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INSTABILITIES IN EXTENSIONAL DEFORMATION POLYMER PROCESSING

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ABSTRACT

Instabilities in extensional deformation polymer processing have been reviewed focusing on the draw resonance, a Hopf bifurcation instability frequently occurring in hyperbolic systems. This draw resonance instability is usually one of the most industrially important productivity issues as well as the academically intriguing stability problem because its nonlinear dynamics is complicated and it always affects in a profound way the typical continuous polymer processing such as fiber spinning, film casting and film blowing where extensional deformation plays a dominant role in shaping and imparting desirable properties to the final polymer product. Experimental and theoretical results on draw resonance instability reported in the literature during the past four decades have been reviewed starting from the first discovery and naming as such in experimental observations, and the first theoretical modeling of each process, and then ending with pertinent recent research results. Also, the most important research topics and directions to be pursued in the future for each process are explained with highlights on several recent results that are showing crucial, relevant progress.

KEYWORDS: Coordinate transformation; draw resonance; extensional deformation; fiber spinning; film casting; film blowing; flow-induced crystallization; helical instability; nonlinear dynamics; orthogonal collocation; polymer processing; sensitivity; stability; transient solution.

1. INTRODUCTION

There are two important facets in the study of instabilities in extensional deformation polymer processing, i.e., instability related to production aspect and that to productivity aspect. As a matter of fact, this statement is germane to any engineering production process: the first production aspect pertains to the stable operation of any manufacturing with least amount of stoppage resulting in loss in production, and the second productivity aspect is concerned with the process efficiency and product quality.

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These two aspects are actually the subsets of, inseparable from, the profitability concept of manufacturing processes. The most important issue and overriding concern at the industrial scene is always the stable production of quality product at the lowest possible cost, agreeable to everybody from the CEO down to the manufacturing engineer. The same is also of paramount concern to academic researchers who constantly strive to develop better manufacturing processes through in-depth analysis of the stability and dynamics involved and the subsequent synthesis of optimal process conditions.

In this review, the instabilities in extensional deformation polymer processing, particularly the continuous polymer processing such as fiber spinning, film casting and film blowing, are reviewed with emphasis on the recent developments reported in the open literature. Two things make this review different from others on polymer processing: one is that this review deals with the processes where extensional deformation plays a dominant role in shaping and imparting desirable properties to polymer products, and the other is that the three processes mentioned here are in nature of continuous operation as compared to other batch-type processes like injection and blow molding, forming, foaming, etc.

Owing to the above two characteristics that have been chosen for this review, it is not just similar instabilities that exist in the three processes, but more importantly the same instability phenomenon actually occurs in all three processes. That is, the so-called draw resonance instability, a typical Hopf bifurcation instability frequently occurring in hyperbolic systems caused by the nonlinear interactions of the disturbance waves propagating in the flow direction of the extrudate of the process. The differences among the three processes are, on the other hand, due to what kind of extensional deformation occurs, i.e. uniaxial, planar or biaxial extension, or how many spatial dimensions are involved in modeling of governing equations, or how fast the process occurs with respect to the material characteristic times like the fluid relaxation time, or how much online orientation and crystallization can possibly occur and affect the resulting product properties, e.g., the flow-induced crystallization, and so forth.

Since the draw resonance is of such importance in both industry and academia in studying instabilities in extensional deformation polymer processes, it has been decided to organize this review with focus on draw resonance in surveying the recent reports in the literature. Also at this juncture it cannot be over emphasized that due to the immensity of the literature involved, any review can’t be complete. This review is of course no exception, and the aim here is thus to provide interested readers with a main story on the subject of draw resonance in extensional deformation polymer processing to the best knowledge of the present authors, concentrating on recent results.

Finally, brief mention about the two general topics included in the present review, i.e., polymer processing and instabilities in polymer processing, is in order. The broad topic called polymer processing encompasses a gamut of processing that is employed to produce final polymer products in many different forms like fibers, films, sheets, bottles, assorted molded parts, etc. Here it suffices listing several famous textbooks on polymer processing published in the last three decades: Middleman [1], Tadmor and Gogos [2], Pearson [3], Dealy and Wissbrun [4], Agassant et al. [5], and Baird and Collias [6].

The second topic of instabilities in polymer processing has witnessed several reviews to appear during the same period. Among those, the three most comprehensive ones are listed here: the first is the one by Petrie and Denn [7] covering many subjects related to instabilities occurring in various polymer processes. Not only draw resonance but also other instabilities like melt fracture were illustrated in this thirty-year old review, and so were in another comprehensive review of instabilities in viscoelastic flows by Larson [8, 9] and in a new book on the same subject edited by Hatzikiriakos and Migler [10] with chapters written on different sub-areas by various authors.

Although there have been many reviews on both polymer processing and instabilities in polymer processing, it has been decided in this review to mention only those enumerated in the above because they are by far the most encompassing in their treatment of the subjects. (The remarks made by Petrie [11] in 1980's on the stability of extensional flows deserve credit for being timely and most relevant.) Figures 1, 2 and 3 show schematic diagrams for fiber spinning, film casting and film blowing.

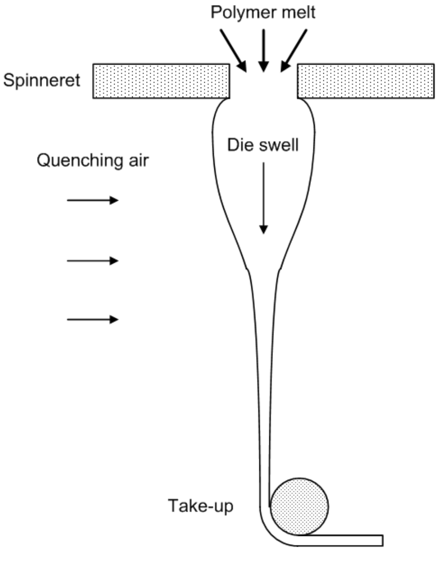

Figure 1: Schematic diagram of fiber spinning.

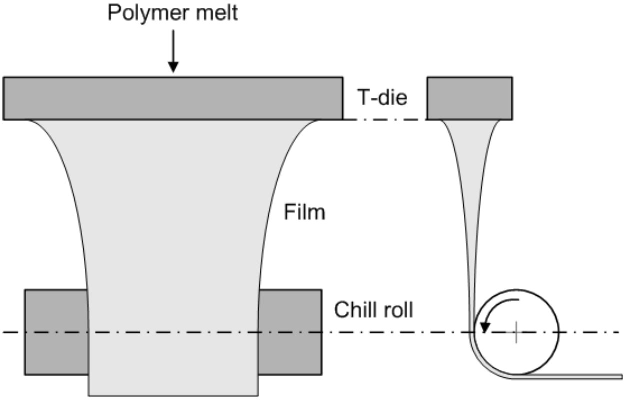

Figure 2: Schematic diagram of film casting.

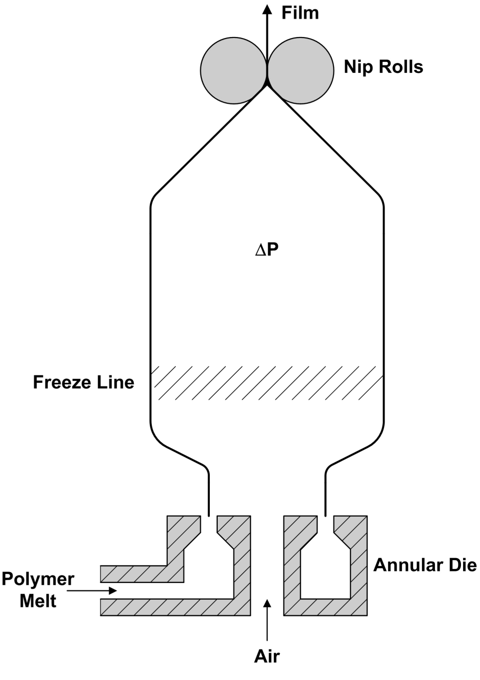

Figure 3: Schematic diagram of film blowing.

2. INSTABILITIES IN THE FIBER SPINNING PROCESS

2.1 Introduction

Although draw resonance was originally discovered in the 1960's in the film casting process [12, 13], fiber spinning quickly took the center stage in the research of the subject in both experiment and theoretical analysis. This was simply because fiber spinning was easier to model and analyze than film casting or film blowing due to its nature of uniaxial extensional deformation, i.e., one-dimensional model, as opposed to two-dimensional extensional deformation in the other two processing. Also, draw resonance occurring in the cross-sectional area of the spinline in fiber spinning is much easier to observe than that occurring in the film thickness in film casting or film blowing. (Draw resonance occurring in the bubble radius in film blowing is also easily observable but with more complicated dynamics involved.)

In this review, melt spinning is the area we concentrate on, neglecting the other two spinning methods, i.e., wet spinning and dry spinning, for two reasons. First, the tonnage of fibers produced by melt spinning, i.e., nylon, polyester and polyolefin, is by far larger than the other two combined, and secondly the dynamics of the other two processes is not much different from that of melt spinning. Actually, the literature on spinning has been predominantly on melt spinning so that melt spinning and fiber spinning have been almost interchangeably used in industry and academia for long time unless otherwise specified.

After draw resonance was first discovered and named as such in the 1960's, a series of excellent research papers began rolling out of the several academic research centers around the world, laying the foundation for many subsequent research efforts in both experiments and theory. Among those early research results it can be said that two stood out as the first of its kind in their respective areas: one in modeling of spinning process and the other in stability analysis of spinning, i.e., Kase and Matsuo [14] for the former and Pearson and Matovich [15] for the latter. Although the pioneer for fiber spinning study was Ziabicki [16,17] opening the whole realm for systematic analysis of its dynamics and stability, Kase and Matuso showed the first simulation results for fiber spinning using dynamic governing equations of the system which included a useful empirical expression for spinline cooling obtained from careful experiments while Pearson and Matovich was the first to demonstrate that the draw resonance instability can be easily derived theoretically using the linear stability analysis technique.

Before moving to the historical reviews on the subject, the list of general reviews on fiber spinning during the last several decades is provided here: Ziabicki [17], Middleman [1], Petrie [18], Denn [19, 20], Tadmor and Gogos [2], Pearson and Richardson [21], Pearson [3], Tanner [22], Ziabicki and Kawai [23], Mewis and Petrie [24], Baird [6], Jung and Hyun [25], etc. have provided the various facets of spinning process including the stability issue in their summarizing writings. Now we move to the historical reviews on the subject starting with experimental results and then theoretical.

2.2 Historical Reviews

2.2.1 Experimental Results

Ever since the first discovery of draw resonance and its naming by Christensen [12] and Miller [13], there was one noteworthy paper by Bergozoni and DiCresce [26] in 1960's and then a steady stream of research results reported on the experimental aspect of draw resonance instability in the 1970's, spearheaded by the first stability analysis by Pearson and Matovich [15]. Weinberger's group [27, 28] apparently was the first to explicitly determine the critical draw ratios triggering the draw resonance instability in isothermal spinning of both Newtonian and Non-Newtonian fluids (around 20 was the critical value for Newtonian fluids). Kase's group [e.g., 29-31] also produced a series of papers reporting the draw resonance in spinning of polymer melts of polyamides and polyesters.

The University of Tennessee group of Bogue [32-34], White [35-43], and Spruiell [39, 44] (White at Akron later on) were the most productive ones pursuing both experimental and theoretical research on the subject to obtain many useful results through thorough analysis. Then there was the University of Delaware group with Denn and others [45-51] providing results mostly of a theoretical nature. During the 1970's, there were of course other groups around the world [52-58] studying the subject, but they also pursued largely the theoretical aspect. The period between the 1980's, and 2000's has seen less research effort on the subject with several exceptions where experimental data were published [59-65]. Among the most notable are Bechtel et al [62], with the careful measurements of spinline diameter discerning the occurrence of the instability, and Cakmak et al [43, 63], Haberkorn et al. [64] and Kolb et al. [65] with online X-ray measurements of the spinline crystalline structure.

2.2.2 Theoretical Results

Unlike the experimental results explained above, there was no paucity of results on the theoretical side of the subject throughout the last forty years. As a matter of fact, since the seminal work by Pearson and coworkers in the 1960's, there have been a continuous research effort by leading researchers to delve into the matter employing various mathematical, theoretical and numerical means. The first such effort was made by those who applied the linear stability analysis to reveal the critical value for the draw ratio triggering the onset of draw resonance instability. After Gelder [66] first solved a simple eigenvalue problem to produce theoretically the critical draw ratio for isothermal spinning of Newtonian fluids, Denn and his coworkers [45-51] launched a systematic approach to the general problem involving viscoelastic fluids with and without nonisothermal conditions to yield valuable stability results.

Along the line of linear stability analysis, other researchers also published their results on the subject: an enumeration list includes Beris et al. [67, 68], Bechtel et al. [69-75], White et al. [35-37, 40], Kase et al. [76], Hyun et al. [77-81], Shultz et al. [82-84], Lee and Park [85, 86], Hout [87], Renardy [88, 89], and Geyling and Homsy [90], etc. Meanwhile, the approaches based on the nonlinear dynamics of the system, such as nonlinear stability analysis [e.g., 82], transient dynamic solutions [e.g., 29-31, 78,

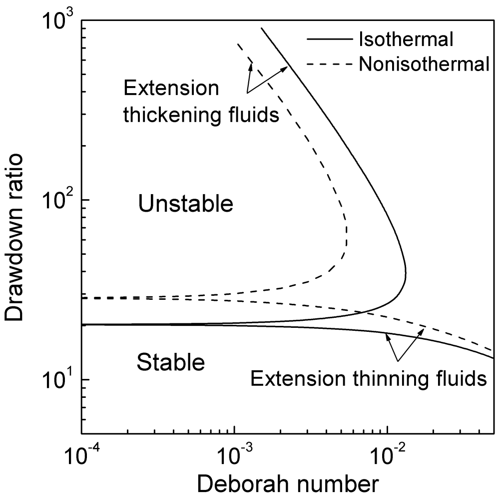

Figure 4: Stability diagram of viscoelastic fluids spinning in both isothermal and nonisothermal cases. (Lee et al. [103])

79, 91-100], sensitivity analysis [e.g., 48, 76, 95, 96, 98, 101-103], perturbation analysis [e.g., 15, 55-58, 69], etc. have also begun to appear in the literature with worthy results. Although the general books dealing with various aspects of stability in dynamic systems are a legion, a few books also useful for studying draw resonance instability include Denn [104], Drazin and Reid [105], Chandrasekhar [106], and Gray and Scott [107]. Figure 4 shows an example of the stability diagram of viscoelastic fluids spinning: draw ratio plotted against Deborah number in both isothermal and non-isothermal cases.

In the 1990's, other important topics as related to the same draw resonance instability also emerged, e.g., flow-induced crystallization (e.g., Doufas and McHugh [108-114] and neck-like deformation (e.g., Kikutani et al. [115-117], Zahoroski [118,119], Ziabicki et al. [120]) occurring on the spinline at high spinning speeds [121], multi-component spinning (e.g., Lee and Park [85, 86]), two-dimensional modeling for multi-phase spinline cross-section (e.g., Doufas and McHugh [111], Joo et al. [122]), etc. The spinning stability becomes complicated when the above aspects of the dynamics are involved and much of the results are thus yet to come out from research groups around the world, which will presumably shed new light on the draw resonance instability in the complicated fiber spinning process where not only attenuation and solidification but also flow-induced crystallization and orientation occur at the same time on the spinline to cause various profound effects on the physical properties of the final fiber product.

Now, two sets of research results deserve special mention: McHugh's group's research on modeling of flow-induced crystallization occurring on the spinline [108-114], and Hyun's group's research on the nonlinear stability analysis when this flow-induced crystallization is included in the model simulation of the spinning process [81, 99, 100]. The former results are quite significant in that they constitute the first significant modeling effort on the spinline flow-induced crystallization to successfully yield very useful steady state simulation results favorably compared with experimental observations. Also the so-called neck-like deformation that was first observed on the spinline in high-speed spinning of polymer melts in 1980's [23] but not yet given a simulation prediction by a full governing model of the spinning process, has finally been theoretically reproduced by simulation without any prior assumptions made about the spinline behavior. Hyun et al. [81, 99, 100], on the other hand, for the first time derived the stability criteria for the spinning process when this flow-induced crystallization mechanism is included into the governing equations, and also the above-mentioned neck-like deformation on the spinline using a simpler one-phase crystallization model, defying the earlier belief that the two-phase crystallization model is prerequisite for the portrayal of any neck-like deformation occurring on the high-speed spinline.

Next, a brief explanation about the kinematic wave theory expounded by Hyun et al. [80, 94, 97, 98, 123] to explain the fundamental reason for the draw resonance to occur on the spinline in extensional deformation polymer processing, is in order. Historically, all the theoretical efforts to explain the draw resonance instability have been focused on the linear stability analysis method, where perturbation variations introduced into the spinline variables are inserted into the linearized governing equations to see when the leading eigenvalue of the system will have a positive real part to make the perturbation grow unchecked, i.e., becoming unstable. Despite the beauty of yielding the critical conditions for the instability of any dynamics systems, this linear stability analysis doesn't give any explanation as to why such unbounded growth occurs, or what the fundamental mechanism for instability is.

Hyun et al. [80, 94, 97, 98] studied the nonlinear transient simulation results of the system to figure out the criterion determining the onset of the draw resonance instability. They found that at the onset of draw resonance instability two characteristic times of the hyperbolic spinning system become identical to each other, while below the critical stage, i.e., stable regime, one time is larger than the other and above the critical stage, i.e., unstable regime of draw resonance, the opposite is true. The two times in question are the traveling times of two unity throughput waves from the spinneret to the take-up plus half the period of draw resonance in between and the traveling times of both maximum and minimum spinline cross-sectional area waves. This criterion was checked on fiber spinning, film casting and film blowing to establish its general validity as the condition for onset of draw resonance [97, 124, 125]. Its approximate version [124, 126] also was found quite useful to reveal ball-park numbers for the critical draw ratio at the onset of draw resonance. Figure 5 illustrates this stability criterion in Newtonian and viscoelastic spinning using the plots of those times against the draw ratio.

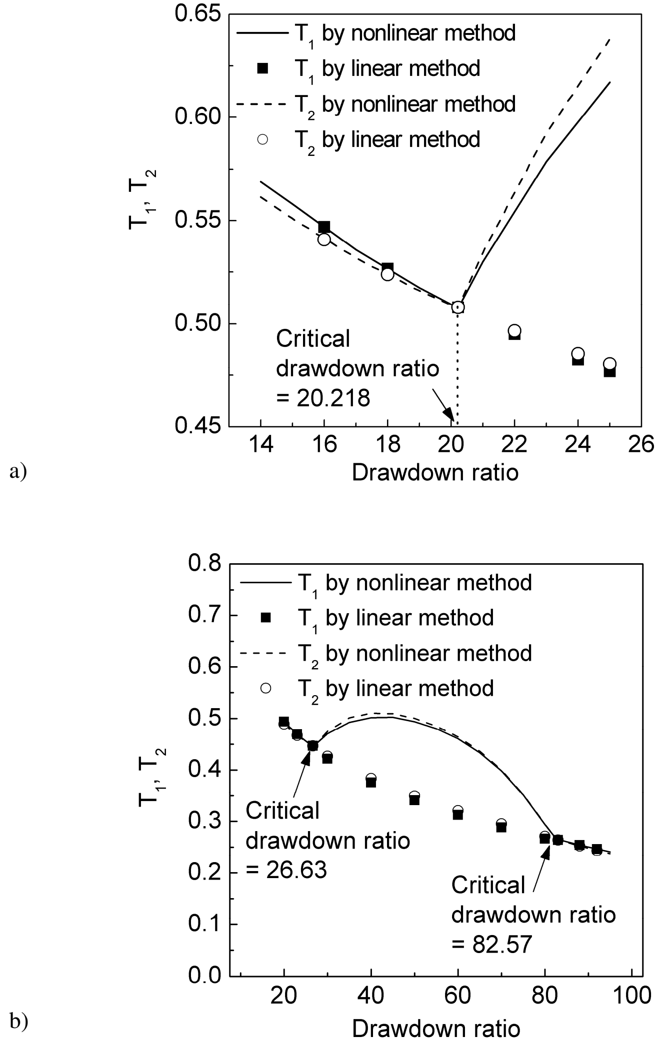

Figure 5: Stability criterion in viscoelastic fluids spinning illustrating the traveling times plotted against draw ratio for (a) Newtonian fluids and (b) PTT fluids, by both linear (symbols) and nonlinear (lines) stability analysis: T_1 = (Traveling time)$_1$ = Traveling times of two consecutive unity - throughput waves plus half draw resonance period , T_2 = (Traveling time)$_2$ = Traveling times of maximum and minimum cross-sectional area waves. (Lee et al. [80]).

Recently Hyun's group [80] reported an important paper proving the fact that the above kinematic wave theory on stability is indeed equivalent to the conventional linear stability analysis, calculating the traveling times of the various waves using the information about the eigenvalues of the linearized system and then checking the validity of the criterion. This is quite significant in that the kinematic stability criterion developed by Hyun's group and the traditional linear stability analysis contains the same information regarding the stability of the system. In other words, the kinematic wave-based stability criterion fills the gap left by the linear stability analysis, which normally doesn't shed any light on the physics or fundamentals of the instability but only provides the critical value of the parameter at the onset of the instability. It can be said that the kinematic wave theory indeed provides the physical reasons for the occurrence of the draw resonance instability in hyperbolic processes.

2.3 Recent Results on Draw Resonance Instability in Fiber Spinning

In this section of recent results on draw resonance instability in fiber spinning, instead of trying to cover the whole field, attention is given to two areas: flow-induced crystallization occurring on the spinline, and the transient solutions and their relations to the stability conditions for the process.

First, it's not new the fact that the flow-induced crystallization does occur on the spinline, but what is new, however, is that a new two-phase model treating separately amorphous and crystalline phases inside the spinline to describe the stress and the dynamics of the spinline, has been proposed and successfully implemented in the governing equations to produce results favorably compared with experimental observations including the so-called neck-like deformation occurring on the spinline. There have been many papers treating the flow-induced crystallization (formerly called strain- or stress-induced crystallization) occurring on the spinline for the past three decades in both experiments, and modeling and simulation: Ziabicki and Kawai [23], Kikutani [115-117], Patel et al. [44], Schultz [127], Kulkarni and Beris [128], etc. Then lately Doufas and McHugh [108-114], as mentioned earlier, reported a series of papers on the subject using their newly-proposed, two-phase crystallization model into the governing equations to produce good steady state results. It represents the first of its kind in incorporating two-phase crystallization model into the spinline dynamic equations, and for the first time to successfully exhibit the so-called neck-like deformation occurring on the spinline in high-speed spinning without assuming any arbitrarily assigned spinline stress conditions.

The second area on which this review focuses attention is the transient solutions of the spinning when flow-induced crystallization is included into the dynamic equations of the system. Hyun et al. [81, 99, 100] produced the transient solutions in both low- and high-speed regimes and also carried out the linear stability analysis to reveal the new stability criterion for the system when flow-induced crystallization accompanies the usual attenuation and solidification of the spinline. Unlike the cases where no flow-induced crystallization is included into the dynamic equations, the spinning stability has a different criterion depending on whether the spinline crystallinity reaches its maximum possible value or not. This is because when the maximum crystallinity is reached on the spinline, the increasing spinline stress results in destabilizing the system, directly opposite to the cases with no or small crystallization where increasing stress is always stabilizing (e.g., Hyun et al. [81, 95, 96, 99, 100]). This is not because increasing the spinline stress all of a sudden becomes destabilizing when accompanied by flow-induced crystallization, but because in the cases of maximum crystallinity reached, the destabilizing effect of the shortened spinning distance available for the spinline stretching overrides the stabilizing effect of the increasing spinline stress. (Increasing the spinline stress does always stabilize the spinning regardless of the flow-induced crystallization on the spinline.) Along this line of research elaborate experimental runs will be needed to ascertain this important conclusion derived from theoretical simulation and stability analysis results.

3. INSTABILITIES IN THE FILM CASTING PROCESS

3.1 Introduction

The instabilities in film casting process are largely very similar to those in fiber spinning explained in the last section with several salient differences between them: The most obvious difference is of course due to the two-dimensional nature of extensional deformation in film casting as compared to the one-dimensional one in fiber spinning (Figure 2). Other differences include a much lower speed with thus less pronounced flow-induced crystallization in film casting, and undesirable phenomena like neck-in and edge beads only occurring in film casting mostly attributable to the two-dimensional nature of the extensional deformation in film casting. There have been several excellent textbooks dealing with various aspects of film casting process: Tadmor and Gogos [2], Pearson [3], Tanner [22], Agassant et al [5], Baird and Collias [6], Kanai and Campbell [129], Co [130], etc. The three general reviews on instabilities in polymer processing mentioned in the last section, i.e., Petrie and Denn [7], Larson [8] and Hatzikiriakos and Migler [10], are equally pertinent in this section on film casting.

3.2. Historical Reviews

3.2.1 Experimental Results

Compared to those on fiber spinning in the last section, the experimental reports on film casting are by no means voluminous, but only a few research results reported in the literature. The first research report on the film casting process was apparently the one by Dobroth and Erwin [131] that played the role of a catalyst in motivating other researchers to pursue both experimental and theoretical investigations dealing with various instabilities occurring in film casting including neck-in and edge beads. Among those the most notable is Agassant's group whose research [132-139] has dealt with not only experimental results but also theoretical analysis and modeling results. Other recent experimental results reported in the literature include draw resonance experiments on PET by Acierno et al. [140], and on LLDPE and LDPE by Co et al. [141, 142].

3.2.2 Theoretical Results

The theoretical analysis of the film casting process has been carried out by several groups, with Yeow et al. [143, 144] starting the stability analysis for the first time using simple fluids in isothermal, one-dimensional model systems assuming constant film width. Co's group [145-149] followed with more realistic viscoelastic fluids in their stability analysis and they also studied multilayer casting cases. Figure 6 shows a stability diagram by Co et al. [145] and Hyun et al. [126] illustrating the effect of fluid viscoelasticity on film casting stability.

Relaxing the above, important assumption on constant film width, new models have been tried by Agassant et al. [135-137] in the same analysis using one- and two-dimensional models with varying film width, thus allowing the neck-in phenomenon to be predicted and explained. Beaulne and Mitsoulis [150] performed the steady state analysis using the same approach. Then, Hyun et al. [79, 125, 151-153] for the fist time performed transient simulation solving this one-dimensional governing equations to yield the transient solutions which in turn allow the confirmation of the same

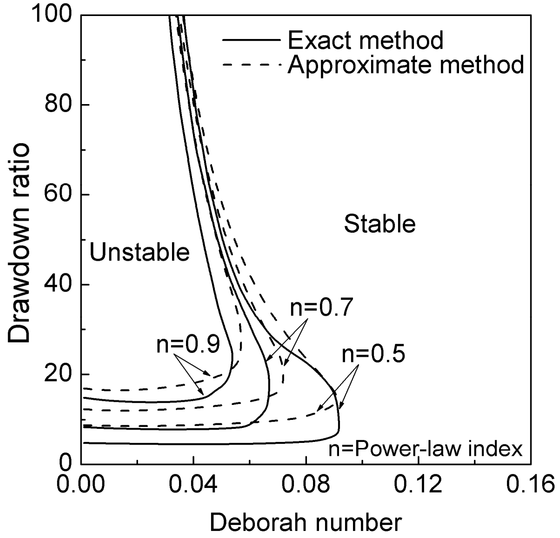

Figure 6: Stability diagram of viscoelastic film casting: neutral stability curves for a modified convected Maxwell model. (Jung et al. [126] and Anturkar and Co [145]).

kinematic wave theory first established on fiber spinning as explained in the last section, in explaining the fundamental physics for draw resonance instability in film casting.

As a natural extension of the theoretical research on film casting, a two-dimensional model has been tried by various groups in order to explain such phenomena as edge beads that have been unexplainable by one-dimensional models. Agassant's group [136, 137] introduced a two-dimensional model to obtain steady state solutions on Newtonian and viscoelastic fluids film casting. Hyun's group (Kim et al. [154]) solved the two-dimensional governing equations for viscoelastic fluids to obtain, for the first time, transient solutions of this film casting process making possible any transient behavior of the system, especially in unstable regimes. Other researchers also performed dynamics and stability analysis using two- or three-dimensional model: Alaie and Papanastasiou [155], Hatzikiriakos et al. [156], Smith and Stolle [157-159], Satoh et al. [160], Ito et al. [161], Sakaki et al. [162], Khayat et al. [163] etc.

3.3 Recent Results on Draw Resonance Instability in Film Casting

As mentioned above, the recent results on the subject can be classified into a couple of sub-areas. The first criterion for this classification is how many spatial dimensions are involved in model equations: so far predominantly one-dimensional models have been developed to be used to produce simulation results with either the constant film width assumed or varying film width assumed. But now it is noticed that more two-dimensional model equations are used for the same purpose and produce more accurate results. The second criterion is how elaborate constitutive equations are employed to portray the viscoelastic behavior of film casting process. Starting with Newtonian fluids to simple viscous fluids and finally to viscoelastic fluids, the governing equations are becoming more encompassing in exhibiting the various nonlinear viscoelastic phenomena occurring in film casting. Finally, the solutions of the governing equations are increasingly sought in the form of transient solutions as opposed to steady state solutions comprising the most previous simulations.

The results by Kim et al. [154] from Hyun's group are the first viscoelastic transient solutions for the film casting process using two-dimensional model with a viscoelastic constitutive model to portray viscoelastic films. Their model can display temporal pictures of the state variables in film casting with such nonlinear behavior as neck-in, edge beads and draw resonance instability easily analyzed varying many process parameters. Papers by Sakaki et al. [162] and by Chae et al. [164] reported steady state results using a three-dimensional model.

The next task in film casting modeling with flow-induced crystallization kinetics included in the governing equations, has been taken up recently by Lamberti and Titomanlio [165, 166] and by Barot and Rao [167] for steady state results, and by Lee et al. [168] for transient solutions.

4. INSTABILITIES IN THE FILM BLOWING PROCESS

4.1 Introduction

The last processing covered in this review, the film blowing process, is the most complicated one as compared to the other two explained so far. The reason is mainly due to the biaxial nature of the drawing performed in film blowing, i.e., the axial drawing by the nip roll rotating with the linear speed larger than the extrusion speed at the die exit, and the circumferential drawing by the air pressure inside the bubble above the outside ambient air pressure (Figure 3). While the continuity equation, the constitutive equation and the energy equation are basically the same in this film blowing process as compared with the other two processes, the equation of motion, i.e., force balance equation, in film blowing consists of two, i.e., axial force balance and circumferential force balance, as compared with axial force balance alone in fiber spinning and film casting.

On top of these two force balance equations, there are two additional complexities in film blowing process: one is caused by the fact that the machine direction and the film direction are not the same and so a non-linear term is involved in the governing equations representing the angle between these two different directions. The other complexity in setting up governing equations in film blowing pertains to the so-called freeze-line appearing on the film bubble caused by the air cooling of the film. As a consequence of these additional complexities in film blowing process as compared with the other two processes of fiber spinning and film casting, the draw resonance instability is exhibited in two conspicuous ways: one draw resonance occurs in the film thickness just like draw resonance in spinline cross sectional area for fiber spinning and in film thickness for film casting, and the other draw resonance occurs in the bubble radius. The draw resonance exhibited in the bubble radius is very easily observable in terms of its magnitude and of its period whereas that in film thickness is hardly detectable with ordinary online measurements.

Ever since the first excellent modeling was introduced by the seminal paper by Petrie and Pearson [169-170] on this film blowing, simulation has been performed by many groups [10, 129, 171-198] to produce steady state profiles of state variables like the bubble radius, film thickness, freeze-line height, and so on. However, due to the extremely complicated dynamics in the film blowing process, no one had yet been successful in obtaining transient solutions of the dynamic system until Hyun et al. [25, 79, 199] finally solved these moving-boundary partial differential equations of the film blowing system to obtain transient solutions, employing various mathematical and numerical ideas including the orthogonal collocation on finite elements on the machine-direction spatial coordinate, a coordinate transformation to covert the free-boundary-value problem into the fixed-boundary-value problems, etc. The temporal pictures thus generated by the transient solutions turn out to closely resemble those experimentally observed on LDPE and HDPE film blowing in terms of the radius of the bubble and the period of the draw resonance oscillation.

Other than the draw resonance instability mentioned above, there is another famous instability that is uniquely characteristic of film blowing, so-called the helical instability, which manifests itself when the blow-up-ratio (BUR) of the bubble takes on a larger value. Two salient points are the trademarks of this helical instability: the bubble is not axi-symmetrical any more but off-center and rotates with another period different from that of draw resonance oscillation. As of today, there is no model yet capable of describing the system in helical instability regimes, which obviously presents itself to all researchers in this field as the most challenging problem for simulation and analysis.

4.2 Historical Reviews

4.2.1 Experimental Results

The reports on film blowing in the open literature have been on the rise in recent years thanks to the stepped-up efforts by several groups to continue ongoing fundamental research into both experimental and theoretical aspects of the process. Ever since the first publication on the subject by Alfrey [200], there have been many significant results during four decades [201-237], i.e., Han et al. [201-206], White et al. [42, 207-211, 230], Fleissner [212], Campbell et al. [222], Rutgers et al. [225, 232] etc. Recently, the Ecole Polytechnique Montreal group of Carreau and Lafleur has led in reporting important results based on their carefully designed experiments [213-221].

4.2.2 Theoretical Results

The theoretical research reports on film blowing have their origin in the seminal work by Petrie and Pearson [169, 170] where the foundation for the modeling work was laid for all the ensuing simulation efforts by researchers in the last 35 years. Adopting the material coordinates to derive the strain rate tensor for this extensional deformation-dominated process and setting up two force balances on two separate drawings of the film, i.e., axial and circumferential drawings (biaxial deformation), the governing equations were well-poised to readily yield the steady state solutions of the system. Actually, these steady state profiles of the film, mostly the bubble radius profiles, have been the mainstay of the simulation programs developed by researchers in the past 35 years.

During the last three decades, much research effort has been expended to produce valuable theoretical results using various variants of the governing equations. The following shows part of those research results complied. In the 1970's, Middleman [1], Han [202], and Yeow [238] contributed to the theoretical results through their modeling and stability analysis. In the 1980's, various aspects of the theoretical analysis of the system like multiplicity and stability of steady states, and different constitutive equations were investigated by several groups: Gupta et al. [174], Cao and Campbell [178-180], Cain and Denn [239], etc. The paper by Cain and Denn constitutes the first effort to delve into the stability, multiplicity issues of the film blowing system to come up with valuable results through a systematic analysis.

In the 1990's, more theoretical results were reported in the literature by various research groups: Papanastasiou et al. [240] using the integral constitutive equation of BKZ model, Campbell et al. [181] with a plastic model handling differently fluids below and above the freezeline, Liu et al. [184] adopting the quasi-cylindrical model for the bubble, Vlachopoulos and Sidiropoulos [186-189] and Akaike et al. [241] on the cooling effect on the film, Andre et al. [176, 177] on moving freezelines, Yoon and Park [242-243] on coextrusion stability of the multilayer film blowing, Housiadas and Tsamopoulos [244-246] on unsteady flow of annular film, etc.

As mentioned in the introduction, in 2004 Hyun et al. [199] for the first time solved the dynamic equations in the form of partial differential equations with moving boundary conditions to successfully produce the transient solutions showing the temporal pictures of the film variables with respect to time. This success was possible owing to several new mathematical and numerical schemes incorporated into the governing equations, and the resulting temporal bubble profiles strikingly resemble those observed experimentally even during the oscillations of draw resonance instability. Figure 7 shows example stability diagrams by Hyun et al. [79, 247] for film blowing obtained from both experiments and theoretical stability analysis and simulations.

4.3 Recent Results on Draw Resonance Instability in Film Blowing

Among the recently published results in 2000's on film blowing (e.g., Sidiropoulos and Vlachopoulos [190], Muslet and Kamal [191], Bhattacharya et al. [192, 229], Pirkle and Braatz [193, 194], Rao and Rajagopal [198], Yoon and Park [242, 243], Housiadas and Tsamopoulos [244-246], Pontaza and Reddy [195], Zatloukal and Vlcek [197], Rutgers et al. [232], Carreau et al. [218-221], Hyun et al. [25, 199, 247], Higuchi et al. [248], Doufas and McHugh [249, 250], etc), three groups deserve special mention in terms of their effects on the subsequent research efforts continuing into the 21st century: McHugh et al. [249, 250], Carreau et al. [218-221] and Hyun et al. [25, 199, 247]. McHugh et al. introduced the first two-phase model to describe the flow-induced crystallization occurring on the film and Carreau et al. put out a series of papers on the bubble instability as related to the freezeline height. Hyun et al produced the first transient solutions enabling the elucidation of the general stability behavior of the process including the draw resonance instability.

There are two important tasks to be performed by researchers in this field in the future: one is to obtain transient solutions of film blowing dynamics when flow-induced crystallization is accompanied on the spinline, and the other is to develop the governing equations capable of generating the helical instability when the BUR takes on a higher value than for draw resonance instability. While the former task would involve some ingenious mathematical and numerical schemes to handle the crystallinity, the latter one truly requires a breakthrough in modeling and simulation to predict the occurrence of helical instability in terms of the rotating speed and rotating radius of the bubble, which is non-axi-symmetrical. This is in direct contrast to draw resonance instability in which the bubble is axi-symmetrical and not rotating. Once this is accomplished, it deserves to be called a triumph of engineering modeling and simulation of a complicated process whose dynamics is truly complex due to the nonlinearity, viscoelasticity and hyperbolicity inherently imbedded in the governing equations of partial differential equations with moving boundary conditions.

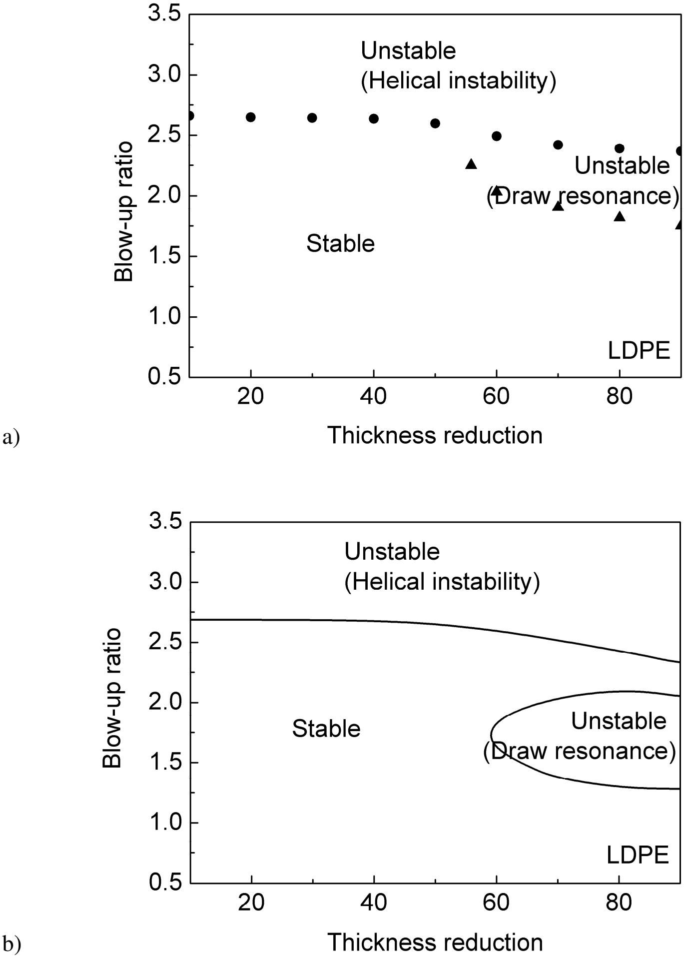

Figure 7: Stability diagram of viscoelastic film blowing: results of (a) experiments and (b) linear stability analysis for LDPE. (Lee et al [247]).

CONCLUSIONS

The instabilities in extensional deformation polymer processing have been reviewed leafing through the results during the past four decades with focus on draw resonance instability, the most important instability profoundly affecting the industrial productivity and also having attracted many academic researchers' attention due to the intriguing nature of its physics, in the three typical continuous extensional deformation-dominant polymer processing such as fiber spinning, film casting and film blowing. Both experimental and theoretical results reported in the open literature have been reviewed with emphasis on the recent results. The future directions of the research related to the instability in the three processes have also been discussed highlighting several recent, relevant results reporting important progress in topics of the flow-induced crystallization, and the transient solutions of the dynamics in the processes. The particular instability occurring in film blowing only, called helical instability, is considered one of the most challenging subjects right now, whose successful solution will surely deserve to be called a remarkable success in the field of engineering modeling and simulation.

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