JOURNAL OF APPLIED POLYMER SCIENCE VOL. 19, 3291–3297 (1975)

Studies on Blown Film Extrusion. III. Bubble Instability

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Synopsis

An experimental study has been carried out to investigate flow instabilities in blown film extrusion. Two types of flow instabilities were observed, depending on whether a bubble was under uniaxial or biaxial stretching. Under biaxial stretching, the phenomenon of a surface wave-type instability was observed, yielding wavy bubble shapes which very much resembled water waves at the free surface. Under uniaxial stretching, another type of instability, frequently referred to as draw resonance, was observed. It was also observed that, once draw resonance occurs, the amplitude and frequency of bubble diameter pulsing increased with stretch ratio. Quantitative information was obtained from a series of motion pictures taken of bubble diameter in both types of flow instability. It was observed further that an increase in extrusion melt temperature enhanced the severity of bubble instability.

INTRODUCTION

It is known in the polymer processing industry that polymers, when melted and extruded through a die, can sometimes give rise to nonuniform extrudate diameters, otherwise known as melt flow instability. In the two decades since the pioneering study of Spencer and Dillon[1] was published, the literature on the unstable flow phenomenon commonly referred to as "melt fracture" has proliferated.[2–7]

Another type of melt flow instability, which is certainly less known and hence less studied than melt fracture, is the phenomenon of "draw resonance," which distinguishes itself from melt fracture in that it occurs only when the extrudate is stretched above a certain critical value. A recent article by Han et al.[8] clearly demonstrates the differences in the cause (or causes) of melt fracture and draw resonance.

In the pursuit of our recent attempt to better understand the blown film process,[9] we have observed two distinct types of flow instability, depending on whether a bubble was stretched uniaxially or biaxially. In uniaxial stretching (i.e., when a bubble was not inflated), draw resonance was observed, very similar to that reported earlier in connection with a study of melt spinning.[8] However, in biaxial stretching, the phenomenon of surface wave-type instability was observed. The latter is believed to be characteristic of the blown film process.

Whether it occurs in tubing extrusion, in fiber spinning, or in blown film extrusion, unstable flow is of practical concern to the polymer processing industry, because it either limits the production rate and/or gives rise to unacceptable product quality. For instance, in blown film extrusion, a nonuniform bubble diameter results in a nonuniform film thickness, giving rise to poor mechanical/physical properties.

In the present study, the third of this series, we shall first present our recent experimental observations made on the two types of flow instability, and then we shall offer an explanation for the occurrence of the observed instability in terms of the processing variables (namely, mass flow rate and extrusion temperature).

EXPERIMENTAL

The apparatus used for blown-film extrusion experiment was the same as that described in part I of this series.[9] In the present study, however, a movie camera (Bolex Super 8) was also used in order to take motion pictures of the time-dependent behavior of the bubble when the phenomenon of bubble instability was observed.

Of the three homopolymers used (low-density polyethylene, high-density polyethylene, and polypropylene), low-density polyethylene showed the most pronounced bubble instability when a disturbance in take-up speed was introduced. A series of motion pictures of unstable bubbles was taken under various extrusion condition of mass flow rate, melt temperature, and take-up speed.

Basically, two types of experiment were carried out, uniaxial stretching and biaxial stretching. In the experiment of uniaxial stretching, the pressure inside the bubble was the same as that outside the bubble, i.e., atmospheric pressure. In the experiment of biaxial stretching, the pressure inside the bubble was slightly greater than that outside the bubble, giving rise to a blow-up ratio greater than unity. When take-up speed was perturbed, each type of experiment (uniaxial and biaxial) responded quite differently. In the case of uniaxial stretching, pulsation of bubble diameter frequently referred to as "draw resonance" was observed, whereas in the case of biaxial stretching the bubble moving upward exhibited a wavy surface resembling the free surface of water waves in the ocean.

In order to quantitatively examine the variations of bubble diameter, it was read off from the projected images of the motion pictures taken. This was done by stopping the projector at a predetermined interval of projection time. With the relation between the projection time and real time shown, it was possible to determine the variations of bubble diameter with real time.

RESULTS AND DISCUSSION

The Phenomenon of Wave-Type Bubble Instability

The shape of a biaxially stretched blown film has been found to be very sensitive to a disturbance in processing variables, such as the mass flow rate, air pressure, temperature, and take-up speed. As may be surmised, a slight variation of these processing variables can significantly affect the thickness of the blown film and hence the mechanical/physical properties.

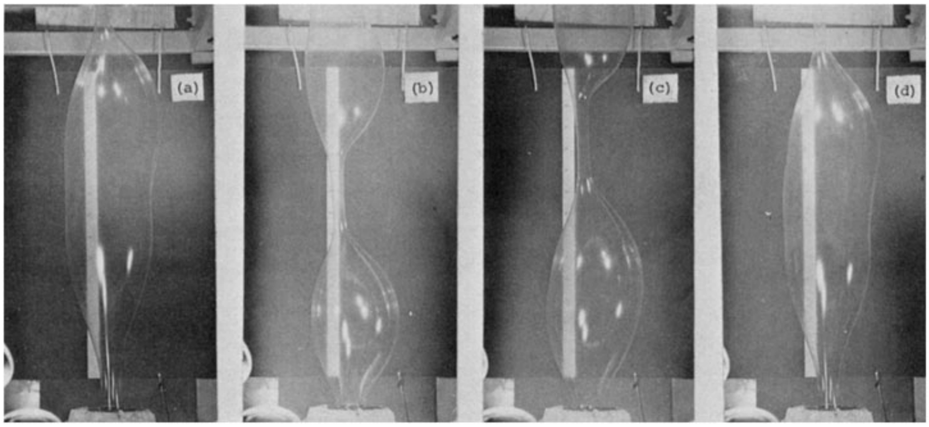

Fig. 1. Pictures of the bubble shape of low-density polyethylene (T = 200°C, Q = 18.3 g/min, v_1 = 0.353 cm/sec, $\Delta P = 0.79 \times 10^{-2}$ psi) for a step change in take-up speed from v_2 = 2.31 cm/sec to v_2 = 6.22 cm/sec: (a) after 4.3 sec; (b) after 9.15 sec; (c) after 11.38 sec; (d) after 15.64 sec.

Figure 1 shows representative pictures taken of a biaxially stretched bubble after it was disturbed by a change in take-up speed from 2.31 cm/sec to 6.22 cm/sec. The material is low-density polyethylene extruded at 200°C. It should be noted that when the size of disturbance was greater than a critical value, the bubble carried a wavy surface moving upward, very much resembling ocean waves. In other words, the surface of the bubble looked like a traveling wave, repeating the same patterns of wavy surface in a cyclic manner. However, when the size of disturbance was small, the bubble disturbance gradually disappeared and the bubble returned to its initial shape after a while.

Figure 2 shows representative pictures of a blown bubble which stabilized by itself at about 18 sec after the take-up speed was suddenly increased from 2.37 cm/sec to 21.18 cm/sec. Note that the material of the bubbles in Figure 2 is low-density polyethylene, the same material as that in Figure 1, and that

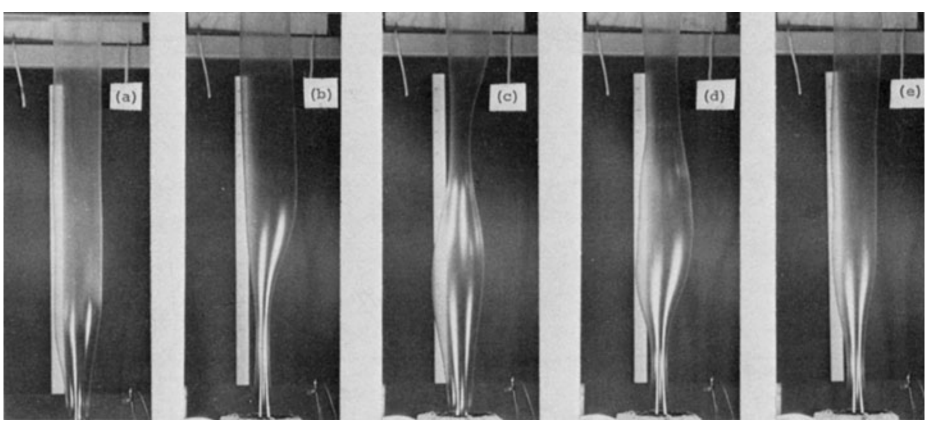

Fig. 2. Pictures of the bubble shape of low-density polyethylene (T = 160°C, Q = 18.3 g/min, v_1 = 0.353 cm/sec, $\Delta p = 1.01 \times 10^{-2}$ psi) for a step change in take-up speed from v_2 = 2.37 cm/sec to v_2 = 21.18 cm/sec: (a) initial shape (t = 0); (b) after 1.17 sec; (c) after 6.01 sec; (d) 9.56 sec; (e) after 18.06 sec.

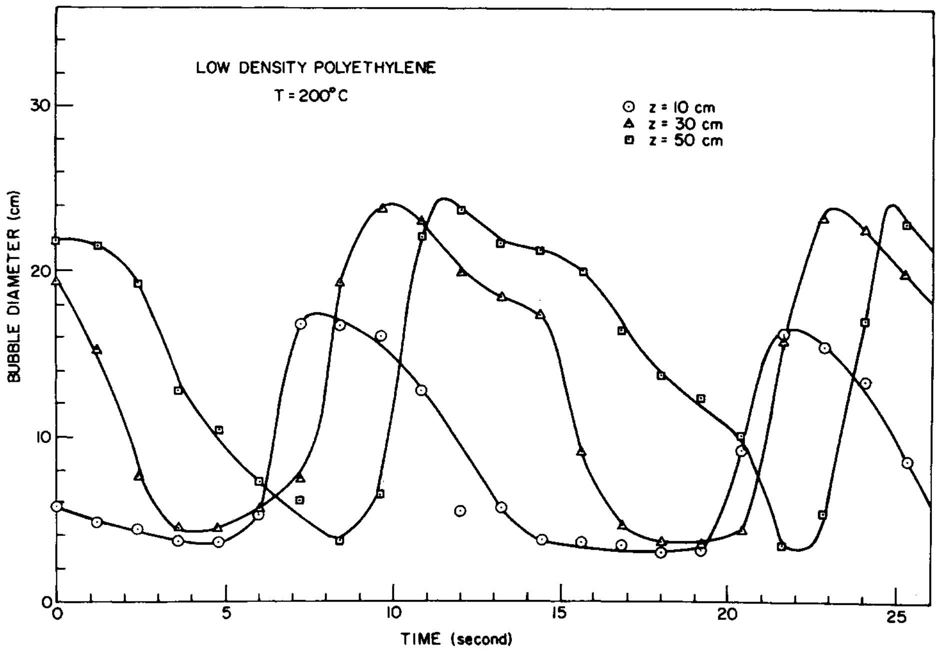

Fig. 3. Plots of bubble diameter vs. time for a biaxially stretched bubble of low-density polyethylene extruded at 200°C. Other conditions are as given in Fig. 1.

all other extrusion conditions are the same in both cases except for the melt temperature. It can be concluded, therefore, from Figures 1 and 2 that lowering the extrusion temperature from 200° to 160°C stabilizes the blown bubble.

In order to demonstrate the time-dependent behavior of a disturbed bubble, the bubble diameter was read off from the projected images of the motion pictures. Figures 3 and 4 show plots of bubble diameter versus time for low-

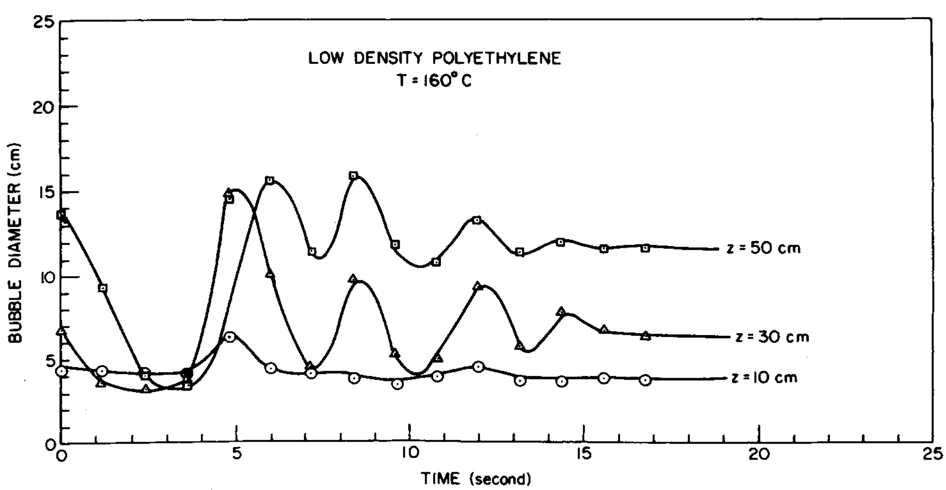

Fig. 4. Plots of bubble diameter vs. time for a biaxially stretched bubble of low-density polyethylene extruded at 160°C. Other conditions are as given in Fig. 2.

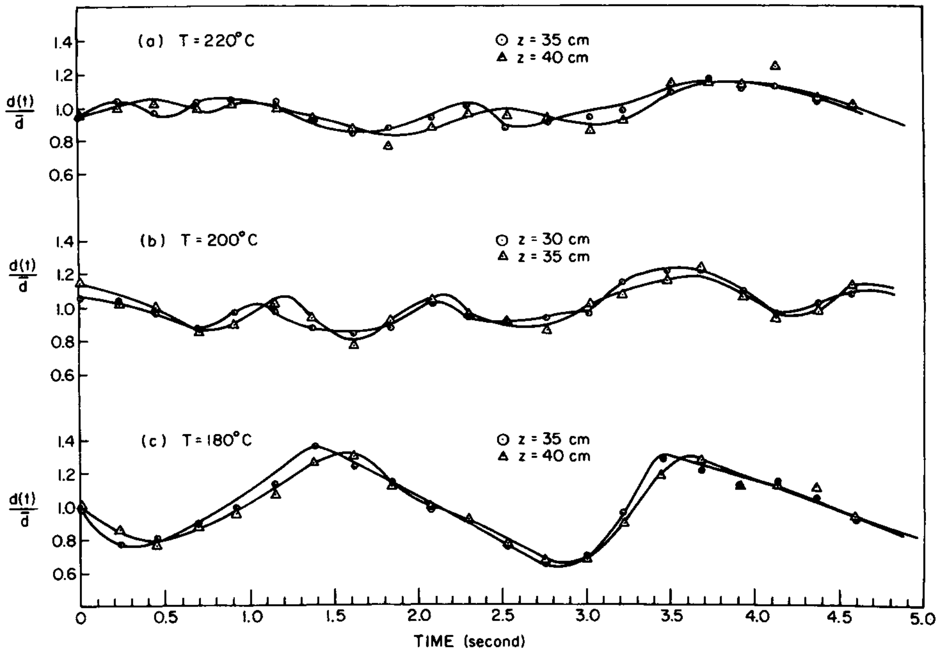

Fig. 5. Plots of normalized bubble diameter vs. time for a pulsing, uniaxially stretched bubble of polystyrene/high-density polyethylene blend (50 wt-%/50 wt-%) at different distances from the die exit: (a) $T = 220°C$; $v_2/v_1 = 111$; (b) $T = 200°C$, $v_2/v_1 = 148$; (c) $T = 180°C$, $v_2/v_1 = 128$.

density polyethylene extruded at 200° and 160°C, respectively. It is seen in these figures that, at an extrusion temperature of 160°C, the disturbance decays and the bubble diameter returns to its initial size, whereas at an extrusion temperature of 200°C the bubble diameter increases and decreases cyclically.

The Phenomenon of Draw Resonance

In the past, several researchers[8,10,11] have reported their observations of the phenomenon of pulsation of thread diameter in melt spinning and pulsation of film width in flat film extrusion. It seems very reasonable to assume that, in both melt spinning and flat film extrusion, the extrudate is under a uniaxial stretching.

As described in part I of this series,[9] the blown film process can give rise to a uniaxial stretching when there is no inflation of the bubble, i.e., when the pressure inside the bubble is maintained at atmospheric. In the present study, when the take-up speed was increased above a critical value, the uniaxially stretched bubble diameter was observed to oscillate, i.e., it exhibited draw resonance. It was also seen that at a fixed throughput rate, the amplitude and frequency of the bubble diameter pulsation increased as the take-up speed increased, ultimately leading to a breakdown of the bubble.

Figure 5 shows plots versus time of the ratio of diameter to average diameter $[d(t)/\bar{d}]$ for the pulsing bubble at different distances from the die exit, at three different melt temperatures.

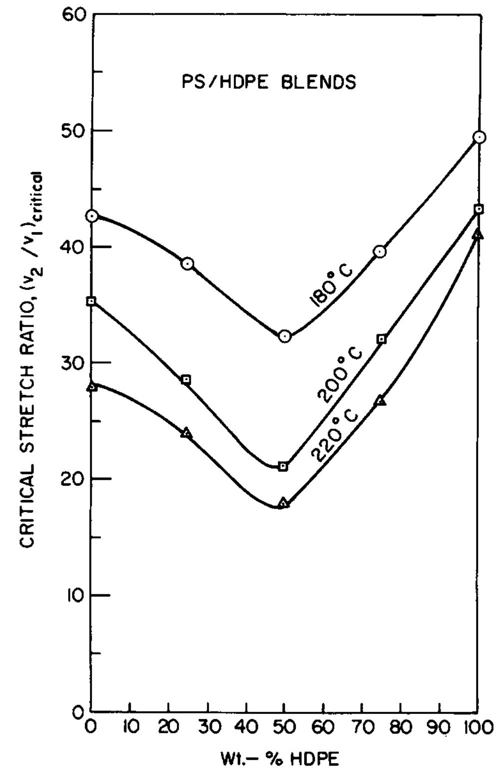

Fig. 6. Plots of critical stretch ratio vs. blending ratio for uniaxially stretched bubble of polystyrene to high-density polyethylene blends extruded at three different melt temperatures: 220°C, 200°C, 180°C.

It is of particular interest to mention that in the present study, all three polymers (low-density polyethylene, high-density polyethylene, and polypropylene) tested exhibited draw resonance. However, in the melt spinning experiment reported earlier,[8] only polypropylene exhibited draw resonance. Our present study indicates that the blown film is much more sensitive to a disturbance in take-up speed than the fiber.

Figure 6 shows plots of the critical stretch ratio versus blending ratio for uniaxially stretched polystyrene/high-density polyethylene blends at three different extrusion melt temperatures. From this figure, it is seen that at a fixed temperature, there is a value of blending ratio at which the critical stretch ratio goes through a minimum. In other words, the blend of polystyrene/high-density polyethylene = 50/50 (by weight percent) appears to give the lowest value of critical stretch ratio at which draw resonance starts to occur. Second, it is seen that the critical stretch ratio increases as the extrusion melt temperature decreases.

CONCLUSIONS

Two types of bubble instability phenomena were observed in blown-film extrusion experiment. It was observed that in uniaxial stretching, the bubble diameter starts to pulse at a critical value of stretch ratio and that the amplitude and frequency of the diameter pulse increases with the stretch ratio, ultimately leading to a breakdown of bubble. On the other hand, it was observed that in biaxial stretching, the bubble shows a surface wave type of instability in response to a disturbance in take-up speed. It is worth noting, however, that the disturbed bubble eventually stabilized by itself when the size of disturbance is small (i.e., below a critical value), but that it continues its unstable flow patterns when the size of disturbance is greater than a critical value. An attempt is made to correlate the occurrence of bubble instability to the operation conditions of the blown film process.

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Received November 5, 1974
Revised April 21, 1975