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Numerical study on the effect of weather parameters on corona discharge performance in a horizontal axis wind turbine

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Abstract

In this paper, a numerical simulation is presented to integrate active load control using corona discharge based on plasma actuators on the trailing edge of the wind turbine blade. Eulerian simulation is done on a 660 kW wind turbine blade with NACA 0012 profile. The electrohydrodynamic incompressible flow created between two electrodes using the combination of the EHD foam solver with the Boyant Pimple foam solver has been implemented in the free and open-access Oppenfoam software. The results have been validated using numerical and experimental work. The effects of environmental parameters such as temperature, relative humidity and environmental pressure on the corona discharge process have been investigated. The results of this research showed that with the increase in temperature, humidity and pressure, the evacuation process is disrupted. The results show a 62% and 35% decrease in the average transfer momentum with an increase in relative humidity and temperature, respectively.

Keywords: climate, axial wind turbine, corona discharge, plasma, numerical simulation, oppenfoam
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1 Introduction

The use of renewable energy has recently become very common in most countries of today's society. Among these renewable energies, wind energy is one of the most attractive methods of mechanical energy production, and different methods of flow control, including active, semi-active and passive, have been investigated by various researchers. To control the fluid flow in an active way on the wind turbine blade, the corona discharge actuator based on plasma technology is considered a method to reduce the fluid flow separation on the wind turbine blade. The main uses of electrohydrodynamic currents in wind turbines are when they are used to control the flow on the blades. Recently, the plasma corona discharge phenomenon is used to increase the momentum at the trailing edge of the turbine blades to reduce the width of the separated area.

Considering that wind turbines are one of the most attractive methods of mechanical energy production and are always exposed to various weather conditions, a clear understanding of the effect of relative humidity and temperature on the electrohydrodynamic flow at the edge of The flight of wind turbines contained a plasma actuator. In some researches, the placement angle of wind turbine blades in relation to the direction of wind speed or the use of fluid flow controllers on the body of wind turbine blades have been suggested by researchers. In this research, a type of plasma

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operator called corona discharge operator and its effects on the aerodynamic efficiency of wind turbine blades at a specific angle of attack have been investigated. Considering the voltage on the surface of the airfoil, an electric field is formed around the airfoil, which causes the generation of ion-induced propulsion or the induction of an electric (ionic) wind near the surface of the airfoil, this electron wind can It affects the boundary around the airfoil and delays the separation of the fluid flow. The induced current from the plasma acts like a volumetric force and turns the fluid close to the wall into a fluid flow jet by moving it, which improves the flow profile of the boundary layer and causes the flow separation to It postpones. But the researchers have not studied the corona wind ionization conditions resulting from the plasma operator in different weather conditions. This operator can have different functions in different weather conditions.

Wind farms can be located far from the sea coast, near the pole or in the African deserts. In each of the mentioned areas, preliminary studies on the annual winds and their direction are examined. The main goal of this research is to apply the plasma actuator to control the flow on the wind turbine blades, taking into account the weather conditions, so that three parameters of relative humidity, pressure and temperature have been investigated in Corona wind speed.

Undoubtedly, climatic studies to know the most suitable place for building and operating a wind farm are essential for the initial design of wind turbines. Recently, the use of plasma actuator to increase the efficiency of wind turbine blades has been recommended by many researchers. But this operator does not create the desired potential to increase efficiency in any situation. Depending on the place of use and the relative humidity of that area, the plasma operator can experience a drop in performance or even produce a photographic result.

Dielectric barrier discharge operators generally consist of two electrodes, which are asymmetrically placed on both sides of a dielectric material, and by considering a high voltage current to these two electrodes, plasma discharge is performed. accept During the mentioned process, a volumetric force is induced to the flow passing through the surface, and the velocity profile near the wall is corrected, or in better words, it prevents the expansion of the boundary layer to the outside, and finally the flow is controlled. take Corona discharge is a self-sustained discharge that occurs in the vicinity of electrodes with a smaller radius of curvature [19]. Ions with the same polarity as the active electrode move towards the earth electrode and transfer the momentum to the surrounding neutral molecules. The induced fluid movement of all particles is called ion wind. Therefore, the corona discharge phenomenon has the most application in industries related to horizontal axis wind turbines. However, researchers are always looking for the most suitable operating conditions for the use of this phenomenon on the escaping edge of the wind turbine blade. Weather conditions such as changes in temperature, pressure and relative humidity can affect the performance of the corona discharge phenomenon. In this research, the aim is to find suitable operating conditions for applying the corona discharge phenomenon on the horizontal axis wind turbine blade. This electrohydrodynamic air flow, with the benefit of non-mechanical components, micro scales and low costs, has great potential in applications such as ionized blowers [13]. Ionized blowers are often used to separate pollutant particles in hospital air conditioning systems. In addition, electrohydrodynamic air flow has been shown in applications such as cooling in hot electronic equipment [9, 2] and recently, flow control on wind turbine blades [3, 7, 10, 12, 17, 18]. It is worth mentioning that recently Khoo et al. reported a motorized flight of an airplane whose propulsion is based on the ion wind caused by the corona discharge [18]. Moreau et al. performed a series of measurements on ion wind speed [6, 15]. In their experiments, corona discharges produced an ion wind with a velocity of 10 m/s under a discharge power of several milliwatts. The behavior of the ion wind induced along the flat plane was also observed by particle imaging velocimetry [5]. They showed that the ionic wind has a great influence on the characteristics of the surrounding air flow and provides effective drag reduction. In Kawamoto's work, the effect of the ion wind was measured using the deformation of the water surface. The calculated electrohydrodynamic force is equal to the amount of changes in the active area and has a radius of 5-8 mm [8, 11].

Kamawato et al.[8] provided a good understanding of the negative corona ion wind by investigating its time-resolved and averaged characteristics in simulation and also studying the effect of dc voltage polarity on the ion wind experimentally for cooling purposes, showing that the ion wind phenomenon is The discharge polarity and regime depend, but the underlying physical mechanisms have not yet been elucidated. In particular, the ion dynamics and field distribution in the negative and positive corona, which may lead to different discharge regimes or ion wind characteristics, need further study. The characteristics of the ion wind generated by the corona discharge process have been studied considering the weather conditions. According to the investigation of the background of the research, it can be seen that the researches are limited to investigating the effect of frequency, voltage and angle of attack and a comprehensive study in relation to the application of parameters such as temperature, pressure and humidity on the performance of the corona discharge phenomenon. not done Therefore, the current article has tried to conduct a comprehensive study to cover the gaps in the previous works in such a way that the ability to derive specific equations indicating the effects of each of the effective parameters on the wind turbine blade is provided. This issue is very important from the aspect of saving in complex and time-consuming calculations for more and more industrial applications. In the current study, considering the wind turbine blade along with the corona discharge actuator, the effect of weather parameters such as temperature, pressure and relative humidity on the amount of momentum produced in the actuator has been investigated.

2 Governing equations

In this research, at first, the formulation related to the creation of electrohydrodynamic (ionic) wind by electrodes is presented. Then by applying the relative humidity equations and considering the heat equation, the direct relationship between the plasma corona discharge phenomenon and the three environmental parameters of relative humidity, pressure and temperature have been taken into account. Maxwell's equations have been used to obtain the electric field. Due to the absence of magnetic induction and magnetic field, the resulting equations for electric potential and charge density will be in the form of relations (2.1) and (2.2) [14, 16].

$$\nabla \cdot (\varepsilon_r \nabla_{\phi}) = 0 \tag{2.1}$$

$$\nabla \cdot (\varepsilon_r \nabla_{\rho_c}) = \frac{\rho_c}{\lambda_D^2}. \tag{2.2}$$

In these relationships, ϕ is the electric potential, λ_D^2 is the Debye length squared, ρ_c is the charge density and ε_r is the electric permeability. Dimensionless boundary conditions have been introduced as equations (2.3) and (2.4) and constant values have been applied to the electrodes and the expansion surface of the operator. After calculating the electric potential distribution and dimensionless charge density, the obtained values have been multiplied by the dimensionless parameters [14, 16].

$$\phi^{\star} = \frac{\phi}{\phi_{\max} f(t)} \tag{2.3}$$

$$\rho_c^{\star} = \frac{\rho_c}{\rho_c^{\max} f(t)}. \tag{2.4}$$

In these relations, $\phi_{\max}$ is the maximum electric potential and max is the maximum charge density. $f(t)$ is the waveform of alternating voltage changes applied to the electrodes. By solving Laplace's equation (2.1) for electric potential distribution and Poisson's equation (2.2) for charge concentration and taking into account that the electric field is equal to the electric potential gradient, the volumetric force applied by the operator can be obtained.

$$E = -\nabla_{\phi} \tag{2.5}$$

$$F_b = \rho_c E \tag{2.6}$$

In this relationship, E is the electric field and F_b is the volumetric force. There are unknowns in the above equations, which are presented below. Equation (2.7) is used to determine the Debye length [14, 16].

$$\lambda_d = 0.2(0.5611\,\mathrm{Arsctan}(170.3(f)^{-5.124})1.768) \times (0.3 \times 10^{-3} V_{app} - 7.42 \times 10^{-4}) \tag{2.7}$$

In relation (2.7), f is the frequency of the sine wave and its unit is kilohertz and V_{app} is the peak voltage in kilovolts. Also, to calculate the length of plasma expansion, it is necessary to solve the algebraic equations (2.8a)-(2.8d) through the Newton-Raphson method [14, 16].

$$a_1^2 l_p^5 + 2a_1 a_2 l_p^4 + a_2^2 l_p^3 = a_3^2 \tag{2.8a}$$

$$a_1 = 16000 c_{g_0} \tag{2.8b}$$

$$a_2 = 16000 c_{d_0} I_e \tag{2.8c}$$

$$a_3 = \sqrt{\rho} f c_{g_0} c_{d_0} I_e (V_{app} - V_{bd})^2 \tag{2.8d}$$

All the above equations have been included in the developed solver in Oppenfoam software. In such a way, Newton-Raphson's iterative steps for calculating the length of plasma expansion exist inside the basic EHDFoam solver, and it is enough to obtain the length of plasma expansion by calling the appropriate boundary conditions. In relation (2.8a)-(2.8d), ρ is the fluid density, I_p is the length of the plasma extension, I_e is the width of the hidden electrode, and V_{bd} is the breakdown voltage. Considering that the set of exposed and hidden electrodes are considered as a series circuit, the capacity of each of the capacitors can be expressed by the relation (2.9a) and (2.9b) [16, 14].

$$c_{g_0} = \frac{2\pi\varepsilon_0}{\ln\left(\frac{0.5t_e+2\lambda_d}{0.5t_e}\right)} \tag{2.9a}$$

$$c_{d_0} = \frac{2\pi\varepsilon_d}{\ln\left(\frac{0.5t_e+2t_d}{0.5t_e}\right)}, \quad \varepsilon_d = \varepsilon_{rd}\varepsilon_0 \tag{2.9b}$$

The permeability of free air is ε_0 and the permeability of the dielectric material is ε_{rd}. t_d is the thickness of the dielectric and t_e is the thickness of the electrodes. Equation (2.10) is used to calculate the maximum charge density [14, 16].

$$\begin{aligned} \rho_c^{\max} &= \frac{\text{Trust}}{\lambda_d(V_{\text{app}} - V_{\text{bd}})f_{\text{corr}}} \\ f_{\text{corr}} &= 0.5\sqrt{2\pi}\frac{a}{l_p^{\text{corr}}}\left[\text{erf}\left(\frac{1}{2}\frac{b\sqrt{2}}{a}\right) + \text{erf}\left(\frac{1}{2}\frac{\sqrt{2}(l_p^{\text{corr}} - b)}{a}\right)\right] \end{aligned} \tag{2.10}$$

The coefficients a and b expressed in the correction factor are 32.0 and 17.0 times the plasma expansion length, respectively, and the thrust induced by the operation of the operator is obtained by equation (2.11) [14, 16].

$$\text{Trust} = [4\rho(2fC_{\text{eq}}(V_{\text{app}} - V_{\text{bd}})^2)^2]^{\frac{1}{3}} \tag{2.11}$$

After calculating the volumetric force applied by the operator, it is necessary to solve the continuity and momentum equations in the computational domain. The stable and incompressible form of the Navier-Stokes equations is as equations (2.12a)-(2.12c) [14, 16].

$$(\overrightarrow{V} \cdot \nabla)\overrightarrow{V} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\overrightarrow{V} + \overrightarrow{f_b} \tag{2.12a}$$

$$\nabla\overrightarrow{V} = 0 \tag{2.12b}$$

$$c_p\frac{\partial\overrightarrow{V}T}{\partial x_j} = -\frac{1}{\rho}\nabla \cdot (k\nabla T) + \frac{1}{2}\tau : (\nabla\overrightarrow{V_j} + \nabla\overrightarrow{V^T}_j) \tag{2.12c}$$

In this relationship, P is the pressure, ν is the kinematic viscosity, T is the temperature, and $\overrightarrow{V}$ is the velocity vector. To consider the effect of relative humidity on the process of ionization and creation of corona wind, the formula of relative humidity has been used for the survival of species.

$$\overrightarrow{V}\nabla\omega_w = D_{\text{eff}(w/a)}\nabla^2\omega_w \tag{2.13}$$

3 Numerical solution network and boundary conditions

The geometric characteristics of the electrodes used in this research are shown in Table 1. The dimensions shown in Table 1 are selected based on the actual values used in wind turbines. In this research, regular meshing is used for meshing the computer domain. In the examined space, the temperature of the moist air around the electrodes is considered to be $27°C$. Due to the ionic wind created around the electrodes, the condition of non-slip on the walls of the electrodes is considered. To create the ionic wind, the EHDFoam solver is combined with the buoyantPimpleFoam solver, in the free and open access OpenFoam software. To consider the relative humidity, equation (2.13) is coded inside the solver integrated with the $C++$ programming language. The highest residual values for the terms energy, speed, pressure, type of relative humidity and parameters involved in the electric field are of the order of -6. Also, the second-order upwind discretization method is used for commutative sentences, and the constrained linear Gaussian discretization method is used for the Laplacian sentences in the governing equations. The boundary conditions related to the relative humidity in the walls and the calculation range at the initial time are considered equal to 20%. Also, the boundary condition related to pressure in the walls is pressure flux, which is the most suitable type of boundary condition for emitting walls. The summary of boundary conditions used in this research is shown in Table 2. In this numerical method, two electrodes are used, which are located inside the airfoil and are considered according to Figure 1. The dielectric geometry is gridded using an organized grid. A view of the computational network produced between two electrodes is presented in Figure 1. As shown in Figure 1, a smaller grid is used in the areas near the surface of the absorbent electrode.

Table 1: The dimensions of the electrodes used in this research [4]

Demisions	**Electrode type**
2 cm	Absorbent electrode
15 cm	Corona electrode

Table 2: Boundary conditions used for simulation

Border	**Type of boundary condition**
Corona electrode	constant speed, pressure flux, formulas (2.3) and (2.4)
Absorbent electrode	constant speed, pressure flux, formulas (2.3) and (2.4)

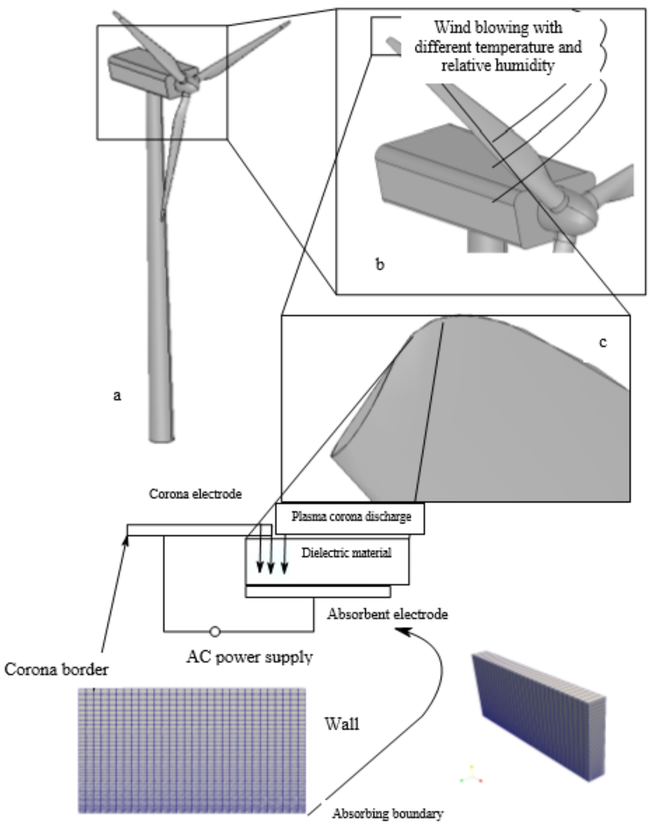

Figure 1: Different views of the wind turbine blade geometry, and the grid around the considered airfoil

4 Verification of the results

Considering that the main focus of this research is on the application of three important and effective parameters of relative humidity, pressure and temperature on the ionic wind created by the plasma operator on the wind turbine blade, Zhang et al.'s research [1] has been used. In their work, the main focus was on creating plasma on three considered areas on the electrode. In this work, they used the method of creating plasma. A comparison between the results of the present work and their work is shown in Figure 2. The ion density created in this work with their work in this form shows the high accuracy of solving the current problem.

In this figure, the amount of ion density is shown in terms of contour on three points. The extended plasma length as well as the width of the plasma formation regions are in very good agreement with the current work. Also, the diagram of the ion density created on the core of the plasma and at a distance of 5 cm from the electrode is shown in Figure 2. The percentage of error calculated in the highest value is equal to 4.4% and is considered based on the root mean error method.

To ensure the independence of the solution from the grid at the angle of attack of 15 degrees with the characteristics of the operator, the frequency of 18 kHz and the peak voltage of 7 kV, a comparison of the ionized density was made

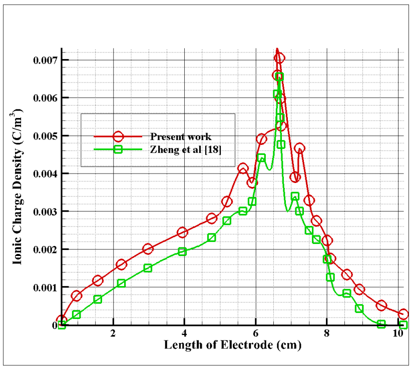

Figure 2: Comparison of the ion density diagram of the current work with the work of Zheng et al. [1]

and it was observed that the number of 3000 grid elements is sufficient to continue the calculations. For this purpose, a type of mesh with 3000 meshes was selected and then the number of elements in each direction was increased by 5.1 respectively. After increasing the elements in each direction, the changes in the ionized flux density have been extracted and compared, and it was observed that no change in the ionized density can be observed after 3000 meshing. The independence of the results from the time step was also done for the current work and it was determined that the most appropriate and optimal time step for the current work is 5-time order. The results related to the independence of the results from the network and the time step are shown in Figure 3.

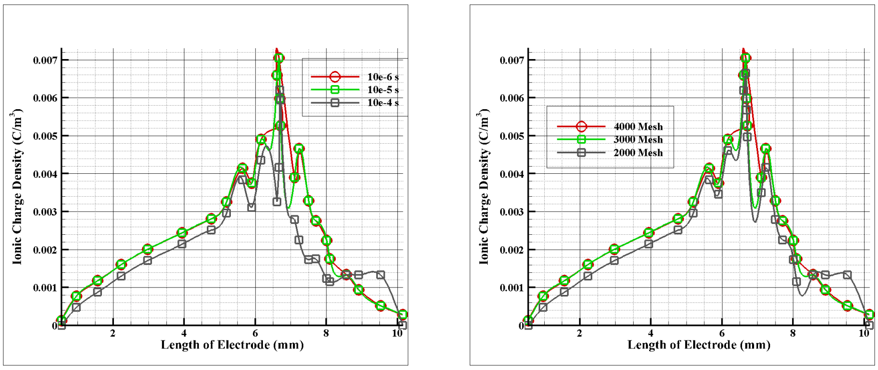

Figure 3: Right side: independence of results from meshing and left side independence of results from time step

5 Results

5.1 Effect of relative humidity on the plasma operator

In this research, 4 different relative humidities were used to form plasma. These relative humidities are: 20, 40, 60 and 80 percent. Undoubtedly, the amount of applied voltage has a tremendous effect on the behavior of the plasma phenomenon. In this research, relatively high voltage is used for this purpose. Each of the considered relative humidities is related to a specific climate for setting up the wind turbine system. It is important to mention that the air pressure around the wind turbine blade is equal to 4.0 bar. The results related to each of the mentioned relative humidities on the speed contour between the two electrodes are shown in Figure 4. Based on this figure, it can be seen that with the increase in the relative humidity of Badioni, it suffers relatively high depreciation. The speed contour has the highest speed distribution in the relative humidity of 20%, but in the relative humidity of 80%, the speed value decreases by 25% near the absorbent electrode. At applied voltage, corona discharge in air developed with higher current intensity for relative humidity of 20%. RH=80%, flow rate is lower at higher relative humidity. This effect is probably due to a decrease in the apparent mobility of ions due to their combination with water molecules with increasing relative humidity. As the pressure and relative humidity increase, the ionization constant decreases, so a lower ionization rate occurs near the tip. As a result, the current produced by the corona discharge is reduced. It is important to mention that the mutual effects of temperature and relative humidity have been ignored. Considering that the ionization constant is proportional to the apparent mobility of the charge carriers, it is lower in the case

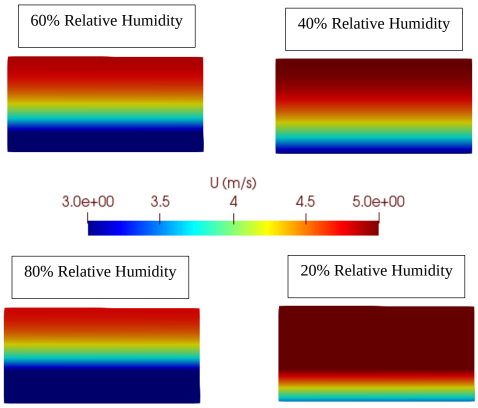

Figure 4: Speed contour according to the types of relative humidities studied in this research at a pressure of 4.0 bar, the higher the speed value is in the higher range, the higher the momentum is transmitted

of positive polarity and this positive polarity is less evident in higher relative humidities, this in itself is a sufficient reason for the decrease in the speed of the ion wind with increasing humidity. It can be relative. Considering that the main purpose of adding a plasma actuator on the wind turbine blade is to create momentum in a direction opposite to the separation of the fluid flow, therefore, whenever the velocity distribution between two electrodes decreases, the momentum also undergoes changes. The obtained results show a 62% decrease in the transfer momentum size with an increase in relative humidity. Therefore, with these interpretations, the plasma operator shows the best performance in environmental conditions with low relative humidity. In the next section, the effect of temperature on the process of creating ion wind is discussed.

Figure 5 shows the changes in momentum caused by the ionic charge in the distance between two electrodes in terms of relative humidities at a pressure of 4.0 bar. The value of the momentum force is obtained from the product of the mass flow rate and the velocity. Based on this figure, it can be seen that with the increase in relative humidity, the transfer momentum from the corona electrode to the absorber electrode decreases. The highest value of transferable momentum was created at 20% relative humidity and has a value equal to 160 newtons. While the highest value of transfer momentum in 80% relative humidity is equal to 150 newtons. All these graphs were obtained at an ambient pressure of 4.0 bar.

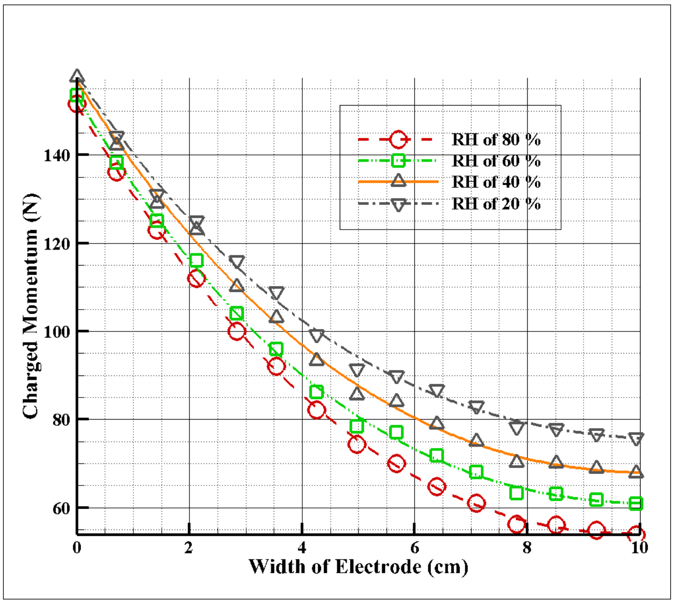

Figure 5: Momentum changes due to ionic charge in the distance between two electrodes according to types of relative humidities at 4.0 bar pressure

5.2 Effect of temperature on the plasma operator

To investigate the effect of temperature on the ionization process between two electrodes, four different temperatures have been considered according to different climates. Each of the considered temperatures is considered for certain climates with constant relative humidity and high applied voltage. In such systems, knowing the effect of ambient temperature on corona discharge behavior is of vital importance. As mentioned, some aspects of this effect are not well understood and need to find a suitable relationship between temperature and corona discharge. In this part of the results, temperatures of -10, zero, 45 and 55 degrees Celsius have been investigated and the effect of these four temperatures on the momentum transfer potential has been analyzed. It is important to mention that the air pressure around the wind turbine blade is equal to 8.0 bar. The corona flow caused by high temperature includes three aspects: (1) promotion of gas molecule ionization due to the increase in kinetic energy of molecules at high temperature. (2) separation of free electrons from negative ions in the drift region under high electric field together with high temperature field. (3) generation of electrons from the cathode surface as a result of reducing the effective work function of the cathode. The results show that in negative temperatures, the plasma actuator applied on the wind turbine blade has the highest temperature distribution compared to higher temperatures. This sub-zero temperature causes the production of electrons at a higher speed than the surface of the cathode and improves the performance of the momentum transfer process. The results showed that, on average, the transfer momentum value decreases by 35% with increasing temperature. In Figure 6, the speed contours are shown according to the types of temperatures studied in this research at a pressure of 8.0 bar. Also, to check the transfer momentum between two electrodes as best as possible; Figure (2.7) diagram is considered. Based on this figure, it can be seen that as the temperature increases, the transfer momentum between the two electrodes decreases. The highest value of transfer momentum is reported for -10 degrees temperature and 8.0 bar pressure, which is equal to 147 newtons. The lowest amount of momentum was obtained near the absorber electrode at a temperature of 55 degrees, which is equal to 37 newtons. From the comparison of the range of changes between Figure 5 and Figure 7, it can be seen that pressure has a significant effect on momentum. In such a way that with increasing pressure, the amount of momentum caused by electrohydrodynamic wind increases.

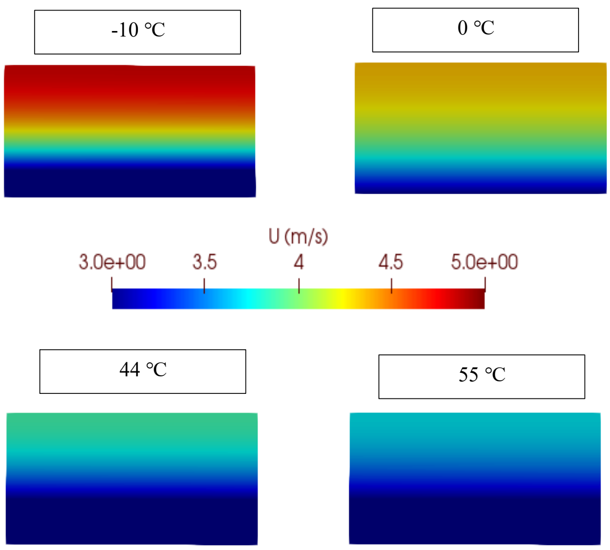

Figure 6: Speed contour according to the types of temperatures studied in this research at 8.0 bar pressure, the higher the speed value is in the higher range, the higher the momentum is transmitted

5.3 The effect of pressure on the plasma actuator

In this part of the research, the effect of pressure on the corona discharge phenomenon on the trailing edge of the turbine blade has been investigated. The apparent mobility of ions decreases with increasing pressure. Increasing the pressure changes the ionization coefficient in the ionization region and changes the mean free path length of the ion λ in the drift region for a constant voltage value between the electrodes. By comparing between Figure 4 and Figure 6, this can be achieved. Wind turbine designs are mainly in high pressure and high altitude areas. The reason for this

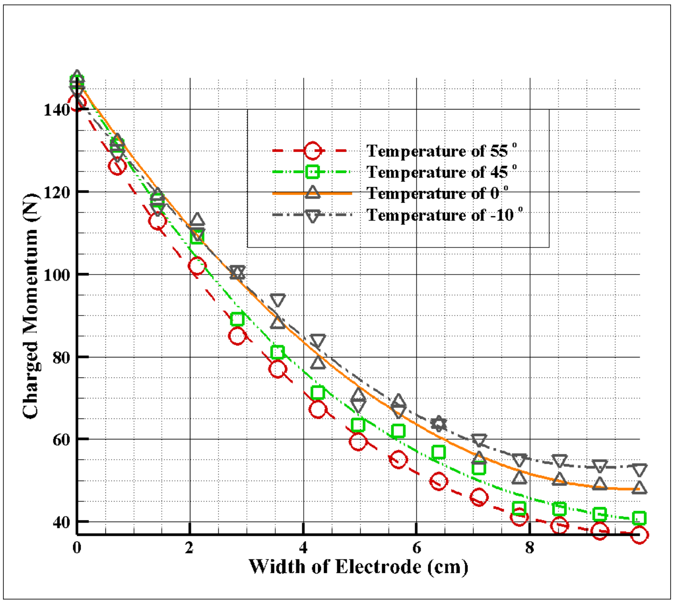

Figure 7: Momentum changes due to ion charge in the distance between two electrodes according to different temperatures at a pressure of 8.0 bar

work is to improve the pressure coefficient and increase it on the surface of the blade to estimate the goals. However, due to the reduction of corona discharge performance with the increase of environmental pressure, one should always look for the most suitable and optimal location of the wind farm.

6 Conclusion

This research, taking into account the plasma corona discharge process on the escaping edge of the wind turbine in order to control the width of the isolated area, has investigated three important and vital parameters of relative humidity, pressure and temperature. After reviewing the background of the research done in this regard, it can be seen that the corona discharge process on the wind turbine blade has been less studied considering the environmental parameters. For this purpose, Oppenfoam software has been used for numerical simulations and verification. In this research, the width and length of the electrodes are considered based on real values. The remarkable innovation of this research is the comprehensive investigation of the ion wind formation on the wind turbine blade caused by the plasma operation, considering a wide range of weather parameters. The considered range of relative humidity is between 20 and 80%, temperature between -10 and 55 degrees Celsius and two pressures of 4.0 and 8.0 bar. As the relative humidity increases, the temperature and pressure of the transfer momentum between the two electrodes decreases. The results show a 62% and 35% decrease in the average transfer momentum with an increase in relative humidity and temperature, respectively.

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