A NEW PARAMETER FOR DYNAMIC CHARACTERIZATION OF PET FILM SURFACE TOPOGRAPHY

by

M. Boutaous and P. Bourgin
University Louis Pasteur
FRANCE

ABSTRACT

It is well-known that handling and winding flexible media involve aerodynamic phenomena which are crucial for the process. Among those parameters which govern the final thickness value of the air layers separating the film layers in a roll of film (for example PET), surface roughness plays an important role. In order to characterize the surface topography of such materials, in a dynamic way, an original experimental set-up was built. It has been described elsewhere, and only its basic features are recalled here. It consists in a polished glass disc with a circular slit connected to a vacuum pump. Having displayed a sample of PET film onto the glass plate, sub-ambient pressure is applied. The air layer which initially separates the film from the plate is partially reduced due to air aspiration: a circular front starts from the slit and propagates towards the center. For prescribed values of the film thickness, the total propagation time depends on sub-ambient pressure and slit diameter (i.e. squeezing surface) through relationships which involve a single parameter characteristic of film roughness.

Here the same experimental set up is used to carry out further investigations dealing with the kinetics of both air layer thinning and front propagation. Using a monochromatic light to insulate the film from above, Newton rings are generated allowing the air gap thickness variation to be measured by means of a CCD camera associated with image processing. The main experimental result is that the air layer at the center decreases linearly versus time, the slope being characteristic of the film surface roughness. A simple theoretical model based on the concept of " equivalent smooth surfqces " is developed in order to predict the circular front propagation. Excellent agreement is observed with the experimental data, namely the front propagation kinetics. These results are extrapolated to the configuration of winding, leading to significant improvement of the existing model for lateral evacuation of the air layers confined between the film layers in a roll of film.

NOMENCLATURE

e_i : initial air layer thickness
e_f : final air layer thickness
h : plastic film nominal thickness
P, P_a, P_1 : current pressure, applied pressure, ambient pressure
Q_v : volumic flow rate
r, R_o, R(t) : current radius, slit radius, front radius
R_a, R_t : average roughness, total roughness
R_h : value of the highest five peak-to-valley distances averaged over a given area
t : time
t_f : final time
μ : air dynamic viscosity
V : volume of air entrapped in the upstream zone
β : dynamic roughness parameter

I - INTRODUCTION:

Fillers are commonly added to plastic films so that to generate some surface roughness. It has been proposed in refs.[3 -6] a first step towards the improvement of the "accretion models" by taking into account the air interlayers in a roll of film. The role of surface topography, which is a key question, has been addressed only by a few authors, see for instance refs.[7 - 10]. Within that framework it is very important to know how surface topography influences air entrainment or exhaust during winding. For that purpose, an experimental study is carried out to characterize the consequence of roughness on the capacity of a film to evacuate an air layer squeezed between two layers under controlled conditions. As a first step, we investigated the effects of rigidity and roughness on the total air evacuation time under prescribed squeezing conditions, ref. [1]. In order to complete these preliminary experimental results, we used an interferometric method coupled with image processing to have access to the reduction kinetics of the air layer thickness as a function of the film properties.

II - EXPERIMENTS

II. 1- FILM SAMPLES

As quoted before, the incorporation of mineral fillers during polymerization confers to the film a specific surface topography.
The concept of "roughness" is somehow difficult to define, because it basically contains much information. For the sake of simplicity, it is useful to characterize "roughness" by one single parameter. For example the total roughness (R_t) or the average roughness (Ra) are classically used for describing metallic surfaces. However, they are not adequate for PET film surfaces, ref. [11]. Therefore it was found it necessary to propose a specific approach involving a more sophisticated

description of the surface topography, which can be achieved by 3D roughness measurement. In our case, a parameter (R_h) which corresponds to the value of the highest five peak-to-valley distances averaged over a given area of the sample is often introduced. The residual thickness of the air layer as a function of the squeezing pressure was measured by means of an electrostatic field. The details of this experiment, carried out by Rhône Poulenc Films Company, cannot be reported here due to confidentiality reasons. Nevertheless, it is possible to give here the following empirical relationship which was proposed: see ref. [5].

$$e_f(P_a) \;=\; (e_f)_0\, e^{-\sqrt{\frac{P_a}{P_0}}} \qquad (1)$$

where: e_f represents the final air layer thickness after applying the squeezing pressure P_a. P_0 denotes some parameter characteristic of the film and $(e_f)_0$ the equilibrium air layer thickness when $P_a = 0$. If we assume that when the sample is displayed on a smooth substrate without pressure (Pa = 0), it lays on its highest five peaks, coefficient $(e_f)_0$ will be assimilated to parameter R_h as defined above.

In which follows, the dynamic behavior of an air layer squeezed between a film sample and a solid substrate is studied. Two sets of samples have been tested. The first one is composed of 3 PET films having the same nominal thickness (h = 12 μm) and different surface topographies (R_h comprise between 1.5 and 1.9 μm). The second set of samples is the counterpart of the first one, i.e.: two films having the same surface topography (R_h = 1.5 μm) but two thickness values: 7 and 12 μm.

II. 2- EXPERIMENTAL SET UP

Only the basic features of the experimental set-up sketched in Figure 1 are summarized here. A more detailed description can be found in refs.[1] and [2].

A polished glass disk is put on a flat support having a circular slit connected to a vacuum pump. In order to study the influence of the disk diameter, several disks were used. A sample of plastic film is displayed on the glass plate and sub-ambient pressure is applied by operating the vacuum pump. The air layer which initially separates the film from the glass plate is partially evacuated and a quasi circular front starts from the slit and propagates towards the center: see Figure 2.

Monochromatic light (wave length λ = 0.589 μm) is used to illuminate the film from above, by means of a two-way mirror. Newton rings are formed and show the shape of the air gap between the film and the glass plate in the vicinity of the propagating front as they move towards the center. A CCD camera coupled with image processing is used to count the number N of black (or white) rings at the center. The reduction of the air interlayer thickness Δe is easily computed by using elementary optics laws: $\Delta e = e_i - e(t) = N\dfrac{\lambda}{2n}$, where e_i is the initial air layer thickness, e(t) the instantaneous air layer thickness, and n the air refraction index. Finally, the total evacuation time is measured for each sample.

II. 3- RESULTS

1) R_o and P_a prescribed: influence of surface roughness

Each sample was squeezed under several values of the sub-ambient pressure, for different values of the slit radius. The time origin (t = 0) corresponds to the time when the vacuum pump starts operating. It has been shown in refs. [1] and [2] that the total evacuation time depends on the film characteristics (roughness, stiffness) and on the operating conditions (pressure, slit diameter). In addition to these global results, the velocity of the rings at the center (and consequently the air layer reduction at the center) and the front kinetics are investigated.
It is observed that the reduction of the air layer thickness is linear, this tendency being valid for any sample and any set of operating conditions (pressure and slit radius). For example, Fig. 3 shows the air thickness reduction as a function of time $\Delta e(t)$, for several films, the squeezing pressure and the slit radius being chosen respectively equal to : P_a = 79000 Pa and R_o = 0.0225 m. The continuous lines correspond to the experimental curves, whereas the browken lines represent the linear regressions.
The following law can be proposed for the instantaneous thickness of the air layer at the center:

$$e(t) = e_i - kt \qquad (2)$$

where t is the time and k is a parameter which depends on roughness, slit radius and squeezing pressure. The determination of the front radius R as a function of time t is done in a straightforward way by interpreting the recording of the pictures, image per image (figure 2).

2) Influence of R_o : Non-dimensional variables

The following non-dimensional variables are introduced:

$$\bar{e}(t) = \frac{e(t)}{R_o}, \qquad \bar{e}_i = \frac{e_i}{R_o}, \qquad \bar{t} = \frac{t}{t_f}$$

where t_f denotes the total evacuation time.
Equation (2) now reads:

$$\frac{e(t)}{R_o} = \frac{ei}{R_o} - \frac{k}{R_o}t \quad \Leftrightarrow \bar{e}(t) = \overline{ei} - \frac{k}{R_o}t \qquad (3)$$

in a previous article [1], we have shown that t_f is proportional to R_0^2: $t_f = \lambda . Ro^2$, where λ is a parameter depending on the film roughness and pressure.

One gets: $$R_o\bar{e}(t) = R_o\bar{e}_i - k\lambda R_o{}^2\bar{t}$$

which can be written as : $\bar{e}(t) = \bar{e}_i - \alpha\bar{t}, \qquad with \ \alpha = k\lambda R_o$

and the final experimental formula becomes:

$$e(t) = e_i - \frac{\beta}{R_o} t \qquad (4)$$

It turns out that the slope k in Figure 3 is equal to $\frac{\alpha}{\lambda R_o} = \frac{\beta}{R_o}$, where β depends on roughness and pressure.

3) Influence of pressure

As already quoted [1], the influence of the squeezing pressure on parameters P_o and β was difficult to identify clearly. Therefore we shall allocate a given value to the pressure and keep it constant in which follows; this value (Pa =79000 Pa) which has been used in our tests is representative of the radial pressure generated in a roll of film.

4) Prediction of the front propagation

The objective is to predict the front evolution R(t) by assuming that the air layer thickness at the center linearly decreases according to the experimental law proposed (figure 4).
The flow is assumed to be a squeeze flow due to an applied pressure P_a equal to the absolute value of the sub-ambient pressure (here Pa =79000 Pa). It is considered to be quasistatic, inertialess and the fluid (air) to be incompressible.
As shown in Figure 4, the flow domain is divided into two zones by the propagating front R(t).

1)- Upstream the front: (0 < r < R(t)), the pressure is equal to P_a and the air layer thickness linearly decreases according to: $e(t) = e_i - \frac{\beta}{R_o} t$. As the front moves towards the center, the volume reduction of this zone is merely equal to :

$$Q_v(t) = -\frac{\partial V}{\partial t} = 2\pi \left(e_f - e(t) \right) R(t) \frac{\partial R(t)}{\partial t} - \pi R(t)^2 \frac{de(t)}{dt}$$

which can be written as, knowing that: $e(t) = e_i - \frac{\beta}{R_o} t$

$$Q_v(t) = -2\pi \left(e_i - \frac{\beta}{R_0} t - e_f \right) R(t) \frac{\partial R(t)}{\partial t} + \pi R(t)^2 \frac{\beta}{R_0} \qquad (5)$$

2)- Downstream the front (R(t) < r < R_o), the flow is a Poiseuille radial flow between two surfaces separated by a gap equal to e_f. Actually e_f is an average value, the rough film being assimilated to an "equivalent smooth surface". As indicated before, the ultimate mean value of the air layer squeezed between a smooth surface and a rough film depends on the applied static pressure, Eq. (1). Assuming that $(e_f)_0$ is equal to R_h equation (1) now reads:

$$e_f(P_a) = R_h\, e^{-\sqrt{\frac{P_a}{P_0}}} \qquad (6)$$

The values of parameter P_0 has been determined through the measurement of the global evacuation time and specified in ref. [1].

Elementary calculation based on Reynolds thin film flow theory leads to the following expression for the volumic flow rate:

$$Q_v = -\frac{\pi}{6\,\mu}\frac{\partial p}{\partial r}\, r\, e_f^{\,3} \qquad (7)$$

where p is the pressure in the gap (p is a function of the current radius r and of time t), and μ stands for air viscosity.

Q_v is independent of the current radius r, which yields to the following expression :

$$r\,\frac{\partial \mathrm{p}}{\partial \mathrm{r}} = \mathrm{A(t)} \qquad (8)$$

where A(t) is some function of time to be determined by the boundary conditions:

$p\ (r = R_o) = P_1 = 0$ ambient pressure (9)

$p\ (r = R(t)) = P_a$ applied pressure (10)

after integration, with conditions (5) and (6), equation (4) becomes:

$$p(r,t) = \frac{P_a}{\ln\frac{R(t)}{R_o}}\ln\frac{r}{R_o} + P_1 \qquad (11)$$

which by insertion into equation (3) gives:

$$Q_v = -\frac{\pi}{6\,\mu}\frac{P_a}{\ln\frac{R(t)}{R_o}}\, e_f^{\,3} \qquad (12)$$

The flow rate (Q_v) is equal to the volume reduction of the upstream zone, given by equation (2). After elementary rearrangements one gets:

$$\frac{\beta}{R_0}R(t)^2\ln(\frac{R(t)}{R_0}) + 2R(t)(-e_i + \frac{\beta}{R_0}t + e_f)\ln(\frac{R(t)}{R_0})(\frac{dR(t)}{dt}) + \frac{1}{6}\frac{P_a}{\mu}e_f^3 = 0 \qquad (13)$$

Recall that e_f is a function of P_a. Using equation (6), expression (13) finally becomes

$$\boxed{\begin{aligned}&\frac{\beta}{R_0}R(t)^2\ln(\frac{R(t)}{R_0}) + 2R(t)(-e_i + \frac{\beta}{R_0}t + R_h e^{-\sqrt{\frac{P_a}{P_0}}})\ln(\frac{R(t)}{R_0})(\frac{dR(t)}{dt}) + \\ &+\frac{1}{6}\frac{P_a}{\mu}(R_h\, e^{-\sqrt{\frac{P_a}{P_0}}})^3 = 0\end{aligned}} \qquad (14)$$

The initial condition allocated to this ordinary differential equation corresponds to the fact that the radius of the front is equal to the radius of the slit just when starting the test :

$$R\ (t = 0) = R_0$$

Equation (10) associated to its initial condition is integrated numerically using the Runge-Kutta method of a fourth order. The solution gives the time evolution of the front radius R(t), for a given set of data R_0, μ and P_a. Parameters e_i, R_h, P_0 and β are obtained from the experiments. The initial thickness e_i is the thickness final value $e_f(P_a)$ plus the total thickness reduction $\Delta e\ (t = t_f)$.

The results from the calculation compared with the experimental data are presented in figure 5.

The general curve shape based on the experiments (dots) is well represented by the theoretical prediction (solid lines). The differences between calculated and experimental data are always less then 15% which corresponds to a fairly good agreement and confirms our proposal to describe the dynamic roughness characteristic of each film by parameters P_0 and β. In Figure 5, the theoretical curve obtained for a squeeze flow by assuming that the air layer thickness at the center remains constant [1] is represented in continuous line; the improvement resulting from the "new" model is clearly observed.

III - APPLICATION : air exhaust during winding

1) Basic features of a simple model

The previous experimental data can be used to evaluate the thickness of the residual air layer in a roll of film. The question is the following one: given the radius R_{rf} of the roll being wound and the radius of the nip roll R_r, how many revolutions are required so that the air layer equilibrium (final) thickness be reached under a given nip force?

⇒ First the initial value of the air interlayer is calculated by means of elastohydrodynamic theory :[12]

$$H = 7.43\, U^{0.65}\, W^{-0.21} \qquad (16)$$

where:

$$H = \frac{e_i}{R_{eq}}, \qquad U = \frac{\mu_{air}\ u}{E_{eq}\ R_{eq}}, \qquad E_{eq} = \frac{2}{\dfrac{1-\upsilon_{rf}^2}{E_{rf}} + \dfrac{1-\upsilon_r^2}{E_r}}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_{rf}} + \frac{1}{R_r}, \qquad W = \frac{F}{E_{eq}\ R_{eq}^2}$$

e_i : initial thickness of the air layer (m)

R_{rf} : film roll radius (m)

R_r : nip roll radius (m)
E_{rf}, E_r : film roll Young's modulus , nip roll Young's modulus (Pa)
E_{eq} : equivalent Young's modulus (P_a)
u : web velocity (m/s)
F : nip force (N/m)
μ_{air} : air dynamic viscosity

⇒ After one revolution, some air is laterally exhausted due to the compression exerted by the nip roll, the flow domain dimension in the transverse direction is the roll width L_0, its dimension in the longitudinal direction is the width of the Hertz contact:

$$a = 2\sqrt{\frac{2FR_{eq}}{\pi E_{eq}}} \tag{15}$$

⇒ Assuming that air lateral exhaust follows the same behavior as is the disc experimental configuration see Fig. 6, the air layer thickness at the center is given by the following expression:

$$e(t) = e_i - \frac{\beta}{\frac{L_0}{2}} t \tag{16}$$

where β depends on the film roughness and on the applied pressure. It involves that the time required for the final (equilibrium) value e_f to be reached is:

$$t_{tot} = \frac{(e_i - e_f)L_0}{2\beta} \tag{17}$$

⇒ At each revolution, the compressive stress exerted by the nip roll is applied during time t_{rev}:

$$t_{rev} = \frac{a}{u} \tag{18}$$

⇒ The number of revolutions required for the equilibrium air layer thickness to be reached (e_f) is :

$$N = \frac{t_{tot}}{t_{rev}} = \frac{(e_i - e_f)Lo}{2\beta}\frac{u}{a} \tag{19}$$

⇒ The thickness of the stack of layers is evaluated by:

$$h_s = N(h + e_i) \tag{20}$$

where: h is the nominal thickness of the film
e_i is the initial thickness of the air layer.

Actually the thickness of the air interlayer decreases from e_i to e_f, but remains far smaller than h.

As an illustration example, the following set of nominal data is chosen:

$u = 10$ m/s, $R_r = 0.1$ m, $R_{rf} = 0.3$ m, $F = 2350$ N/m, $E_{rf} = 5$ MPa,
$E_r = 0.2$ MPa, $L_0 = 0.6$ m, $\mu_{air} = 16\ 10^{-6}$ Pa.s, $\upsilon_{rf} = 0.3$, $\upsilon_r = 0.5$.

Note that the nip force value (F = 2350 N/m) has been chosen so that the mean pressure exerted on the Hertz zone is $P_a = 79000$ Pa, which corresponds to the experimental value of the test.

The velocity u, the width L_0 and the film roughness coefficient (β) will be considered as variable parameters.

It has been plotted in figure 7, the stack thickness which is necessary before reaching the equilibrium thickness of the air interlayer, as a function of the web velocity, for five values of the roll width and two different films having the same nominal thickness (12 μm; one smooth (1) and one "rough" (2)).

It is found that the equilibrium thickness is generally not attained during winding, which means that the roll state is expected to change afterwards. This trend is all the more marked as the velocity or the width increases. The "rough" film behaves slightly better from this point of view. The influence of the nip roll radius is shown in figure 8: a small diameter of the roll is more efficient than a large diameter one.

CONCLUSION

The present work is devoted to the dynamic characterization of the surface topography of plastic films. The kinetics of air exhaust in a squeeze flow experiment is connected to the film surface topography. An elementary model based on the concept of "equivalent smooth surfaces" is proposed. It exhibits a good agreement with experimental data. The mechanism of lateral air exhaust during film winding is improved.

Future developments would consist in linking this dynamic behavior to an adequate static description of a film surface. This is actually a difficult challenge to be achieved.

REFERENCES

[1] M. Boutaous and P. Bourgin, *Proc. 4th. Int. Conf. Web Handling*, Stillwater, OK, USA, 224 (1997).

[2] M. Boutaous, *PhD Thesis*, Université Louis Pasteur de Strasbourg, France (1998).

[3] J. D. Pfeiffer, Proc. 1990 *TAPPI Finishing and Converting Conf. TAPPI Press, Atlanta, GA, 233* (1990).

[4] P. Bourgin and F. Bouquerel, Trans. ASME., Adv. Info. Storage Sys. 5, 493 (1993)

[5] F. Bouquerel, *PhD Thesis*, Ecole Centrale de Lyon, France (1993).

[6] J. K. Good and M. W. Holmberg, *Proc. 2nd. Int. Conf. Web Handling*, Stillwater, OK, USA, 246 (1993).

[7] J. K. Good and Y. Xu, *Proc. 2nd. Int. Conf. Web Handling*, Stillwater, OK, USA, 213 (1993).

[8] A. W. Forest Jr. and V. L. Anderson, *Proc. 4th. Int. Conf. Web Handling*, Stillwater, OK, USA, 44 (1997).

[9] M. Handa, *Proc. 4th. Int. Conf. Web Handling*, Stillwater, OK, USA, 512 (1997.

[10] P. Bourgin, *Proc. 4th. Int. Conf. Web Handling*, Stillwater, OK, USA, 161 (1997).

[11] B. Bhushan, *Tribology and Mechanics of Magnetic Storage Devices*, Chap. 2, Springer, 2nd. Edition (1996).

[12] B.J. Hamrock and D. Dowson, Ball bearing lubrication: the Elastohydrodynamics of Elliptical Contacts, J. Wiley & Sons, New York, 1981.

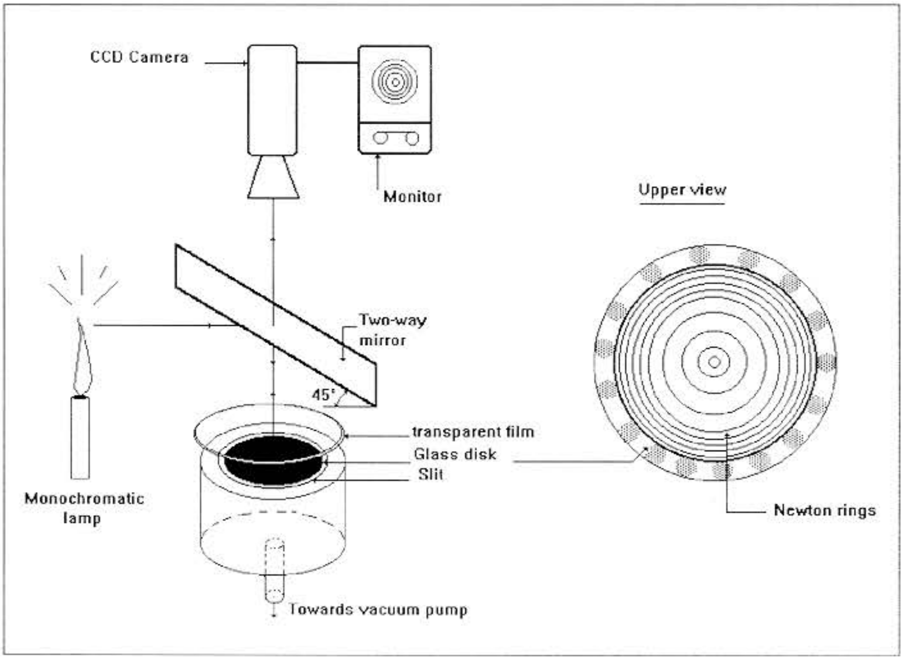

Figure 1: Experimental set up

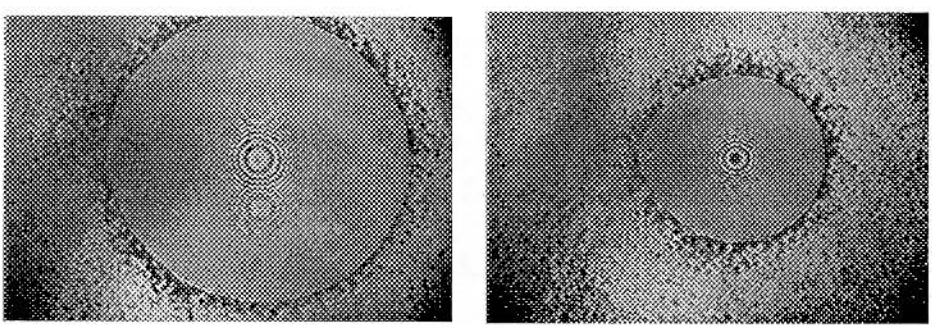

Figure 2: Evolution of the front at two different times.

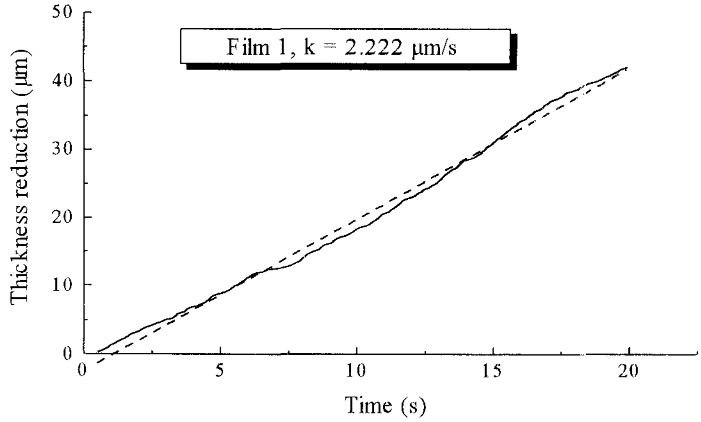

Fig. 3a: Film 1, R_h = 1.5 µm, β = 5e-8 m²/s

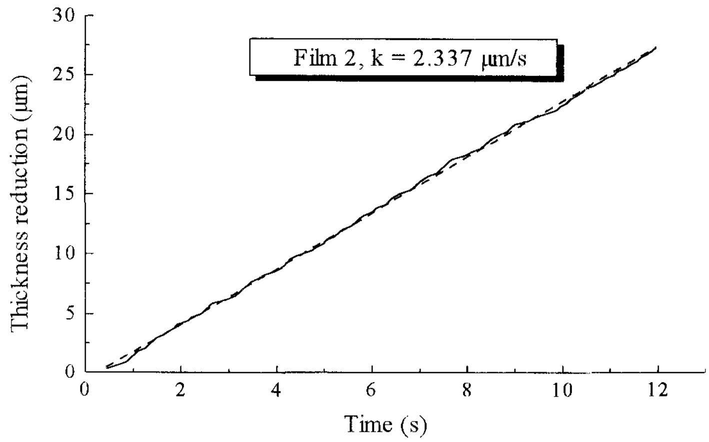

Fig. 3b: Film 2, R_h = 1.9 µm, β = 5,26 e-8 m²/s

Figure 3: Air thickness reduction as a function of time, Δ e = e_i - e(t)

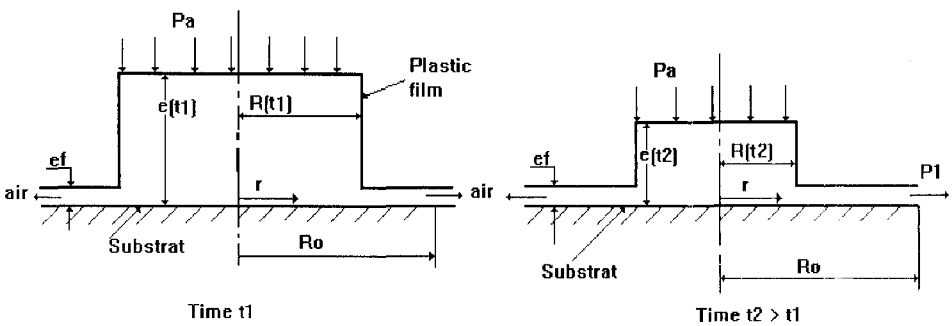

Figure 4: Model features

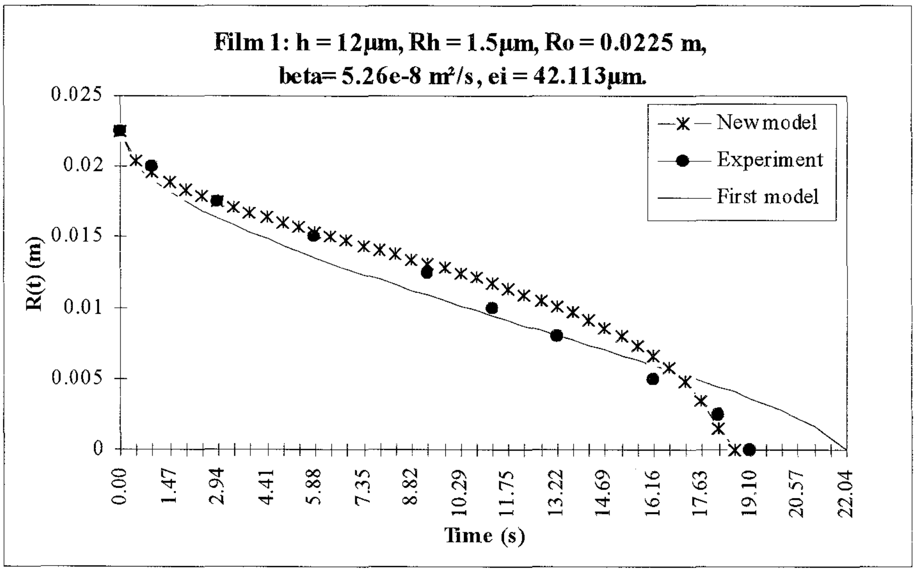

Figure 5: Evolution of the front radius versus the time comparison between the different squeezing models and the experiment

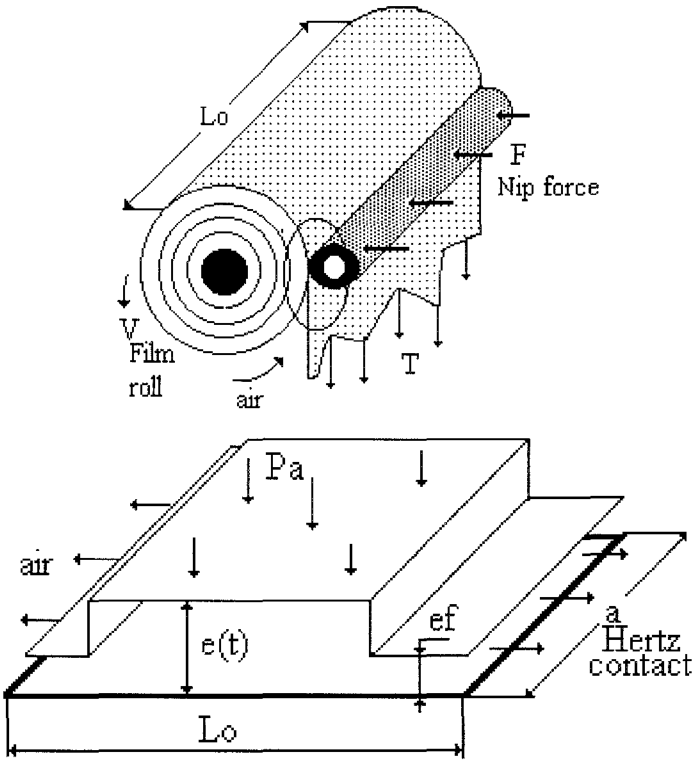

Figure 6: Lateral air exhaust under nip roll

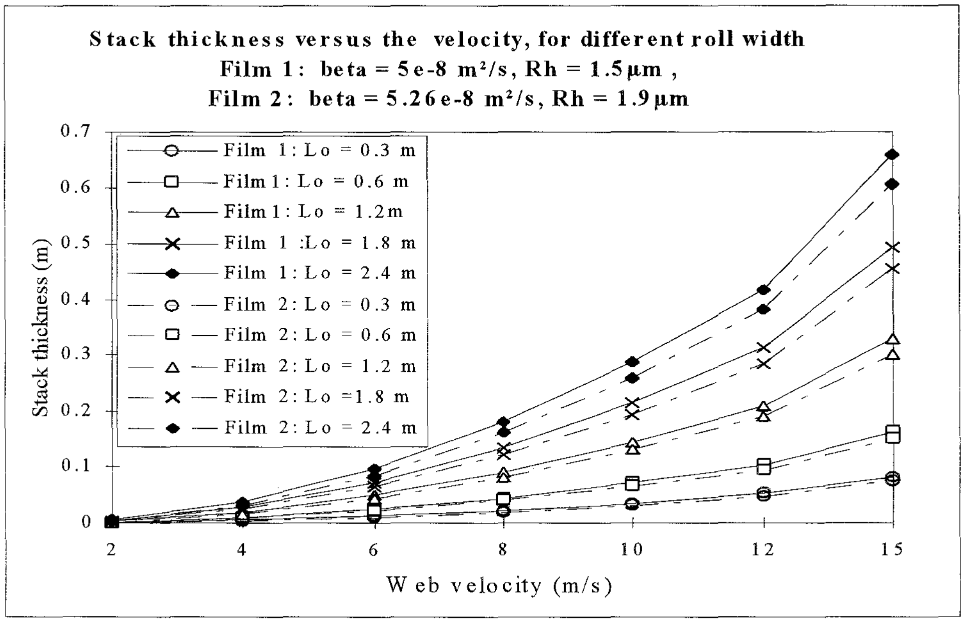

Figure 7: Stack thickness versus the Web Velocity: Influence of the roll width.

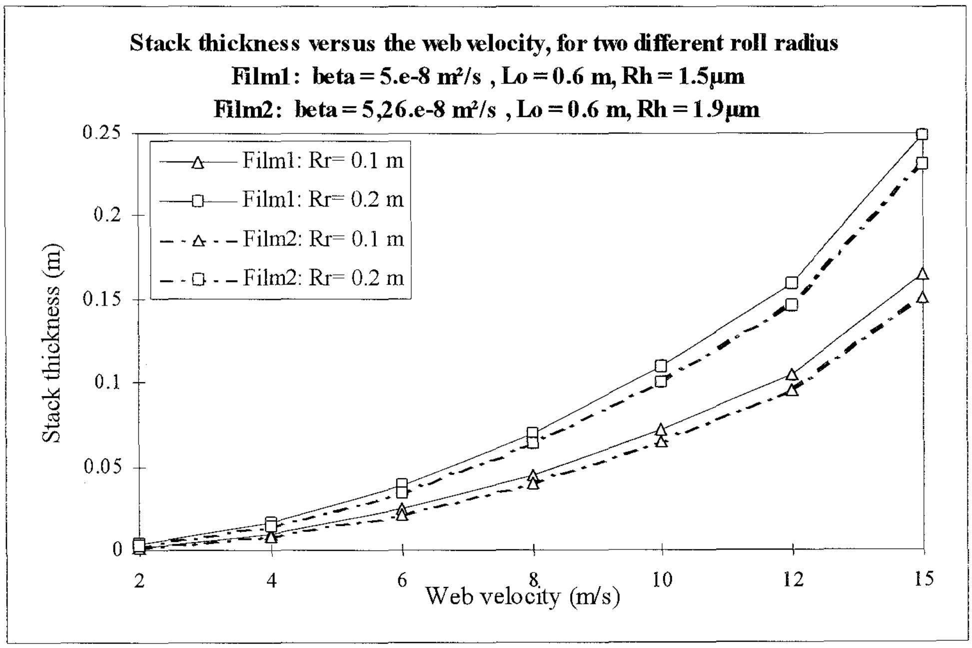

Fig. 8: Stack thickness versus the web velocity: Influence of the nip roll radius

M'hamed Boutaous, P. Bourgin

A New Parameter for Dynamic Characterization of PET film Surface Topography Law

6/8/99 Session 3 10:15 - 10:40 a.m.

Question – Brian Rice – Kodak

How did you measure the change in thickness? I understood the ring is going out from the sensor.

Answer – M'hamed Boutaous, University Louis Pasteur

We measure by image processing the number off Newton rings having the same color. And then we have a simple formula to get the equivalent of the thickness reduction.

Question – Michael Holmberg, Rexam

Regarding your system that you used for measuring the Newton rings: Is that a full wound roll that you are putting inside this apparatus? It doesn't mention dimensions. The material that you actually measured in your apparatus. How big a roll is that you're putting inside there?

Answer – M'hamed Boutaous, University Louis Pasteur

It is a single sheet. The film must be transparent to use these techniques.

Question – Dilwyn Jones, Dupont

I had two questions. One, going from your lab tests to the prediction of air escape in the roll. In the lab test you have the rough surface of the film against the smooth surface of the glass. But in the roll you have two effects. One is that you have two rough surfaces together now, film against film, and secondly, you seem to say that all the air exhaust is due to the lay-on roll pressure coming once per revolution. Whereas, in fact, the depths that your results show you would actually develop a high roll pressure between the layers anyway; just from the successive winding.

Answer – M'hamed Boutaous, University Louis Pasteur

We have employed several approximations when we apply this parameter to the roll analysis. There was not a final version, rather just to see how this parameter affects the wound roll. Really you have two rough faces. Here we have just one, because the plate is smooth. For the second question, please repeat.

Question – Dilwyn Jones, Dupont

When you were presenting the time at depths below which the air would be full exhausted. You seem to be saying that the pressure that does that is just a repeated application of the lay-on roll.

Answer – M'hamed Boutaous, University Louis Pasteur

Yes it is. We have the addition of layer after layer. We project the thickness of the stack which will be wound after the considered layer, until reaches an equilibrium state. But are not interested by what has happened in this stack.

Question – Dilwyn Jones, Dupont
I think that I understand that calculation. It's just that, even if you had no lay-on roll, there would still be a pressure in the rolls.

Answer – M'hamed Boutaous, University Louis Pasteur
If we have just one layer, the time we measure the reduction of the L air which is given by using our line of flow, just for one revolution. And we have the time is equal to the time of one revolution on the velocity of the web. For each time we can have the reduction of the L air. And we make all of the reductions and then we have the final total time, assuming always the same pressure in the Hertz contact zone.

Question -- Sinan Muftu - MIT Haystack
You considered the squeeze film effect, it seems like in leaving the air out. In your opinion do you think that the shear also has an effect in overall pressure and perhaps retarding the air bleeding real applications.

Answer – M'hamed Boutaous, University Louis Pasteur
Really, yes. That is what has happened. But in squeezing, we haven't any shear. We squeeze and we have a normal pressure and the parameter which governs this is the applied pressure and the LA which is confined I think, the web displacement is just perpendicular to the substrate.