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Transient modeling of fiber spinning with filament pull-out

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ABSTRACT

Flow instabilities of wet-spun fibers in the form of draw resonance can result in radius fluctuations which impose limitations on either fiber quality or production rate. Also, at high winding velocities, if the fluid strength is sufficiently high, a filament can pull out of the capillary. Filament pull-out complicates the stability analysis of fiber spinning in the sense that the upstream boundary conditions now depend on the position in the spinneret. In addition, the filament length varies in time. Intuitively, one would expect that including filament pull-out will stabilize the spinning process since the change in filament length adjusts the spinning force to result in a process similar to spinning with a constant take-up force, which is always stable. However, from a linear stability analysis on a thin filament fiber spin model including filament pull-out, we obtained the least stable solution in a straight capillary with minimal restriction on the movement of the detachment position, see van der Walt et al. (2012) [1]. In this paper we extend the stability analysis to a fully axisymmetric transient isothermal fiber spin model including filament detachment from the capillary wall using the eXtended Pom-Pom (XPP) constitutive model. Using finite elements, we develop a numerically efficient algorithm for the dynamics of the detachment point. A comparison between the stability results of the axisymmetric and the thin filament model shows that the axisymmetric model is more stable than the thin filament pull-out model but less stable than the thin filament fixed length model for the same De (Deborah) number. We are also not able to confirm from the axisymmetric model the assumption of the force being a function of the detachment position in the thin filament model. Revisiting the integral momentum balance at the detachment point derived by Bulters and Meijer (1990) [2] we find that their force balance is not valid. There is a transient region near the detachment position from the integrated normal stress to the spinning force.

1. Introduction

Fiber spinning is an important industrial process for creating polymer fibers. It is a specialized form of extrusion that uses a spinneret to form multiple continuous filaments. Wet-spinning, considered in this paper, is the oldest type of fiber spinning process. After a polymeric fluid is pushed through a spinneret die, the extrudate is taken up downstream at a pre-determined velocity and cooled in e.g. a water bath to form a filament. The take-up velocity is much higher than the extrusion velocity. Hence, the filament is stretched considerably in length and therefore it decreases in diameter. This drawing pulls the molecular chains together and orients them along the fiber axis, resulting in stronger filaments. However, a periodic variation in filament diameter or thickness can occur beyond a critical draw ratio DR, the ratio between the average extrusion and take-up velocity. This fluctuation is a flow instability in the form of draw resonance which imposes limitations on the production rate.

The issue of draw resonance has been frequently addressed in literature and mathematical models exist to describe the unwanted instability of diameter fluctuations [3–10]. Draw resonance is a hydrodynamic instability and its onset can be predicted by employing a linear stability analysis, see for example Jung et al. [11]. Determining the correct boundary conditions is not always trivial. In Schultz and Davis [12] the effect of take-up boundary conditions on the stability characteristics for a viscous dominated fiber in one-dimensional fiber spinning is discussed. According to Schultz and Davis [12] a fiber displays draw resonance instability if a constant take-up velocity condition is applied. However, this instability disappears if a constant take-up force condition is imposed. The constant take-up force boundary condition was also presented in Pearson and Matovich [4]. Renardy [13] revisited the above downstream boundary conditions for viscous flows. He

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additionally discussed the stability of prescribing the cross-sectional filament area, with the aim of maintaining uniform filament thickness at take-up, as well as controlling the drawing velocity in response to changes in the filament cross section or force.

Besides filament breakage being a common failure at high stretching forces, the filament can also pull out of the die, i.e., the filament detaches from the die wall, if the fluid strength is sufficiently high (see Sridhar and Gupta [15] and Bulters and Meijer [2]). Filament pull-out requires a fluid with high Trouton ratio (the ratio between the extensional viscosity and the shear viscosity), which is well known in isothermal solution spinning of spiders (see for example Breslauer et al. [16]) and high performance polymers and industrial wet-spinning of UHMPE solutions (see Bulters and Meijer [2]). In wet-spinning the air gap is small and the residence time short, hence the area of interest, from the detachment point to the water bath, can be considered isothermal. Fig. 1 illustrates this pull-out phenomenon.

Different boundary conditions at the spinneret die for Newtonian and viscoelastic fiber spin models have also been investigated. For example, Tsou and Bogue [14] studied the effect of die flow on the stability of isothermal melt spinning. They investigated the onset of draw resonance as a function of the stresses in the die through different inlet stress boundary conditions. However, filament pull-out complicates the stability analysis in the sense that the upstream boundary conditions are no longer constant but depend on the deformation history of the polymeric fluid in the spinning die. Moreover, the upstream boundary conditions depend on the position of the detachment point as the filament length varies in time. Intuitively one would expect that including filament pull-out will stabilize the spinning process since the change in filament length adjusts the spinning force to result in a process similar to spinning with a constant take-up force as in [4,12,13].

In van der Walt et al. [1] we performed a linear stability analysis on an thin filament isothermal fiber spinning model including filament pull-out. According to Bulters and Meijer [2], the force balance between the integrated normal stress that occurs during flow in the upstream region and the spinning force determines the position of the detachment point when the filament detaches from the spinneret wall. Towards that end we assume in van der Walt et al. [1] that the filament detachment position is a function of the spinning force. The detachment point is included into the fiber spin model by allowing the position to vary according to the prescribed slope S of the upstream integrated normal stress. We compared the stability regions of the thin filament model with pull-out, using different S values, to fiber spinning without pull-out. For $S = 0$ we obtain fiber spinning with a constant force at pull-out, but the critical DR is greatly reduced, we refer to Fig. 2. This is in contrast to fixed length fiber spinning at a constant force which is known to be stable for any DR. This brings us to the purpose of this paper. Since the thin filament pull-out model in [1] produced counterintuitive results for $S = 0$, we want to investigate spinning with a constant force further using a full transient model. We will focus on the detachment of the filament inside a sufficiently long straight capillary without the contraction part.

In this paper we present the stability results of a fully axisymmetric transient isothermal fiber spin model including filament

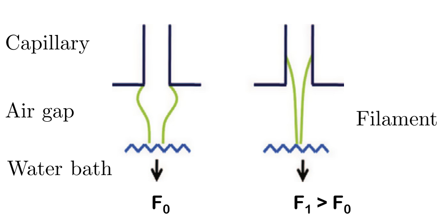

Fig. 1. Pull-out as induced by increasing the pulling force.

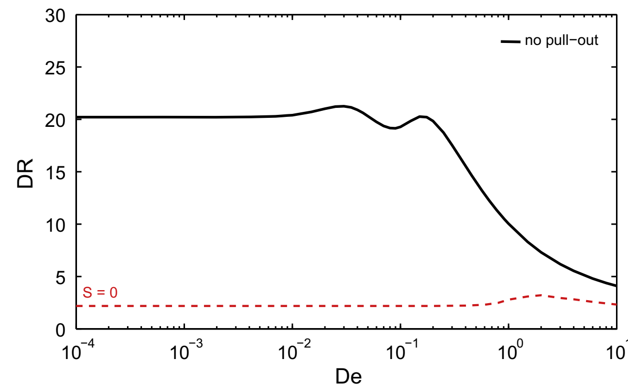

Fig. 2. Stability diagram resulting from the thin filament fiber spin model without pull-out (solid line) and with pull-out for $S = 0$ (dashed line). For a chosen line all DR and De numbers below that line are stable, correspondingly all numbers above that line are unstable. For more details see van der Walt et al. [1].

detachment from the capillary wall. In Section 2 we describe the governing equations and boundary conditions. Next, in Section 3 the dimensionless system of equations is given along with a brief comparison between the thin filament pull-out and transient model. This is followed by the numerical methods in Section 4 where the detachment algorithm is presented in Section 4.5. The results are presented in Section 5 starting by determining the stability region of the transient fiber spin model with a fixed filament length. The filament detachment results are discussed in Section 5.2 where we take a closer look at the force balance determining the detachment position as presented in Bulters and Meijer [2].

2. Problem description

In practice, the shape of the fiber spinning die consists of a contraction followed by a uniform capillary region; the detachment of the filament inside the capillary region is studied in this paper. An isothermal axisymmetric flow inside a cylindrical capillary is assumed with filament elongation along the axial direction z. The axial and radial velocities are given by $u_z(r,z,t)$ and $u_r(r,z,t)$, respectively. The free surface of the polymer filament is quantified by a varying radius function $R(z,t)$ of the axial position z and time t. The radius of the die exit is given as R_0, see Fig. 3 for the adapted filament geometry. The initial average velocity u_0 at the capillary inlet depends on the throughput Q and the die radius R_0. The capillary length is chosen sufficiently long as not to influence the downstream solution. Hence, we can expect a fully developed flow at the inlet. We further consider the initial filament detachment position to be inside the capillary where the filament has an initial length L_0. At the end of the die, the filament is taken up at a constant end velocity u_L. The draw ratio DR, a degree of filament stretching in fiber spinning, is defined as the ratio of the velocities u_L and u_0.

2.1. Governing equations

The equations of motion for an incompressible fluid, when neglecting inertia and gravity, are given by the following mass and momentum balance equations, respectively

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

$$\nabla p - \nabla \cdot \boldsymbol{\tau} = \boldsymbol{0}, \tag{2}$$

with $\boldsymbol{u}$ the velocity vector, p the pressure, and $\boldsymbol{\tau}$ the polymer extra-stress tensor. We neglect a Newtonian solvent contribution to the