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Experimental Study of Fluid Flow Around Cylinder in the Presence of EHD Actuators

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Abstract: The external flows around bluff bodies play an important role in industrial applications and have been studied by many researchers. The major problem in such studies is decreasing total drag. In this study experimental results of flow control over a cylindrical configuration by means of an EHD actuators represented. Wire-plate actuators were investigated in this study. This study performed by placing a cylindrical cross section in a wind tunnel and measuring pressures in several positions. Results are given in two ground electrode arrangements, In the first case whole surface of cylinder is covered with a flush mounted electrode as ground electrode and one or two wires electrodes positioned at distance from cylinder, In the second case, only 30 degrees of cylinder used as ground electrode. In all cases the wire electrode was set up in three different degrees from leading edge (i.e., 0°, 50°, 100°) and three radial distance from the surface of the cylinder (i.e., h = 10, 20, 30 mm). The electrical fields were produced by means of a DC constant high voltage power supply. In this study experiments are limited to laminar flow around the cylinder with Reynolds number less than 1000. The experimental results show that, total drag reduction in the partly flush mounted plate electrode has better performance than the case which electrode covers all surface of the cylinder. Maximum total drag reduction in cathode, partly flush mounted plate electrode geometry at position of 100° from the leading edge, which reported to be about 8%.

Key words: Boundary layer control, circular cylinder, drag reduction, EHD actuator, electrode arrangement

INTRODUCTION

Due to wide applications of the flow around bluff bodies, recently many of researchers interested in this field. The most encountered problem in such studies is flow control around cross section of bluff bodies in order to decrease total drag. Flow control techniques consist of two different methods: active and passive. Active flow control methods require external power source but in the other hand passive methods don’t need any external power supply.

In this study Electrohydrodynamic (EHD) is used for flow control which can be categorized as an active flow control technique. EHD phenomena can be described by injection of electrons from a high voltage electrode, when a high voltage difference is applied between high voltage and ground electrode in a dielectric fluid (i.e., air). It forms an electrostatic field inside the medium and electrons begin to inject from high voltage electrode (in case of negative corona). Presence of electrostatic field force injected electrodes to travel towards ground electrode. This electrons collide neutral molecules of the fluid in their path and transfer their momentum to them. Velocity of secondary flows created by this mechanism is often of order of 0.1 to 1 m sec^{-1} and can be used for flow control around bluff bodies.

Application of EHD for flow control has many advantages over other active methods such as ability of usage in special environments (micro gravities or with zero gravity environment) for example spacecrafts, rapid controlling by changing electrical field intensity and Low electrical consumption in most of application (Yabe, 1991). Usage of EHD actuators is not limited to above and implemented successfully in variety of industrial application like micro-pumps, CFC-Free refrigeration and heat exchangers.

Although several studies have been carried out to analyze the effect of EHD phenomena on heat transfer two decades ago, a few papers can be found in the literature dealing with the flow control with EHD actuators and this field of study is in its early stages of development.

Hauksbee (1719) and Chattock (1899) proposed ionic wind phenomenon but the results of Stuetzer (1959) and Robinson (1961) founded the bases of it. Yabe *et al.* (1978) developed corona discharge flow analysis extensively. They built an experimental system consisted

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of a plate which was fixed on a platinum electrode wire by diameter of 40 mm. They measured density and pressure of flow utilizing dried nitrogen and drew electrostatic field lines. Ohadi *et al.* (1991) experimentally investigated heat transfer enhancement air flow in tube in laminar and turbulent flow regimes by the means of corona discharge. The results showed that the heat transfer is considerably increases just in laminar and transient flow regimes and by the single wire electrode installed along central line of tube. Artana *et al.* (2002) has also tested this phenomenon, they studied flow control around cylinder in the presence of EHD actuators in Reynolds number limit (23000<Re<58000). Artana *et al.* (2001) studied the modifications of the near wake of a cylinder with EHD actuations. Chang *et al.* (2006) investigated on-set of EHD induced turbulence for cylinder in cross flow experimentally. Gronskis *et al.* (2007) performed Direct Numerical Simulations (DNS) of flow past around rotating cylinder with EHD actuators.

The purpose of this study is analyzing the effect of EHD wire-plate actuators on total drag reduction in flow around a bluff body with cylindrical cross section. To achieve this aim, several geometries and electrode configurations are tested, the results of which are represented in detail.

MATERIALS AND METHODS

In this study, The effect of a D.C. electric field on pressure drop and total drag reduction in a cylindrical cross section is examined. The experimental apparatus is shown in Fig. 1. It consists of a subsonic wind tunnel and high voltage supply. Length and width of the tunnel are 0.96 and 0.43 m, respectively. A cylinder is placed in the middle of the subsonic wind tunnel. Tests are conducted for five Geometrical configurations (cases). Arrangement of cylinder model and electrodes are shown in Fig. 2. The air flows in low velocity and all other related experiments conducted in two (800 and 1000) laminar Reynolds numbers.

In the first configuration, as presented in Fig. 3, two wire electrodes serve as a distributor (anode) and a plate electrode covering external surface of cylinder as a collector (cathode), connected to high potential supplier (20 KV). Anodes are placed in distance of L from center of cylinder and in 2a distance from each others. These wire electrodes are placed symmetrically with regard to the horizontal axis of cylinder.

In second configuration, illustrated in Fig. 4, one wire electrode has been used instead of two wire electrodes. In this case a = 0.

The schematic arrangement of electrode in third, forth and fifth case is shown in Fig. 5. It consist of a wire electrode as a distributor (anode) and a plate electrode covering 30° section of the cylinder acting as collector (cathode). Wire electrode have been employed in $\alpha = 0$ (third case), in $\alpha = 50$ (forth case) and the angles upper than 90°: (α = 95, 100, 110, 120°C, respectively) (fifth case). After placing wire and plate electrodes in their position, wind tunnel begins to work.

EHD number which can be thought as ratio of electro-hydro-dynamic forces to viscous forces is defined as:

$$N_{EHD} = \frac{h \cdot I}{\rho . u_{\infty}^{2} . \beta . S} \qquad (1)$$

Electohydrodynamic numbers for all understudy cases in this study, are represented in Table 1.

To calculate pressure drag coefficient from measured pressure data, the method described by Yabe *et al.*

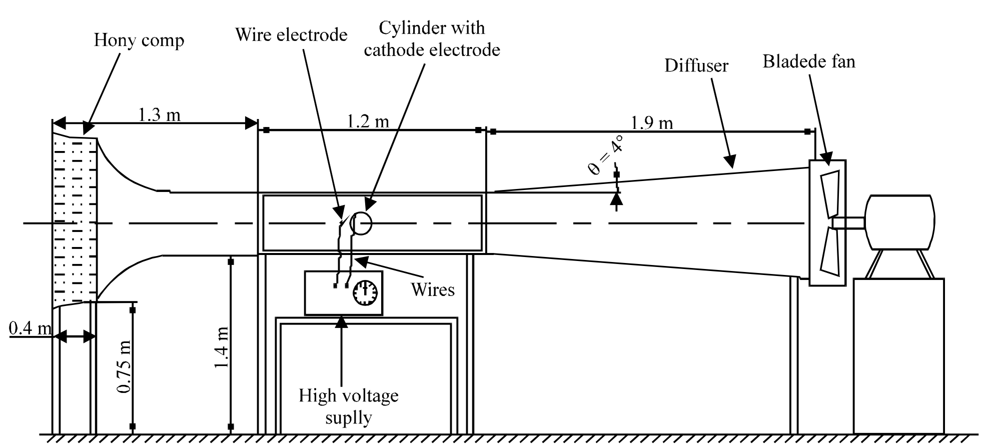

Fig. 1: Experimental setup

Table 1: Current, voltage and N_{EHD} for understudy cases

Re = 800	h/r = 1, N_{EHD} = 1.6	h/r = 1/2, N_{EHD} = 1.205	h/r = 1/3, N_{EHD} = 0.94	N_{EHD} = 0
	I = 0.3 mA, V = 20 KV	I = 0.5 mA, V = 15 KV	I = 0.65 mA, V = 10 KV	I = 0, V = 0
Re = 1000	h/r = 1, N_{EHD} = 1.6	h/r = 1/2, N_{EHD} = 1.205	h/r = 1/3, N_{EHD} = 0.94	N_{EHD} = 0
	I = 0.3 mA, V = 20 KV	I = 0.5 mA, V = 15 KV	I = 0.65 mA, V = 10 KV	I = 0, V = 0

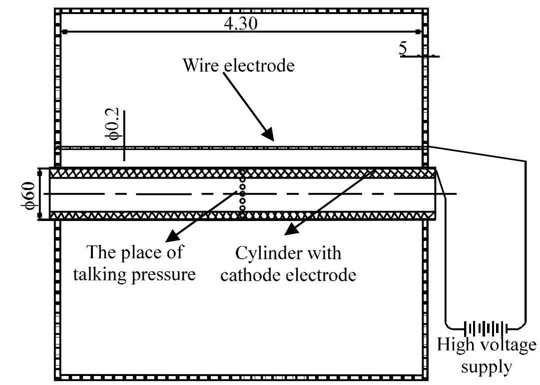

Fig. 2: Arrangement of cylinder model and electrodes

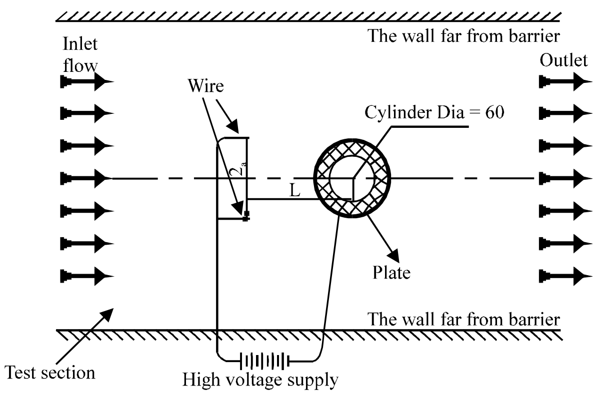

Fig. 3: First geometrical configuration

(1978) utilized, if P_i indicates static pressure in i-th pressure sensor, force on cylinder surface element is determined by the following equation:

$$\Delta F_P = P_i \Delta A \tag{2}$$

Pressure drag force resulted from p_i which is the same as applied horizontal pressure force obtained by:

$$\Delta D_P = P_i \cos(\theta_i)\, r\Delta\theta \times 1 \quad \Delta A = r\Delta\theta \times 1 \tag{3}$$

where, θ_i is the angle of pressure force vector.

Total pressure drag force will be:

$$D_P = \sum_{i=1}^{n} P_i \cos(\theta_i)\, r\Delta\theta \times 1 \tag{4}$$

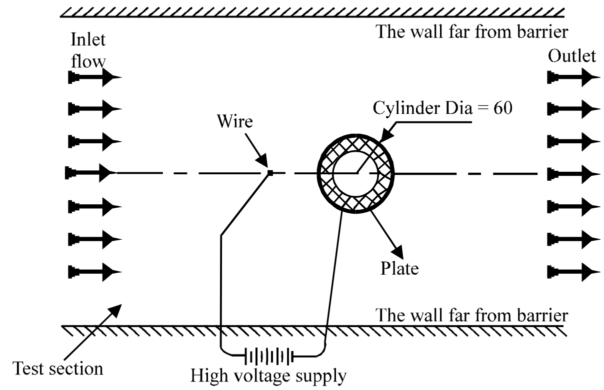

Fig. 4: Second geometrical configuration

In order to obtain pressure drag coefficient, The following relation is used:

$$D_P = \frac{1}{2} C_D \rho u_\infty^2 A_S \tag{5}$$

where, ρ, U_∞ and A_s are fluid density, free flow velocity and area of surface, respectively. So, CD (pressure drag coefficient) reads:

$$C_D = 2\,(D_P)/\rho u_\infty^2 A_s \tag{6}$$

Since, the experiments are carried out in wind tunnel in a closed environment, blockage coefficient correction caused by influences on drag force should be taken into account. This drag coefficient has to be corrected. In this case, we use BR, blockage coefficient which is the ratio of cylinder diameter to height of wind tunnel. Consequently, Ota *et al*. (1994) correction on drag coefficient thus is applied:

$$C'_D = C_D\,(1\text{-}1.8\,PR) \tag{7}$$

In geometries and arrangements studied in this study, influence of the pressure drag is more than friction drag, especially at Re>1000. So, For total drag reduction, it is important to control pressure drag and decrease it.

Error analysis is an important part of any experimental study to ensure if errors are within the acceptable rang or not. Error analysis by experiment apparatus for this study is summarized based on errors depend on P_i, U_∞ as follows:

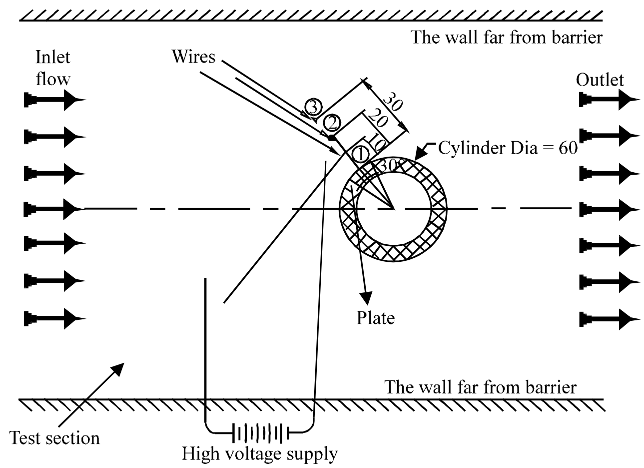

Fig. 5: Understudy cases in third, Fourth and Fifth configuration

$$\frac{\Delta C_D}{C_D} = \left[(\frac{\Delta P_i}{P_i})^2 + (2.\frac{\Delta u_\infty}{u_\infty})^2 \right]^{\frac{1}{2}} \quad (8)$$

It is obvious that the test errors are about 1-2%. Thus the errors are negligible.

RESULTS AND DISCUSSION

In the first case, shown in the Fig. 3, the distance between wire electrodes and their distance from center of cylinder are 2a and L, respectively. In this configuration, experiments were conducted for a/r = 0.67, a/r = 1.67 and L/r ratio of 4.In choosing L/r ratio, dielectric break-down distance is of great importance. This number must always be greater than break down distance of understudy fluid. Results manifested that applying EHD slightly increases pressure coefficients in this case (Fig. 6). In a/r = 1.67, this enhancement is negligible. Calculation of pressure drag coefficients by using Eq. 5 and 6 results in C_d, 0.643 and 0.617 for a/r = 0.67 and a/r = 1.67, respectively. This values for drag coefficients are higher than Non-EHD actuation case. Thus it can be conclude that arrangement of electrodes in this electrode configuration is not effective for drag reduction.

Results for the second case are depicted in Fig. 7. As can be seen in this Fig. 7, applying EHD increase pressure coefficient except for some points. This difference is negligible in some points especially at the back of the cylinder. By applying EHD results in, C_d = 0.601 when L = 10 cm and C_d = 0.571 when L = 20 cm. Without applying EHD C_d is 0.567. EHD causes slightly increase in drag coefficient by 0.7-5.7% in both cases. Due to special arrangement of wire electrode related to plate electrode which covers completely surface of cylinder, the number of N_{EHD} in Eq. 1 is reduced. Thus, EHD effect on drag reduction is undesirable.

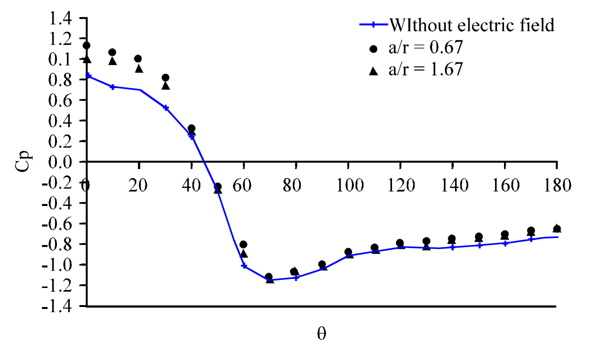

Fig. 6: Comparison between pressure coefficients in two electrodes experiments (case 1)

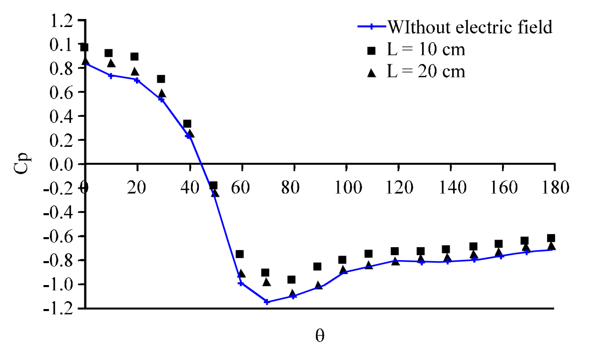

Fig. 7: Comparison between pressure coefficients in single electrode experiments

For the third case, the results are represented in Fig. 8.In this case experiments were conducted with a wire electrode placed in two different distances of cylinder surface in α = 0.

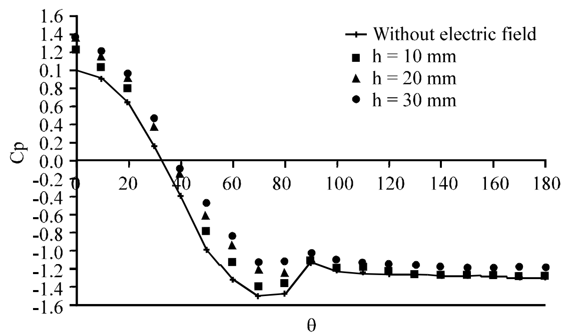

Fig. 8: Comparison between pressure coefficients in several wire to plate distances (α = 0)

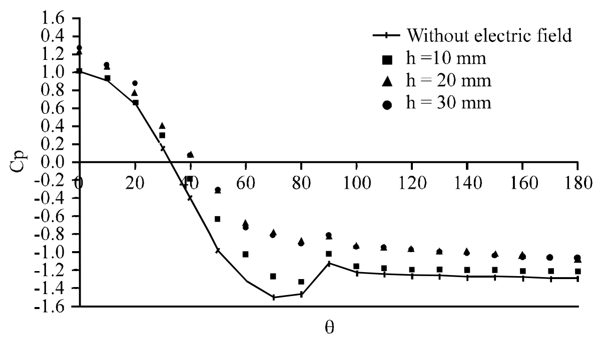

Fig. 9: Comparison between pressure coefficients in several wire to plate distances (α = 50)

According to Fig. 8, application of EHD actuator slightly increases pressure coefficient in 40°<θ<100°. Also the secondary flows in opposite direction, force the flow to separate from surface earlier. Comparison of drag coefficients in three cases shows small enhancement of drag coefficient due to EHD actuation. The enhancements are 10, 15 and 17.5% in h = 10, 20 and 30 mm, respectively. For gaps greater than 20 mm, the drag coefficient enhancement is negligible. This can be described by considering long distance between high voltage electrode and the cylinder. Charged electrodes can not transfer their momentum to air molecules around body and EHD is not able to postpone separation, therefore, separation occurs in the same place.

Forth case similar is to the third, except that wire electrodes is settled in a upper position with α = 50° related to leading edge of cylinder. Pressure coefficients around cylinder in three different distances and EHD actuation are shown in Fig. 9.

Applying EHD significantly increases pressure coefficient in 40°<θ<100° and there is little difference in separation point in EHD or without EHD actuation. Comparing coefficients in four distances, makes obvious that by means of EHD, drag coefficient increases slightly by, 5.4, 6.3 and 8.4% in h = 10, 20 and 30 mm, respectively. Thus, This arrangement of electrodes is not suggested for changing separation condition and reduction wake zone area.

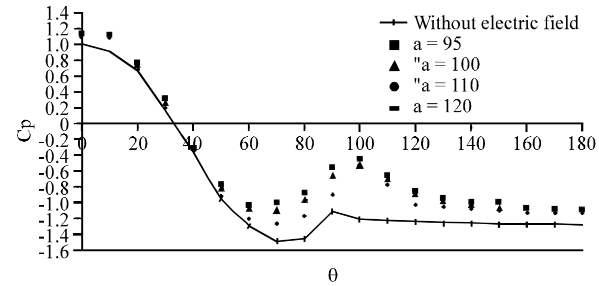

Fig. 10: Comparison between pressure coefficients in the forth case h = 30 mm and V = 10 Kv and several wire electrode angular positions

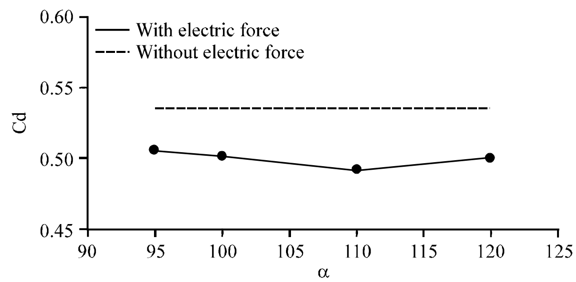

Fig. 11: Total Drag coefficients in fifth case for 95°<θ<120°

Experimental results for the fifth case are presented in Fig. 10. In this case, drag reduction around the cylinder is investigated using geometrical parameters h = 30 mm and V = 10 KV.

It is clear that application of EHD causes a relatively tangible pressure coefficient augmentation, which especially increases in the region 60<θ<120°. Nevertheless, applying EHD filed reduces total drag coefficient in comparison with No-EHD case from C_d = 0.571 to 0.545. Calculated total drag coefficients are 0.506, 0.501, 0.492 and 0.5 in angles α = 95°, 100°, 110°, 120°, respectively. Maximum total drag reduction occurs in α = 100°. Where drag coefficient has minimum value.

Drag coefficients for 95°<θ<120° are given in Fig. 11. Again, drag reduction can be described by considering the secondary flows generated by the EHD actuator. In the absence of the EHD field, because of adverse pressure gradient at the back of cylinder, air velocity tends to slow across cylinder as crosses the cylinder section. Therefore, its momentum decreases to a point in which separation occurs and wake behind the cylinder begins to develop. Separation angle behind a cylinder without EHD effect is about $\theta = 81°$.

If an EHD actuator is used properly, it generates secondary flows that interacts with external flow in a desirable direction and consequently, increases velocity and momentum inside the boundary layer. Augmentation of momentum of air particles usually results in later separation of boundary layer from the cylinder and therefore narrower wake region.

In this case, by using an EHD actuator, boundary separation point can be postponed till $\theta = 100°$ in $\alpha = 110°$ which results in 7% total drag reduction. In the angles greater than 110 degrees, increasing $\alpha = 110°$ cause the total drag to increase. Hence, $\alpha = 110°$ is the optimum position of the wire electrode.

CONCLUSION

In this study is manifested that EHD phenomena around bluff body has a complex nature and electrode arrangement and position have a very important role in controlling drag coefficients. Based on experimental results presented in above section, it can be concluded that:

- In some electrode arrangements, using an EHD actuator increases total drag coefficient, This is an undesirable effect and must be avoided
- EHD actuation is more effective in decreasing drag coefficient when a part of cylinder is used as plate electrode. In this condition, low gaps between high voltage and plate electrode cannot be used because of the breakdown phenomena in dielectrics. In case of higher gaps, all parts of EHD field is weak and ions can not transfer their momentum to air because of a gap between cylinder and wire electrodes, therefore, the effect of EHD is very small
- When a plate electrode covers only a part of the cylinder, leads to increased electrode angle and causes the drag coefficient reduction. This total drag reduction occurs in $85°<\alpha<120°$, $\alpha = 120°$. Drag reduction in this point is reported to be about 8%. By Increasing over this value, total drag coefficient starts to increase again.
- In case that plate electrode covers the cylinder completely, reduction of EHD effects, by increasing distance of wire from plate electrodes observed
- In cases that plate electrode covers a part of the cylinder, corona wind is limited to this area when EHD number is small (Due to limited coverage of plate electrode)

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