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Research Paper

ENHANCEMENT OF NATURAL CONVECTION HEAT TRANSFER BY THE EFFECT OF HIGH VOLTAGE D.C. ELECTRIC FIELD

Ritesh Kumar[1] and Amit Kumar[1]*

*Corresponding Author: Amit Kumar, ✉ amitnidhi31@yahoo.com

Generated corona discharge between a sharp electrode and a grounded heated surface usually induces an ionic wind, whose momentum can be used for enhancement. The influence of the active-vortex induced by corona discharge is clearly emphasized to have access to better and illuminating understanding of the enhancement mechanism. An electrostatic blower employs a long stretched thin wire electrode, which is confined by two inclined wings. The latter bestows a longitudinal nozzle for the airstream as well as electric shield. The heat transfer coefficient can be easily increased, as compared with a Natural convection mechanism. A linear relationship is achieved between the Nusselt number and Reynolds number. Senftleben number is found useful in correlating EHD enhanced Natural convection with working fluid air. Proposed empirical correlations will become a powerful tool for designers for such devices employing EHD enhanced Natural convection. Empirical correlations for predicting the extent of electrohydrodynamic enhancement of Natural convection heat transfer from heated horizontal cylinder are skilfully presented. The said correlations are validated with the measured results from different experiments. Nusselt number enhancement is correlated in terms of electrical Rayleigh number (Ra_{El}). Ra_{El} is also found to account for the effect of nonuniform electric field on Natural convection. To investigate the influence of D.C. high voltage electric field on the Natural convection heat transfer of a vertical heated plate in dielectric liquid, boundary layer equations are solved. A considerably large heat transfer enhancement over a wide area is expected. The heat transfer duty of heat exchangers can be augmented by heat transfer enhancement technique. The active technique requires high voltage D.C. electric field. This paper can be used as the first guideline for the researchers in using EHD technique for Natural convection heat transfer enhancement.

Keywords: Ionic wind, Corona discharge, EHD, Natural convection, Electric-field

INTRODUCTION

EHD stands for electro hydrodynamics which is the study of a flow fluid under the influence of an electric field. The presence of a high electric field between a discharged and a grounded electrode induces an air motion

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[1] Department of Mechanical Engineering, National Institute of Technology, Patna 800005, Bihar, India.

which is termed as the corona wind, electric wind or the ionic wind. Corona discharge between a sharp electrode and a grounded heated surface generally induces an ionic wind, whose momentum can be utilized for enhancement of heat transfer from heated surface. Both phenomena are caused by the ionization of air molecular in the intense electric field region around the sharp electrode that accelerates ions and drags the air molecules towards the grounded surface (Yabe *et al.*, 1978). Proposed that the corona wind is generated by the Coulomb force acting on the ions. They showed experimentally that positive ions predominate over electrons in the entire space except in an extremely narrow region near the wire. In positive corona, the positive ions include chiefly positive charged oxygen molecules. In negative corona, the charge carrying particles include ions which are created when electrons are captured by neutral molecules having an electron affinity (oxygen). In this case, the electrons travel some distance before being captured (the ionization region), which is ascertained by the attachment coefficient and field strength. For atmospheric pressure in air for field strength of, the distance is about 2 mm (Sher *et al.*, 1993). In any case, the ions are accelerated towards the blunt electrode, while exchanging their momentum with neutral molecules in the drift region. The rate of momentum exchange depends much on the mobility of the charge carriers. An electrostatic blower functioning on this principle directly converts electric energy into the kinetic energy of the moving gas stream. The practical merit and utility of an electrostatic blower is limited by an efficiency of operation in the vicinity of 1-5% (Robinson, 1961; and Bonder and Bastein, 1986). However, owing to lack of moving parts, the electrostatic blower has a significant merit over conventional fans in areas of such applications where high-voltage low current power is available, where gyroscopic influences and noise cannot be sustained and where simple sturdy construction is needed.

THEORETICAL CONSIDERATIONS

Governing equations convective heat transfer in the presence of corona discharge is influenced by the distribution of space charge density and electric field. The combination of the buoyancy body force and corona-driven flow can potentially induce several flow patterns. The electric body force can be expressed as (Panofsky and Phillips, 1962):

$$F_E = {}^{\circ}{}_{c}E - \frac{1}{2}\left|E\right|^2 \nabla £_0 + \frac{1}{2}\nabla\left[\left|E\right|^2 {}^{\circ}\left(\frac{\partial £_0}{\partial {}^{\circ}}\right)_T\right] \quad ...(1)$$

The first term on the right side of the Rquation (2.1) *qE* is the electrophoretic or coulomb force that results from the net charges in gas. In the symbolic notation, vectors are designated by bold-faced letters, while scalars are denoted by italic letters. The second term, called as the dieletrophoretic force, arises from permittivity gradients. The last term, known as the electrostrictive force, is significant only for compressible fluids. The corona wind arises entirely from the electrophoretic force term. Hence, only the first term contributes to the corona wind generation. The bulk flow is laminar and two-dimensional. The buoyancy effect is estimated using the Boussinessq approximation. The governing equations are the following (Melecher, 1981).

$$\nabla \cdot \left({}^{\circ} u \right) = 0 \qquad ...(2)$$

$$\nabla \cdot \left({}^{\circ} u u \right) = -\nabla p + « \nabla^2 u + g \quad \left(T - T_{\infty} \right) + {}^{\circ}{}_{c} E \qquad ...(3)$$

$$u \cdot \nabla T = \sim \nabla^2 T + \frac{{}^{\circ}{}_{cb} \left| E \right|^2}{{}^{\circ}{}_{cb}} \qquad ...(4)$$

The second term on the R.H.S. is Joule heating caused by ionic current. The electric field around the sharp tip, which is responsible for ionization, is distorted by the free charges in the ionized medium and is governed by the Poisson's equation:

$$\nabla \cdot E = \nabla \cdot \left(-\nabla \ddot{} \right) = \frac{{}^{\circ}{}_{c}}{£_0} \qquad ...(5)$$

The generated ions move from the high voltage electrode towards the grounded surface through the electric force. The transport of ions is governed by the charge conservation equation:

$$\nabla \cdot J = 0 \qquad ...(6)$$

where the current density is defined by:

$$J = {}^{\circ}{}_{cb} E - D_i \nabla {}^{\circ}{}_{c} \qquad ...(7)$$

The ion mobility and ion diffusion coefficient are typically $b = 1.88 \times 10^{-4} m^2 v^{-1} s^{-1}$ and $D_i = 3.50 \times 10^{-5} m^2 s^{-1}$, respectively.

To understand the origin of vortex formation, the derivation of the vorticity transport equation may be helpful in understanding clearly the mechanism of rotational flow generation in the discharge medium. By taking the curl of momentum Equation (3), the vorticity transport equation in the steady state condition can be determined as:

$$u \cdot \nabla \mu = \mu \cdot \nabla u + {}^{3}\nabla^2 \mu + \quad g \times \nabla T + \frac{1}{{}^{\circ}} \nabla {}^{\circ}{}_{c} \times E \qquad ...(8)$$

The vorticity is generated by two source terms (third and fourth terms on the R.H.S.) and is transported by vortex stretching and diffusion mechanisms. The third term is generated by buoyant force and the fourth one by the electrophoretic body force. Equation (8) indicates the physics of vortex generation in the presence of corona discharge. An EHD vortex is produced by a nonparallel gradient of charge density and electric field. The strength of vortices depends wholly on the strength of electric field and the associated charge density in the air. The maximum of both gradient of charge density and electric field take place around the electrode tip. Contrastically, the gradient of charge density becomes smaller around the ground electrode. The thermal gradient in the air also generates vorticity. The third term is associated to the thermal gradient vorticity generation and its direction is opposite in respect with the electrohydrodynamic vorticity source term in the present case. That is why; the momentum equation balance depends on the magnitude of these two source terms.

$$2 \times 10^1 \le Ra_{El} \le 1.0 \times 10^3$$

ANALYTICAL MODELLING AND PARAMETRIC STUDY

Summarizes pertinent calculated values of increase in Nusselt number due to applied electric field (ΔNu) for several values of electric Rayleigh number (Ra_{El}) for electro hydrodynamic enhancement of Natural convection for organic fluids. The final form of an empirical correlation developed is the following:

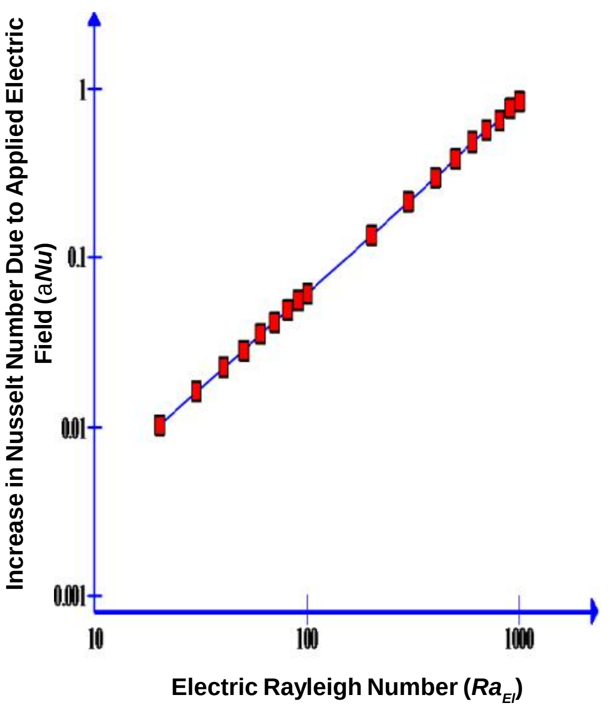
$$\Delta Nu = 0.000344 \; Ra_{El}^{L13} \qquad ...(9)$$

[A developed empirical correlation based on parametric trend analysis as well as linear Regression analysis encompassing a wide range of regressive data]

The Resulting plot is shown in Figure 1.

Figure 1: Variation of Increase in Nusselt Number Due to Applied Electric Field with Electric Rayleigh Number for EHD Enhancement of Natural Convection

$$\left[2 \times 10^1 \le Ra_{El} \le 1 \times 10^3\right]$$



Mechanism: Decreasing bound layer thickness.

Range of Applicability: For organic fluids data are represented when compared with experimental data by Ashmann and Kronig (1950) to within ±10% error band.

Summarizes pertinent calculated values of Average Nusselt number $(\overline{N}_u)$ for several values of Senfteben number (St_N) due to high voltage D.C. electric field in Natural convection for a heated wire in air.

$$\overline{N}_u = 0.473(St_N)^{1/4} \qquad \text{...(10)}$$

where $St_N = \dfrac{(¥ \cdot E_s)\ (t_w - t_\infty)x^2}{v^2}$

¥ = Temperature dependence of the electric susceptibility

E_s = Electric field at the surface of the wire

d = Wire diameter

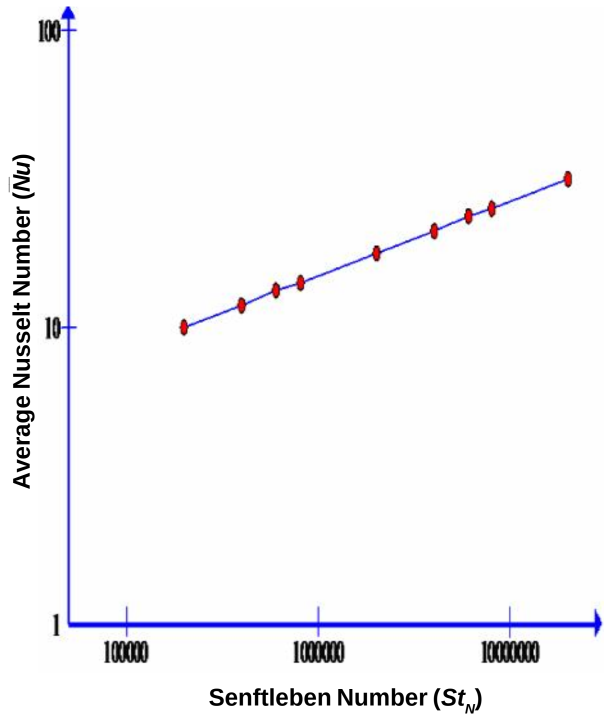
Laminar Flow Range

(An empirical correlation developed is based on parametric trend analysis as well as linear regression analysis encompassing a wide range of regressive data).

Mechanism: Corona discharge

Basis of Correlation: The senftleben number (St_N) behaves in much the same way as the

Figure 2: Variation of Average Nusselt Number with Senftleben Number Due to High D.C. Voltage Electric Field in Natural Convection for a Heated Wire in Air



Grashof number if the gravity force (g) is replaced by $\left(\frac{\text{¥} \cdot E_s}{d}\right)^2$ one obtains senftleben number. The above correlation is only applicable in Natural convection with working fluid air St_N is an electric Grashof number.

The Resulting plot is revealed in Figure 2.

Range of Applicability

$2 \times 10^5 \le St_N \le 2 \times 10^7$

Working fluid = air

Data are represented when compared with experimental data (Eckert and Robert) to within 19% error band.

CONCLUSION

The essential conclusions of this analytical investigation are itemized as follows:

- In single-phase heat transfer, the boundary layers that form on the thermally-active surface offer a significant resistance to the flow of heat which in gaseous systems can dominant the resistance to the flow of heat which in gaseous systems can dominant the resistance offered by the solid works. Enhancing techniques are therefore employed to alter the boundary layer structure of the flow and in Natural convective situations, to increase the flow velocity.
- A decrease of boundary layer thickness by the effect of columbic force working on space charge generated in fluid is the primary cause of heat transfer enhancement.
- One of the objectives of this analytical dissertation is to extend the range of applicability of existing correlations to higher electric Rayleigh numbers, and to develop the means of generalizing the correlation so that they can be applied for cases with nonuniform electric field.

  The correlation developed allows for prediction of Natural convection enhancement over a large range of electric field strengths, with either a uniform or non uniform electric field.
- Measured experimental results for 'aviation kerosene' and 'Transformer' by other investigators are fairly correlated in terms of and a voltage parameter $\left(\text{¤}\frac{\sqrt{\text{£}_0}}{\text{«}}\right)$.

RECOMMENDATIONS

By solving some problems and by pointing out related problems that have and have not been solved, it is expected to indicate fruitful lines of research and to suggest useful methods of solutions to further researchers. From the experience gained in performing this analytical investigation the following recommendations are made:

- It is recommended to develop an analytical study in the near future, taking into account the difference of electrostatic force effect between a positive and a negative applied voltage and nonlinear current voltage characteristics between the electrodes.
- The effect of EHD on single-phase heat transfer characteristics on a horizontal surface has been studied by a number of researchers. However few papers have presented studies for a vertical surface. Hence, enhancement of Natural convection

heat transfer by the effect of high voltage D.C. electric field for vertical surface is to be carried out and it is recommended for further work.

- A computational method is applied to an electrostatic precipitator. This particular study is recommended for further work.
- Numerical modelling of the effect of number of electrodes and electrode arrangement on Natural convection heat transfer enhancement in a bank of tubes is to be carried out as a further work and is hereby recommended. This work is also analytical in nature.

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APPENDIX

Nomenclature

A	Plate surface area (m^2)
b	electrode gap (mm) ion mobility ($m^2v^{-1}s^{-1}$)
c_p	specific heat at constant pressure (J $Kg^{-1}k^{-1}$)
c_{pl}	specific heat of liquid (J $Kg^{-1}k^{-1}$)
d	wing gap (m)
D	heater surface diameter (m)
D_i	ion diffusion coefficient (m^2s^{-1})
De	charge diffusion coefficient ($m^2V^{-1}s^{-1}$)
E	electric field strength (Vm^{-1})
E_0	electric field (Vm^{-1})
$E_{\max}$	breakdown voltage (Vm^{-1})
E_f	nondimensional parameter of electric force
El	electrical number
F_E	EHD body force (Nm^{-3})
F_g	electric force density on a liquid dielectric (Nm^{-3})
g	Gravitational acceleration (ms^{-2})
Gr	Grashof number, $g\ \Delta T L^{3\circ 2} / «^{2}$
Gr_s	Grashof number, $g\ \left(T_w - T_\infty\right) s^3 v^{-2}$
h	Convective heat transfer coefficient ($wm^{-2}k^{-1}$)
h_E	Heat transfer coefficient under electric field ($wm^{-2}k^{-1}$)
h_{fg}	latent heat of vaporization (KJ Kg^{-1})
H	Electrode height (mm)
i	corona current (μA)
I	Total current (A)
J	current density (Am^{-2})
K	Thermal conductivity ($wm^{-2}k^{-1}$)
L	Inter-electrode gap (m); vertical distance between electrode (m)
L_1	length scale used (m)
L_2	length scale used (m)
l_w	length between wire electrode (m)
L_W	Length of wire-electrode (m)
N	Number of electrodes
Nu	Nusselt number

APPENDIX (CONT.)

$\overline{Nu}$	average Nusselt number (hsk^{-1})
Nu_x	Local Nusselt number (hxk^{-1})
ΔNu	Increase in Nusselt number due to applied electric field
p	pressure (NM^{-2})
p	Power (w)
Pr	Prandtl number ($c_p\mu k^{-1}$)
q	electric field space charge density (cm^{-3})
q”	heat flux (wm^{-2})
Qw^*	heat flux (wm^{-2})
Q	rate of heat transfer (w)
r	coronona wire radius (m)
R	electric resistance (Ω)
Ra	Rayleigh number
Ra_{El}	Electric Rayleigh number
R^*	nondimensional parameter of relaxation time
Re	Reynolds number
Re_x	local Reynolds number (U_0xv^{-1})
s	characteristic length (m)
s^*	nondimensional parameter of electrical conductivity ratio
t	time (s)
T	temperature (°C)
Tw	plate surface temperature
Ts	heater surface temperature
T_∞	pool temperature (°C); dielectric liquid temperature (°C) or ambient temperature (°C)
ΔT	temperature difference
u	velocity (ms^{-1})
u_c	electric characteristics velocity (ms^{-1})