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Transient solutions of dynamics in fiber spinning and film casting accompanied by flow-induced crystallization

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Abstract: In the transient solutions of fiber spinning and film casting process dynamics accompanied by spinline flow-induced crystallization was investigated incorporating flow-induced crystallization kinetics into the mathematical model of the system and then devised proper numerical schemes to generate the temporal pictures of the system. It turns out that the difficulty obtaining the transient solutions of the processes accompanied by flow-induced crystallization lies in, among these, the extremely high sensitivity of the spinline velocity towards the fluid stress level. The transient solutions thus obtained will be used for developing optimal strategies to enhance the stability and productivity of the processes.

Key words: fiber spinning; film casting; flow-induced crystallization; stability; transient solutions

1 Introduction

The dynamics of extensional deformation processes (e.g., fiber spinning, film casting and film blowing) has been studied by many research groups throughout the world during the last four decades. The stability, steady state process sensitivity, and various other aspects of the dynamics have steadily attracted researchers' interest both in academia and industry, resulting in a voluminous body of information accumulated on the process[1−2]. Especially, the interesting instability phenomenon called draw resonance, frequently observed in these processes, has been responsible for many important research results. This draw resonance instability, a Hopf bifurcation instability, is not only an academically interesting stability subject but also an industrially important productivity issue.

The transient solutions of fiber spinning and film casting process dynamics accompanied by spinline flow-induced crystallization has not been reported yet in the literature, whereas the steady state behavior has been well understood and simulated by various researchers as well as the transient behavior without crystallization.Transient simulation of the system has naturally become an important subject as steady state solutions of the process had been readily available solving a set of governing partial differential equations covering various dynamics occurring in fiber spinning and film casting. Unfortunately, however, this transient solution has turned out extremely difficult to obtain if flow-induced crystallization (FIC) is involved, while it is rather simple to obtain without it. We have thus addressed this particular problem, i.e., obtaining transient solutions when flow-induced crystallization occurs on the spinline, since it is indispensable to developing strategies for stabilization and optimization of fiber spinning and film casting process.

2 Modeling

A nonisothermal model with crystallization kinetics was used in this study to obtain transient response of the spinning and casting process (Fig.1). A phan-thien-tanner (PTT) constitutive equation, known for its robustness and accuracy in describing extensional deformation processes, was employed as a viscoelastic fluid model. An one-phase crystallization model was adopted for the spinline fluid similar to those used by other researchers like JOO et al[3], and PATEL et al[4], and the simulation for low speed condition was conducted, where the nonlinear behavior called the spinline necking was absent. The two-phase crystallization model that handled the amorphous and crystalline phases in the fluid separately and was considered suitable for simulating high speed spinning with the necking[5] was thus not employed in this study. To avoid duplication, the governing equations for the fiber spinning were only presented in this paper.

Equation of continuity:

$$\frac{\partial a}{\partial t}+\frac{\partial (av)}{\partial z}=0 \tag{1}$$

Equation of motion:

$$C_{in}\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial z}\right)=\frac{1}{a}\frac{\partial (a\tau)}{\partial z}+C_{gr}-C_{a.d.}v^{1.19}a^{-0.905} \tag{2}$$

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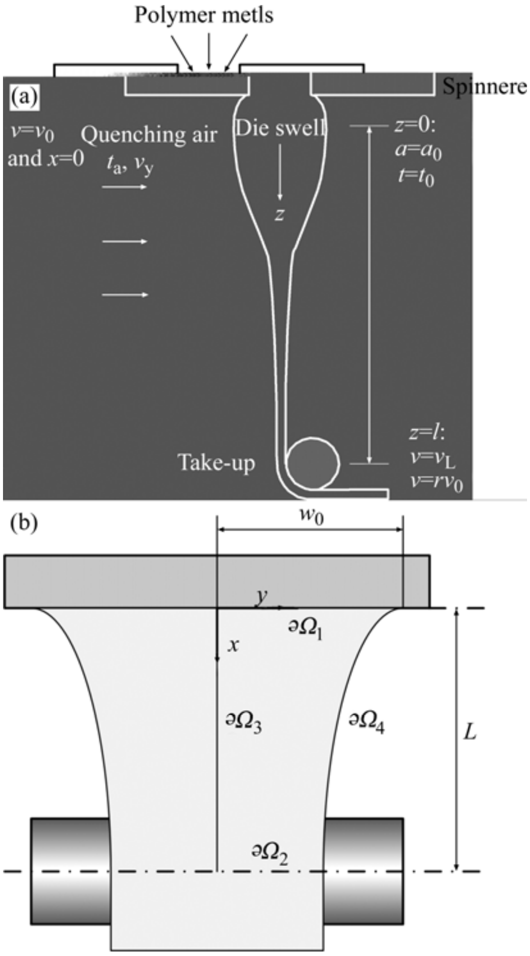

Fig.1 Schematic diagram of extensional deformation processes (a) Fiber spinning; (b) Film casting

Constitutive equation (PTT fluids):

$$K\tau + De\left[\frac{\partial \tau}{\partial t} + v\frac{\partial \tau}{\partial z} - 2(1-\xi)\tau\frac{\partial v}{\partial z}\right] = \frac{\eta}{\eta_0}\frac{\partial v}{\partial z} \tag{3}$$

where $De = De_0 \exp\left[\frac{E_0}{Rt_0}\left(\frac{1}{\theta}-1\right) + (\alpha - 3.2)x\right]$,

$$\eta = \eta_0 \exp\left[\left[\frac{E}{RT_0}\left(\frac{1}{\theta}-1\right) + \alpha x\right]\right].$$

Equation of energy:

$$\frac{\partial \theta}{\partial t} + v\frac{\partial \theta}{\partial z} = -S\lambda v^{1/3}a^{-5/6}(\theta - \theta_a)$$

$$\left[1 + 64\left(\frac{v_y}{v}\right)^2\right]^{1/6} + \Delta H_f\left(\frac{\partial x}{\partial t} + v\frac{\partial x}{\partial z}\right) \tag{4}$$

Equation of crystallinity:

$$\frac{\partial x}{\partial t} + v\frac{\partial x}{\partial z} = (1-x)\kappa_{\max}\exp\left[-4\ln 2\left(\frac{\theta-\theta_{\max}}{d}\right)^2\right] +$$

$$2\kappa\tau De_0 \tag{5}$$

Boundary conditions:

$$a_0=1,\ v_0=1,\ \theta_0=1,\ x_0=0 \text{ at } z=0 \text{ and } \lambda \geqslant 0 \tag{6a}$$

$$v_L=r \text{ at } z=1 \text{ and } \lambda=0 \tag{6b}$$

$$v_L=r(1+\delta) \text{ at } z=1 \text{ and } \lambda>0 \tag{6c}$$

In the present study, isotactic polypropylene (iPP) has been selected as an example fluid for spinning with flow-induced crystallization to be compared with experimental results in the literature. Some of the rheological properties and model parameters of iPP were selected from Ref.[6]. And the PTT model parameters for iPP resin were selected from the literature considering the nature of its extension thinning behavior[7]. The flow-induced crystallization enhancement factor (κ) that the spinline crystallinity profiles are acutely sensitive to, has taken on the value of 8.2 for iPP as determined from the experimental crystallinity data[6].

3 Results and discussion

According to the experimental results reported in Ref.[6], the flow-induced crystallization occurs for iPP resins even at low speeds in fiber spinning and film casting. The spinline profiles of many state variables then exhibit very different shapes as compared with the no-crystallization cases, with the temperature increasing quite substantially triggered by spinline crystallization and the plateau region of velocity profile after the crystallization.

The transient solutions of the two cases, with and without crystallization on the spinline, have been obtained in this study and are displayed in Fig.2, with the temporal pictures in (a) and phase trajectories in (b). Although the both cases are stable ones, the case with crystallization emerges as less stable, taking more time converging to the steady state, showing that the spinline crystallization destabilizes the iPP spinning process. Sensitivity analysis as experimentally conducted by TAKARADA et al[8] clarifies the effect of crystallization on the process stability. Under the same periodically oscillating take-up velocity condition (ω=100) as an input, the amplitude of oscillating cross-sectional area at take-up with crystallization is larger than that without crystallization case as shown in Fig.3. The origin of the stability change in the low-speed spinning process accompanied by flow-induced crystallization is due to the shorter spinline length, which can induce the drastic extensional deformation. Although the same extensional deformation is occurred at the same drawdown ratio, compared with no-crystallization cases, the feasible deformation length is shortened and the rate of deformation is highly increased because of the reduced

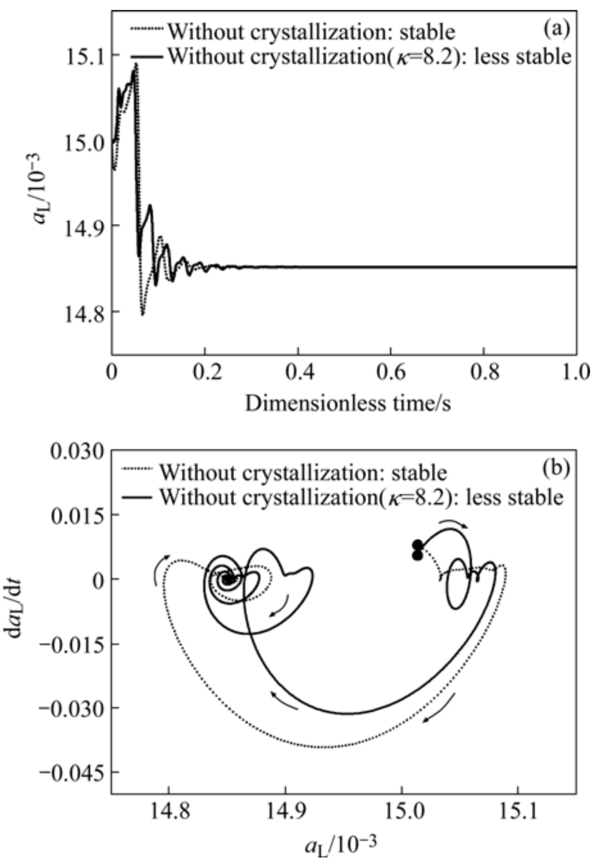

Fig.2 Transient solutions of iPP fiber spinning with and without crystallization at r=66.67, v_0=0.6 m/min, v_L=40 m/min, λ_0=0.04 s, t_a=25 ℃ and t_0=210 ℃
(a) Temporal pictures; (b) Phase trajectories

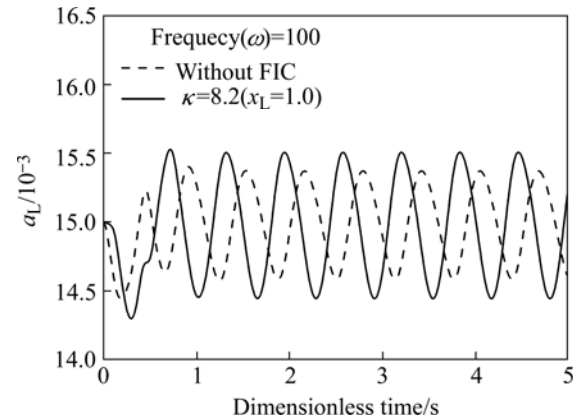

Fig.3 Temporal pictures with periodic oscillation of take-up velocity for sensitivity analysis of iPP spinning with and without crystallization under same operating conditions in Fig.2

spinline residence time. Contrary to low-speed spinning case of our study, TAKARADA et al[8] concluded that flow-induced crystallization has the stabilizing effect in high-speed spinning system, because the severe fluctuation of spinning variables near the solidification position by the crystallization has been attenuated by the further necking formation. It is noted here that stability analysis of the high-speed spinning with necking now becomes one of the challenging theoretical issues.

Once the numerical modeling of this study proves capable of producing transient solutions of the spinning with spinline crystallization, other studies about sensitivity and stability analysis for the various process materials and conditions can be easily performed as well. As Fig.4 shows, the fluid viscoelasticity or Deborah number (*De*) in this study has the destabilizing effect in iPP spinning, agreeing with the literature for extension thinning fluids[7]. Moreover, it is found that iPP spinning process is more aggravated when the crystallization kinetics is incorporated in the spinning system. The above analysis of the effect of flow-induced crystallization on spinning dynamics and stability has only been possible with the transient solutions available. These transient solutions then further make stability and the optimal strategies of the process are pursued for productivity enhancement.

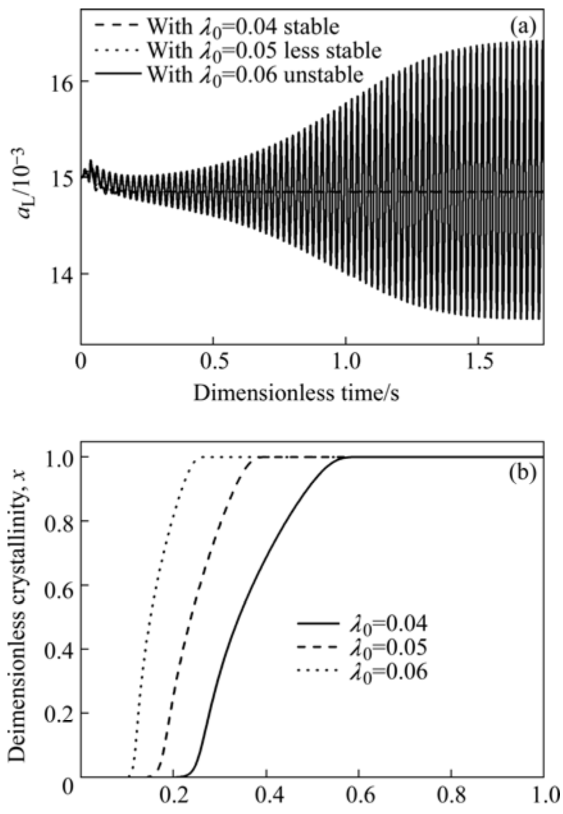

Fig.4 Transient solutions for iPP fiber spinning with different fluid relaxation times (λ_0=0.04, 0.05, and 0.06 s) at r=66.67, v_0=0.6 m/min, v_L=40 m/min, t_a=25 ℃ and t_0=210 ℃
(a)Temporal pictures;
(b) Crystallinity profiles with different fluid relaxation times

4 Summary

The transient solutions of extensional deformation processes accompanied by flow-induced crystallization have been obtained. iPP was selected as an example fluid in this simulation study to compare with literature results. With the successful transient solutions of fiber spinning and film casting process involving flow-induced crystallization on the spinline available as reported in this study, the stabilization and optimization of fiber spinning and film casting can be readily pursued using the information on the transient behavior of the process.

Acknowledgments

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