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OpenFOAM Analysis over a Flat Plate Using Plasma Actuation

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ABSTRACT

The boundary layer flow control is very important for an aerospace application. The plasma actuators are promising technology in flow control for future and the study of the plasma actuator is very important. The current work focused on the boundary layer flow control using the plasma actuators in OpenFOAM solver. The aim of the current research is to study the flow over a flat plate analysis with reduced order modelling physics using OpenFOAM. Recently, OpenFOAM gained a lot of importance to solve the numerical problems especially, in computational fluid mechanics but users are very less due its complexity. An OpenFOAM own solvers were created and tested for the plasma based reduced modelling. A flat plate without plasma actuation has been benchmarked with the Blasius analytical solution. The flow over a flat plate with plasma actuation has been analysed using reduced order modelling. From the results, it was found that flat plate with plasma actuation showed the 125 percent induced velocity improvement compared to a flat plate without plasma actuation. Hence, the plasma actuation is promising for a flow control in real world applications.

1. Introduction

Blasius [1] derived the analytical solution for laminar boundary layer over a flat plate, which has the significant importance in fluid mechanics. Ozturk *et al.,* [2] presented the flow over a circular cylinder placed on a flat plate at Reynolds number 750 to 9600 and they investigated the flow structure over a flat plate. Takhar *et al.,* [3] discussed the heat transfer analysis over a flat plate with a constant velocity. They were noticed the effect of impulsive motion on the flow over a flat plate surface. Sarker *et al.,* [4] analysed the transonic flow over a flat plate for different height steps. They discussed the pressure, velocity and temperature variation for different height steps. Plasma is a hot ionized gas and it is named as fourth state of matter. It consists of ions (both negative and positive) and electrons shown in Figure 1.

Recently, plasma actuator for a flow control is promising in practical conditions. For the DBD plasma actuators, air around the expose electrode becomes ionized and plasma is formed. The plasma produces a body force which modifies and accelerates the surrounding air to induce a near

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wall jet. The induced wall jet is able to reach velocities up to 8 m/s in the wall-tangential direction [5]. Despite the large potential differences required to ignite the plasma, the power consumption of the plasma is in the range of 0.05-0.5 W/m [6]. This low power consumption coupled with the ability to deliver a real-time response to the surrounding fluid makes plasma actuators importantly most attractive devices. Particularly a single dielectric barrier discharge (SDBD) plasma actuators gained a popularity among other types due to its simplicity in design and with no moving parts. Enloe *et al.,* [7-8] presented a review of the plasma actuator physics and its fundamental mechanisms. Plasma actuation has been applied for the different applications like transition delay, separation control, drag control, boundary layer control [9-15] etc. It is very important to study and understand the deeper physics and underlying mechanisms for any booming technology. Wang *et al*., [16] presented a review article on the importance of dielectric barrier discharge (DBD) plasma actuators and mentioned that these are simple, yet very powerful that create new aerodynamic applications possible. They surveyed the promising DBD plasma actuator applications i.e. separation control, turbulent drag control and transition delay and detailed examination of plasma applications. Wang *et al*., [17- 18] introduced the new types of plasma actuator models for flow control in multi directions effectively.

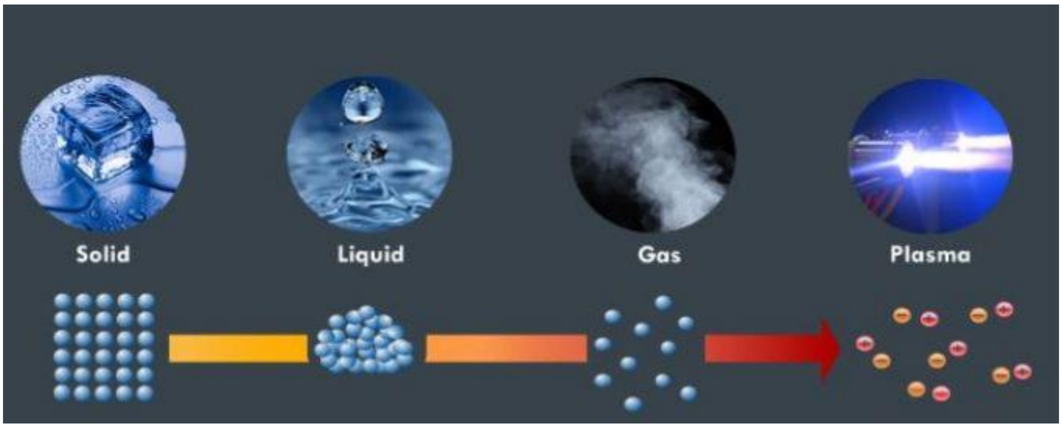


Fig. 1. The fourth state of matter [19]

The previous studies presented the work using ANSYS and other simulation commercial packages, those software's does not allow user to choose the large number of mesh cells and not flexible like OpenFOAM. OpenFOAM is an open source solver, where user can create our own solvers and it offers a lot of flexibility. It offers the special solvers for the plasma research, which cannot available in the other solvers and the commercial packages. In the present work, we focused on the plasma body force generation using OpenFOAM. There is gap between the traditional flow control applications and the advanced flow control technologies for the boundary layer flow control. Here, we presented the combination of the active flow control technology using reduced order modelling for flow control in OpenFOAM. The study will be very useful to understand the flow control in OpenFOAM as well as reduced order modelling physics. We present the benchmark study and discuss the plasma-based flow control capabilities over a flat plate. The velocity contours and plasma body forces contours are presented.

2. Numerical Model

2.1 Reduced-Order Modelling

Plasma actuators are very popular as a flow control device. We consider the dielectric barrier discharge (DBD) plasma actuators in the current work due to simple in construction, shown in Figure

2. Such actuator contains a grounded electrode and an exposed electrode, divided by a dielectric material. The implementation of the DBD plasma actuator on a flat plate is simple because it does have any moving parts, and it can be laminated to the surface of a flat plate.

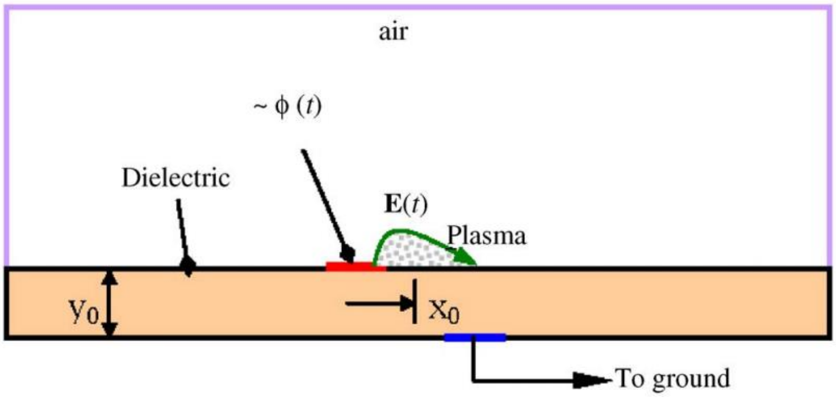


Fig. 2. DBD plasma actuator showing a plasma discharge [20]

Based on first-principle analysis, Singh and Roy [20] approximated a functional relationship between electrodynamic force and physical and electrical control parameters and tested them numerically for air. The electrodynamic force was approximated as follows:

$$f_x = \frac{F_{x0}}{\sqrt{{F_{x0}}^2 + {F_{y0}}^2}} \exp\left(-\left(\frac{(x-x_0)-(y-y_0)}{y-y_0+y_b} \right)^2 - \beta_x (y-y_0)^2 \right) \tag{1}$$

$$f_y = \frac{F_{y0}}{\sqrt{{F_{x0}}^2 + {F_{y0}}^2}} \exp\left(-\left(\frac{(x-x_0)}{y-y_0+y_b} \right)^2 - \beta_y (y-y_0)^2 \right) \tag{2}$$

Where the F_{x0} = 2.6, F_{y0} = 2.0, $\beta_x = 8\times10^{15}$, $\beta_y = 10^7$, x_0 = 0.146. The effect of plasma was taken from the average electrodynamic force obtained by solving air-plasma equations. x_0 is the center point between rf electrode and embedded electrode and y_0 is the height of the dielectric surface. F_{x0}, F_{y0} are electro dynamic force constants. β_x and β_y are functions of the dielectric material.

2.2 Navier-Stokes Equations

The following continuity and momentum equations are the governing equations for flow over a flat plate.

$$\nabla \cdot U = 0 \tag{3}$$

$$\frac{\partial}{\partial t}(\rho v) + \nabla(\rho v v) = -\nabla P + \nabla \tau + \rho g + F \tag{4}$$

where, U is the flow velocity, t is time, ρ is density, g is acceleration due to gravity, $-\nabla P$ is the pressure gradient, F is the plasma body force, v is the kinematic viscosity, $\nabla\tau$ is the diffusion term, $\nabla(\rho v v)$ is the convective term respectively.

2.3 OpenFOAM Structure

Figure 3 shows the OpenFOAM (Open Field Operations and Manipulations) case structure [21-23]. It contains three major files those are case, constant, and system files and again these three files have sub files for any problem. The beauty of the OpenFOAM is one can write their own code and create own solver. we developed our own codes for the flow over a flat plate with plasma actuation. It is very challenging to simulate the plasma actuation in OpenFOAM. We used finite volume method in the current work.

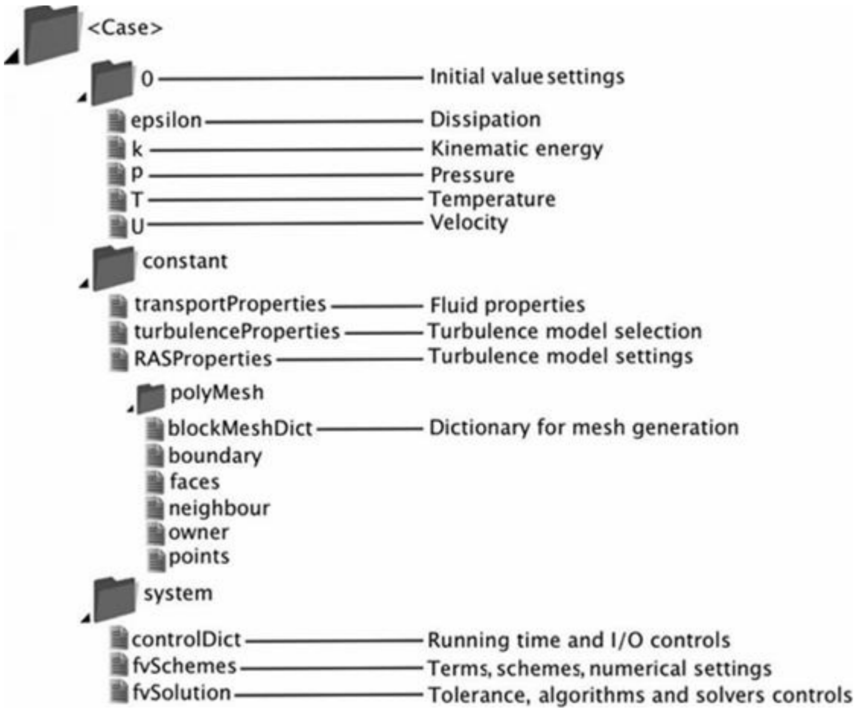


Fig. 3. OpenFOAM case structure

3. Methodology

3.1 Problem Description

The computational domain for the flow over a flat plate is shown in Figure 4. A flat plate length (L) in the x-direction is 0.293 m, height (H) in the y-direction is 0.06 m with a velocity of 2 m/s. The plasma body force is located at the center of the flat plate which is 0.146 m. The Reynolds number is based on the velocity and length of the plate. The Reynolds number at the center of the plate and end the plate are 20058.46, and 40116.93 respectively. We use the icoFoam solver for a flat plate without plasma actuation whereas for the flow over a flat plate with plasma actuation, we generated our solver using icoFoam as a reference.

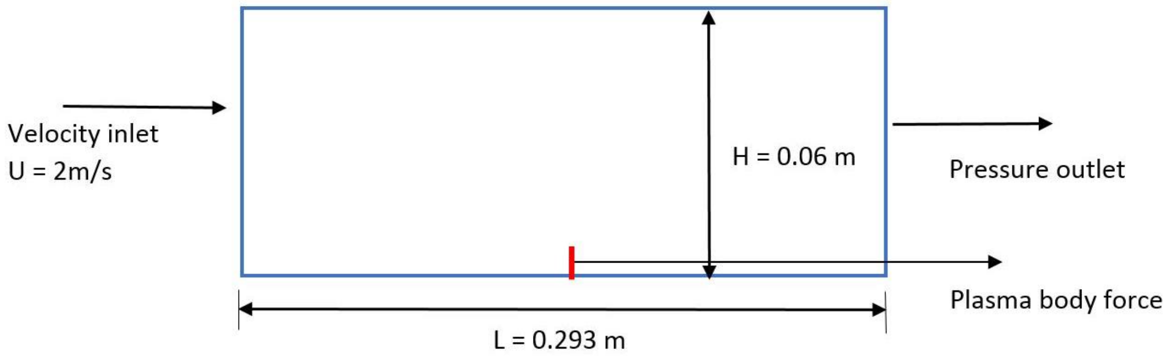


Fig. 4. Computational domain of flow over a flat plate

3.2 Mesh and Boundary Conditions

The velocity inlet is selected at the entrance of the plate and pressure outlet is selected at the exit of the plate. The velocity boundary condition at y = δ u = 0.99 U_∞. Figure 5 shows the mesh for the flow over a flat plate and the zoomed view of the mesh. The grid independence test was carried out to investigate the mesh resolution used in the work and selected the optimum mesh to get the accurate result. We tested coarse grid with 4000 cells, medium grid with 8000 cells with and fine grid with 12000 cells, respectively. The error percentage was less than 0.005 % for all meshes at the center and end of a flat plate. For the current work, we selected the non-uniform fine mesh with 12000 cells and the mesh size of (100×100) in x and y directions at the bottom of the plate and (100×20) in x and y directions respectively at the upper part of a flat plate. We used the finite volume-based solver in which the solution is calculated on each control volume and also used our own solver in OpenFOAM to solve the problem and integrated the solver in icoFoam. OpenFOAM is used to generate the meshing structure which provides the efficient and accurate meshing than other commercial software's. The convergence criteria for the residuals were order of 1.0 $\times 10^{-5}$ in magnitude. For temporal discretization, a first order implicit scheme was used, and the second order upwind scheme was used for the spatial discretization. The incompressible solver from OpenFOAM 4.0 was used and simple algorithm was adopted for velocity-pressure coupling.

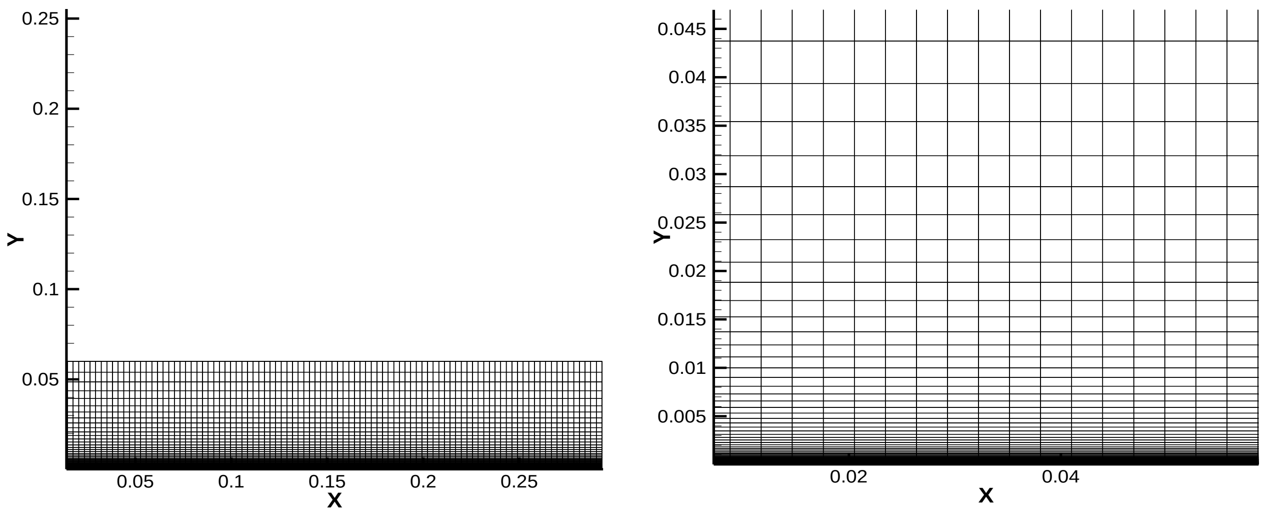


Fig. 5. Mesh for the flow over a flat plate

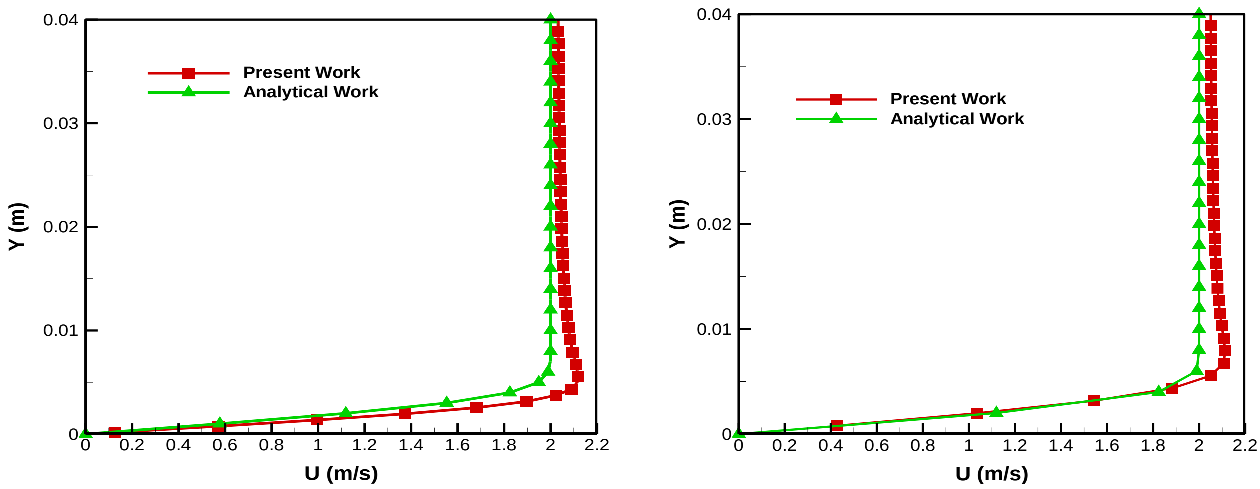
4. Results and Discussion

4.1 Flow Over a Flat Plate without Plasma Actuation

Figure 6 depicts the velocity profiles for center of a flat plate and end of a flat plate. We compared and validated the flow over a flat plate without plasma actuation with the blasius solution [1]. The Eq. (5) defines the laminar boundary layer thickness for the flow over a flat plate.

$$\delta = \frac{5.0x}{\sqrt{\text{Re}_x}} \tag{5}$$

Where, Re is Reynolds number and δ is boundary layer thickness. Figure 6(a) shows the velocity profile at the center of the plate. From the figure, it shows that the present OpenFOAM solution is y at 0.0052 m and the blasius analytical solution was 0.005172 m. The error percentage is 0.5413 %. Similarly, for the velocity profile at the end of the plate (see Figure 6(b)), the present OpenFOAM solution is y at 0.00725 m and the blasius analytical solution at the end of the plate was 0.007314. The error percentage is 0.8750 %.



(a) (b)

Fig. 6. Velocity profiles at (a) center and (b) end of the geometries for a flat plate

Figure 7 shows the U-velocity contours for the flow over a flat plate. The boundary layer concept was first introduced by Ludwig Prandtl [24]. The velocity boundary layer is developed slowly from the entrance of a flat plate to end of a flat plate with the gradual increment in the velocity boundary layer thickness, which is in green colour. The zoomed view of the velocity contour showed in the right side.

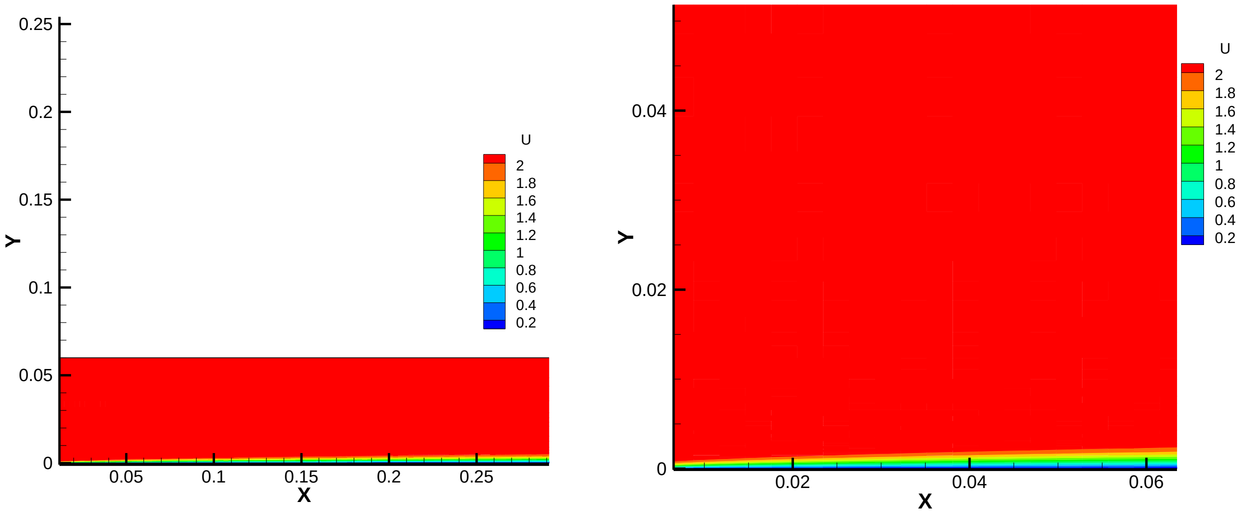


Fig. 7. Velocity contours for the flow over a flat plate

4.2 Flow Over a Flat Plate with Plasma Actuation

Figure 8 presents the velocity contour for flow over a flat plate with the plasma actuation. The improvement in induced velocity due to the plasma body force. In the previous section, we have showed the flow over a flat plate without the plasma actuation, where the flow is moving in one direction but here due to the plasma actuation, flow is moving in the multi directions that we can see especially at the center of the plate 0.146 m. The effect of DBD plasma is stronger at center of a flat plate and body force mechanism accelerates the surrounding air to induce a near wall jet.

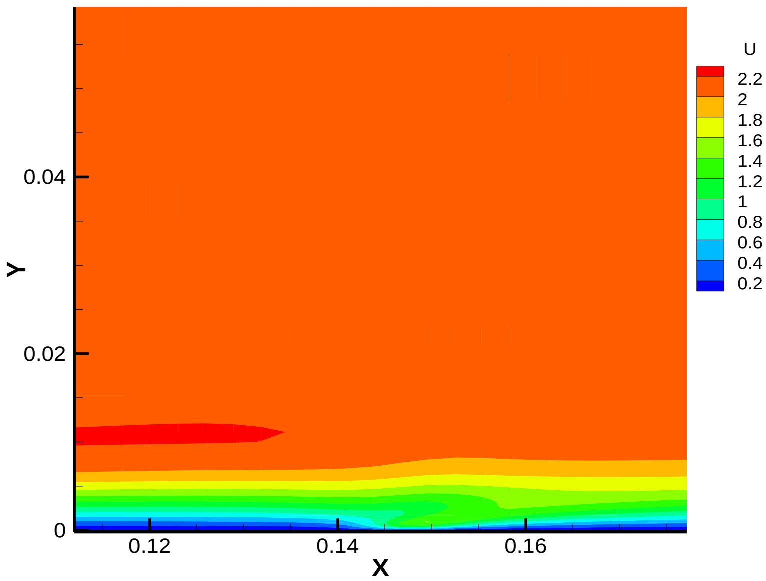


Fig. 8. Velocity contour with the plasma actuation

Figure 9 depicts the Fx, Fy plasma body force contours in x and y directions respectively. We used the simplification of the first principles method based reduced order modeling to generate the plasma body force on the surface of a flat plate in OpenFOAM. The plasma simulation region consists of two electrodes divided by a dielectric material. The grounded electrode is laminated to the surface and exposed electrode is open to air. The potential difference between the upper electrode and grounded electrode creates an electric field near the surface, which causes the air to ionize, and form a wall jet. The wall jet controls the flow and enhances the induced flow velocity.

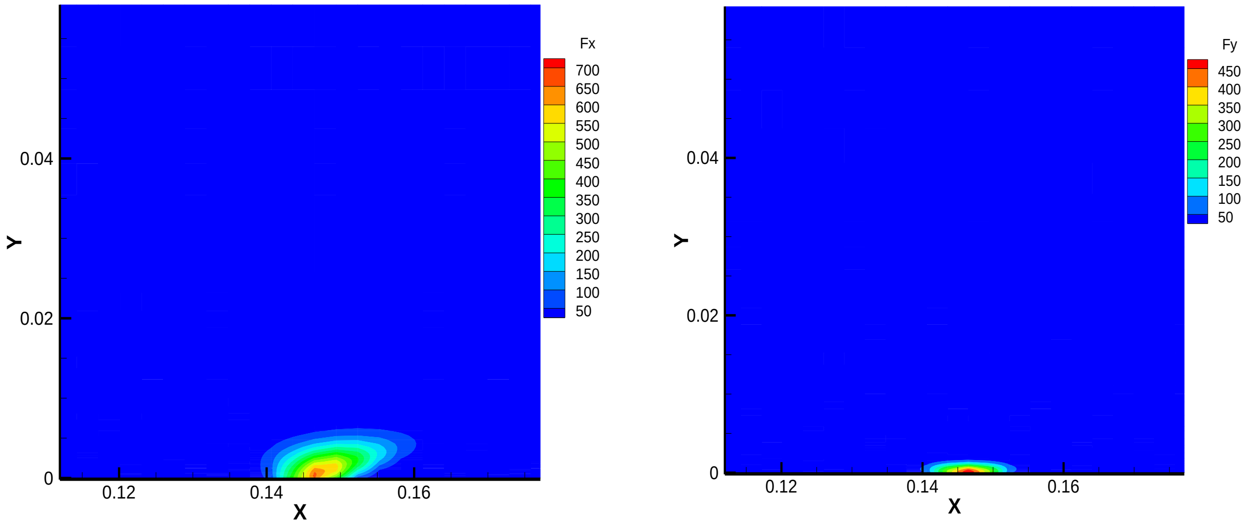


Fig. 9. Fx, Fy body force contours with the plasma actuation

Figure 10 shows the comparison of U-velocity for flow over a flat plate with and without plasma actuation are in green and red colors respectively. From the analysis, the flow over a flat plate with plasma actuation showed the 125 percent improvement in the induced velocity compared to no plasma actuation at the center of the geometry location. For a flat plate with plasma actuation, the shape of the curve is tangential because of the near wall jet effect on the surface of the plasma.

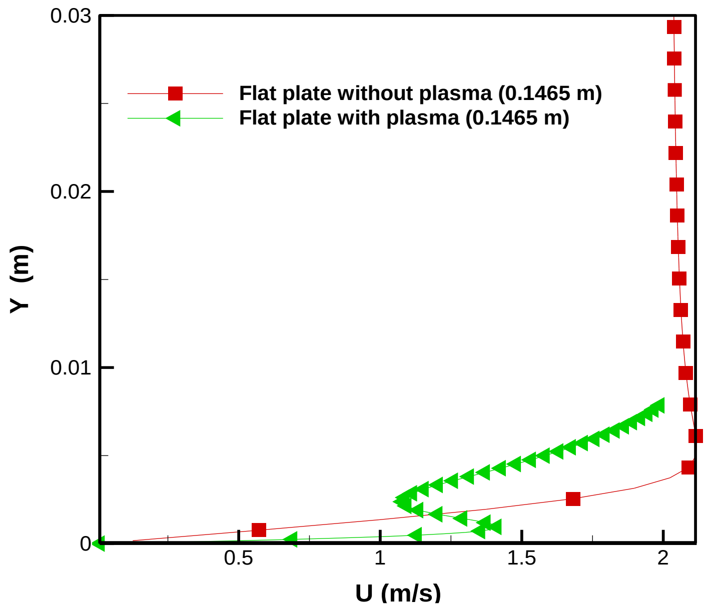


Fig. 10. Comparison of U-velocity with and without plasma actuation for a flat plate case

5. Conclusions

We have presented the numerical model of the flow past a flat plate with and without plasma actuation. The OpenFOAM CFD platform is used to develop our own plasma solver. The flat plate without plasma actuation results were benchmarked and validated with published literature. From the results, flow over a flat plate with plasma actuation showed 125 percent induced velocity improvement at the center of a flat plate compared to flat plate without plasma actuation. The increment in induced velocity due to near wall effect on the surface of the plasma. The dielectric barrier discharge plasma actuators are key to produce the beneficial positive effects on the surface of a flat plate. The flat plate analysis showed the importance of a flow control remarkably to induce the increment in fluid velocity. It is evident that plasma actuators are promising technology in the practical applications.

Acknowledgement
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