16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

NUMERICAL SIMULATION OF HEAT TRANSFER ENHANCEMENT IN THE PRESENCE OF AN ELECTRIC FIELD AT LOW REYNOLDS NUMBERS

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Abstract
One way for optimization of the rational use of energy in thermal systems is to increase their rate of heat transfer. In this study, the effects of an electric field on the fluid flow and temperature field as an active method of enhancement is numerically investigated. The hydrodynamics and heat transfer behaviors of laminar duct flow with specific boundary conditions in the presence of an EHD actuator was taken into consideration. The partial difference equations of flow field and electric field namely continuity, momentum and energy equations for fluid flow and electric current and Poisson's equations for electric field was numerically solved with finite volume method. At first, the electric equations were solved and then their results were imported to the fluid field for improvement of the body forces. The aim of this study is an application of the EHD actuator on local heat transfer enhancement by using wire-plate electrodes in laminar duct flow. The obtained results show for the flows with $\mathrm{Re} \leq 1000$ this method is suitable.

Introduction
If a high voltage electric field applies between a thin wire and conductor plate, the dielectric fluid in surrounding will be affected by ions injection from wire. These ions move towards the plate electrode and impact with neutral fluid molecules and change their momentum. This phenomenon creates a secondary flow in cross wise of the main flow in duct and effects on its heat transfer rate.
The EHD actuator is an active method of heat transfer enhancement. It has several advantages: It is noiseless, low power consumption and easily controllable, applicability in complex geometries and etc.

The enhancement effect will be augmented by increasing the applied voltage. The electrical breakdown strength of fluid must be known and should not exceeded. Poor design may result in electrical breakdown, which make the EHD actuator system useless [1, 2].

Marco and Velkoff (1963), for first time used corona wind as an active method of heat transfer enhancement. They used this method in natural convection of a vertical plate with constant heat flux and could enhance the mean value of heat transfer rate up to five times as much [3].

Yabe et al (1978) in an experimental and numerical study could determine the pressure and density of ions over a horizontal surface of a receiver containing dry nitrogen. They could be able to recognize the recirculation region of the fluid caused by corona wind provided by a wire-plate actuator. Also the enhancement of heat transfer in the zone of stagnation point of impingement jet of corona wind over the plate with constant temperature has been minutely obtained [4].

Takimoto et al (1988) applied this technique for heat transfer enhancement in internal flow [5]. They used the wire electrode in the central axis and ground electrode over upper and lower surface of duct. Their experimental and numerical results were conveniently conformed.

Ohadi et al (1991) used the wire-plate electrodes for forced convection enhancement in pipe flow. They showed that the two-wire electrode design provided a modestly higher enhancement than did 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 [6].

Seyed-Yagobi and Owsenek (1997), investigated the theoretical and experimental works on EHD heat transfer enhancement through wire-plate corona discharge in air flow over a horizontal surface with constant heat flux [7].

Allen and Karayanis (1995) and the Seyed-Yagobi and Bryan (1999) published the review papers for enhancement of heat transfer and mass transport in single-phase and two-phase flows with electrohydrodynamics. They showed the importance of this method in vast application [8, 9].

The momentum and energy equations are coupled through the temperature dependence of the permittivity and thermal conductivity of the fluid. So it is noted that analytical solution of the EHD coupled momentum and energy equations is not possible [10]. But fortunately in air flow applications because of negligible term of Joule heating in energy equation the problem becomes uncoupled. Hence, in this work the heat transfer enhancement of laminar duct flow has been numerically investigated for uncoupled field.

Theoretical approach and Governing equations
It is assumed that the material properties are constants and the corona is directed from wire to the plate. Since this corona wind is generally stable. Neglecting the end effects in rectangular cross section of duct, a plane two-dimensional electrohydrodynamic model can be assumed. The analyze of the flow behavior with electric field can be done by numerical solution of the corresponding governing equations for steady, incompressible EHD flows.
The governing equations of both fields are:

- Gauss's law:

$$\nabla^2 V_e = -\frac{\rho_e}{\varepsilon} \tag{1}$$

- Conservation of charge:

$$\vec{\nabla}.(V_e \rho_e) = \vec{\nabla}.(D\vec{\nabla}\rho_e) + \beta\vec{\nabla}.(\rho_e \vec{\nabla} V_e) = 0 \tag{2}$$

- Electric field or electrical potential relation:

$$\vec{E} = -\vec{\nabla} V_e \tag{3}$$

- Conservation of electric current

$$\vec{\nabla}.\vec{J} = 0 \tag{4}$$

$$\vec{J} = \rho_e.\beta.\vec{E} \tag{5}$$

By substitution of $\vec{J}$ in equation (4) the final case of conservation of electric current becomes:

$$\varepsilon_0.\vec{E}.\nabla\rho_e = -\rho_e^{\ 2} \tag{6}$$

In equations (1)- (6), V_e is electrical potential, ρ_e is the charge density, D is the ion diffusivity in gas, β is the mobility, $\vec{E}$ is electric field intensity vector, ε is the permittivity of the medium and $\vec{J}$ is the electric current.

- Continuity for gas flow:

$$\vec{\nabla}.\vec{u} = 0 \tag{7}$$

- Conservation of momentum:

$$\vec{u}.\vec{\nabla}\vec{u} = -\frac{1}{\rho}\vec{\nabla}P + \nu\nabla^2\vec{u} + \rho_e\vec{E} \tag{8}$$

- Energy equation:

$$\vec{\nabla}(\rho\vec{u}c_pT) = \vec{\nabla}.(K\vec{\nabla}T) + \beta\rho_e\vec{E}^2 \tag{9}$$

In this work, the mobility of ions in air is about $\beta = 10^{-6}m^2/V.s$ so in equation (9) the Joule heating term ($\beta\rho_e\vec{E}^2$) becomes negligible. In equations (7)- (9) $\vec{u}$ is air flow velocity vector, ρ is fluid density, P is the fluid pressure, ν is fluid kinematic viscosity, T is the fluid temperature, c_p is specific heat of fluid at constant pressure and K is thermal conductivity of fluid.

Equations (1)- (9) show that, in general, the electrical potential , the charge density ,the gas velocity and the gas temperature are coupled. These coupled system of equations for some simple cases can be solved numerically [10]. But in our study, as it is said before the Joule heating term in equation (9) becomes negligible and in equation (8) the last term of coulomb force ($\rho_e\vec{E}$) is the only influence of electric field in the fluid field. Hence, we assumed the equations are uncoupled for iterative solution of problem. At first we solve numerically the electric equations independent from the fluid equations and then from the results we improve the body force in equation (8) by replacing the values of Coulomb force as a source term in momentum equations.

Numerical Procedure and Boundary Conditions

Equations (1) and (6) for electric field are discritized in the standard form of the finite volume method by using the upwind scheme. As it seen in equation (2) there are two terms in the conservation of charge. The first term is diffusion of ions in media and the second term is the ions mobility term. In this case the first term is negligible in comparison with the second one. So the equation (2) becomes:

$$\nabla(\rho_e\beta\vec{E}) = 0 \tag{10}$$

In this condition the movement of charge is only from up to down of electric field. So, if we discrete the domain of solution, the movement of ions is only in the longitudinal direction. Therefore it is rational to use the upwind scheme in discretization of electric field equations. For fluid flow SIMPLE algorithm and Hybrid scheme are applied for numerical procedure.

Duct geometry and the Boundary Conditions

Figure (1) shows the schematic of the solution domain. The test duct is 1000mm length, 140mm height, the distance of wire from upper surface of duct has three values which will be mentioned in discussion of the results. Wire to inlet domain is 320mm, wire to outlet domain is 680mm and its diameter is 4mm.

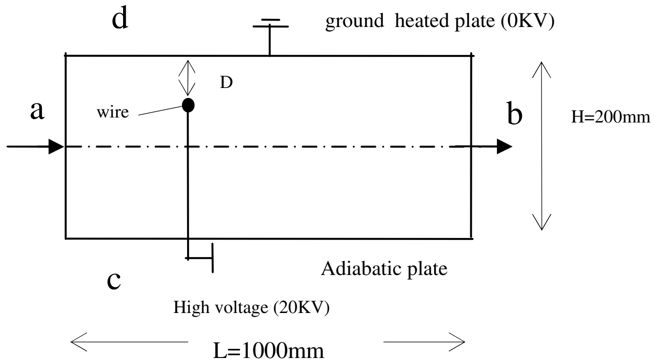


Figure 1.Schematic geometry of main problem.

For the geometry shown in Fig. 1 the following electric boundary conditions are used:

Along a (inlet condition): $\frac{\partial\rho_e}{\partial x} = 0,\ \frac{\partial E}{\partial x} = 0$ (11)

Along b (outlet condition): $\frac{\partial\rho_e}{\partial x} = 0,\ \frac{\partial E}{\partial x} = 0$ (12)

Along wire surface: $E = E_0$ (13)

For wire surface charge density, a method of try and error iteration is used. In first step, a primitive value for ρ_e is guessed then the electric current from wire to plate is calculated. From the assumption has been used by a large number of authors in past ([5], [8], [9] and [13]) and for prevention of breakdown phenomenon in dielectric media, it is recommended to limit the intensely of electric current around μA to few mA. In the next steps the values of ρ_e are corrected.

In the recent work of Ahmadi et al [10], based on the Peek's formula of the onset of electric field strength [12], for a coronating wire they use:

$$\vec{n}.\vec{\nabla}E = E_{onset} \tag{14}$$

Where $\vec{n}$ is the local unit normal vector that points into the wire, $\vec{\nabla}E$ is the gradient of voltage on the wire, and E_{onset} is the electric field threshold strength for corona onset. E_{onset} is calculated with Peek's formula for an iterative procedure applying the charge density condition on the wire.

Along c (lower surface of duct):

$$\frac{\partial E}{\partial x} = 0,\ \frac{\partial E}{\partial y} = 0 \tag{15}$$

Along d (upper surface of duct, ground electric)

$$E = 0 \tag{16}$$

For the flow of air in domain we have:

Along a: $u = U_0$, $v = 0$, $T = T_0$

Along b: $\frac{\partial u}{\partial x} = 0$

Along wire surface: $u = 0$, $v = 0$

Along c: $u = 0$, $v = 0$, $\frac{\partial T}{\partial y} = 0$

Along d: $u = 0$, $v = 0$, $T = T_d$

The main purpose of this work is the cooling of upper heated surface with constant temperature by the air flow in presence of an EHD corona wind. Hence, the previous boundary conditions for the flow and heat transfer have been considered.

Result and Discussion

The air flow is laminar and Reynolds number is extended up to 1000. Inlet temperature $T_o = 273^{\circ}C$, upper surface temperature of duct $T_d = 300^{\circ}C$ and constant physical properties of air: $\rho = 1.225 kg/m^3$, $\nu = 1.787 \times 10^{-5} m^2/s$, $C_p = 1007 J/kg.K$ and $\Pr = 0.71$. Applied voltage is in the range of 5 to 20 KV.

In the numerical procedure, the mesh is refined and its final size independence for solution has been gained for 250 cells in stream wise and 35 cells in crosswise direction.

In beginning, for validation and the accuracy of the calculation, we used an especial geometry which is shown in Fig. 2. From this geometry, we could compare our results with the experimental and numerical work of Jerzy et al [11].

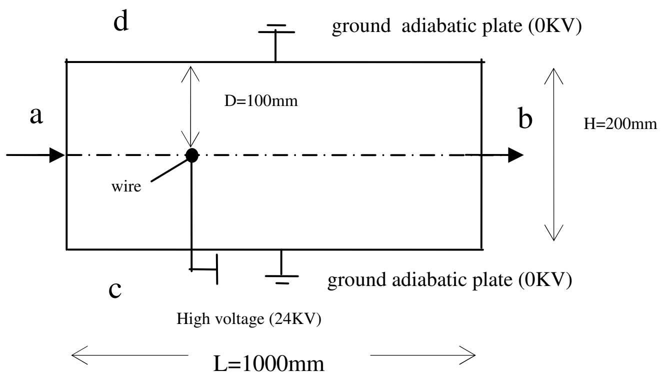


Figure 2.Geometry of domain for comparison with [11].

In this case the intensity of electric current remains between $400\,\mu A$ to $500\mu A$. The applied voltage was $24KV$ from wire to plates. Mean inlet air velocity of fluid is $0.2\,m/s$ and its Reynolds number becomes around 2000. Therefore this Reynolds number is a little more than the case of laminar flow, it is required to introduce for flow field a turbulence model with moderate intensity of turbulence in inflow. We used the standard $k-\varepsilon$ model and solved the momentum equations coupled with electric field. Fig. 3 represents our numerical results for velocity vector distribution in domain. The results obtained by Jerzy et al [11] from their numerical procedure and experimental work has been taken for comparison in our work. The boundary conditions in all of these results are the same. Their experimental work was taken by an image of flow visualization which was obtained by PIV method. The results are fairly agreement between them.

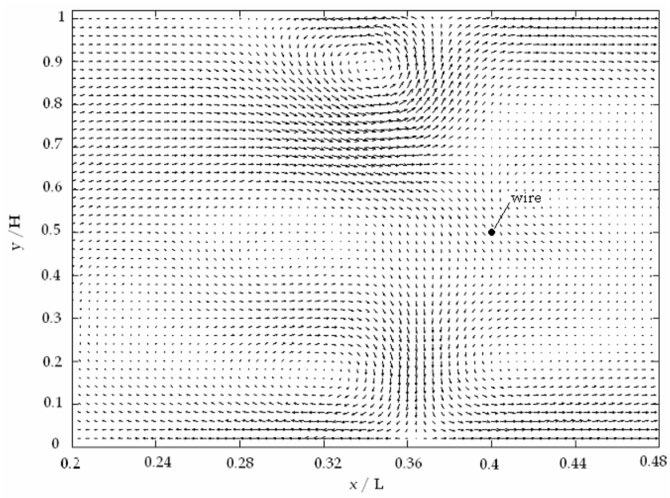


Figure 3. Velocity vectors in this work.

In main problem, the Reynolds number is extended from 100 to 1000, therefore it remains laminar in all cases. Table 1 represents for the distances of wire from upper surface (D) and applied voltage, the electric current calculated by iteration in fluid medium.

Table 1. Electric current values obtained by iteration method

	D=48mm	D=60mm	D=72mm
5KV	I=117 μA	I=90 μA	I=60 μA
10KV	I=260 μA	I=200 μA	I=140 μA
15KV	I=402 μA	I=309 μA	I=250 μA
20KV	I=642 μA	I=495 μA	I=400 μA

Fig. 4 represents the velocity profiles in both cases of non electric fields and applying $20KV$ for $D = 60mm$ and three Reynolds numbers 100, 500 and 1000.

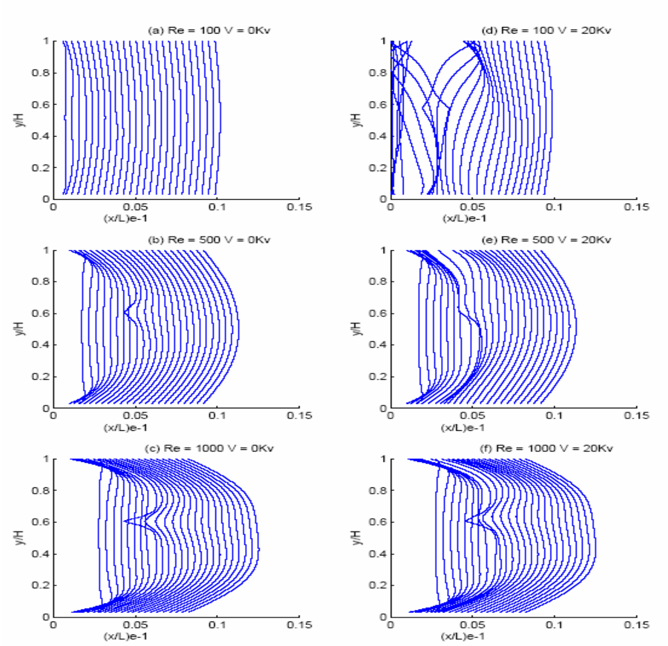


Figure 4. Comparison of the velocity profiles.

As it is seen, the local effects of the secondary flow caused by corona wind are manifested in the velocity profiles closed to the electrodes. The distortion of profiles becomes important for low Reynolds numbers. In fig. 5, for the same conditions as before, the temperature contours are depicted. As it is illustrated, for low Reynolds numbers from the secondary flow of EHD, the distortions of temperature field are intensively affected around electrodes.

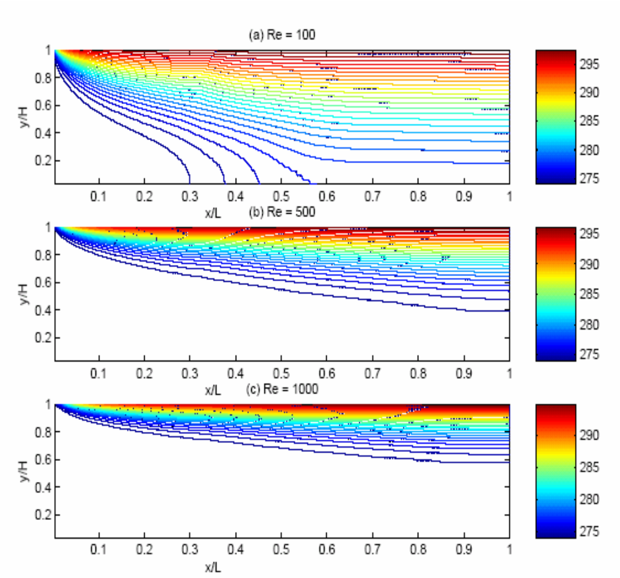


Figure 5-a. Without applied voltage

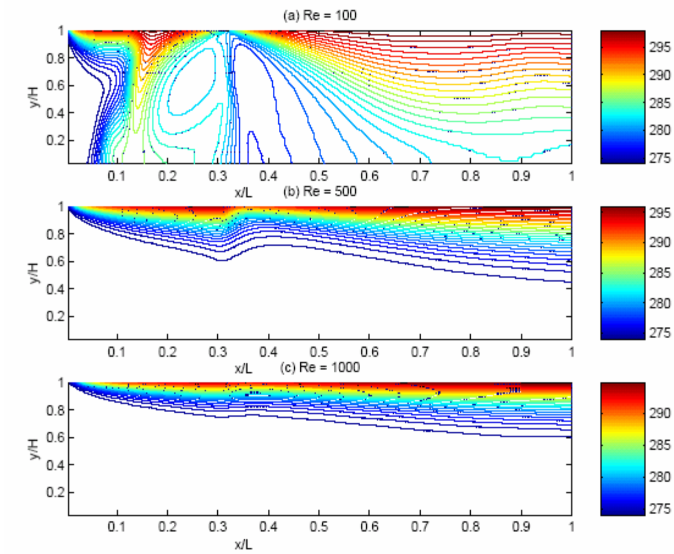
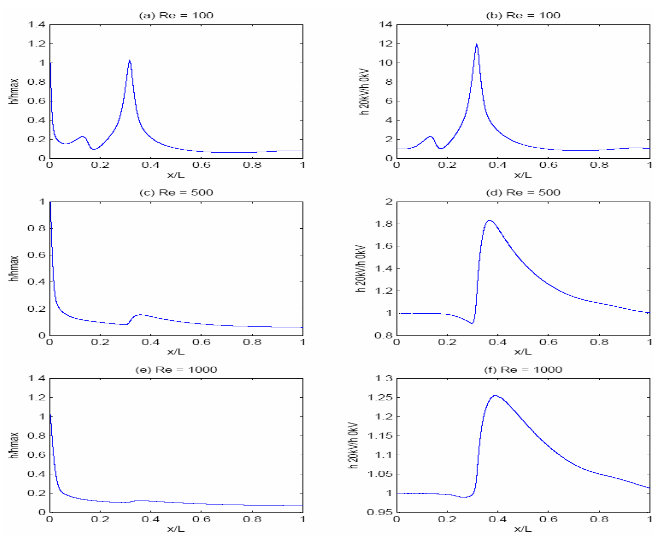


Figure 5-b. With applied voltage (20KV)

Figure 5. Comparison of the temperature contours in two cases (a),(b).

In Fig. 6 the heat transfer coefficients illustrated in two manners. In first way, the curves of a, c and e (left) represent $h/h_{\max}$ versus x/l. Where $h_{\max}$ is the maximum value of h just in the beginning section of domain. In second way, the curves b, d and f (right) which are plotted for h_{20}/h_0 versus x/l. Wherein h_0 is the heat transfer coefficient without corona wind and h_{20} with $20kV$ applied voltage. As it seen, for low Reynolds numbers, h locally increased and extended downstream. The heat transfer coefficient h, enhanced above ten times more than that of h_0. It is also mentioned, the enhancement for $\mathrm{Re}=100$ becomes 10 time of $\mathrm{Re}=1000$.

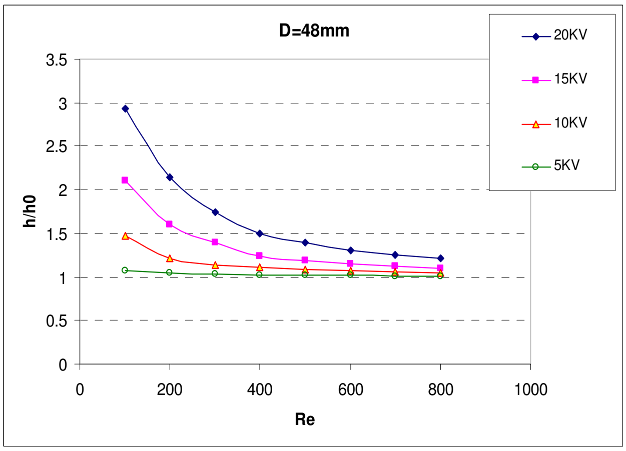
For other applied voltages, similar result was achieved. It is obvious, for high voltage and small distances of wire to plate, the enhancement is important.



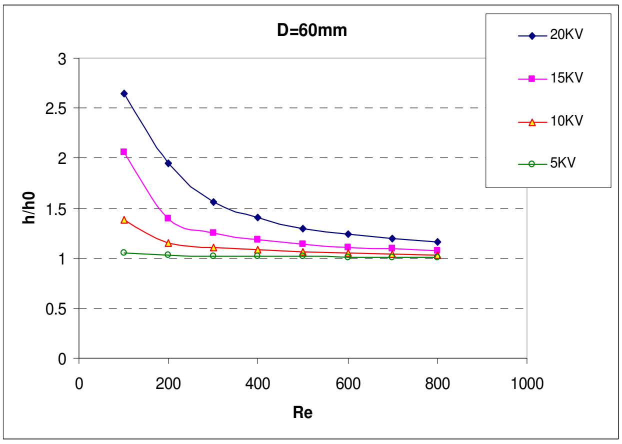
(left) (right)

Figure 6. Heat transfer coefficient ratio versus x/l for Reynolds (left) $h_{20}/h_{\max}$, (right) h_{20}/h_0.

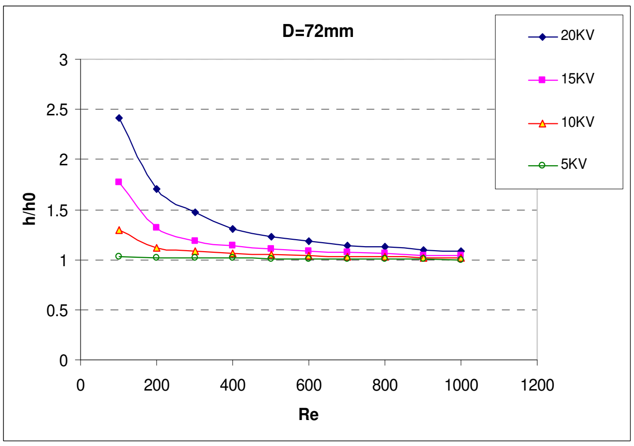
In fig.7(a, b and c), the ratio of h/h_0 (h with EHD and h_0 without it) are plotted versus Reynolds numbers. The applied voltage was in the range of $5kV$ to $20KV$ and the distance of wire to upper plate has been taken for three values of $48, 60$ and 72 mm. As it is shown by increasing Reynolds numbers and decreasing applied voltages, the enhancement of heat transfer decreases for all of electrode distances.



(a)



(b)



(c)

Figure 7. Variation of h/h_0 versus Re for $5KV \le V \le 20KV$ and D=48, 60 and 72mm.

The effect of location and displacement distance of wire electrode to upper plate in the enhancement phenomenon is illustrated for $20KV$ applied voltage in Fig. 8. From this figure the variation of h_{20}/h_0 versus D/H becomes nearly linear. In all conditions of investigation, the slop of variation for low Reynolds numbers are steeper than others.

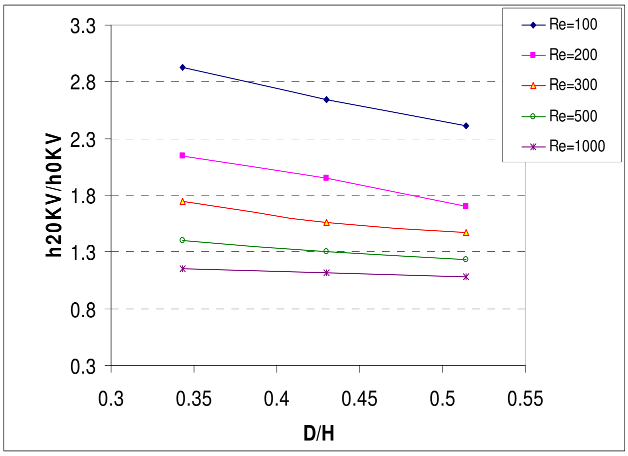


Figure 8. Effect of distance D on enhancement of heat transfer for diverse Re and $20kV$ voltage.

Conclusion

The ability of our calculation code based on finite volume method is proven for prediction of an active method of heat transfer enhancement by using EHD phenomenon in duct flow. The results show for local and mean values of heat transfer enhancement in laminar duct flow up to 1000 Reynolds numbers, a single wire-plate electrodes is suitable. In this geometry and boundary conditions for low Reynolds numbers, high voltage and short distance of wire to plate it is possible to enhance the mean heat transfer up to three times more than the case without EHD corona wind.

Acknowledgments

This work has been supported by contract No.39/2239 of the research council department of the University of Tabriz.

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