비등온 필름 캐스팅 공정의 동력학과 안정성 분석

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Dynamics and stability of nonisothermal film casting process

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Introduction

The film casting process is a high-speed process for making highly oriented film where a molten film is extruded through a slit die, rapidly stretched in the machine direction by rotation of the chill roll and cooled before reaching the chill roll. However, many kinds of process disturbances inevitably affect the productivity and uniformity of the film. The defects caused by these disturbances are typically classified into three different modes. First, draw resonance which is characterized by periodic oscillations of state variables such as film thickness, film width, and tension, arises as the drawdown ratio is increased beyond its critical value. The same phenomenon also occurs in other extensional deformation processes, e.g., fiber spinning and film blowing. Because of its academic and industrial importance as a research topic or a productivity issue, draw resonance has attracted many researchers to carry out important stability studies of the processes during the past four decades. Second, there is also the problem of the reduction of the film width, called neck-in: the width of polymeric film extruded from a flat die shrinks along the machine direction due to the strong extensional deformation effected by the pull of the chill roll. To prevent this neck-in, it is common to keep the distance between the die and chill roll as short as possible. Third, edge beads or dog-bone phenomenon also arises in the film casting process: thicker beads at the film edges than those at the center are formed. These thicker beads are cut off for the uniformity of the final film product.

In this study, the nonlinear dynamics and stability of the 2-D film casting process have been scrutinized using the up-to-date FEM numerical techniques for steady and transient computations. For the transient simulations of 2-D viscoelastic film castings with free surfaces, the Arbitrary Lagrangian Eulerian (ALE) algorithm with spine method was employed. The robust numerical schemes provide all the essential information about the dynamics and stability of the process.

Modeling

For viscoelastic Phan-Thien Tanner (PTT) fluids, the governing equations for nonisothermal 2-D film casting process are shown below based on Kim et al. (2005). Fig. 1 depicts schematic geometry and boundaries for this system.

Equation of continuity: $\frac{\partial e}{\partial t}+\nabla\cdot e\mathbf{v}=0$ (1)

Equation of motion: $\nabla\cdot e\boldsymbol{\sigma}=0$ (2)

Constitutive equation: $K\boldsymbol{\sigma}+De\left[\frac{\partial\boldsymbol{\sigma}}{\partial t}+\mathbf{v}\cdot\nabla\boldsymbol{\sigma}-\mathbf{L}\cdot\boldsymbol{\sigma}-\boldsymbol{\sigma}\cdot\mathbf{L}^{T}\right]=2\frac{De}{De_0}\mathbf{D}$ (3)

Equation of energy: $\frac{\partial\theta}{\partial t}+\mathbf{v}\cdot\nabla\theta=-h\left(\theta-\theta_a\right)$ (4)

Boundary conditions:

Inlet ($\partial\Omega 1$): $v_x=v_0$, $v_y=0$, $e=e_0$, $T=T_0$ for all t

Outlet ($\partial\Omega 2$): $v_x=v_L$, $v_y=0$ for $t=0$, $v_x=v_L(1+\delta)$, $v_y=0$ for $t>0$

Center ($\partial\Omega 3$): $\sigma_{xy}=0$ for all t

Edge ($\partial\Omega 4$): $\frac{\partial w}{\partial t}+v_x\frac{\partial w}{\partial x}=v_y$, $\boldsymbol{\sigma}\cdot\boldsymbol{n}=0$ for all t

Several assumptions are included in this model. Isotropic pressure is equal to the normal stress (τ_{zz}). Crystallization, extrudate swell and secondary forces are not considered. Material parameters and process conditions are referred to the literatures.

Results and discussion

Dynamics and stability of nonisothermal film casting process were analyzed with process parameters such as, draw ratio (Dr) and aspect ratio (Ar). Also the analysis was carried out with the material parameters such as Deborah number (De) and heat transfer coefficient (h). The effect of process conditions and material properties on the dynamics and stability of the system has been examined using steady state and transient solutions. Neck-in and edge bead phenomenon (steady state defects) have been predicted for both extension thickening (strain hardening) and extension thinning (strain softening) fluids through the steady state solutions. As aspect ratio was decreased and fluid viscoelasticity, i.e. De was increased, neck-in of film width was decreased, whereas bead ratio (ratio of edge film thickness to center film thickness) was increased. And thus the uniformity of the final film was improved. Extension thickening fluids showed more uniform thickness profile and less neck-in and small bead ratio. (Figure 2) If the cooling of the extrude film, i.e. nonisothermal condition, was considered in the simulation model, neck-in of the final film width was decreased, and uniformity of the film thickness was enhanced.

Draw resonance, typical instability mode in extensional deformation processes has been predicted in film casting process. Nonlinear stability analysis of this two dimensional model has been also carried out to scrutinize the effect of process conditions and material properties. According as the draw ratio was increased, the process became unstable. Beyond the critical draw ratio draw resonance was arisen with the periodic oscillation of film width, center film thickness and edge film thickness. Using these temporal profiles of state variables, the dynamics and stability of the process were investigated. When the fluid viscoelasticity was increased for extensional thickening fluids, the severity of the draw resonance was decreased. On the other hand, the severity was increased for the extension thinning fluids. Therefore, the process stability shows different results according to the rheological characteristics of extensional flow. Aspect ratio makes the system stable. It is considered as increased aspect ratio plays a crucial role in the cooling of stretched film. In the same manner the temporal profiles of the nonisothermal model showed more stable results. (Figure 3) These kinds of trend have a thread of connections between the two other extensional deformation processes such as film blowing and fiber spinning.

This stability analysis can readily be applied to strict process control and furnish the better understanding about film casting process with flow-induced crystallization. The same approach is applicable to other extensional deformation process like fiber spinning, film blowing, and so on.

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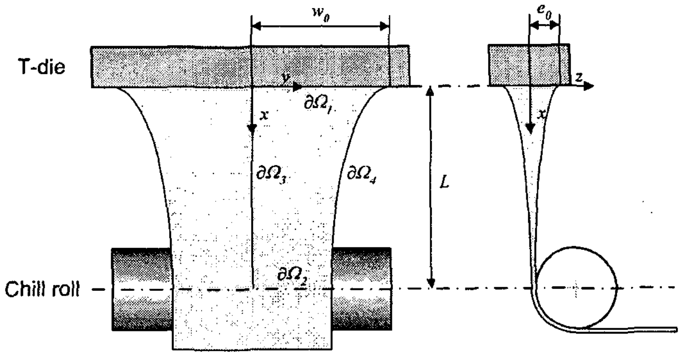
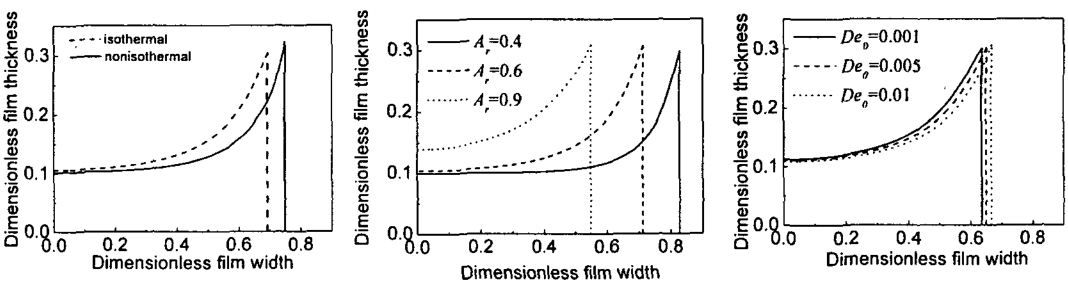


Figure 1. Schematic diagram of the film casting process.



(a) (b) (c)

Figure 2. Neck-in and edge bead instability (a) effect of cooling condition, (b) effect of aspect ratio, (c) effect of fluid viscoelasticity at Dr=10, T_0=200°C, De_0=0.01, Ar=0.6, h=0.5, ε=0.015, ξ=0.1.

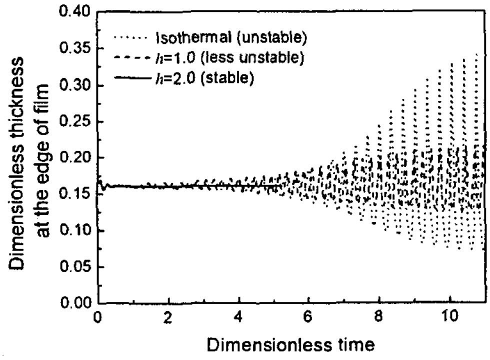


Figure 3. Draw resonance instability under nonisothermal condition at Dr=32, T_0=200°C, De_0=0.001, Ar=0.6, h=0.5, ε=0.015, ξ=0.1.