

# AN ATMOSPHERIC-PRESSURE PLASMA JET TREATMENT OF POLYETHYLENE POLYMER FILMS FOR WETTABILITY ENHANCEMENT

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## ABSTRACT

An atmospheric-pressure plasma jet (APPJ) is used to increase the wettability of polyethylene polymer films. Reduction in contact angle from 94.32 to 58.33 degrees was measured for treatment times of 1 - 5 seconds. Contact angle reductions of PE as a function of treatment time with APPJ and PE surface at various oxygen percentages admixtures in He gas, suggest that the surface reaction mechanism is related to the atomic oxygen density produced in the APPJ.

**Keywords:** Atmospheric-Pressure Plasma Jet, Polyethylene Films, Surface Modification

## INTRODUCTION

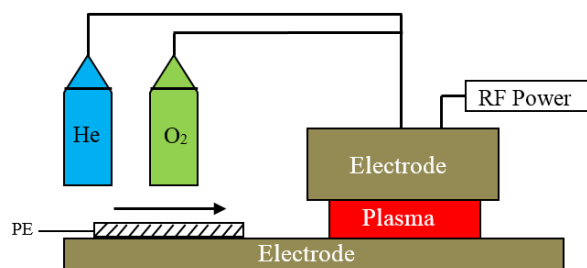
Polymers such as polyethylene (PE) are used in many applications, from food containers to surgical implants, and packaging to textiles (Friedrich *et al*, 1993). The applications for these polymers rely on the fact that they are a thermoplastic with a good resistance to heat, chemicals, and fatigue. It is also semi-rigid and translucent. One of the few downsides to these polymers, for manufacturers who want to adhere inks or glues to its surface, is that it has low wettability. Nowadays, non-thermal plasmas are commonly used to improve the surface properties of these polymers to allow better adhesion and printing (Chan, 1994). Since these plasmas only treat the surface of the polymer film, the integrity and properties of the bulk material are not compromised.

A wide variety of plasma systems, both at traditional low-pressure and at atmospheric pressure, have been used to treat PE films to improve their surface properties, as reported by (Ruddy *et al*, 2006; Hegemann *et al*, 2008; Wei, 2004; Muhlhan *et al*, 1999). Despite the fact that many of these plasmas operate under very different conditions, i.e., operating gases, voltage waveforms and frequencies, and geometries, they all are capable of improving the adhesion properties of PE surfaces. It is believed that the poor adhesive properties of untreated polymer films are due to a lack of polar groups on the surface (Salimi, 2012). The plasma can change this by either adding polar groups to the surface, or breaking surface bonds, creating polar end groups. Although this general concept is fairly well established, the details of the chemical processes involved both at the surface as well as inside

the plasma are not fully understood. In other words, by what mechanisms is the polymer film surface modified and how can the plasma design be optimized to achieve maximum modification in the least amount of time? This paper we will make a link between direct measurements of plasma radical densities and changes in polymer surface properties for a variety of operating conditions of an atmospheric-pressure plasma jet. The overall aim of this research is to investigate the underpinning plasma chemistry that is at play in surface modification of PE films in order to optimize the plasma design and operating conditions for industrial applications.

## Experimental Arrangement

The atmospheric-pressure plasma jet (APPJ) that was used is schematically shown in Fig. 1.



**Fig. 1:** Schematic Diagram of Laboratory Plasma for PE Surface Modification

It is a well-characterized device in terms of its plasma composition and chemistry, as reported by (Knake *et al*, 2008; Wolter *et al*, 2009 and Morsy *et al*, 2006). It consists of two parallel, stainless steel electrodes, sandwiched between 2 quartz glass plates, creating a plasma channel of 1 x 1 x 30 mm. Helium gas with admixtures of 0.2% up to 1% oxygen flow through this channel at 1 standard litre per minute (slm). One of the electrodes is driven, via a matching network, with a radio-frequency (rf) voltage of 13.56 MHz, creating plasma inside the plasma channel. This plasma flows out of the device, into open air, creating a neutral, radical-rich effluent that is made to interact with PE films. The APPJ is facing vertically downwards towards a PE sample surface. The change in the surface properties of the treated PE

films was monitored by measuring the change in wettability using a contact angle analyzer (Shaw *et al*, 2015). It consists of a camera that looks across the polymer surface, and a syringe with a needle tip to drop droplets of water onto the surface. Images from the camera are used to measure the contact angle between the water droplet and the polymer surface. The polymer films used in this work were PP with a thickness of 100  $\mu\text{m}$  (Goodfellow Cambridge Ltd).

## RESULTS

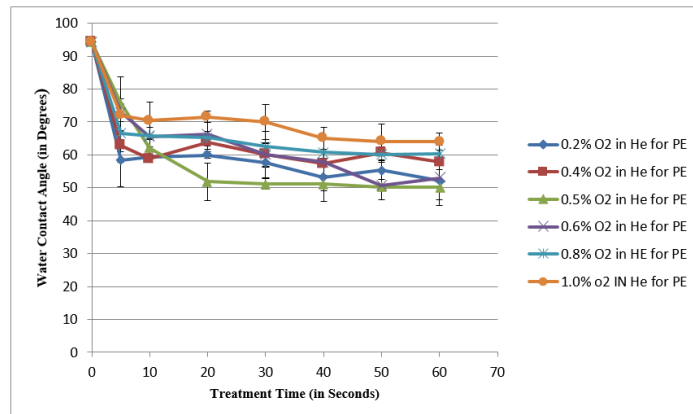
Important parameters for industrial applications of these treatments are the maximum amount of change in wettability that can be achieved and the duration of the treatment that is needed to achieve the desired change. To investigate the required treatment time, we exposed samples of PE film to a range of durations of plasma treatment times of 5-60 seconds with the APPJ. The APPJ was operated with 1 slm of He gas with admixtures of 0.2%, 0.4%, 0.5%, 0.6%, 0.8% and 1.0%  $\text{O}_2$  and 35 W of RF power from the generator. The distance between the APPJ nozzle and the PE surface was 3 mm. The measured contact angles after the various treatment durations and  $\text{O}_2\%$  in He are shown in Table 1. Figure 2 shows the plots of contact angles (in degrees) as a function of treatment time at various  $\text{O}_2\%$  admixtures in He for PE surface.

**Table 1:** Treatment Time (in Sec.) and Contact Angle (in Degrees) at Various  $\text{O}_2\%$  from APPJ for PE Treatment

Treatment Time (in Sec.)	0.2% $\text{O}_2$ in He	0.4% $\text{O}_2$ in He	0.5% $\text{O}_2$ in He	0.6% $\text{O}_2$ in He	0.8% $\text{O}_2$ in He	1.0% $\text{O}_2$ in He
	Contact Angles (in Degrees)					
0	94.32	94.32	94.32	94.32	94.32	94.32
5	58.33	62.77	75.64	72.88	66.59	72.04
10	59.32	58.80	62.10	65.48	65.83	70.37
20	59.92	63.86	52.03	66.33	65.39	71.53
30	57.67	60.05	51.22	60.03	62.47	69.94
40	53.08	57.31	51.07	57.74	60.86	65.10
50	55.29	58.38	50.21	50.75	60.08	64.04
60	52.12	57.74	50.14	53.03	60.29	63.94

A significant change in the PE wettability can already be seen for short APPJ treatment times; of about 1-5sec treatment reduces the contact angle from 94.32 to 58.33 degrees. For many industrial applications speed is important and a 20 degree reduction in contact angle is often sufficient. Nevertheless, it takes roughly 10-sec treatments to reach the full effect of APPJ treatment; a reduced contact angle of about 58.33°. Longer treatment times do not decrease the contact angle further. The observed relation with treatment time suggests that the surface reactions reach saturation after a certain time of after about 20 sec. All the sites on the surface available for modification by the plasma have undergone change and no further reduction in wettability can be achieved. To further investigate the plasma chemistry at play, the treatment distance, i.e., the distance between the APPJ nozzle and the polymer surface was varied between 3 and 50 mm. For each distance, several PE samples were treated for times ranging from 5 to 60 seconds. A similar saturation behavior as was observed for all treatment distances.

That is, after about 50 - 60 seconds the maximum change in contact angle has been reached. The variation of oxygen admixture to the helium feed gas was observed. An APPJ treatment time of 60 sec was chosen, which was verified to be enough to reach contact angle saturation for all admixtures. It can be observed from fig. 2 that there is an optimum effect that is the minimum contact angle for 0.2%  $\text{O}_2$ . Both smaller and larger  $\text{O}_2$  admixtures result in contact angle reductions of about 25 degrees less than what is observed at 0.5%.



**Fig. 2:** Measured contact angle of PE film as a function of treatment time with the APPJ at various  $\text{O}_2$  admixtures.

It is well known that these types of APPJs produce large quantities of several reactive oxygen species, e.g.,  $\text{O}$ ,  $\text{O}_3$ ,  $\text{O}_2^*$  (singlet delta oxygen (SDO)), which have been measured directly for varying operating conditions (Waskoenig *et al*, 2010; Sousa *et al*, 2011; and Ellerweg *et al*, 2010). Knake *et al* (2008) measured 2D maps of the absolute O densities in the effluent of an APPJ and found that the density drops exponentially from the nozzle up to about 50 mm. We observe a reduction in the effect of the plasma treatment of PE with distance between the APPJ and the surface, similar to the measured O densities, suggesting a relation between the two. Furthermore, Knake *et al* (2008) also measured O densities as function of oxygen admixture and found an optimum at 0.5%. Again, this correlates directly to what is observed in Fig. 2, a maximum effect of surface modification at conditions with maximum O production.

In contrast Sousa *et al* (2011) measured SDO densities for varying oxygen admixtures and found a decreasing trend with increasing admixture. Furthermore Ellerweg *et al* (2010) measured an increase of ozone with increasing oxygen admixture. Neither of these trends corresponds to what is measured in Fig.2 suggesting that they are not the primary species responsible for the surface modification of PE. Therefore, we conclude that our experiments indicate that the surface modification of PE is related to atomic oxygen, O, from the APPJ.

Even though exact reaction mechanisms cannot be derived from our experiments, it is possible from Figs. 2 to gain some general insight into the types of reactions that take place on the surface of the PE sample. If the reactions were limited by the number of surface sites that are available, the total effect would scale with the total flux of O to the surface. In other words, even if

the density of O at the surface is lower, applying the treatment for longer would compensate this and the same total flux would result in the same final effect, which all surface sites have been modified. This is not what is observed, if the O density at the surface is smaller, the minimum contact angle is not as small as when the APPJ is closer to the sample, even when the treatment time is increased. This suggests that for the reactions at the surface, the density of O is important, not the total flux.

Detailed modeling of both the chemistry inside the plasma and plasma effluent as well as the interactions with the PE surface, in combination with experiments directly measuring relevant species at the polymer surface, are needed to further clarify the exact reaction mechanisms at play. This increased understanding of the process can aid with the design and optimization of future plasma devices for specific applications.

#### Acknowledgement

We acknowledge the support from the Nigerian Tertiary Education Trust Fund (TETFund) for Academic Staff Training Development.

#### REFERENCES

- Chan C.-M (Ed.) (1994). Polymer Surface Modification and Characterization. Carl Hanser Verlag Publishers, Vienna.
- Ellerweg D; Benedikt J; Von Keudell A; Knake N and Schulz-Von G.V (2010): Characterization of the Effluent of a H<sub>2</sub>/O<sub>2</sub> Microscale Atmospheric Pressure Plasma Jet by Quantitative Molecular Beam Mass Spectrometry, New Journal of physics, **12**, 013-021.
- Friedrich, J. F; Rohrer, P; Saur, W; Gross, Th. Lippitz, A; and Unger, W; (1993). Improvement in Polymer Adhesivity by Low and Normal Pressure Plasma Surface Modification. Surface and Coating Technology, **59**, 371-378.
- Hegemann D., Brunner H., Oehr V. (2008). Plasma Treatment of Polymer for Surfaces and Adhesion Improvement, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 208, 281.
- Knake, N; Niemi, K; Reuter, S; Schulz-von der Gathen, V. (2008). Absolute Atomic Oxygen Density Distribution in Effluent of a Microscale Atmospheric Pressure Plasma Jet. J. Physics D: Appl. Physics, **41**, 194006.
- Morsy F. A; Elsayad S. Y; Bakry A. and Eid M. A. (2006). Surface Properties and Printability of Polypropylene Film Treated by Air Dielectric Barrier Discharge Plasma, Surface Coatings International, Part B: Coatings Transactions Vol. **89**, B1, 1-98.
- Muhlhan C; Weidner S. Friedrich J. and Nowack H, (1999). Improvement of Bonding Properties of Polypropylene Film Treated by an Atmospheric Pressure Plasma, Surface and Coatings Technology, 116-119, 783.
- Ruddy A.C., McNally V, Nersisyan G., Graham W.G., Murphy W.R. (2006). The Effect of Atmospheric Glow Discharge (APGD) Treatment on Polyetherimide, Poly-Butyleneterephthalate and Polyimides, Journal of Plastic Film and Sheeting, **22**, 103.
- Salami A. (2012). Characterization of Nano Scale Adhesion at Solid Surface of Oxidize PP wax/PP blends, International Journal of Adhesion and Adhesives, **33**, 61.
- Shaw, D.R; Gyuk, P.M; West A.T; Momoh M. and E. Wagenaars (2015). Surface Modification of Polymer Films Using an Atmospheric-Pressure Plasma Jet, 22<sup>nd</sup> International Symposium on Plasma Chemistry, July 5-10, 2015; Antwerp, Belgium.
- Sousa, J.S; Niemi, K; Cox, L.J; Algwari, Q. T; Gans, T; O'Connell, D; (2011). Cold Atmospheric Pressure Plasma Jets as Sources of Reactive Oxygen Species for Biomedical Applications, Journal of Applied Physics, **109**, 123.
- Waskoenig, J; Niemi, K; Knake, N; Graham, L.M; Reuter, S; Schulz-von der Gathen, V; Gans, T; (2010). Atomic Oxygen Formation in RF-Driven Micro-atmospheric Pressure Plasma Jet, Plasma Sources Science and Technology, **19**, 045018.
- Wei, Q.F. (2004). Surface Characterization of Plasma Treated Polypropylene Fiber., Materials Characterization, **52**, 231.
- Wolter M; Bornholdt S; Hackel M; and Kersten H. (2009). Atmospheric Pressure Plasma Jet for Treatment of Polymers, Journal of Achievements in Materials and Manufacturing Engineering, Vol. **37** (2).