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EFFECT OF TEMPERATURE ON SURFACE TENSION OF A BUBBLE AND HIERARCHICAL RUPTURED BUBBLES FOR NANOFIBER FABRICATION

by

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Short paper
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Polymer bubbles can be used to fabrication of nanofibers using the bubble electrospinning. Temperature is one of the most effective parameters to control the spinning process. Suitable choice of inner and outer temperatures results in a minimal surface tension. A bubble under electronic field will be broken to form daughter bubble cascades, which can be used for nanofiber fabrication.

Key words: *bubble, surface tension, bubble electrospinning, nanofiber*

Introduction

Electrospinning is the simplest way to producing ultrafine fibers with diameters ranging from 10 μm down to 10 nm by forcing a viscous polymer solution or melt through a spinnerette with an electric field [1, 2]. When the electric force overcomes its surface tension of the Taylor cone, a charged jet is formed.

The surface tension for the polymer solution can be expressed in the form [3]

$$\sigma = Ae^{-B/\eta} \tag{1}$$

where σ is the surface tension, η – the viscosity, and A and B are constants. According to Mark-Houwink formulation [4, 5], a higher molecular weight of a solution yields a higher viscosity:

$$\eta \propto M_\mathrm{w}^{\alpha} \tag{2}$$

where M_w is the molecular weight, and α – the scaling exponent; the value of α lies between 1/3 and 1.

When the molecular weight/viscosity increases to a threshold, the polymer solution becomes coagulated, and can not be used for fabrication of ultrafine fibers by the classical electrospinning [6]. To overcome the problem, few technologies were appeared, among which the vibraition-electrospinning [6] and the bubble-electrospinning [7-10] have been caught much attention.

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Bubble-electrospinning

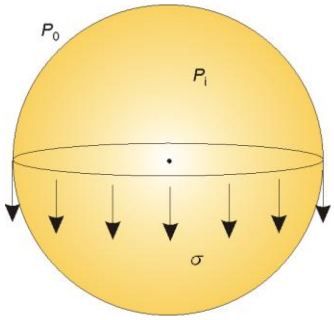

Figure 1.

The bubble electrospping [7-10] is to use an electronic field to overcome the surface tension of a polymer bubble. It is interesting to be noted that the surface tension of a bubble does not depend upon solution properties but its size and temperature. Consider a bubble made by a polymer solution, and assume that the air pressures inside and outside the bubble are respectively P_i and P_0, its radius is r (fig. 1).

According to the force balance, we have the following equation:

$$2 \cdot 2\pi r\sigma = \pi r^2 (P_i - P_0) \tag{3}$$

The surface tension of a bubble can be expressed in the form:

$$\sigma = \frac{1}{4} r (P_i - P_0) \tag{4}$$

That means the surface tension of a bubble geometrically depends upon its size. For a nanobubble, it requires a very small force to overcome the surface tension of a polymer bubble for fabrication of nanofibers. So far we produced nano-fibers with diameter of about 20 nm [11].

Effect of temperature on a bubble's surface tension

According to the station equation, the gases inside and outside of a bubble follow the relationships:

$$\frac{P_i}{\rho_i} = \mathrm{R} T_i \tag{5}$$

and

$$\frac{P_o}{\rho_o} = \mathrm{R} T_o \tag{6}$$

where R is the gas constant, T_i and T_o are the absolute temperatures inside and outside of the bubble, respectively, and ρ_i and ρ_o – the densities of the air inside and outside of the bubble, respectively.

By a simple derivation, we have:

$$\sigma = \frac{1}{4} r \mathrm{R} (T_i \rho_i - T_o \rho_o) \tag{7}$$

In case $T_i \rho_i - T_o \rho_o$ is very small, *i. e.*:

$$T_i \rho_i - T_o \rho_o \ll 1 \tag{8}$$

the surface tension of a polymer bubble becomes extremely small, any a small external force can be used to pull the bubble for fiber fabrication.

Hierarchical ruptured bubbles for nanofiber fabrication

As illustrated above when a smaller bubble has less surface tension regardless of its viscosity/molecular weight, temperature can also be used effectively to adjust the bubble's surface tension, when $T_i \rho_i - T_o \rho_o = 0$, the surface tension vanishes completely, and any a small external force can pull upwards to produce ultrafine fibers.

When an electric field is present, it induces charges into the bubble surface, these quickly relax to the bubble surface. The coupling of surface charge and the external electric field creates a tangential stress, resulting in the deformation of the bubble. Once the electric field exceeds the critical value needed to overcome the surface tension, the bubble is broken, and smaller daughter bubbles are formed around the broken bubble, see fig. 2, and sub-daughter bubbles are formed when a daughter bubble is broken due to the electronic field, the process continues until some a hierarchical ruptured bubble is pulled upwards to form a charged jet, which is then received on the metal receiver as nanofibers. This event typically occurs within milliseconds, Bird *et al.* [12] demonstrated, both experimentally and numerically, that the curved film of a ruptured bubble can fold and entrap air as it retracts. The resulting toroidal geometry of the trapped air is unstable, leading to the creation of a ring of smaller bubbles.

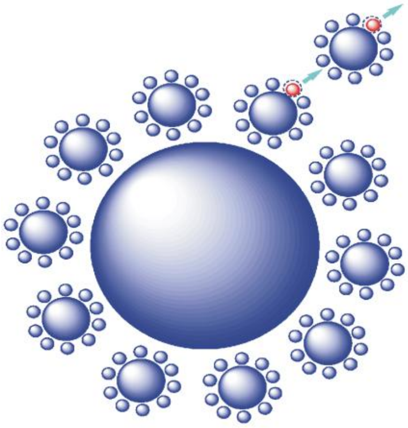

Figure 2. A broken bubble and daughter bubble cascades used for nanofiber fabrication

Conclusions

Temperature is an effective factor to adjust the surface tension of a polymer bubble, when the temperatures inside and outside of the bubble satisfy the relationship: $T_i \rho_i - T_o \rho_o = 0$, any small external force can be used to pull bubbles for ultrafine fiber fabrication. The process requires a minimal energy consumption, and the bubble-spinning offers a more challenging opportunity of mass production of nanofibers.

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