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Prediction of angular and mass distribution in meltblown polymer lay-down

S. Sinha-Ray [a], A.L. Yarin [a,*], B. Pourdeyhimi [b]

[a] Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, 842 W. Taylor St., Chicago, IL 60607-7022, USA
[b] 3427 The Nonwovens Institute, Box 8301, North Carolina State University, Raleigh, NC 27695-8301, USA

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ABSTRACT

Predictions of the properties of meltblown polymer nonwovens require knowledge of the angular fiber distribution in lay-down, as well as the deposited mass distribution. In the present work these two important characteristics are predicted using our previously developed model describing multiple three-dimensional viscoelastic polymer jets in meltblowing and their deposition onto a moving screen normal to the blowing direction. The results are important for predictions of strength of meltblown nonwovens.

1. Introduction

Meltblowing is widely used to form nonwovens in the textile industry. In meltblowing, polymer melt is supplied through a die nosepiece. After that, polymer jets are pulled vigorously by the surrounding hot gas jets with velocities comparable to the speed of sound [1,2]. Under the action of the aerodynamic forces polymer jets rapidly thin to the final diameter of the order of 3–10 μm and solidify. Recently an improved meltblowing process even resulted in submicron fibers [3]. Historically, meltblowing was triggered by the need for micro-denier fibers in filters to monitor the radiation from nuclear tests [4–6]. Even though meltblowing process is more than 50 years old and employed by the multi-billion nonwoven industry, the process is still not fully understood due to complexity of the interaction between three-dimensional polymer viscoelastic jets and turbulent non-isothermal gas jets.

The recent works of the present group contributed to the understanding of the basic mechanisms of meltblowing process and its modeling [7–9]. The role of turbulence in the surrounding gas jet was elucidated in [7]. Then, the linear and nonlinear theory of viscoelastic polymer jets in meltblowing was developed [8,9], and the first numerical predictions of nonwoven lay-down were provided [9].

The present work is based on the numerical model of [8,9], which is used to predict the mass and angular distributions in nonwoven lay-down on a moving collector screen. The paper is structured as follows. Section 2 briefly discusses the modeling approach and its physical foundations. Section 3 describes the numerical results on the angular distribution of fibers in nonwoven lay-down. Section 4 is devoted to predictions of the mass flow rate and the mass distribution over the collector screen. Section 5 deals with the effect of polymer polydispersity. Conclusions are drawn in Section 6.

2. Numerical modeling and comparison with experiment

The governing equations for modeling of meltblowing process were introduced in our previous publications [7–9]. The flow sketch is depicted in Fig. 1a. It shows that we are dealing with multiple polymer jets driven by high-speed air flow toward a collector screen moving normally to the blowing direction. The model subdivides the jet into a short straight part where the jets are still too thick to bend before they are sufficiently stretched, and the part where the aerodynamically-driven bending is quite visible. The experimental image in Fig. 1b fully corroborates such subdivision.

The model of [7–9] employs the quasi-one-dimensional equations of free liquid jets [10]. In brief, the continuity and momentum balance equations for an individual three-dimensional polymer jet in meltblowing read

* Corresponding author. Tel.: +1 312 996 3472; fax: +1 312 413 0447.
E-mail address: ayarin@uic.edu (A.L. Yarin).

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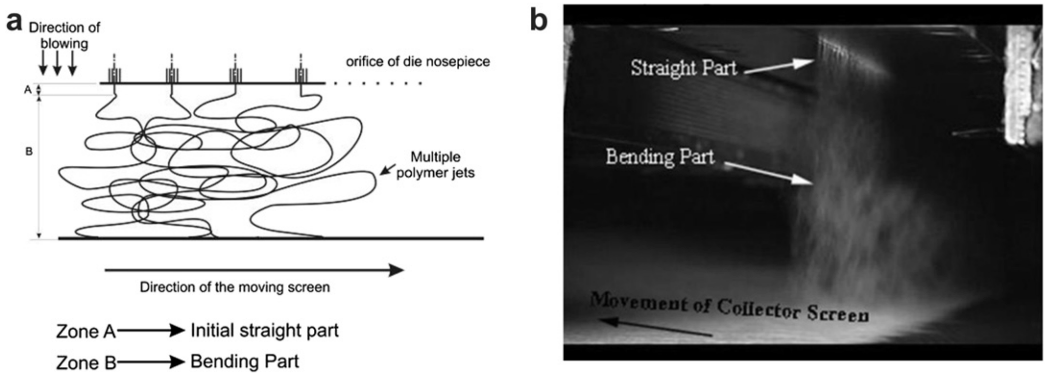

Fig. 1. (a) Schematic of the meltblowing process. (b) A snapshot of the meltblowing process captured using a high speed camera at 20,000 fps. (Courtesy of Hollingsworth & Vose).

$$\frac{\partial \lambda f}{\partial t}+\frac{\partial Wf}{\partial s}=0 \quad (1)$$

$$\frac{\partial \lambda f\mathbf{V}}{\partial t}+\frac{\partial Wf\mathbf{V}}{\partial s}=\frac{1}{\rho}\frac{\partial P\boldsymbol{\tau}}{\partial s}+\lambda\mathbf{F}f+\mathbf{q}\frac{\lambda}{\rho} \quad (2)$$

where Eq. (1) expresses the mass balance (the continuity equation), and Eq. (2) – the momentum balance. The latter equation is written in the momentless approximation, i.e. the shearing force in the jet cross-section, as well as the associated with it the moment-of-momentum equation are neglected, which is possible for sufficiently thin jets. In Eqs. (1) and (2) t is time, s is an arbitrary parameter (coordinate) reckoned along the jet axis, and $f(s,t)=\pi a^2$ is the cross-sectional area, W is the liquid velocity along the jet relative to a cross-section with a certain value of s, the stretching factor $\lambda=|\partial \boldsymbol{R}/\partial s|$, where $\mathbf{R}(s,t)$ is the position vector of the jet axis, $\mathbf{V}(s,t)$ is the absolute liquid velocity in the jet, ρ is liquid density, $P(s,t)$ is the magnitude of the longitudinal internal force of viscoelastic origin in the jet cross-section which is determined separately in the framework of the upper-convected Maxwell model. In addition, $\boldsymbol{\tau}$ is the unit tangent vector of the jet axis, $\mathbf{F}$ is the acceleration of a body force, and $\boldsymbol{q}$ is the overall aerodynamic force imposed on a unit jet length by the surrounding gas, which is calculated independently using the boundary-layer theory of the turbulent gas jet surrounding the polymer jet. Boldfaced characters denote vectors. In the case of non-isothermal melblowing, the governing equations are also supplemented with the thermal balance equation [8]. The details on the transformation of the governing Eqs. (1) and (2) for the numerical solution, and the supplementary rheological constitutive and thermal balance equations, as well as the initial and boundary conditions involved are surveyed briefly in the Appendix.

The physical mechanisms involved in meltblowing which were uncovered in [7–9] and embedded in Eqs. (1) and (2), and Eqs. (A1)–(A20) in the Appendix can be summarized as following. The sketch in Fig. 2 depicts the distributed drag and lift forces acting on a polymer jet section subjected to the surrounding gas flow from left to right. The polymer jet is prone to the bending instability facilitated by the distributed lift force associated with the basically potential flow mechanism. The viscous forces are responsible for the drag force. In addition, random forces imposed by turbulent eddies are also shown in Fig. 2.

Large turbulent eddies in the high speed gas jet with the eddy frequencies of the order of 10^3 Hz impact the polymer jet and introduce bending perturbations. However, a visible lateral excursion of polymer jet results only from multiple rapid eddy impacts, since the jet is relatively "massive" compared to the eddies. The bending amplitude resulting from the eddy bombardment is swiped by a relatively slow (with the frequencies of about 10–100 Hz) propagation of bending perturbations along the polymer jet. This propagation process is of the elastic origin (since the jet is viscoelastic) and is also accompanied by the longitudinal compression stretching waves of the elastic origin). Bending perturbations propagate along the polymer jet and reach the sections which are practically unloaded (being relatively far from the die exit). There, the severe restrictions on large amplitude bending imposed by strong stretching do not exist, and the turbulence energy stored in the bending perturbations of the viscoelastic polymer jet can be released resulting in a significant further bending/flapping. In addition, the bending perturbations are always amplified by the distributed aerodynamic lift force. Accordingly, polymer jets in meltblowing simultaneously extract kinetic energy from both mean flow of the surrounding gas jet and turbulent pulsations in it. As the polymer jet enters the region where the surrounding gas jet is already severely decelerated, self-intersection can begin, since the head elements of the polymer jet move slower than the tail ones. This can be diminished by the jet cooling and solidification. At some distance, polymer jets are deposited onto a collector screen moving normally to the blowing direction (Fig. 1).

Two representative examples of the numerical predictions of meltblowing based on Eqs. (1) and (2) [Eqs. (A1)–(A20) in the Appendix] similar to those published in more detail in our previous works [8,9] are given in Fig. 3, where the predicted pattern of

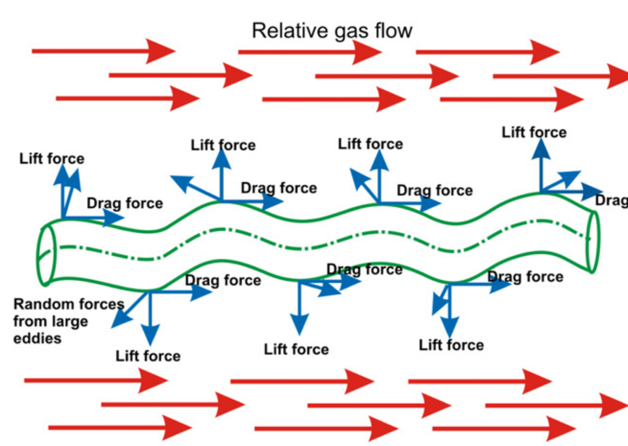

Fig. 2. Distributed forces acting on polymer jets subjected to the surrounding high speed gas flow.