EFFECT OF EHD ON FORCED CONVECTION IN A TUBE BY USING HELICAL ELECTRODE

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Abstract

An experimental research was conducted to investigate the level of heat transfer enhancement that can be achieved by negative EHD in the developing region of a circular tube by helical electrode. The study focused on laminar to lower range of turbulent flows with Reynolds number ranging from 1500 to 10,000 and voltage from 0 to 17.1 kV. Three different constant heat fluxes were applied on the outer surface of tube. The working fluid in all experiments was air. Maximum enhancement occurred at Re=2500 and 4000, namely in the transition flow.

Keywords: Corona wind; EHD; Heat transfer; Enhancement; Tube; Helical electrode.

1. Introduction

It has long been established that coupling of an electric field with a flow field can significantly affect convective heat and mass transfer rates. Intense electric fields affect and change the flow and thermal behavior of dielectric fluids. This phenomenon can be used to improve the thermal performance of systems. This approach, which is referred to as the electrohydrodynamic (EHD) enhancement technique, has the potential to improve the convective heat transfer coefficient of heat exchangers.

The high-intensity electric field around the wire breaks down the insulating property of the surrounding air partially, and electric current passes through the air [1].

An important aspect of corona discharge is the generation of corona wind. In this research, we used corona wind to enhance heat transfer in the developing region of a tube.

Ohadi et al. [2] studied experimentally the effect of single and double wire electrode configuration. Chang et al. [3] reported that a higher inlet temperature in pipe flows increases the instability of corona discharge and reduces the corona current. In contrast, a higher gas flow rate stabilizes the flow. In a study by Tada et al. [4], it was shown when electrodes are placed parallel or perpendicular to air flow in a channel, the Nusselt number increases with the applied voltage at lower Reynolds numbers. Wangnipparnto et al. [5] used EHD to enhance heat transfer from heat pipes. Molki et al. [6-8] studied heat transfer enhancement in the developing and fully developed flows in ducts. The preliminary experimental results of the effect of an electrostatic field on turbulent aided mixed convection in a short vertical annulus were reported in [9].

Studies on electrohydrodynamically enhanced forced convection in a horizontal channel have revealed the existence of oscillatory flows. In a study by Lai and Tay [10], it has been shown that heat transfer can be significantly enhanced when operating in this oscillatory flow mode.

The present research deals with the EHD enhancement of local convective heat transfer in the developing region up turbulent region of a tube.

2. Experimental setup and procedure

The experimental setup is shown in Figure1. The main components of the setup are: test section, exhaust tube, charged electrode, and blower. A high-voltage DC power supply (Heinzinger electric GmbH, PNC 40000-5 umb,

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Germany) was used to charge the electrode. The ranges of voltage and current of the high-voltage power supply were 0–40 kV and 0–5 mA, respectively. The resolutions of the digital voltmeter and ampere meter were 0.1kV and 0.01mA, respectively.

Temperature was measured during the experiments using sheathed flexible thermocouple, type ‘K, connected to a digital thermometer of 0.1˚C resolution, (STANDARD ST-612).

The humidity of air in laboratory environment was determined using a temperature/humidity data logger (Testo 177 H1). The relative humidity varied between 21 to 23%.

Details of the test section are shown in Figure2. The test section was a seamless steel tube (k= 22 W/mK). The inner diameter, wall thickness, and length of the tube were 52, 2.7, and 1545 mm, respectively. A copper electrode wire having a diameter of 0.3 mm was coiled around the wooden core in center of the steel tube and was charged with negative high voltage.

The choice of the inner diameter of the test section tube was based on the electric field intensity between the tube and electrode. A large diameter tube would reduce the electric field intensity and weaken the corona wind. On the other hand, if the tube diameter was too small, spark would occur at low voltages.

In order to minimize axial heat conduction in the test section, Teflon pipes (k=0.35 W/mK at 300K) were used at either end of the test section. With this arrangement, the effective length of the test section, i.e. the total tube length minus the length covered by the Teflon disks, was 1500 mm. In order to prevent the downstream hydrodynamic effects, the test section was extended by a 1800 mm long piece of insulated exhaust tube.

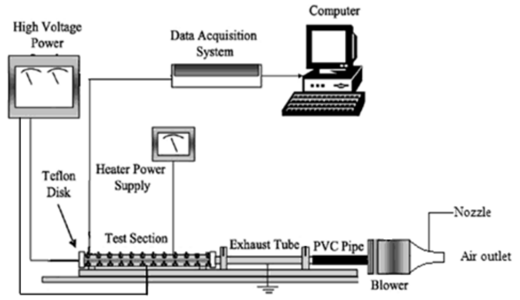


Figure1. Schematic of the experimental apparatus

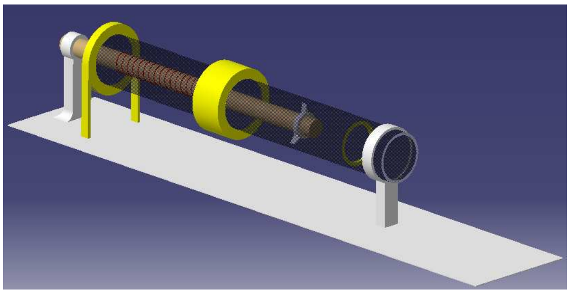


Figure2. The test section and the exhaust tube

A heater was wrapped around the test section with a pitch distance of 4 mm. This pitch was enough to provide a nearly uniform heating on the outer surface of the test section tube. Heater was powered by a variable AC power supply (Philips- PE 1646) that could provide 0–75 V, 6A. Two KAISE- SK-6111 digital multitester were used for measurements of voltage and current applied to the heater.

To locate thermocouples for measurement of the tube temperature, holes were drilled into the tube wall to within 0.8 mm from the inner surface of the tube. Ten thermocouples were used along the test section, and two for the air temperature at two ends of the tube. To control the convection losses from the test section and other components, foam insulation and fiberglass insulation were used. The length of core insulation was 1900 mm. The diameter of the electrode was 0.3 mm. The voltage applied to the electrode was a negative DC voltage.

3. Data reduction

Hydraulic diameter of the test section (29 mm) was used in the calculation of Nusselt number and local convective heat transfer coefficients. To account for wall conduction and non-uniformity of heat flux at the inner surface of the tube, local heat flux was determined from a computational program using MATLAB software (R2008a). Air properties were considered as constant [11].

In all of these relations, temperature unit is Kelvin degree. It must be noted that the tube length is divided to nine parts, so called element. Whereas the first thermocouple at both ends of the tube situates in 75 mm from the test section edges and the distance between each two thermocouples is 150 mm, the heat flux for each element is calculated as q_t (whole of the heat generated by the heater) divided to 10.

$$q_t = R\,I^2 = V\,I \quad (1)$$

$$q_i = \frac{q_t}{10} \quad (2)$$

$$q_l = q_t - \dot{m}\,c_p\,(T_1 - T_2) \quad (3)$$

In relation (1), R is the total resistance of the heater wire (Ω), and I is its current (A).

The second term in right hand of the relation (3) shows the amount of heat flux that the air receives passing through the tube. T_1 and T_2 are the inlet and outlet air temperature of the test section, respectively. The total heat flux minus this term, gives the heat loss from the whole of the test section tube, due to conduction across the tube and natural convection to environment. Calculations revealed that heat loss accounts for 5-10% of total heater output.
Heat transfer coefficients with and without applying EHD are denoted by h and h_0, respectively and their ratio (E_r=h/h$_0$) is used as a measure of heat transfer enhancement.

4. Results and Discussion

Effect of changes in applied voltage, and applied heat flux on heat transfer enhancement in the tube was investigated.
Figure 3 shows the voltage of corona versus current in an electrode gap of 1.45cm (distance between the core insulation and the inner surface of the tube). Just after the inception voltage there is a sharp rise in the voltage. Then the curve continues with a mild slope until the breakdown phenomenon occurs, at which point the corona becomes unstable [12].

4.1 Effect of applied voltage on EHD enhanced heat transfer

Three voltages (i.e. corona inception voltage, mid voltage of 15.6 kV, and a high voltage of 17.1 kV - near the spark over) and three different heat fluxes are used in the experiments to investigate the convective heat transfer coefficients along the test section tube. Figure 4 shows the changes of E_r versus the applied voltage for heat flux of 90 W at Reynolds number 1500. Figure 5 and 6 show similar results for two other heat fluxes. As is seen, an increase in the applied voltage leads to an increase in the local convective heat transfer coefficients.

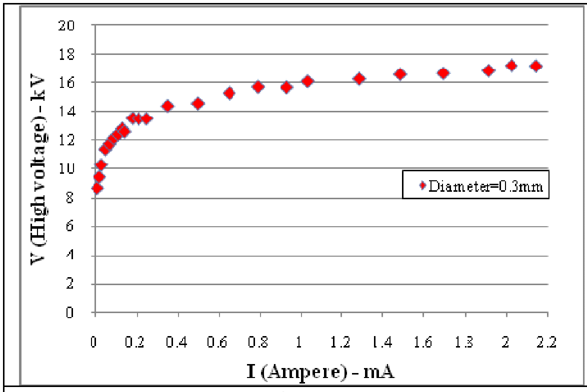


Figure3. V-I curve for coiled wire electrode (Re=1500-10,000)

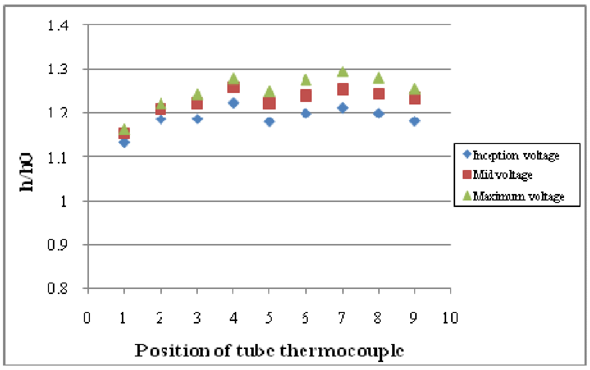


Figure4. Effect of applied voltage on E_r, q_t=90W, Re=1500

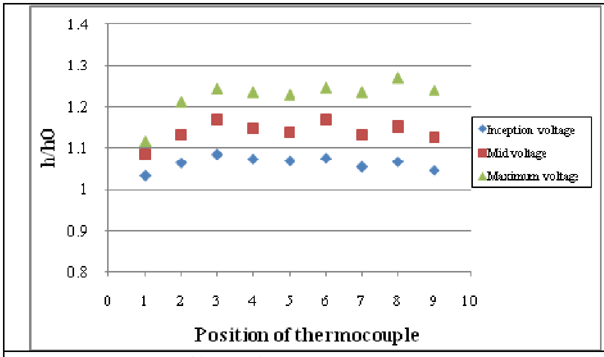


Figure5. Effect of applied voltage on E_r, q_t=125W, Re=1500

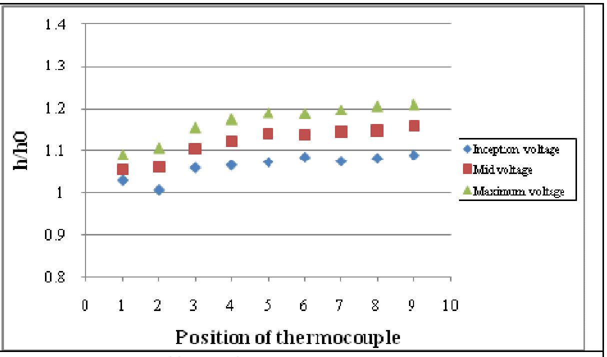
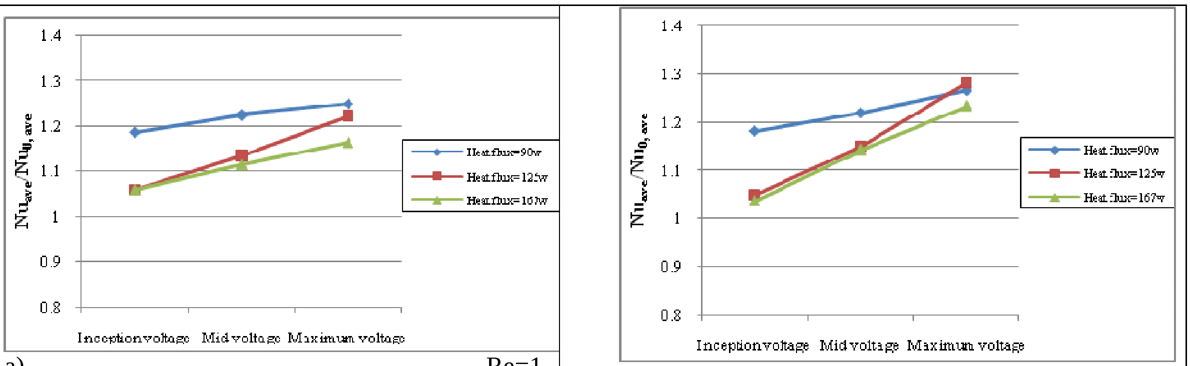


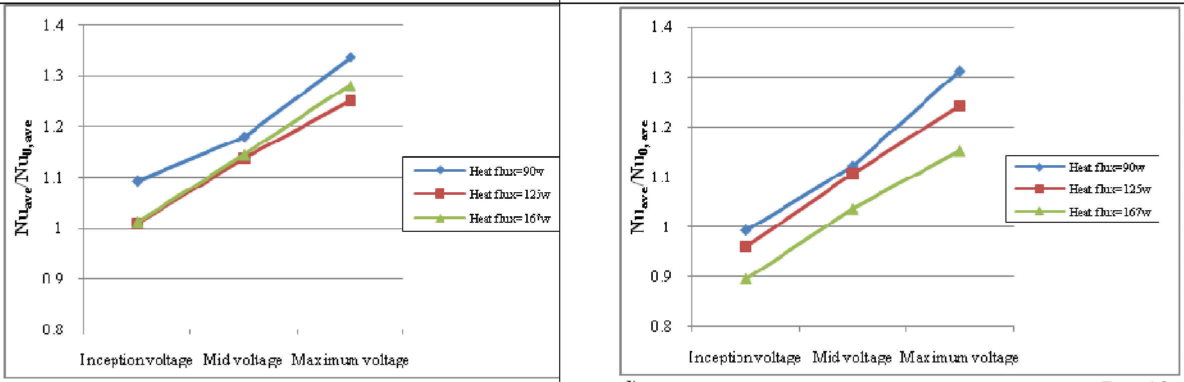
Figure6. Effect of applied voltage on E_r, q_t=167W, Re=1500

Figure7 shows the effects of applied voltage on the relative average Nu number for different Reynolds numbers and heat fluxes. The results indicate that at a fixed applied voltage, the relative average Nu number decreases as heat flux increases. In other words, EHD is more efficiently used at lower heat fluxes.



a) Re=1500

b) Re=2500



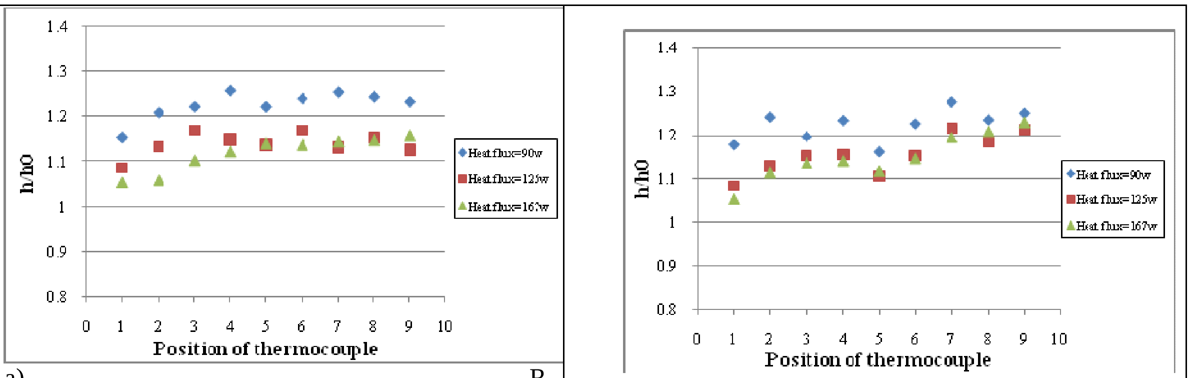
c) Re=4000

d) Re=10000

Figure7. Effect of applied voltage on Nusselt number

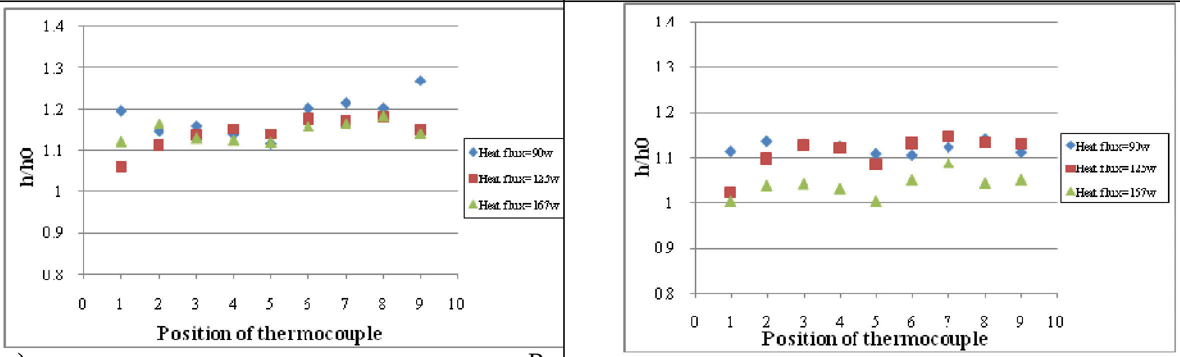
4.2 Effect of heat flux on EHD enhanced heat transfer

Changes of relative convective heat transfer coefficient along the tube at different Reynolds numbers due to changes in the applied heat fluxes are depicted in Figure 8 for middle applied voltage. Similar results were obtained for inception voltage and maximum voltage as well. As is seen in this figure, an increase in heat flux, is associated by a decrease in E_r(=h/h_0), though absolute values of both h and h_0 may have been increased.



a) R
e=1500

b) Re=
2500



c) R
e=4000

d) Re
=10000

Figure8. Effect of increasing heat flux on E_r, Mid voltage

5. Conclusion

In this study, Electrohydrodynamic (EHD) was used for enhancement of convective heat transfer in a tube of constant wall heat flux. Effect of several parameters such as applied electric voltage, wall heat flux, and Reynolds number were investigated. The results can be summarized as followings:

1- By increasing the applied voltage and current, convective heat transfer is increased.
2- By increasing the applied heat flux, the convective heat transfer coefficient is increased with or without applying EHD, but the ratio of these two coefficients (E_r) is decreased.
3- EHD is more effective at lower wall heat fluxes and for the Reynolds numbers corresponding to the transition regime (i.e 2500-4000).

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