + 0.6535 \tag{9}$$

(2) $\operatorname{Re}_{D_{h}} = 2000$: Arrangement 1:

$$\overline{\eta}_{e} = 8 \cdot 10^{-39} I_{EHD}^{3} - 6 \cdot 10^{-26} I_{EHD}^{2} + 2 \cdot 10^{-13} I_{EHD} + 0.5925$$
(10)

(3) $\operatorname{Re}_{D_{h}} = 3000$: Arrangement 1:

$$\overline{\eta}_{\rm e} = -4 \cdot 10^{-37} I_{\rm EHD}^3 + 2 \cdot 10^{-24} I_{\rm EHD}^2 - 2 \cdot 10^{-12} I_{\rm EHD} + 1.5437$$
(11)

Arrangement 2:

$$\overline{\eta}_{\rm e} = 3 \cdot 10^{-36} I_{\rm EHD}^3 - 3 \cdot 10^{-24} I_{\rm EHD}^2 + 5 \cdot 10^{-13} I_{\rm EHD} + 0.8814$$
(12)

Conclusions

This study revolved around the enhancement of heat transfer from flush-mounted ribbons in a channel flow using an active method. Two new parameters η_e and I_{EHD} have been introduced. The parameter of η_e deals with the simultaneous effects of heat transfer enhancement and consumed power ratio (the pressure loss ratio) on the cooling performance. The parameter I_{EHD} embraces the interaction effects of EHD secondary flow and forced convection main flow together. The parameter of I_{EHD} is ratio of EHD flow term to forced convection main flow term and is similar to Richardson number. The following conclusions emanate from the experimental study are listed.

- The power of corona wind (secondary flow) in low Reynolds flows is higher than in high Reynolds flows, signifying that the corona wind in low Reynolds numbers is better than in high Reynolds numbers.
- The active method for low Reynolds numbers with laminar flows is advantageous. The average and local heat transfer enhancement climbs up to 130% and 137%, respectively.
- For the same Reynolds numbers and wire arrangements, the heat transfer enhancement
 was increased with increments in voltage of the wire electrodes. At high voltages, the
 density of electric charge and the electric field around of wire electrodes is high. Therefore the corona wind in high voltages has been affect on main flow better than low voltages.
- In same Reynolds numbers and voltages of wires, the heat transfer enhancement was increase in arrangement 1 than other arrangements. Density of electric charge around of wire electrodes in arrangement 1 is higher than other arrangements. Therefore, the arrangement 1 is better than arrangements 2, 3, 4, and 5, respectively.
- Active method for low Reynolds numbers has higher average PEC = 0.69. The power of corona wind in low Reynolds numbers is higher than in high Reynolds numbers. Therefore, the corona wind in low Reynolds numbers has been affect on main flow better than in high Reynolds number.
- For the boundary conditions used, the correlations for the average of PEC ($\overline{\eta}_e$) vs. EHD strength (I_{EHD}) for different Reynolds numbers can be introduced. These correlations showed that the effects of Reynolds numbers and arrangement on average of PEC. Density of electric charge around of wire electrodes in arrangement 1 is higher than arrangement 2. Therefore the arrangement 1 is better than arrangement 2.
- The voltage of wire electrodes becomes constant after the corona wind. After corona, the voltage of wire electrodes can not changes and only electric current of wire electrodes changes. This phenomenon has been ignored in most of numerical literature works.
- With decrements in the laminar Reynolds number, the interaction strength of EHD secondary flow was increased. In turbulent Reynolds numbers, the interaction strength of EHD flow was decreased.

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Nomenclature

- area of orifice, $[m^2]$ A – mobility of ions, $[m^2V^{-1}s^{-1}]$ b $r_{\rm eff}$ - distance between wire and ground Celectrodes, [m] S D - diameter of pipe, [m] - diameter of orifice, [m] Т d $D_{\rm h}$ - hydraulic diameter, [m] и - heat transfer enhancement ratio $E_{\rm t}$ u_i Ŵ E_{lost} – consumed power ratio E_0 - electric field, [Vm⁻¹] Η - channel height, [m] h - heat transfer coefficient, $[Wm^{-2}K^{-1}]$ - heat transfer coefficient for plain case, h_s α $[Wm^{-2}K^{-1}]$ I_0 - electric current of corona wind, [A] β $I_{\rm EHD}$ – EHD strength $\eta_{\rm e}$ L - width of flush mounted ribbon, [m], Ð characteristic length, [m] $\rho_{\rm f}$ L_1 - length of upstream region, [m] $\rho_{\rm e}$ L_2 - length of downstream region, [m] Δ $N_{\rm EHD}$ – EHD number Р - pressure, [Pa]
- q''_{rib} constant heat flux from flush mounted ribbon, [Wm⁻²]
- q_{e0} electric charge of one electron, [Coulomb]
- Re Reynolds number
- $\operatorname{Re}_{D_{h}}$ Reynolds number based on hydraulic diameter

- *r* radius of wire electrode, [m]
- *r*_{eff} effective radius of wire to ground electrode, [m]
- *S* separation between flush mounted ribbons, [m]
- T = temperature, [K, °C]
- u velocity, [ms⁻¹]
- u_i velocity of electric ions, [mgs⁻¹]
- W width of channel, [m]
- x, y, z Cartesian co-ordinates

Greek symbols

- α view angle between wire and ground electrodes
- the ratio of orifice to pipe diameter
- e performance evaluation criteria
- kinematics viscosity, $[m^2 s^{-1}]$
- $\rho_{\rm f}$ density of fluid, [kgm³]
- $\rho_{\rm e}$ density of electric charge, [kgm³]
- Δ difference

Subscripts

- f fluid
- ref. reference condition
- w flush mounted ribbon wall

Superscripts

- " flux
- – average

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