Tubular Film Blowing - Myths and Science

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INTRODUCTION

Film blowing "is a process which is geometrically complex and where there is a strong desire for simple ideas. There is no guarantee that such simplicity can be found, and part of the theorist's task here is the rather negative one of curbing the enthusiasm of would-be simplifiers" [1]. This paper uses the simplest model of the process to address some persistent misunderstandings (e.g. about so-called intuitive and counter-intuitive behaviour) and to review the complex interaction between all the processing parameters. An elementary approach to some questions about bubble stability is discussed.

FILM BLOWING

The process involves the inflation and stretching of a tubular bubble of polymer which is molten between an annular die, from which it is extruded, and a frost line (or freeze-line) above which it has solidified. Between the die and the guide rolls (see Figure 1) the bubble is axi-symmetric and then it is collapsed to a layflat film from which polymer sheet or, for example, a roll of plastic bags may be made.

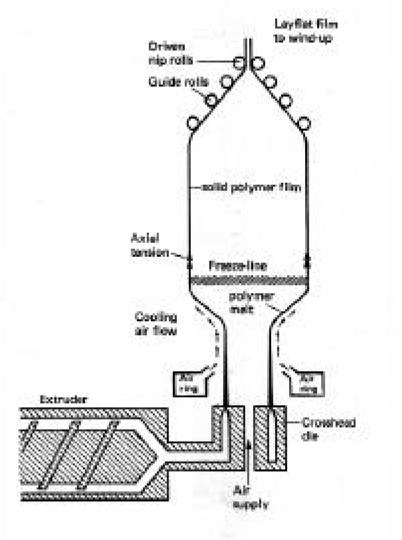

Figure 1. The film blowing process (schematic) [2]

Key features of the process are the cooling, inflation and stretching of the thin film. The operation is controlled by the supply of cooling air, the amount of air inside the bubble and the velocity of the nip rolls (as well as the flow rate, melt temperature, die diameter and die gap - as well as polymer properties, air ring design and height of the nip rolls above the die).

MODEL [2,3,4,5]

We define dimensionless bubble radius, *r*, velocity, *u*, and film thickness, *h*, all functions of distance, *x*, above the die. These are scaled so that *r(0)=1*, *u(0)=1* and h*(0)=1* and *X* is the frost-line height, *Z*, divided by die radius, r_0. The slope, *è*, of the bubble profile is defined by

$$r'(x) = \tan q \quad . \qquad (1)$$

We shall use continuity (with a constant density, *ñ*) to eliminate *h*. The mass flow rate, *M*, given by

$$M/(r_0 h_0 u_0) = 2prr(x)h(x)u(x) \qquad (2)$$

is constant. A simple force balance for a Newtonian fluid (viscosity ç), with the neglect of inertia, gravity, surface tension and air drag, gives

$$2r^2(H + r^2B)q'(x) = 3\sin 2q + r(H - 3r^2B), \qquad (3)$$

$$4u'(x) = -2u\tan q + (H + r^2B)\sec^2 q \quad .(4)$$

In order to solve the three differential equations, we need three boundary conditions; *è(X)=0* is added to *r(0)=1* and *u(0)=1* [3]. The dimensionless parameters in equations (3) and (4) are a pressure, *B* (*Ä* is the excess pressure inside the bubble) and a force, *H* (*F* is the total axial force at any cross-section):

$$B = \frac{pra_0^3\Delta}{hM} \ , \ H = \frac{ra_0F}{hM} \ . \qquad (5)$$

We shall ignore the fact that the flow is not isothermal and assume (for simplicity in discussions below) that viscosity is constant; it is computationally no harder to include variation in viscosity, *ç*, based on a given (or measured) temperature profile [5] and this can give good fits to measured bubble shapes (but not such good predictions of rates of strain and stresses).

PROCESS OPERATION

In order to make calculations with our model we need operating variables *Ä*, *F*, *Z* and *M* as well as polymer properties *ç* and *ñ* and die dimensions r_0 and h_0. In the normal operation of the film blowing process, these are not directly controlled and indeed some (the pressure and the take-up force in particular) are not measured. What will normally happen is that the process is run with a given die to produce a given product (film thickness, h_1, and layflat width, pr_1). Once the extruder is set to supply a chosen flow rate of melt at a chosen temperature, the nip roll speed, u_1, can be calculated from

$$u_1 = (u_0 r_0 h_0) \big/ (r_1 h_1) = M \big/ (2\pi\rho r_1 h_1) . \qquad (6)$$

Then the amount of air inside the bubble will be adjusted to give the required BUR (blow ratio, r_1 / r_0). This is a measure of the stretching in the transverse direction, TD, while the DR (draw ratio, u_1 / u_0) is a measure of the stretching of the film in the machine direction, MD. In normal operation of the process the mass of air inside the bubble is fixed - the air supply shown in Figure 1 is used to adjust the bubble in starting steady operation. The cooling air flow is adjusted to alter the FLH (frost line height, *Z*) which will affect bubble stability and film properties.

The four operating variables which are adjusted: melt flow rate, cooling air flow rate, nip roll speed and mass of air inside the bubble, interact in a complicated way to determine the final film dimensions and properties. This is a particularly important point in connection with studies of the effect of operating variables on film properties and on bubble stability. It is not enough to state, for example, that the impact strength of the film increases with BUR - one must know whether the DR was changed also (in order to keep the film thickness the same) and whether cooling air flow was adjusted to keep the FLH the same (or to avoid bubble instability, perhaps). Similarly if one increases the DR to observe the onset of instability it is important to recognize that, if the only operating variable to be altered is nip roll speed, then bubble shape, FLH, BUR and film thickness will all be liable to change, not to mention inflation pressure and take-up force.

INTUITION

It has been claimed [6] that a prediction that BUR increases if inflation pressure decreases is "counter-intuitive". This is the prediction of the simple model outlined here; Figure 2 [4] shows this for constant FLH and film thickness (or constant FLH and take-up force).

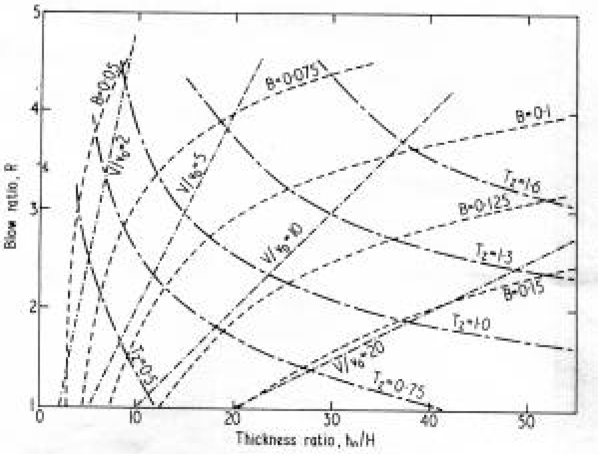

Figure 2. BUR against drawdown, fixed FLH [4]

It may be noted that things are not quite so simple if constant FLH and DR are considered and there is in fact the possibility of two steady states for operation, with different BUR and the same inflation pressure. The experimental evidence [7] seems to allow BUR to go up or down with an increase in inflation pressure and this reflects the interaction between the variables discussed above.

The question of correct intuition is illuminated by thinking about a soap bubble (or a rubber balloon). In a soap bubble the excess pressure is inversely proportional to the radius (being proportional to the curvature of the soap film) and this is precisely what is called counter-intuitive by Liu and others. Inflation does involve blowing air into a bubble so that the mass of air must increase, but the volume can increase and the pressure decrease provided that their product increases (treating air as an ideal gas at fixed temperature).

BUBBLE STABILITY

There is a variety of forms of instability associated with film-blowing and there have been attempts (not reviewed here) at understanding some of them. Here we offer one simple idea which may help to explain the observed bubble instability for BUR close to 1.

If we consider a cylindrical bubble (perhaps neglecting bubble inflation near the die and scaling by final bubble radius rather than initial bubble radius) the bubble shape equation (3) requires that $H - 3r^2 B = 0$ and the velocity equation (4) leads to $\mathrm{DR} = \exp(4HX / 3)$. Since the bubble volume for the cylinder is proportional to r^2 and the bubble pressure is proportional to r^{-2}, the mass of air inside the bubble is independent of *r*. Looking at this from the opposite point of view, if we are given the mass of air inside the bubble, the bubble radius is undetermined. This suggests that there will be instability (since the bubble radius can change in response to minute fluctuations in any external condition). This is consistent with observations of instability at BUR close to 1.

We may contrast this with the situation for a soap bubble where the pressure difference is $2\Gamma / r$ and the volume is $4\pi r^3 \big/ 3$, giving a mass of air inside the soap bubble proportional to $8\pi\Gamma r^2 \big/ 3$ and hence a well-determined (and stable) situation.

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