Chemical Engineering Science 174 (2017) 277–284

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Stability analysis of bilayer polymer fiber spinning process

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## HIGHLIGHTS

- Stability of two-layer polymer fiber spinning flow is examined.
- The rheological stratification significantly alters the stability behavior.
- Stability diagram constructed provides guidelines to suppress the draw resonance.
- The stability of highly elastic spinning flow is enhanced by coating the fiber with less elastic polymer.

## ARTICLE INFO

*Article history:*
Received 20 April 2017
Received in revised form 11 August 2017
Accepted 30 August 2017
Available online 1 September 2017

*Keywords:*
Melt spinning
Bilayer fibers
Draw resonance
Linear stability
Entangled polymers

## ABSTRACT

The linear stability of a bilayer fiber spinning process is analyzed for axisymmetric disturbances under isothermal conditions. The co-extruded fiber consists of two concentric layers of rheologically stratified polymeric fluids. While the core fluid is an entangled polymer melt described using the eXtended Pom-Pom (XPP) model, the sheath layer is a low molecular weight unentangled polymer modeled as an Upper Convected Maxwell (UCM) fluid. The analysis indicates that, for fast extensional flows, such an arrangement enhances the critical draw ratio of the process over that found from the spinning of XPP fluid alone, thus delaying the onset of draw resonance and stabilizing the system. Further, the range of flow Deborah number for stable spinning is found to be much broader than that for the UCM fluid alone. For low to moderately elastic flows, the stability behavior is governed mainly by the rheology of the more-elastic core layer (XPP fluid), whereas for the highly elastic flows, the stability behavior is dominated by the less-elastic sheath layer (UCM fluid). The sensitivity of the stability diagram with respect to various spinning flow parameters, like the relative fraction of core and sheath layers, the rheological stratification of two fluids, and the spine-line dimensions, has also been examined in order to identify the region of enhanced stability such that the draw resonance is suppressed.



## 1. Introduction

The fiber spinning process is the most commonly employed technique to produce high strength polymeric fibers for various technological applications. In melt spinning process, the extruded polymer melt undergoes a strong extensional flow by mechanical drawing of the filament in the air-gap. The drawn fiber is then quenched in a water bath before being wound on to a rotating spool at the fiber take-up point. The extensional flow field in the air-gap region plays a major role in orienting the polymeric chains along the fiber axis before crystallization or solidification takes place, thus ensuring enhanced mechanical strength of the product fiber. The degree of extension rate is controlled by the fiber velocity at the take-up point (rotating spool) which is kept higher than the extrudate velocity (at the spinneret), with the ratio termed as the *draw ratio*. The draw ratio $DR$ characterizes the strength of the extensional flow in the air-gap. High draw ratio is desirable to produce thinner fibers with very high mechanical strength. However, when the imposed draw ratio $DR$ is higher than a certain critical value $DR_c$, the extensional spinning flow exhibits a traveling wave instability known as *draw resonance* which manifests in the form of sustained periodic oscillations in the fiber cross-section area (Christensen, 1962). The phenomenon of draw resonance in the spinning flow of a single fluid has been thoroughly studied over the years. A very good review of the earlier experimental and theoretical studies is presented by Petrie and Denn (1976). The mechanism of draw resonance is explained by Hyun (1978a) with the help of kinematic theory. The draw resonance occurs when a throughput or kinematic wave that travels along

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http://dx.doi.org/10.1016/j.ces.2017.08.029

the spin-line is faster than the fluid residence time in the air-gap. For spinning of Newtonian fluids under isothermal and creeping flow conditions, both the kinematic theory and the linear stability analysis predict the onset of draw resonance at critical draw ratio of 20.218, much in agreement with experiments (Matovich and Pearson, 1969; Pearson and Matovich, 1969; Fisher and Denn, 1975a; Fisher and Denn, 1976). It is important to note that this value of critical draw ratio for Newtonian fluid fiber spinning is irrespective of the length of air-gap or the extrudate velocity.

For polymeric fluids, the rheology becomes complex due to the entangled state of polymeric chains under deformation. Here, the deformation rate dependent extensional viscosity plays a significant role in the onset or suppression of draw resonance. Hyun (1978b), Jung and Hyun (1999) and Hyun (1999) show that for spinning of polymeric fluids, the critical draw ratio is less than the Newtonian value of 20.218 when the polymer exhibits a deformation rate thinning viscosity, while the critical draw ratio is greater than 20.218 when the polymer exhibits a deformation rate thickening viscosity. Hence, the critical draw ratio is a function of flow Deborah number, where the flow Deborah number characterizes the fluid viscoelasticity. However, the viscoelastic models used, namely the Upper Convected Maxwell (UCM) and the Phan-Thien-Tanner (PTT) models, are only an appropriate description of unentangled polymers of low molecular weight. For high-molecular-weight entangled polymers, both rate thinning and rate hardening effects are realized depending upon the flow time scale in comparison to the characteristic relaxation time for polymer chains. Moreover, since the Maxwell model exhibits divergence of the extensional viscosity at a certain Deborah number, the range of Deborah number covered in the previous studies is very limited, offering insufficient insights for high-strength fiber spinning. Therefore, the viscoelastic model that best describes the nonlinear extensional rheology of an entangled fluid under spinning conditions needs to be analyzed for the stability behavior. Recently, van der Walt et al. (2012) employed a variant of the tube model called the eXtended Pom-Pom (XPP) model (Verbeeten et al., 2001) to model the dynamics of entangled polymers and study the linear stability behavior of the spinning flow. Therefore we too adopt the XPP model that has been proven to perform well in a broad range of polymer flow conditions (Inkson et al., 1999).

Many fiber spinning studies in the past have analyzed a single phase extensional flow, however, the theoretical analyses of co-extrusion fiber spinning (multiphase extensional flow) are relatively less despite being industrially relevant. It is known that when two polymer melts with significantly stratified rheology are simultaneously co-extruded through an annular die to produce bilayered compound fibers, each material suppresses the associated drawing problems of the other. For example, branched polyethylene (b-PE) may exhibit greater stability to draw resonance than linear polyethylene (l-PE), however, b-PE is prone to rupture when stresses in melt exceed the cohesive strength. By co-spinning b-PE and l-PE, the onset of draw resonance is delayed while maintaining the spinnability (Park, 1990). Apart from the advantage of better spinnability, composite fibers may also be required for further downstream applications (Zhang et al., 2015). Lee and Park (1994) show that when LLDPE and LDPE are spun together, the presence of the more viscoelastic LDPE layer delayed the onset of draw resonance of the LLDPE to a higher draw ratio, and that the delay is dependent on the rheological properties of the LDPE. Certain studies also investigate structure formation and crystallization in bilayer fiber spinning that may arise due to the energy loss along the spin-line (Kikutani et al., 1996; Radhakrishnan et al., 1997; Blanco-Rodríguez and Ramos, 2011). The structure formation especially due to flow-induced-crystallization may lead to higher degree of orientation resulting in enhanced stability, however it is beyond the scope of current studies. The current analysis considers the extensional flow to occur in a short isothermal air-gap with an instantaneous solidification in a quench bath. Park (1990) and Lee and Park (1995) study the stability of bilayer fiber spinning with a Newtonian core and a UCM fluid sheath layer. The authors find that the maximum attainable draw ratio of UCM fluid increases and the critical draw ratio is higher than those obtained by spinning of individual materials. Ji et al. (1996b) and Ji et al. (1996a) too had made a similar inference, using a Newtonian/PTT fluid in a respective core/sheath setup. Suman and Tandon (2010) investigated the tri-layered fiber spinning process under isothermal and non-isothermal conditions, where a power-law fluid constitutes one layer with two Newtonian layers. In this interesting approach, the authors scale the critical draw ratio depending upon the power index.

The existing studies on stability of the multi-layered fiber spinning process have not considered the rheological behavior of high and ultra-high molecular weight entangled polymers, due to the choice of constitutive equation. As stated earlier, in this analysis we employ the eXtended Pom-Pom (XPP) model for the dynamics of entangled polymers. Only recently the XPP model has been used to describe the dynamics of entangled polymers in extensional flow studies (Auhl et al., 2011; van der Walt et al., 2012; van der Walt et al., 2014; Gupta and Chokshi, 2015; Gupta et al., 2016). In the single fluid fiber spinning stability studies of van der Walt et al. (2012) and Gupta and Chokshi (2015) a neutral stability curve on a $DR_c - De$ plane is constructed to identify stable operating regime from an unstable one. However, in the elastic flow regime of interest to produce high strength fibers $(1 < De < 100)$ the process is found to be prone to destabilization (low $DR_c$ predictions), and thus in this article we also investigate bilayer fiber spinning as a method to enhance the stability in the $1 < De < 100$ regime.

## 2. Mathematical model

In a bilayered polymer fiber spinning process, a spinneret with annular dies extrudes filaments with two concentric immiscible layers. The core consists of a concentrated solution of high molecular weight entangled polymer, while the sheath consists of a dilute solution of an unentangled polymer. The analysis considers one such filament spinning line. The spin-line undergoes significant thinning aimed at orienting the polymeric chains in the flow direction to obtain a fiber with enhanced mechanical strength. The thinning of the fiber takes place in the air-gap, as shown in Fig. 1, at the end of which the fiber is quenched in a water bath and wound onto a take-up roller for further drawing under solid state. The focus of the present study is the flow of polymeric fluid through the air-gap, which is considered from the die-exit $(z = 0)$ to the take-up point $(z = L)$. The polymer chains are subjected to uni-axial extensional flow to get a thin fiber with nearly perfectly aligned polymeric chains. For polymeric flow, the viscoelastic stresses are dominant, and other forces like inertia, gravity and surface tension are negligible and are hence ignored. For simplicity, isothermal conditions are assumed. The formulation is further simplified by using the slender-body approximation, justifying the one-dimensional model. Hence, all variables, like fiber layer areas, velocity and stresses, are functions of the position along the spin-line. Further, both the layers are assumed to have the same velocity profile and do not separate from each other, and neither do they slip along the interface. Lastly, all other interface effects are negligible.

The fiber layer areas $a^c$ (core) and $a^s$ (sheath) are non-dimensionalized by $a_0$ (cross-section area at $z = 0$). The velocity $v$ is non-dimensionalized by $v_0$ (velocity at $z = L$). The mass and momentum conservation equations are