Characterization Of Dielectric Barrier Discharge (DBD) Produced In Air At Atmospheric Pressure And Its Application In Surface Modification Of High-Density Polyethylene (HDPE)

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The low surface energy of HDPE limits its industrial uses as it is not suitable for printing and adhesion. The main aim of this work is to improve the wetting properties of high-density polyethylene (HDPE) using air dielectric barrier discharge (DBD) operating at the line frequency (50 Hz). The estimation of electron temperature and electron density has been done by electrical and optical methods. The surface roughness of the control and plasma treated polymer film is analysed by contact angle (CA) measurement, surface energy measurement and scanning electron microscope (SEM) analysis. The contact angle was found to be suppressed from $93.10 \pm 2.00$ to $64.00 \pm 1.00$ after 10 sec of plasma treatment which implied that the surface property had changed to a hydrophilic state caused by an increase in the surface roughness.

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I. Introduction

High Density Poly Ethylene (HDPE) is a recyclable thermoplastic polymer made from petroleum product which is the most versatile plastic materials around, and used in a wide variety of applications, including plastic bottles, toys, soda bottles, trash cans, traffic cones bleach bottles, cutting boards, and piping [1]. The main reason for its wide range of applications is its superb characteristics viz., high chemical resistance, good mechanical properties (high flexibility, high tensile strength and ease of material processing), high recycling potential and low cost [2,3]. However, the surface energy of HDPE is quite low due to the absence of polar functional groups in PE molecular chains [4,5], which limit their potential application in various fields. As a result, its surface properties such as hydrophilicity, adhesivity and printability do not often meet the requirement for industrial applications. [5]. In order to spread its uses in different sectors, its surface modification is necessary. Different physical (dry) as well as chemical (wet) methods have been in practice since the decade for the modification of the polymer surface. However, the chemical method is water-wasting and environment polluting. In contrast, the physical method has attracted much attention in recent years [6-9].

Plasma treatment is one of the versatile physical methods for surface modification of polymers as it does not leave any chemical residue on the treated surface [10-12]. Because of the heat sensitivity of the polymer, non-thermal plasma also called cold plasma is suited for its surface modification and processing. Non-thermal plasma has the ability to modify the surface of the polymer by adding specific functional groups without altering the bulk properties of the material [13-15]. But the generation of non-thermal plasma in low pressure and high frequency needs a vacuum system which increases the budget of the operation and also makes it inconvenient for large scale treatment.
Thus, in order to minimize the operation cost and elaborate its uses in industrial level, the use of atmospheric pressure plasma is grooming day by day [16-18]. In this paper, the effect of pretreatment of the polymer surface with non-thermal plasma produced at atmospheric pressure using line frequency (50 Hz) has been discussed. Non-thermal plasma generated by ac voltage source operating at the line frequency is used to modify the surface of the HDPE sample. The surface properties of the treated materials were studied in terms of contact angle and surface energy measurements. It was observed that both the contact angle and surface energy of the material changed after being treated with the non-thermal plasma.

II. Materials and Methods

Fig. 1 shows the typical experimental set up and nature of the discharge used for the present study. The reactor system consists of a transparent cylinder of height 10 cm, diameter 10 cm and thickness 0.5 cm. An orifice is made on the cylinder and a fibre optic cable is inserted there and sealed.

Both the electrodes used in the study are made of brass (5.1 cm × 5.1 cm × 1.0 cm). A polycarbonate sheet of 2 mm thickness is inserted between the two electrodes which serves the purpose of the dielectric barrier. The reactor consists of two pipes. One of the pipes is connected to a vacuum pump while the other pipe is connected to the analogue pressure gauge. The reactor is designed in such a way that it can be made to operate in both the atmospheric and reduced pressure (as low as 5300 Pa). For all DBD treatments the gap between the electrodes was fixed at 3.5 mm. The ac voltage applied to the reactor was measured by using a high-voltage probe (PINTEX HVP-28HF) and monitored on a digital oscilloscope (Tektronix TDS 2002, 60MHz). The attenuation ratio of the high voltage probe is 1000:1. For displaying the waveform of the discharge current on the oscilloscope, the reactor lower electrode was grounded through a current measuring resistor of 10 KΩ. A spectrometer of Ocean Optics (USB 2000+) has been used for the measurement of emission spectra. In this work, the operating ac
and the current peaks of the falling part correspond to reverse negative polarity in which the accumulated charges are changed. The current density $J$ was obtained by dividing the discharge current, $I$ by the cross-sectional area of plasma, $A$.

$$J = \frac{I}{A} \quad (1)$$

The average electron density $n_e$ can be calculated from the following equation [19,20].

$$n_e = \frac{J e \mu_e E}{e m \nu_m} \quad (2)$$

In our case, the cross sectional area of the plasma = cross sectional area of the electrodes = 20.41 cm². Discharge current = 22.8 mA, Applied Voltage = 11.76 kV (rms), inter-electrode distance $(d) = 3.5 \text{ mm} = 0.35 \text{ cm}$, electron mobility $\mu_e \approx 552 \text{ cm}^2/\text{Vs}$ [20, 21]. The electron mobility can be calculated as follows:

$$\mu_e = \frac{e}{m \nu_m} \quad (3)$$

Here, $e$ represents the electronic charge, $m$ represents the mass of the electron and $\nu_m$ represents the effective collisional frequency.

The value of effective collision frequency for nitrogen is found to be [21]:

$$\nu_m = 4.2 \times 10^9 \text{ s}^{-1} \text{ torr}^{-1}$$

Substituting these values in Eq. (2), the electron mobility is estimated as

$$\mu_e = 1.67 \times 10^{15} \times \frac{1}{3.192 \times 10^{12}} \quad (4)$$

$$\rightarrow \mu_e \approx 552 \text{ cm}^2/\text{Vs} \quad (5)$$

Using all these values in Eq. (2), the electron density was found to be in the order of $3.7 \times 10^8 \text{ cm}^{-3}$. 

III. Results and Discussions

III.a) Electrical Characterization

![Figure 2](image-url)

**Figure 2:** Typical current and voltage waveforms for 50 Hz DBD

Fig. 2 shows the typical current and voltage waveform of DBD generated in air at atmospheric pressure condition. The current peak appears on both the rising and falling of the discharge voltage. The current peaks on the rising part correspond to positive polarity where some of the charges accumulate on the dielectric barrier.
Fig. 3 shows the voltage-versus-charge plot or the so-called Lissajous figure of the discharge operating using line frequency at atmospheric condition. The energy dissipated per cycle is found to be 0.4184 mJ per cycle.

### III.b) Optical Characterization of the discharge

Fig. 4 shows the spectra of the discharge and their corresponding intensities at atmospheric pressure condition.

The line intensity ratio method was employed for the estimation of electron temperature [22,23]. In this method four suitable lines; two for N I (413.7640 nm, 439.241 nm) and two for N II (411.1039 nm, 437.9585 nm) were chosen from spectral lines of Nitrogen obtained from the discharge.

\[
\frac{R_1}{R_2} = \frac{I_1}{I_2} = \frac{I_3}{I_4} = \frac{(A_{pq} \lambda_{pq}) (g_p \lambda_{pq}) (A_{xy} \lambda_{xy}) (g_x \lambda_{xy})}{(A_{pr} \lambda_{pr}) (g_r \lambda_{pr}) (A_{ur} \lambda_{ur}) (g_u \lambda_{ur})}
\]

\[
\exp \left[ -\frac{E_p - E_r - E_x + E_u}{k T_e} \right]
\]  

(6)

Here, in Eq. (6), \( R \) is the ratio of the intensity of two lines, \( I \) is the intensity of the spectral line, \( A_{ij} \) is the transition probability of the transition \( i \to j \), \( g_i \) is the statistical weight of the upper level, \( \lambda \) is the wavelength of the line radiation, \( E_i \) is the energy of the upper level, \( k \) is the Boltzmann constant and \( T_e \) is the electron temperature. The values of \( \lambda \) and \( I \) are obtained from the observation, and the values of \( A_{ij} \), \( g_i \) and \( E_i \) are obtained from the National Institute of Standards and Technology (NIST) Atomic Spectra Database [24].

Tab. 1 shows the corresponding values of the ratio of the intensity of the spectral lines with the change in electron temperature.

| Electron Temperature \( T_e \) | Ratio of Intensity of Spectral Lines \( \frac{R_2}{R_1} \) |
|--------------------------------|----------------------------------|
| 0.8                           | 2.00173                         |
| 0.9                           | 1.05178                         |
| 1.0                           | 0.62855                         |
| 1.1                           | 0.41248                         |
| 1.2                           | 0.29038                         |
| 1.3                           | 0.21576                         |
| 1.4                           | 0.16727                         |
| 1.5                           | 0.13415                         |
| 1.6                           | 0.1106                          |
| 1.7                           | 0.09327                         |
| 1.8                           | 0.08017                         |
| 1.9                           | 0.07001                         |
| 2.0                           | 0.06197                         |
From Fig. 5, the electron temperature is found to be about 1.05 eV. This temperature is favourable for the surface modification of the polymeric films as the discharge used for material processing typically have densities of $10^9$-$10^{12}$/cm$^3$ and electron temperature in the range 1-10 eV [25,26].

### III.c) Polymer wettability

The wettability of polymer indirectly indicates its susceptibility to molecular interaction with the liquid phase and the presence of polar groups on the surface. WCA measurements can provide some qualitative information about the polymer surface modification [27].

For an ideal, smooth and homogeneous surface, the water contact angle and surface free energy are measured at the equilibrium according to the Young's equation and Owens Wendt Kaeble methods respectively [28,29].

$$\cos \theta = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}}$$  \hspace{1cm} (7)

Where, $\gamma_{sv}$ is the surface free energy of the solid substrate, $\gamma_{sl}$ is the interfacial tension (interfacial free energy) between the solid and the liquid and $\gamma_{lv}$ is the surface tension of the liquid.

For two liquids j and k,

$$\gamma_{ij}(1 + \cos \theta) = 2(\gamma_{ij}^{p} \gamma_{ij}^{d})^{1/2} + 2(\gamma_{ij}^{P} \gamma_{ij}^{P})^{1/2}$$  \hspace{1cm} (8)

$$\gamma_{ik}(1 + \cos \theta) = 2(\gamma_{ik}^{d} \gamma_{ik}^{d})^{1/2} + 2(\gamma_{ik}^{P} \gamma_{ik}^{P})^{1/2}$$  \hspace{1cm} (9)

Using the values of the surface tension, polar and dispersion components of the test liquids, components of surface free energy of the solid, i.e. $\gamma_{s}^{p}$ and $\gamma_{s}^{d}$ can be determined by solving the Eqs. (8) and (9). The sum of these two quantities eventually gives the total surface energy of the solid.

The influence of treatment time on the wettability was investigated, using a Rame Hart contact angle goniometer (model 200) using two test liquids (water and glycerol) on the surface of the HDPE.

![Figure 6: Water contact angle of control (a) and plasma treated(b) HDPE thin films for 60 seconds.](image)

Fig. 6 shows the images of the untreated and plasma treated high density polyethylene films for 60 seconds. When polymers are exposed to plasma, basically two phenomena occur simultaneously. First is etching of the polymer surface through the reaction of atomic oxygen with the surface carbon atoms, giving volatile reaction products. Second is the formation of oxygen functional groups at the polymer surface through the interaction between the active species in plasma and the surface atoms [30].

![Figure 7: Variation of the contact angle as a function of treatment time.](image)

Fig. 7 shows the water contact angle (WCA) of DBD-treated HDPE films as a function of treatment time. Here, the water contact angle of the untreated sample of HDPE was found to be $93^\circ\pm2^\circ$. After 10 sec of plasma treatment, the water contact angle was significantly decreased to $64^\circ\pm1^\circ$ as depicted in Fig. 7 exhibiting that DBD treatment can be used for improving the surface wettability. This might be due to the
incorporation of new oxygen related functional groups on the surface. However, the extension of the treatment time did not result in further improvement of polymer hydrophilicity and the WCA of plasma modified HDPE attained saturation value of around 54.1°±0.3°. This might suggest that the etching and the oxidation come to a saturation when the surface of samples are exposed to the air-DBD [30,31].

**Figure 8:** Variation of the surface free energy as a function of treatment time.

Fig. 8 shows the variation of surface energy as a function of treatment time. The surface energy of the untreated HDPE film was 24±1 mJ/m². Plasma treatment appears to increase the surface energy up to 30 seconds exposure time; and thereafter tending to saturate. This may be due to the lack of any change in the oxygen content incorporated into the surface, as the exposure time increased. Finally, the surface energy saturates at 48±1 mJ/m². Similar trend is observed for the polar component. It might be due to the incorporation of polar groups such as C=O, -OH, -COO etc. [31,32]. The dispersive component almost remains constant. This component does not have any contribution to increase the wettability of HDPE films. Hence the increase in surface energy is mainly due to the incorporation of polar groups onto the HDPE surface. The details of this oxidation, leading to the enhanced hydrophilicity observed has been assessed by ATR-FTIR, XPS analyses by various researchers [30-32].

**III.d) Ageing effect:**

One of the most important challenges in plasma processing is to achieve a long-lasting treatment effect. The change in the contact angle of the 60 seconds plasma treated HDPE films was monitored for 10 days. Distilled water was only used for the measurement of contact angle.

**Figure 9:** Variation of contact angle with storage time

It is seen that the water contact is found to be changed more rapidly for the first few hours and then changes very slowly to reach a stable value of about 68° which is still smaller than the untreated HDPE films. The change in the contact angle might be due the change in the polymer chain motion, reorientation of the polar group into the polymer bulk or only within the modified surface. The decay in wettability might be due to the reduction of the hydrophilic functional groups and partially due to hydrocarbon re-adsorption.

**III.e) Surface morphology:**

During plasma treatment, energetic plasma species bombard and cause etching of HDPE films surface, leading to an increase in the surface roughness [32,33].

**Figure 10** shows the SEM morphology of untreated and plasma treated HDPE films at 60 seconds. The morphology of the control sample is smoother than that of the plasma-treated one. The gradual increment in the particle grain size with the image scan area can be realized. The increase in the surface roughness of the HDPE film could have been caused by the excited reactive species from the discharge plasma in the ambient air. These highly reactive species could have etched and roughened the film surface. This
increase in the surface roughness might be responsible for the decrease in the contact angle.

![SEM images of the control(untreated) and Plasma treated HDPE films](image)

Figure 10: SEM images of the control(untreated) and Plasma treated HDPE films

Several other authors have also reported a similar roughness trend for the plasma-treated polymers [31-35].

### IV. Conclusions

In this work, an atmospheric pressure plasma has been used to modify HDPE film surfaces using line frequency (50 Hz). Electron density and temperature of the discharge were found to be $3.7 \times 10^8$/cm$^3$ and 1.05 eV respectively. The plasma treatment can greatly change the surface chemistry as well as morphology of HDPE films. The polar functional groups generated due to plasma treatment on the surface of HDPE films cause decrease in contact angle and rise in surface energy. The reduction of the water contact angles on treated HDPE films as compared to the untreated (control) one shows the strong increased wettability induced by the air-DBD even after such short treatment time. This behaviour can be attributed to strong surface oxidation. The molecular oxygen which is in contact with the air is activated, ionized and dissociated in the discharge to give extremely reactive oxygen species which can readily react with the HDPE films. Ageing effect showed that the so-called hydrophobic recovery of the HDPE films occurred as the storage time increased. The results from the SEM measurement showed a gradual increase in the surface roughness of the plasma treated surface with treatment time. The morphological changes made on the surface of HDPE films lead to increase in hydrophilic properties. It is further seen that there is a direct relationship between the roughness of the surface and the wettability. The results from sessile drop examination confirmed that contact angle of HDPE decreases as surface roughness increases. The effect will find attraction on industrial applications. In the present study, it is evident that more than 40% decrease in the value of water contact angle is achieved in just 30 second of exposure to plasma. Therefore, quick hydrophilization of HDPE using cost-effective plasmas devices could be the novelty of the present work. Thus, the results from our experiment showed that the atmospheric pressure plasma treatment operating at 50 Hz could be a cost-effective technology to improve the wettability of HDPE films as compared to rf-sources operating at high frequencies.

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### VI. References

[1] G. Wypych, “HDPE high density polyethylene, Handbook of Polymers”, *Elsevier*, p.150-156, 2012.

[2] H. Ulrich, “Introduction to Industrial Polymers”, 2nd edition, *Hanser Publishers*, New York, 1993.

[3] S. Bhowmik, P. K. Ghosh, and S. Ray, “Surface modification of HDPE and PP by
mechanical polishing and DC glow discharge and their adhesive joining to steel”, Journal of Applied Polymer Science, 80(8), 1140–1149, 2001.

[4] J.-S. Lim, M.-S. Kook, S. Jung, H.-j. Park, S.-H. Ohk and H.-K. Oh, “Plasma Treated High-Density Polyethylene (HDPE) Medpor Implant Immobilized with rhBMP-2 for Improving the Bone Regeneration”, Journal of Nanomaterials, 1–7, 2014.

[5] H. Drnovská, L. Lapčík, V. Buršíková, J. Zemek and A. M. Barros-Timmons, “Surface properties of polyethylene after low-temperature plasma treatment”, Colloid and Polymer Science, 281(11): 1025–1033, 2003.

[6] U. M. Joshi and D. P. Subedi, “Surface treatment of high-density polyethylene (HDPE) film by 50 Hz dielectric barrier discharge produced in air and argon/air mixture at atmospheric pressure”, Int. Journal of Engineering Research and Applications, 5(3): 1-9, 2015.

[7] W. Kun, L. Jian, R. Chunsheng, W. Dezhen and W. Younian, “Surface Modification of Polyethylene (PE) Films Using Dielectric Barrier Discharge Plasma at Atmospheric Pressure”, Plasma Science and Technology, 10(4): 433–437, 2008.

[8] J. Gruenwald, K. Fricke, M. Fröhlich, J. F. Kolb and M. Polak, “Deposition of Copper Oxide Coatings with an Atmospheric Pressure Plasma Source: II -Characterization of the Films”, Plasma Processes and Polymers, 13(8), 766–774, 2016.

[9] R. P. Guragain, S. Gautam, R. Shrestha, and D. P. Subedi, “Surface modification of polycarbonate by treatment with 50Hz dielectric barrier discharge at near atmospheric pressure", International Journal of Science and Research,, 5(2), 1468–1470, 2016.

[10] M. J. Shenton and G. C. Stevens, “Surface modification of polymer surfaces: atmospheric plasma versus vacuum plasma treatments”, Journal of Physics D: Applied Physics, 34(18), 2761–2768, 2001.

[11] Rory A. Wolf, “Atmospheric Pressure Plasma for Surface Modification”, John Wiley and Scrivener Publishing, 2012.

[12] M. Strobel, C.S. Lyons and K.L. Mittal, “Plasma Surface Modification of Polymers: Relevance to Adhesion”. CRC Press, 1994.

[13] M. Nitschke, “Plasma Modification of Polymer Surfaces and Plasma Polymerization”. In: Stamm M. (eds) Polymer Surfaces and Interfaces. Springer, Berlin, Heidelberg, 2008.

[14] A.P. Napartovich, “Overview of Atmospheric Pressure Discharges Producing Nonthermal Plasma”, Plasmas and Polymers, 6, 1–14, 2001.

[15] R. P. Guragain, S. Gautam, D. P. Subedi and R. Shrestha, “Effect of Plasma Treatment on the Surface of Polyethylene Terephthalate with 50Hz Dielectric Barrier Discharge at Near Atmospheric Pressure”, International Journal of Recent Research and Review., 9(4),34-37, 2016.

[16] S. K. Nemani, R. K. Annavarapu, B. Mohammadian, A. Raiyan, J. Heil, M. A. Haque, H. Sojoudi, “Surface Modification of Polymers: Methods and Applications”. Advanced Materials Interfaces, 1801247: 1-26, 2018.

[17] H. M. S. Iqbal, S. Bhowmik, and R. Benedictus, “Surface modification of high-performance polymers by atmospheric pressure plasma and failure mechanism of adhesive bonded joints”. International Journal of Adhesion and Adhesives, 30(6), 418–424, 2010.

[18] H. Dvořáková, J. Čech, M. Stupavská, L. Prokeš, J. Jurmanová, V. Buršíková, J. Ráhel and P. St'ahel, “Fast Surface Hydrophilization via Atmospheric Pressure Plasma Polymerization for Biological and Technical Applications”. Polymers (Basel), 11(10): 1613, 2019.

[19] F. Martinek, “Thermodynamic and electrical properties of nitrogen at high temperatures”. in Proc. Int. Symp. Thermal Properties, IN, US, p. 130, 1959.

[20] A. El-Zein, M. Talaat, G. El-Aragi, and A. El-Amawy,“Electrical Characteristics of Nonthermal Gliding Arc Discharge Reactor in Argon and Nitrogen Gases”. IEEE Transactions on Plasma Science., 44(7),1155–1159, 2016.

[21] J. P. Rajzer. “Gas discharge physics”. Berlin: Springer, 1997.

[22] C. S. Wong, & R. Mongkolnavin. “Elements of Plasma Technology”, Springer Briefs in Applied Sciences and Technology., 2016.

[23] H. B. Baniya, R. Shrestha, R. P. Guragain, M. B. Kshetri, B. P. Pandey and D.P. Subedi,
“Generation and Characterization of an Atmospheric-Pressure Plasma Jet (APPJ) and Its Application in the Surface Modification of Polyethylene Terephthalate”, International Journal of Polymer Science, 1687-9422, 2020.

[24] A. Kramida, Y. Ralchenko, J. Reader, and NIST ASD Team. NIST Atomic Spectra Database, 2019. https://physics.nist.gov/asd

[25] E. H. Lock, R. F. Fernsler and S. G. Walton. “Experimental and theoretical evaluations of electron temperature in continuous electron beam generated plasmas”, Plasma Sources Science and Technology., 17(2), 025009, 2008.

[26] H. B. Baniya, R. P. Guragain, B. Baniya and D. P. Subedi, “Experimental Study of Cold Atmospheric Pressure Plasma Jet and Its Application in the Surface Modification of Polypropylene”, Reviews of Adhesion and Adhesives, Scrivener Publishing, 1-14, 2020.

[27] K. G. Kostov, T. M. C. Nishime, L. R. O. Hein, and A. Toth, “Study of polypropylene surface modification by air dielectric barrier discharge operated at two different frequencies”, Surface and Coatings Technology, 234: 60-66, 2013.

[28] Y. Yuan and T. R. Lee, “Contact angle and wetting properties,” in Surface Science Techniques, G. Bracco and B. Holst, Eds., vol. 51 of Springer Series in Surface Sciences, Springer, Berlin, Heidelberg, 2013.

[29] D. K. Owens, and R. C. Wendt, “Estimation of the surface free energy of polymers”, Journal of Applied Polymer Science, 13(8), 1741–1747, 1969.

[30] M. Morra, E. Occhiello, and F. Garbassi, “Surface characterization of plasma-treated PTFE”, Surface and Interface Analysis, 16(1-12): 412–417, 1990.

[31] M. Noeske, J. Degenhardt, S. Strudthoff and U. Lommatzsch, “Plasma jet treatment of five polymers at atmospheric pressure: surface modifications and the relevance for adhesion”, International Journal of Adhesion and Adhesives, 24(2): 171-177, 2004.

[32] A. P. Kharitonov, G. V. Simbirtseva, A. Tressaud, E. Durand, C. Labrugère, and M. Dubois, “Comparison of the surface modifications of polymers induced by direct fluorination and rf-plasma using fluorinated gases”, Journal of Fluorine Chemistry., 165: 49–60, 2014.

[33] G. Borcia, C. A. Anderson, and N. M. D. Brown, “Dielectric barrier discharge for surface treatment: application to selected polymers in film and fibre form”, Plasma Sources Science and Technology., 12(3), 335–344, 2003.

[34] C.-S. Ren, K. Wang, Q.-Y. Nie, D.-Z. Wang, and S.-H. Guo, "Surface modification of PE film by DBD plasma in air", Applied Surface Science., 255(5): 3421–3425, 2008.

[35] V. Švorčík, K. Kolářová, P. Slepička, A. Macková, M. Novotná, and V. Hnatowicz, “Modification of surface properties of high and low-density polyethylene by Ar plasma discharge”, Polymer Degradation and Stability, 91(6),1219–1225, 2006.

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