Electrospun jets launched from polymeric bubbles

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ABSTRACT

In this paper the launching of liquid polymer jets from the apex of gas bubbles on the polyvinylpyrrolidone in ethanol (PVP) solution surface due to an applied electrical potential is investigated. Jets of polymer launched from bubble provide an alternative method for electrospinning polymer nanofibers that may be scalable for commercial production. Bubbles were experimentally created on the surface of a polymer solution by forcing air through a syringe into the polymer solution. An electric potential was applied to the solution to launch the jets. The polymer solution concentration was varied to determine the optimum concentration. The semi-angle of the apex of bubble just prior to jet launch was observed to be close to the theoretical value of 49.3 degrees for a pendant drop.

INTRODUCTION

The launch of liquid jets from the apex of the curved films of soap has been reported [1]. The jets launch from soap bubbles when the bubbles are charged in an electric field strong enough to overcome interfacial forces. This same approach can be applied to launch liquid jets from the apex of the polymeric bubbles.

Jets of polymer solution are known to launch from electrically charged pendant drops to form nanofibers. This process is known as electrospinning [2,3,4,5]. In this work jets launched from gas bubbles on the surface of a polymer solution are compared to those launched from pendant drops.

EXPERIMENTAL APPROACH

Polyvinylpyrrolidone (PVP) from Sigma Aldrich with molecular weight of 1,300,000 was used as the polymer. The solution was prepared by stirring the PVP for 6 hours with ethanol to make solutions of 5%, 10%, 12%, 15%, and 18% by mass. The PVP solution was placed in a small Petri dish. A copper wire electrode was submerged into the polymer with one end hung over the rim of the dish to connect by a wire to the power supply. A stainless steel wire mesh of 1 mm wires and 3mm x 3mm square openings was used as the grounded collector. The collector was placed 10 cm above the polymer surface as shown in *Figure 1*.

FIGURE 1. Experimental set up

Bubbles were created by injecting air into polymer solution. The tip of a 22 gauge metal needle on a 5cc syringe (RYVMED Medical Products) filled with air was submerged about 5 mm under the surface of the polymer solution. The air inside of the syringe was slowly injected into the polymer solution to form a single gas bubble that rose to the surface of the solution. The volume of air injected was varied to create bubbles of desired diameters.

The polymer solution was positively charged relative to the collector by applying a voltage potential between the wire electrode in the dish and the collector. The electric potential difference between the wire and collector was adjusted until a liquid jet launched from the apex of the bubble. Electric potentials for launching liquid jets were measured for several bubble diameters and polymer concentrations. The jets launched from the apex of the bubbles were recorded with a high frame rate camera (*Figure 2*). Polymer viscosity and polymer surface tension were measured at different polymer concentration by a Brookfield viscometer and drop weight technique. Experimental data are listed in *Table 1*.

TABLE 1. Average electric field strength (kV/m) required to launch liquid jet form the apex of polymeric bubble at different bubble diameter (cm) with polymer viscosity (cP) and polymer surface tension (dyne/cm).

Bubble Diameter (cm)	Concentration (%wt)				
	5.0	10.0	12.0	15.0	18.0
0.45	549.12	492.93	482.23	496.76	506.64
0.50	521.71	470.00	447.50	471.22	492.29
0.55	512.28	465.00	415.71	445.67	477.95
0.60	447.37	435.63	373.33	426.67	463.60
0.65	442.11	426.25	346.25	421.67	449.26
0.70	442.11	390.00	309.17	333.33	449.00
0.75	401.90	387.00	274.56	330.00	425.83
0.80	377.93	367.50	239.94	310.83	385.00
0.85	353.97	347.47	205.33	315.00	380.00
0.90	330.00	329.29	170.72	266.84	377.00
0.95	306.04	311.10	136.10	241.29	373.75
1.00	282.07	292.92	101.49	215.74	352.50
Viscosity (cP)	59.65	220.65	372.32	816.12	1788.90
Surface Tension (dyne/cm)	21.79	21.97	22.25	23.42	26.99

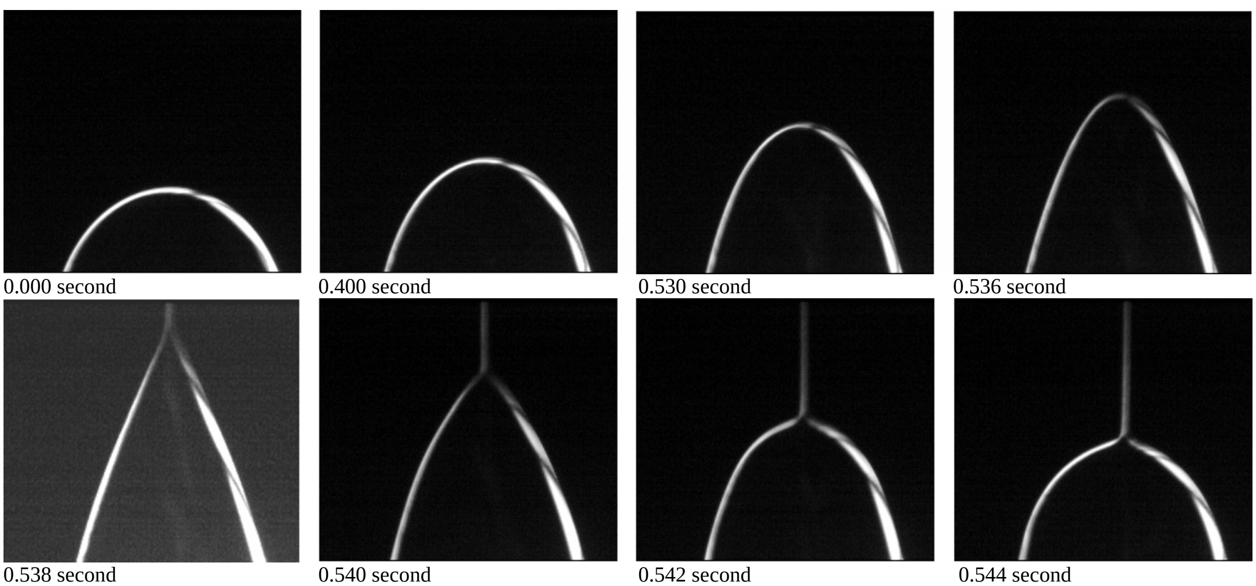

FIGURE 2. Images from a high frame rate camera showing the launch of a liquid jet from the apex of a polymeric bubble. The image was adjusted make the jet more visible. Time zero was taken to be the frame that electrical potential was applied to the PVP solution. These images were taken at speed of 500 frames per second.

RESULTS AND DISCUSSION

Similarities occur between the launch of jets from bubbles and from pendant drops. One of the similarities is the formation of a Taylor cone. The series of images from a high frame rate camera in *Figure 2* show the bubble shape deforms just prior to and after the launch of a jet from the apex of the bubble. The apex is located at the upper most point of a symmetric bubble on a horizontal flat film. The conical shape of the bubble is similar to the shape deformation that occurs to pendant drops from Ref [6] (shown in *Figure 3*). The bubble deformations are also similar to the deformations of soap and water bubbles in electric fields [1,7]. The theoretical semi-vertical angle is 49.3 degrees for the launch of jets from a stable conical shaped liquid drop within an electric field [2,8]. The apex of the conical shape has greatest charge density in the drop and this is location where the electrical forces can exceed the interfacial forces and hence is location where most liquid jets launch [9]. Similarly, a bubble changes shape due to the influence of an external applied electric field [1,10]. The shape of the bubble elongates in the direction of the electric field due to vertical component of the electric stress from the electric field and grows as a spheroid due to horizontal and vertical component of electric stresses [10].

Shown in *Figure 4*, the semi-angle of the bubble just prior to the liquid jet launch from the apex is approximately 46 degrees. *Figure 3* shows images of the deformation of a pendant drop of polyethylene oxide due to an applied electrical field. The polymer solution was placed in a spoon with a hole at the bottom and hydrostatic forces pushed the polymer solution through the hole at the bottom to form the pendant drop. The drop hung from the hole and maintained its shape by surface tension force. The shape of the drop changed into the conical shape due to the electrical potential. The tip of the polymer became sharper and liquid jet launched from the apex of the drop when electrical force overcame the interfacial forces. After the liquid jet launched from the apex of the drop, the shape of the drop became more spherical again.

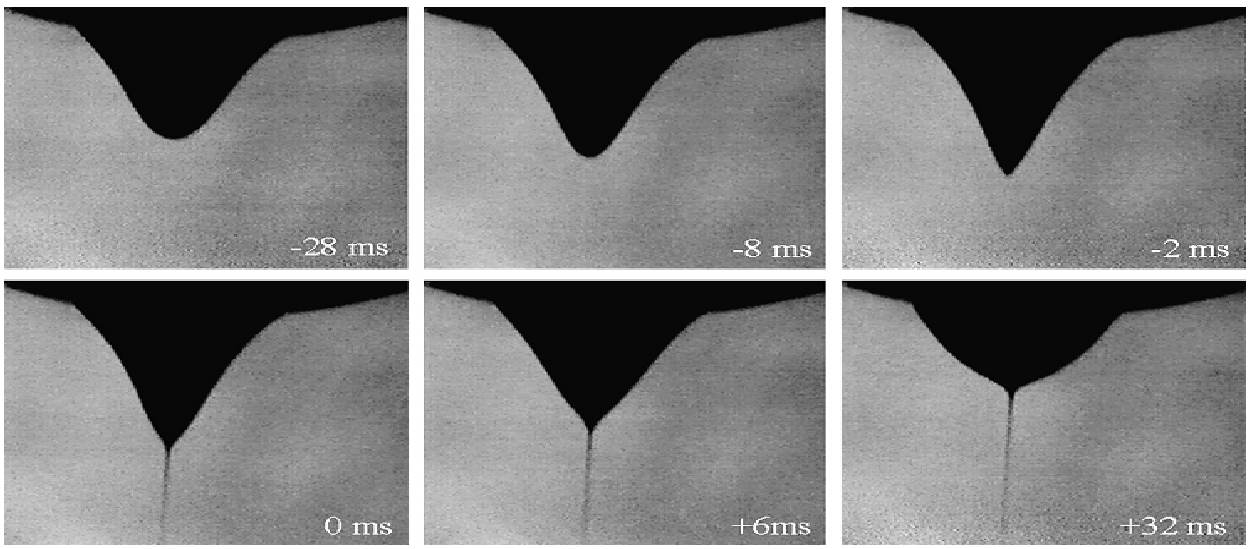

FIGURE 3. Image sequence from high frame rate camera of electrified pendant drop. The time zero was taken to be the frame in which the jet first appeared from the polyethylene oxide droplet. Experimental conditions are described in reference [6]. Reprinted by permission from Salem, David R. (Ed.), Structure Formation in Polymeric Fibers, Hanser Publications, Munich (2001).

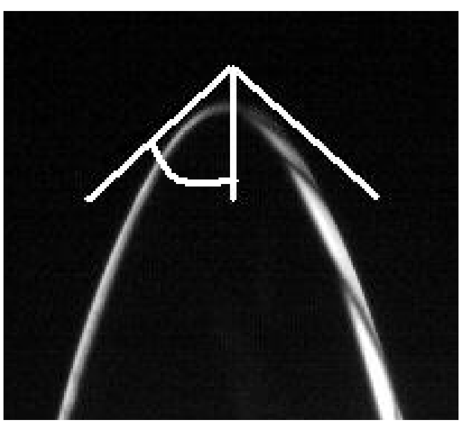

FIGURE 4. Semi-angle of polymeric bubble before liquid jet launch from the apex.

The electrical potential to launch liquid jet from the apex of the bubble or from the apex of the droplet is related to the radius of the bubble or the drop and the surface tension of liquid [7]. Taylor proposed the correlation for equilibrium of the deformed drop under the action of surface tension and an electric field to be $E\sqrt{R_0/T} = const$. In his work this constant value is approximately 1.57 – 1.65[7] where E is electric field strength in electrostatic units, R_0 is radius of bubble in m and T is surface tension in kg/s^2. For bubbles T is replaced with 2T because there is an inside and outside interface. Our results show that this quantity which we call the bubble constant ranges from 15 to 60. This value varies with the polymer properties as shown in *Figure 5*.

The bubble constant shown in *Figure 5* is decreases as the bubble size increases. The bubble constant seems to have a minimum relative to the polymer viscosity at a viscosity of about 372 cP which corresponds to a polymer concentration of 12% wt.

Figure 6 shows a plot of the electric field strength required to launch jets from the bubbles to the polymer viscosity. Similar to *Figure 5*, the required electric field decreases as the bubble size increases and a minimum occurs at a viscosity of about 372 cP.

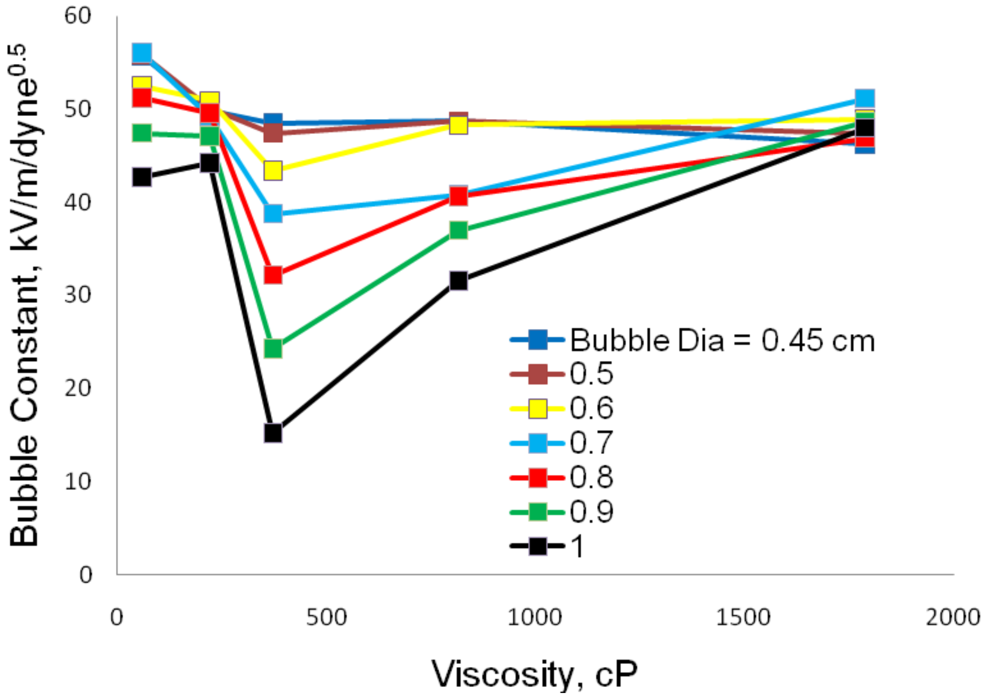

FIGURE5. Variation of Bubble Constant with Polymer Viscosity

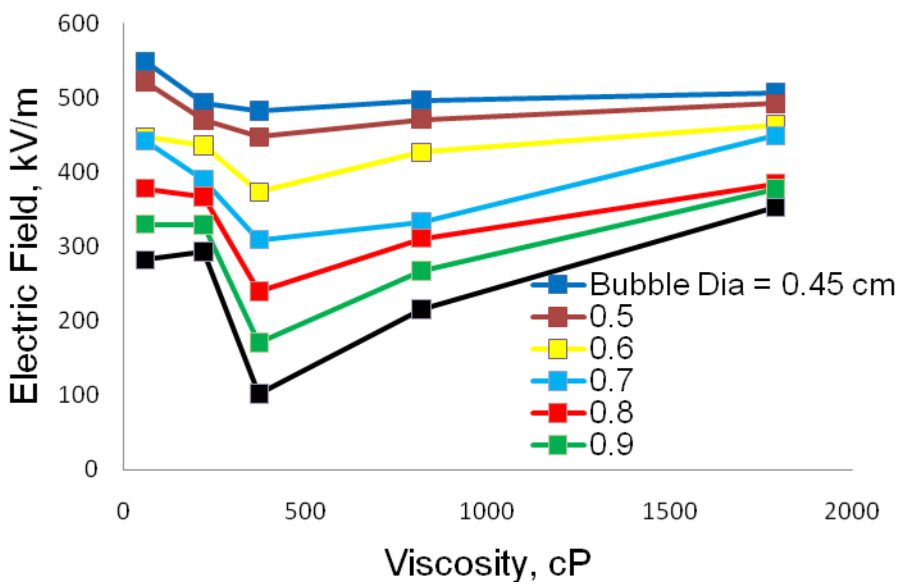

FIGURE 6. Graph plot between electric field with Bubble Diameter and Polymer Viscosity.

In *Figure 6* the electric field strength required to launch jets appears to be proportional to the bubble diameter and related in a more complicated way to the viscosity. The electric field strength is also expected to be a function of the of the polymer surface tension. Therefore, we propose to fit the electric field strength to a polynomial relation of bubble diameter, polymer viscosity and polymer surface tension.

Mathematical results show correlation cannot be fitted by dimensionless analysis developed from [7]. By some trial and error the best polynomial fit is

$$E_c = -12610 + 11057 d_b - 0.704\mu + 764\,\sigma$$

$$-24192 d_b^2 - 11.1\sigma^2 + 22104 d_b^3 - 7279 d_b^4 \qquad (1)$$

where the bubble diameter d_b is in cm the viscosity μ is in cP, the surface tension σ is in dyne/cm and the potential E_c is in kV/m. Here, R^2= 0.893 showing a reasonable fitting of the experimental data.

CONCLUSION

Air bubbles in polymer solution change to conical shape similar to pendular drops when exposed to applied electric fields. When the electric potential applied to a bubble exceeds a critical value, a liquid jet launches from the apex of the bubble. The required field strength to launch the jets has been investigated as a function of bubble diameter, viscosity, surface tension. Other parameters such as conductivity and polymer type will be investigated in future work.

ACKNOWLEDGEMENT

This work supported by the Coalescence Filtration Nanomaterials Consortium: Ahlstrom Paper Group, Donaldson Company, Cummins Filtration, Hollingsworth and Vose, and Parker Hannifin. This work was also supported by the National Science Foundation grant number DMI 0403835.

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