# AIR ENTRAINMENT IN WEB HANDLING: TO BE AVOIDED OR MASTERED?

by

P. Bourgin
Universite Louis Pasteur
France

## ABSTRACT

The presence of ambient air is of prime importance in various industrial processes involving web handling. This paper is an attempt to answer the following questions: how does air influence the quality of the final product? How is it possible to cope with such a situation?

After a brief description of a few basic problems of fluid mechanics, namely: (i) the development of boundary layers on moving webs and (ii) the flow structure and pressure generation in wedges (i.e. « corner flows »), several illustrative examples are presented.

(1) When a flexible web passes over a spindle, a thin air layer is formed between the two surfaces. This is typically a foil bearing configuration, which is important to master in order to reduce wear reduction or to avoid any misfunction at the head-tape interface. A brief survey of the historical works on this topic will be given.

(2) In wound roll models, the stress field generated in the roll depends on the winding conditions (i.e. geometry and processing parameters) and on the flexible media bulk properties (elasticity or viscoelasticity) and surface properties (topography). It is well known that there is a stong link between the roughness of a surface (resulting from microparticles added to the resin) and its behavior in terms of air entrainment and evacuation. A first attempt to study the complex mechanisms governing this link is proposed.

(3) In high velocity coating flows which are present in numerous processes (magnetic tape manufacturing, paper industry,...) some air can be entrained between the solid substrate and the liquid layer being coated on it. After a qualitative description of the complex phenomena occuring in the vicinity of the three-phase junction, the amount of air likely to be entrained is evaluated on the basis of a theoretical model.

As a conclusion, a few recommendations for practical applications will be tentatively drawn.

## INTRODUCTION

Air is the most common and also the most mysterious fluid. It has long been a dream for men to play with air like birds do. However, the development of aircrafts and rockets should not let us forget that air plays an important role -although not well known- in many industrial processes. The aim of this lecture is to stress the importance of surrounding air in every situation involving flexible media being transported.

After having recalled a few basic features, namely the development of boundary layers on moving continuous surfaces and the flows in sharp corners, several illustrative examples will be considered. In each case, suggestions for future developments will be proposed.

## MOVING SURFACES AND BOUNDARY LAYERS

When a solid surface moves through a bounding fluid, it entrains a surrounding volume of fluid. Due to the viscous nature of any fluid (including air!) and to the fact that any fluid sticks at the surface of any solid, a thin layer (called "boundary layer") forms along the moving surface and a drag force is exerted opposite to the motion direction.

Boundary-layer theory is a very old branch of fluid mechanics. The characteristics of boundary-layers which develop along surfaces of finite width, such as wings for example, have been extensively studied : see for instance Schlichting [1]. However, Sakiadis [2], [3] was the first to investigate the behavior of boundary-layers on continuous surfaces, such as a flexible web or a thread transported between two rolls, or a polymer sheet or wire extruded from a die. The main difference between the two situations lays on the fact that the boundary conditions are not the same ones. In the case of a moving surface of finite length, the boundary-layer limits are imposed by the geometry, i.e. the leading and trailing edges of the surface. In the case of a continuous surface, the origin and termination are not identified to any physical part of the surface but results from the boundaries of the system itself, i.e. the neighborhood of the moving surface. Sakiadis [2], [3] found that the drag force on the continuous flat surface was different from that on an equivalent surface of finite length: higher for the laminar boundary-layer, lower for the turbulent boundary-layer. Burley [4, 5, 6] has applied these concepts and demonstrated the effects of entrained air flows, particularly in the case where the entrained flows converge within a region where the bounding surfaces are under convergent motion. For example, in coating flows, some air must eventually be dragged towards the liquid / solid region of contact where it must be either admitted along with the solid surface, or rejected. The same holds for the converging zone between a flexible web and the nip-roll or the wound roll. In each case, and in similar ones, a brief description of flows in sharp corners is necessary to identify the basic phenomena.

## CORNER FLOWS

The flow configuration of interest within the framework of air entrainment in web handling is that of two convergent moving surfaces, where a bearing force is generated and eventually tends to separate the surfaces, leading to a leak flow in the apex: see fig.1.

The flow domain is split into two zones:

(1) The « upstream zone » where the pressure is not high enough to lead to any significant « lifting effect »and to affect the shape of the boundaries. The main part of the air inflow is rejected and complex flow patterns, involving recirculations and eddies, take place. The air flow in this zone is typically a « corner flow », i.e. the flow of a viscous

fluid near a sharp corner between two planes . Such a flow has been studied for various boundary conditions. The plane creeping (i.e. inertialess) flow due to a source or sink at the intersection of two plane boundaries seems to have been first considered by Jeffery in 1915 [7], followed by Hamel in 1917 [8]. The general flow near a corner between plane boundaries at rest or between two plane free surfaces has been studied by Moffat [9] who has discussed the existence of eddy patterns. Moffatt's analysis basically consists in searching for the stream function under the form of a truncated series in planar coordinates (r, θ). The boundary conditions express the classical no-slip condition at the wall.

In order to take into account the existence of a « contacting zone », i.e. a zone where a small amount of fluid (air) passes throughout the corner, a leak flow is imposed at the apex. It has been shown that Moffatt's analysis still applies [10].

Two illustrative examples are given in figures 2a and 2b. Figure 2a corresponds to the case of two plane surfaces converging towards each other at the same velocities, whereas in figure 2b, the upper surface is steady. The main features are: (1) the existence of a stagnation point, (2) large reverse jets upstream the « neutral stream-line » (i.e. the stream-line which corresponds to the stagnation point) and (3) a « contacting zone », downstream the « neutral stream-line » where the fluid (air) is admitted and the pressure field is generated. Note that the stagnation point is located on the steady surface (Fig.2b).

(2) In the « contacting zone », close to the (apparent) intersecting line of the two moving surfaces, the pressure increases and a bearing force is created which tends to separate the two surfaces from each other. The shape of the gap results from the balance of the forces exerted on each surface, namely: (i) the tension T (or surface tension in the case of a liquid surface), (ii) the lifting force F and (iii) a possible additional « pinning force » A. Such a situation is sketched in figure 3.

The problem is that of a coupling between fluid mechanics and deformable solids and can be solved by means of iterative procedures. Such a situation prevails in three examples which will be further developed: (1) the so-called « foil bearing » ; (2) the three-phase junction in coating flows (in this case, one of the intersecting surfaces is a liquid sheet being coated onto a moving solid substrate) and (3) film winding (in this case, the air layers which separate the film layers in a wound roll are a consequence of air entrapment between the film roll and the film sheet being woud around it and air exhaust due to the superimposed film layers).

## FOIL OVER A GUIDE : APPLICATION OF FOIL BEARING THEORY

A flexible foil pulled around a cylindrical guide, roller or magnetic head is a situation which commonly occurs in drives for magnetic tape, paper and other such materials. Due to the basic phenomena described before, an ultra-thin air layer will separate the two surfaces. Mastering the conditions under which this layer is formed is fundamental to avoid (or reduce) problems such as wear degradation, demagnetization phenomena or any misfunction at the head-tape interface.

Figure 4 illustrates the sort of problem which is to be analysed: the basic configuration is that of a foil bearing. A web approaches a spindle of radius $R_0$ at a velocity U. The wrap angle Θ is considered as known. As the web passes over the cylinder, it entrains an air film and a pressure fied is generated in the contacting zone. The problem consists in finding the air film profile (i.e. its thickness as a function of the distance around the spindle) as a function of the spindle radius, air viscosity and controlling variables such as the tape velocity, tension and others.

The first publication in the field of foil bearings was perhaps that of Block and van Rossum [11] who found experimentally that the film thickness remains constant over most the region except in the exit zone where deflection occurs. A relatively large amount of literature has been devoted to this problem. The aim of the present lecture is not to propose an axhaustive bibliographical survey but to mention the papers which can be considered as significant contributions to this field : see references [11] to [32].

The form of the problem is such that analytical methods based on perturbation analysis and matched asymptotic expansions be applied [12]-[20].

Typically, the analysis revolves around the dimensionless group $\mu U/T$, for steady cases and for transient ones as well. For instance, assuming that:

- the foil is perfectly smooth, perfectly flexible, and inertialess ;
- the tension is uniform ;
- the fluid (air) is incompressible and inertialess,

Eshel and Elrod [13] have proposed the following expression for the nominal value h* of the film thickness:

$$h^*/R_0 = O.6430\ (6\mu U/T)^{2/3} \qquad (1)$$

Improvements have been intoduced by using less restrictive assumptions. For instance, the effects of bending stiffness of the tape, or of the compressiblity of air, or of transient variations of the tension have been studied numerically (see also for example references [21] to [25]).

Contrarily to the large amount of theoretical work which has been done in the field of foil bearings, there is less experimental work. This is probably due to the extreme difficulties in measuring so tiny distances between two solids, one of these being moving and flexible. One of the pionneering works is that of Ma [26] in 1965, followed by Licht [27], [28]. Licht's results are in very good agreement with Barlow's theoretical predictions [21]. Ma and Licht used capacitance probes. Although not very recent, it is worth mentionning a review of the various techniques (listed as capacitive, inductive and optical) given by Lin [29].

Having mastered the basic phenomena, the next step would consist in modifying the operating conditions in order to either reduce or increase the air layer thickness. For instance, Eshel [30] has shown that small corners in the solid wall over which the foil passes tend to significantly reduce the air layer. On the contrary, it may be useful to avoid any solid/solid contact during transient regimes (starts-up and stops). Wildmann et al. [31] have shown that the effect of even small external pressurization is very important. This can be achieved by feeding air into the region of wrap through orifices or capillaries : see for example [32].

Due to the very small dimensions of the gap separating the web and the spindle, two effects must be taken into account :

1) the gap is of the same order of magnitude as the molecular mean free path (the Kudsen number becomes of order 1). Burgdorfer [33] introduced a new boundary condition at the wall (slip boundary condition) and deduced a modified Reynolds equation, which predicts a reduction in the bearing capacity. This result was confirmed qualitatively by Tseng's experiments [34]. This work has been followed by numerous papers written by various authors, see for instance [35] or [36].

2) the gap is of the same order of magnitude as the surface roughness, which means that the Reynolds equation no longer holds. Theoretical work in that field seems to have been initiated by Tzeng and Saibel [37], followed by Christensen and Tonder [38], then many others (see for instance : [39]). This domain is very difficult and there are still many open questions, among which a few will be adressed further on.

## AIR ENTRAINMENT AND FOIL WINDING

Setting apart the defects such as wrinkles which are mainly due to disymmetrical conditions applied to the web prior to winding, for example the misalignment of one (or more) transport roll, it is generally acknowledged that winding defects generated within the roll of a flexible medium are strongly connected to its stress state. In other words, the conditions for a defect to occur can be related to the fact that at least one component of the stress is greater than some critical value.

For instance, if a roll is wound « too loosely », two types of defects may occur :

- One, commonly called « telescoping » corresponds to lateral slippage of the layers.

- One, called « starring» results from circumferencial buckling of the layers.

In the contrary, winding a roll too tightly can lead to the following defects :

- A phenomenon called « blocking »: adjacent layers « stick » to each other. More generally any minor defect occurring locally (for example a dust particle entrapped between two layers) can be enhanced under excessive radial compression.

- The generation of « screw » shaped defects, i.e. buckling in the axial direction due to lateral negative (i.e. compressive) stresses resulting from stretching in the longitudinal direction (Poisson effect).

In order to achieve a satisfactory stress field within a roll, it is necessary to adapt the processing conditions (tension, velocity, nip force, location and mechanical properties of the nip roll, characteristics of the core,...) to the bulk and surface properties of the web being wound (typically paper or plastic film). For that purpose, various wound roll theoretical models have been developed as guide-lines for the choice of optimum processing conditions.

All the models which have been proposed for evaluating the internal stresses are based on the theory of accreted bodies [40]. They can be ranked into two categories:

1) Models where the radial modulus is prescribed *a priori*. The first application of the theory of continuously accreted bodies is probably due to Altmann [41] and Tramposh [42]. Altmann assumed the roll to be an elastic, anisotropic body, with elastic properties (Young's moduli and Poisson ratios) constant throughout the roll. Yagoda [43] then Connolly and Winarski [44] accountered for core deformation. Pfeiffer [45] introduced an exponentially varying radial modulus.

2) Models where the roll radial properties are not known *a priori*, but vary during winding because they result from the stress generated during winding, the stress field itself being dependent on the roll radial properties (among others!).

These « second generation » models are consistent with the experiments devoted to the compressive behavior of stacks of films where the effects of both surface roughness and air interlayers can be evaluated. For example, Pfeiffer [46] showed that the compression and decompression cycles exhibit an hysteresis, and also rate dependent properties. Such phenomena are due to the presence of air interlayers. Forrest [47] has carried out experiments in a vacuum in order to eliminate any air effect and correlated the stack compression responses to surface topography parameters. Good and Xu [48] developed a model, based on the classical theory of rough surfaces in contact (see for instance Greenwood and Williamson [ 49]).

Hakiel [50] was the first to introduce a pressure dependent radial modulus into his wound roll model.

If one considers that the non-linear behavior of the roll in its radial direction is directly connected to the amount of air being kept beween the web layers (see Good and

Holmberg [51]), it is necessary to propose a global approach in which the winding process presents two steps closely linked to each other (see Bourgin and Bouquerel [52], [53], [54]) :

(i) At each revolution, the roll is compressed by the superimposed film layer and by the nip roll, which consequently changes its residual stresses (elastic phenomena) and squeezes away a certain amount of air throughout the roll edges (irreversible phenomenon leading to the increase of the radial modulus).

(ii) The thickness of the air layer entrained between the roll being formed and the upper film layer is a function of the radial mechanical properties of roll, which in turn depends on the underneath film layers and residual air interlayers.

All the « second generation » models give rise to the following problems, which will be briefly discussed:

(1) How to evaluate the initial thickness of the first entrapped air layer?

(2) How to characterize the radial mechanical properties of a wound roll assimilated to a composite stratified material ?

(3) How to evaluate the amount of air which escapes at each revolution and consequently the residual amount of air?

The answer to **question (1)** depends on the conditions of air entrapment. For instance, the foil bearing theory can be readily applied to evaluate the thickness of an air film which separates a web and an idler roller, provided that the wrap angle be not too large. Good and Holmberg [51] extended this result to the condition of centerwinding without a rider roll. However, in the case of a configuration with a nip roll, as sketched in Figure 5, different theories should be used. Owing to the fact that there is strong coupling between pressure generation in the wedge due to air entrainment and elasticity effects (both the wound roll and the nip roll are highly deformed at the contact), elastohydrodynamic theories can be applied. For example, Hamrock and Dowson [55] proposed a formula built on non-dimensional parameters which gives the minimal film thickness $h_0$ as a function of velocity V, load per unit width F, viscosity $\mu$ of lubricant (air in the present case) and parameters characteristic of the rolls (radii $R_1$ and $R_2$, Young's moduli $E_1$ and $E_2$, and Poisson ratios $\nu_1$ and $\nu_2$, respectively):

$$H = 7.43U^{0.65}\ W^{-0.21} \tag{2}$$

where H, U and W are defined as follows:

$$H = h_0/R_{eq}\ ;\ U = \mu V/R_{eq}\ E_{eq} \text{ and } W = F/R_{eq}\ E_{eq},$$

with : $1/R_{eq} = 1/R_1 + 1/R_2$

and : $2/E_{eq} = (1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2$

This theory is valid for purely elastic solids, which makes it questionable its use in the case considered here.

Let now comment on **question (2)** : it can be seen that the underneath layers influence the upper air underlayer thickness through the intermediate of the wound roll radial Young's modulus ($E_1$). More than that, the hypothesis of reversible, linear elastic behaviour is certainly not true! As quoted before, the behaviour of the wound roll in the radial direction is a complex combination of roughness effects and of air escape. Good and Covell [56] considered three distinct cases : (i) the air film thickness is less than the mean surface roughness and then the radial modulus is governed by the asperities only, (ii) no asperity contact occurs between adjacent web surfaces and then the radial modulus can be deduced from considerations dealing with compression of air between smooth surfaces, (iii) the air film thickness is high enough to prevent all the asperities from contacting, but a few do: this is an intermediate case.

Additional theoretical and experimental work, based on a more sophisticated description of the interactions between two rough surfaces close to each other is certainly needed.

This is also the case for **question (3)** which is concerned with the difficult problem of a viscous flow between complex boundaries. The first step would consist in describing the surface topography in an adequate way. In the case of plastic films added with fillers, the surface is composed of a sparse distribution of protusions on an underlying smooth surface. This is different from a metallic surface which could be better assimilated to a « wavy » surface. Therefore, the numerous studies dealing with lubrication of « rough contacts » (i.e. metals) should be applied with the greatest precaution.

The concept of « equivalent smooth surfaces » seems to be promising. Actually, it is necessary to know the following features at a first step :

(1) the limiting value of the average gap between two rough surfaces under prescribed compression. Experiments reported in [53] lead to an empirical relationship between the limiting value of the gap, the applied pressure and parameters related to surface roughness. Further tests are probably needed following this way.

(2) the gap reduction resulting from prescribed compression applied during a given time lag. An experimental set-up, described in [57] made it possible to study the response of several film samples submitted to given compression conditions: starting from a certain value of the mean gap, the time requested to reach the « equilibrium value », which corresponds to the pressure applied, is proportionnal to the area of the facing surfaces through parameters related to surface topography. This result can be used to simulate air evacuation from a roll (during and after winding), keeping in mind the following features:

1) the volume of air laterally expelled is proportionnal to the apparent contact area ;

2) air will continue to escape from two adjacent layers until the average value of the gap reaches its limiting value associated with the applied pressure.

Improvements need to be made in order to better cope with the microscopic description of the adjacent surfaces and its relationship with the conditions of squeeze flow should be carefully investigated.

From the experimental point of view, it is necessary to develop a comprehensive desription of what a film surface is. It probably involves the introduction of new pertinent parameters.

Mathematical tools called « homogeneisation techniques » are commonly used in the case of heterogeneous media (composite materials or concentrated suspensions) and allow an « equivalent homogeneous material » to be defined. The concept of an « equivalent smooth surface » should be introduced in the same spirit as in these techniques. Work is in progress : see for instance [57] or [58].

## AIR ENTRAINMENT AND HIGH VELOCITY COATING

Many industrial processes require the spreading of a viscous fluid on a solid substrate. The liquid may be of various types, depending upon the application which is sought for : paint, photography, magnetic media,...Industial coating processes are extremely varied in type and design, from the simple tank which treats a continuous surface by direct contact with the bulk solution to the extremely accurately designed thin film coating machines which transfer, directly onto a substrate, the final thin film of coating liquid. In all these coating processes, the solid substrate is generally a flexible solid surface (plastic film, paper, woven and non-woven fabrics,...). As all coating operations take place in an environment of surrounding air, it is to be expected (and it is found!) that air interferes with the quality of the finished layer. Actually, the onset of air entrainment is the ultimate limiting factor!

Experimental studies concerned with the mechanisms of air entrainment have been carried out in detail by several authors since 1972, see for instance [59], [60], [61]. Many studies summarized in [62] have shown that above a prescribed coating speed, the coating layer becomes unstable and discontinuous, and air is eventually entrained between the solid surface and the liquid layer.

In parallel, this problem has been tackled theoretically, the step being to evaluate the amount of air likely to be entrained. A first approach, based on a simplified model for the meniscus has been proposed by Emonot [63]. In this context, the concept of a « triple line » (i.e. the three phase junction: solid-liquid-air) has been reconsidered [64], [65]. A novel approach of the free surface problem consists in writing the local dynamic balance of the meniscus submitted to bulk forces, including the bearing force created in the air wedge (see figure 3). The triple line is rejected to infinity and the amount of air likely to be entrained is predicted on the basis of the technique of matched asymptotic expansions [66]: the thickness of the air layer at infinity is proportionnal to $Ca^{2/3}$ and Bo, where Ca denotes for a modified Capillary number, in the sense that it is built on the viscosity of air (and not of the liquid as classically defined) and Bo is the Bond number.

For practical applications, it could be proposed to reduce air entrainment by using aspiration nozzles or even vacuum boxes (if possible!).

## CONCLUDING REMARKS

Surrounding air influences many industrial processes involving web handling and hence cannot be neglected. In most cases (except, maybe, in high velocity coating), it should not be eliminated because its role is useful when mastered in an adequate way. For example, the solid/solid contact (and wear as a consequence) between the magnetic tape and the recording (or reading) head is prevented by a tiny air layer, the thickness of which can be easily controled. In plastic film winding, the suppression of the air interlayers would lead to very compact rolls, which would be hardly possible to unwind, because of the action of short distance forces!

The phenomena involved are complex for the following main reasons (not exhaustive!):

- Strong coupling between a fluid (air) and highly deformable solids (web, wound roll) ;
- Flows in confined geometries with no « characteristic dimension » (the gap separating the film layers is of the same order of magnitude as the asperities).

Empirical adjustments of the process parameters have reached their limits. Fundamental experiments with the aim of understanding the basic phenomena should be encouraged. The development of theoretical models should be carried on in order to propose guidelines for further improvements of the processing conditions.

## REFERENCES

[1] Schlichting H., "Boundary Layer Theory", Mc Graw Hill, New York, 1955.

[2] Sakiadis B.C., Boundary Layer Behavior on Continuous Solid Surfaces: I. Boundary-Layer Equations for Two-Dimensional and Axisymmetric Flow, A.I.Ch.E. Journal, Vol. 7, N° 1, pp. 26-28, 1961.

[3] Sakiadis B.C., Boundary Layer Behavior on Continuous Solid Surfaces: II. The Boundary-Layer on a Continuous Flat Surface, A.I.Ch.E. Journal, Vol. 7, N° 2, pp. 221-225, 1961.

[4] Burley R., Fluid Behaviour between Horizontal Pad Rollers, J. Text. Institute & Industry, Vol. 9, N° 8, pp. 164-188, 1971.

[5] Burley R., Grigg P., A Solid State Pulser for the Hydrogen Bubble Flow (Flow Visualization Technique), J. Phys. E Scientific Instrum., Vol. 3, pp. 1018-1020, 1970.

[6] Burley R., Low induced by a Continuous Surface between Rollers, Chem. Eng. J., Vol. 2, pp. 215-217, 1971.

[7] Jeffery G.B., On the two-dimensional steady motion of a viscous fluid, Phil. Mag., Vol. 29, p. 455, 1915.

[8] Hamel G, Spiralformige Gewegungen zäher flüssigkeiten, Jahresbericht der Deutschen Mathematiker Vereinigung, Vol. 25, p. 34, 1917.

[9] Moffatt H. K., Viscous and resistive eddies near a sharp corner, J. Fluid Mech., Vol. 18, p. 1, 1964.

[10] Bourgin P and Tahiri N., Generalized Jeffery-Hamel flow : application to high velocity coating, Proc.First European Coating Symposium, Leeds, pp. , 1995.

[11] Block H. an van Rossum J.J., The foil bearing-A new departure in hydrodynamic lubrication, Lub. Engng., Vol. 9, N°6, pp. 310-320, dec. 1953.

[12] Langlois W.E., The lightly loaded foil bearing at zero angle of wrap, IBM Journal of Research and Development, Vol. 7, N°2, pp. 153-154, 1963.

[13] Eshel A. and Elrod H.G. Jr., The theory of the infinitely wide, perfectly flexible, self-acting foil bearing, A.S.M.E. Trans., J. Basic Engng., pp. 831-836, dec. 1965.

[14] Eshel A. and Elrod H.G., Jr., Stiffness effects on the infinitely wide foil bearing, A.S.M.E. Trans., J. Lub. Tech., Vol. 89, pp. 92-97, jan. 1967.

[15] Barlow E.J., Self-acting foil bearings of infinite width, A.S.M.E. Trans., J. Lub. Tech., Vol. 89, pp.341-345, july 1967.

[16] Eshel A., Compressibility effects on the infinitely wide, perfectly flexible foil bearing, A.S.M.E. Trans., J. Lub. Tech., Vol. 90, pp. 221-225, jan. 1968.

[17] Eshel A. and Wildmann M., Dynamic behavior of a foil in the presence of a lubricating film, A.S.M.E. Trans., J. Applied Mech., Vol. 35, pp. 242-247, june 1968.

[18] Eshel A., The propagation of disturbances in the infinitely wide foil bearing, A.S.M.E. Trans., J. Lub. Tech., Vol. 91, pp. 120-125, jan. 1969.

[19] Eshel A., On fluid inertia effects in infinitely wide foil bearings, A.S.M.E. Trans., J. Lub. Tech., Vol. 92, pp.490-494, july 1970.

[20] Barnum T.B. and Elrod H.G., JR., A theoretical study of the dynamic behavior of foil bearings, A.S.M.E. Trans., J. Lub. Tech., Vol. 93, pp. 133-142, jan. 1971.

[21] Barlow E.J., Derivation of governing equations for self-acting foil bearings, A.S.M.E. Trans., J. Lub. Tech., Vol. 89, pp. 334-340, jul. 1967.

[22] Stahl K.J., White J.W. and Deckert K.L., Dynamic response of self-acting foil bearings, IBM J. Res. and Devop., pp. 513-520, nov. 1974.

[23] Eshel A., Numerical solution of the planar hydrostatic foil bearing, A.S.M.E. Trans., J. Lub. Tech., Vol. 101, pp. 86-91, jan. 1979.

[24] Clurman S.P., A simple tape wrap around a guide: some complexities, IEEE Trans. on Magnetics, Vol. Mag-17, N° 6, pp. 2754-2756, nov. 1981.

[25] Tadjbakhsh I.G., Ahmadi G. and E.A. Saibel, A numerical technique in the hydrodynamic theory of foil bearings, Int. J. Engng. Sc., Vol. 21, N° 7, pp. 781-789, 1983.

[26] Ma J.T.S., An investigation of self-acting foil bearings, A.S.M.E. Trans., J. Basic Engng., pp. 837-846, dec. 1965.

[27] Licht L., Preliminary experiments with foil bearings, A.S.M.E. Trans., J. Basic Engng., pp. 1-3, march 1966.

[28] Licht L., An experimental study of elastohydrodynamic lubrication of foil bearings, A.S.M.E. Trans., J. Basic Engng., pp. 199-220, jan. 1968.

[29] Lin C., Techniques for the measurement of air-bearing separation - A review, IEEE Trans. on Magnetics, dec. 1973.

[30] Eshel A., On controlling the film thickness in self-acting foil bearings, A.S.M.E. Trans., J. Lub. Tech., Vol. 92, pp. 359-362, april 1970.

[31] Wildmann M. and Wright A., The effect of external pressurization on self-acting foil bearings, A.S.M.E. Trans., J. Basic Engng., pp. 631-640, sept. 1965.

[32] Eshel A., Transient analysis of a planar hybrid foil-bearing model, A.S.M.E. Trans., J. Lub. Tech., Vol. 96, pp. 432-436, jul. 1974.

[33] Burgdorfer A., The influence of the molecular mean free path on the performance of hydrodynamic gas lubricated bearings, A.S.M.E. Trans., J. Basic Engng., pp. 94-100, mar. 1959.

[34] Tseng R.C., Rarefaction effects of gas-lubricated bearings in a magnetic recording disk file, A.S.M.E. Trans., J. Lub. Tech., Vol. 97, pp. 624-629, oct. 1975.

[35] Sereny A. and Castelli V., Experimental investigation of slider gas bearings with ultra-thin films, A.S.M.E. Trans., J. Lub. Tech., Vol. 101, pp. 510-515, oct. 1979.

[36] Hsia Y.T. and Domoto G.A., An experimental investigation of molecular rarefaction effects in gas lubricated bearings at ultra-low clearances, A.S.M.E. Trans., J. Lub. Tech., Vol. 105, pp. 120-130, jan. 1983.

[37] Tzeng S.T. and Saibel E.W., Surface roughness effect on slider bearing lubrication, A.S.L.E. Trans., Vol. 10, pp. 334-338, 1967.

[38] Christensen H. and Tonder K., The hydrodynamic lubrication of rough bearing surfaces of finite width, A.S.M.E. Trans., J. Lub. Tech., Vol. 93, pp. 324-330, jul. 1971.

[39] Elrod H.G., A general theory for laminar lubrication with Reynolds roughness, A.S.M.E. Trans., J. Lub. Tech., Vol. 101, pp. 8-14, jan. 1979.

[40] Brown B.C. and Goodmann L.E., Gravitationnal stress in accreted bodies, Proc. Roy. Soc. Lond., Vol. A, N° 276, pp. 571-576, 1963.

[41] Altmann H.C., Formulas for computing the stresses in center wound rolls, TAPPI J., Vol. 51, N° 4, pp. 176-179, 1968.

[42] Tramposch H., Anisotropic relaxation of internal forces in a wound reel of magnetic tape, A.S.M.E. Trans., J. Applied Mech., Vol. 32, pp. 888-894, 1967.

[43] Yagoda H.P., Resolution of a core problem in wound rolls, A.S.M.E. Trans., J. Applied Mech., Vol. 47, pp. 847-854, 1980.

[44] Connolly D. and Winarski D., Stress analysis of wound magnetic tape, Proc. A.S.L.E. Intern. Conf., San Diego, 1984.

[45] Pfeiffer J.D., Internal stresses in a wound roll of paper, TAPPI J., Vol. 49, N° 8, pp. 342-347, 1966.

[46] Pfeiffer J.D., Prediction of roll defects from roll structure formulas, TAPPI J., Vol. 62, N° 10, pp. 83-85, 1979.

[47] Forrest A.W., Jr., A mathematical and experimental investigation of the stack compression of films, Proc. Second Intern. Conf. on Web Handling, Stillwater, Oklahoma, USA, pp.196-212, 1993.

[48] Good J.K. and Xu Y., Computing wound roll stresses based upon web surface characteristics, Proc. Second Intern. Conf. on Web Handling, Stillwater, Oklahoma, USA, pp. 213-27, 1993.

[49] Greenwood J.A. and Williamson J.B.P., Contact of nominally flat surfaces, Proc. Roy. Soc. London, Vol A, N°295, pp. 300-319, 1966.

[50] Hakiel Z., Nonlinear models for wound roll stresses, TAPPI J., Vol. 70, N° 5, pp. 113-117, 1987.

[51] Good J.K. and Holmberg M.W., The effect of air entrainment in centerwound roll, Proc. Second Intern. Conf. on Web Handling, Stillwater, Oklahoma, USA, pp. 246-264, 1993.

[52] Bourgin P. and Bouquerel F., Winding flexible media: a global approach, Trans. A.S.M.E., Adv. Info. Storage Syst., Vol. V, pp. 493-512, 1993.

[53] Bouquerel F., Etude théorique et expérimentale de l'enroulement d'un film plastique mince - Rôle des effets aérodynamiques, Thèse de Doctorat en Mécanique, Ecole Centrale de Lyon, 1993.

[54] Bouquerel F. and Bourgin P., Irreversible reduction of foil tension due to aerodynamical effects, Proc. Second Intern. Conf. on Web Handling, Stillwater, Oklahoma, USA, pp. 246-264, 1993.

[55] Hamrock B. and Dowson D., *Ball Bearing Lubrication - The Elastohydrodynamics of Elliptical Contacts*, Ed. John Wiley & Sons, p. 281, 1981.

[56] Good J.K. and Covell S.M., Air entrapment and residual stresses in rolls wound

with a rider roll, Proc. Third Intern. Conf. on Web Handling, Stillwater, Oklahoma, USA, pp. 95-105, 1995.

[57] Boutaous M. and Bourgin P., Experimental study of squeeze film flow between one smooth surface and one « rough » surface, Fourth International Conference on Web Handling, Stillwater, Oklahoma, USA, 1997 (accepted).

[58] Bourgin P. and Woehl P., Modélisation de l'écoulement entre deux surfaces rugueuses par homogénéisation périodique, Cinquièmes Journées de la Matière Condensée (a conference sponsored by the French Physical Society), Orléans (France), 1996.

[59] Deryagin B.M. and Levi S.M., *Film Coating Theory*, Focal Press, London, 1964.

[60] Burley R. and Kennedy B.S. (in) *Wetting, Spreading and Adhesion*, ed. J. Padday, Acad. Press, London & New York, 1978.

[61] Burley R. and Jolly R.P.S., Entrainment of air into liquids by a high speed continuous solid surface, Chem. Eng. Sci., Vol. 39, N° 9, pp. 1357-1372, 1984.

[62] Burley R., Air entrainment and the limits of coatability, JOCCA, Vol. 5, pp. 192-202, 1992.

[63] Emonot J., Contribution à l'étude du contact dynamique entre une nappe de liquide et un substrat solide, Thèse de Doctorat en Mécanique, Université Claude Bernard, Lyon, 1993.

[64] Emonot J., Bourgin P. and Burley R., Micro fluid mechanics of air entrainment in high speed coating processes, Proc. Intern. Symp. on Two-Phase Flow Modelling and Experimentation, Rome, 1995.

[65] Bourgin P., Burley R. and Tahiri N., Triple line : myth or reality?, Proc. A.I.Ch.E. Spring National Meeting, New Orleans, 1996.

[66] Tahiri N., Bourgin P. and Saintlos S., High velocity dynamic contact between a viscous liquid and a solid substrate: analytical and numerical study, Euromech Symposium on Fluid Mechanics of Coating Processes, Strasbourg, Jul. 1997 (accepted).

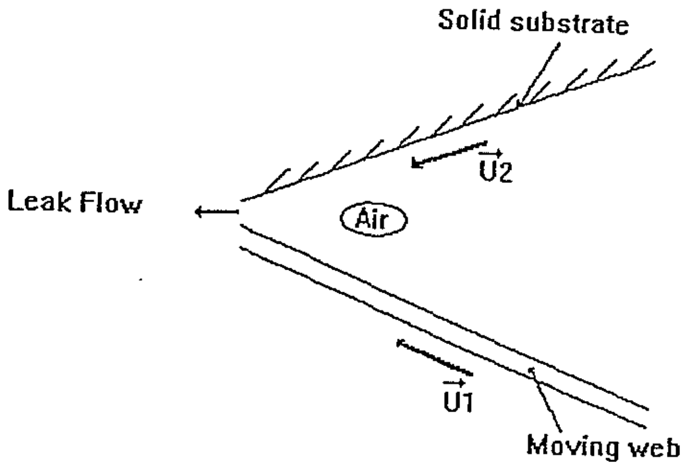

Figure 1 - Flow basic configuration

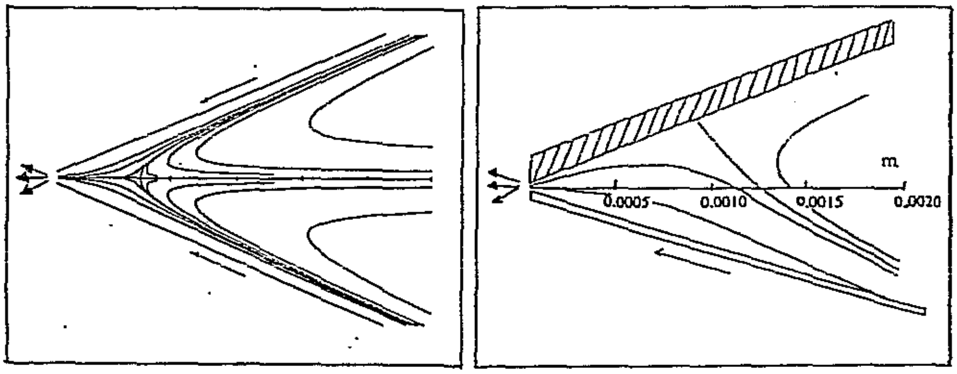

Figure 2a - Two moving surfaces Figure 2b - One steady surface

Figure 2 - Corner flows with a leak

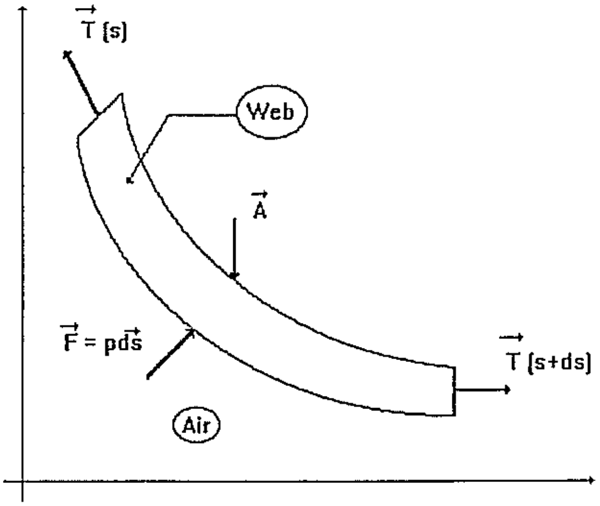

Figure 3 - Balance of forces in the contacting zone

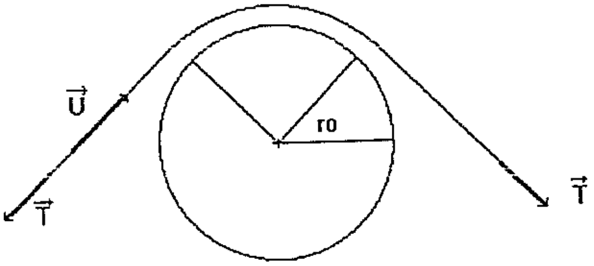

Figure 4 - Foil bearing configuration

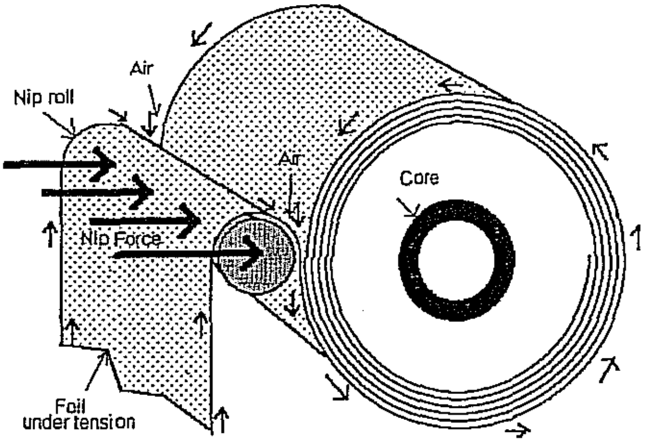

Figure 5 - Center winding with a nip-roll

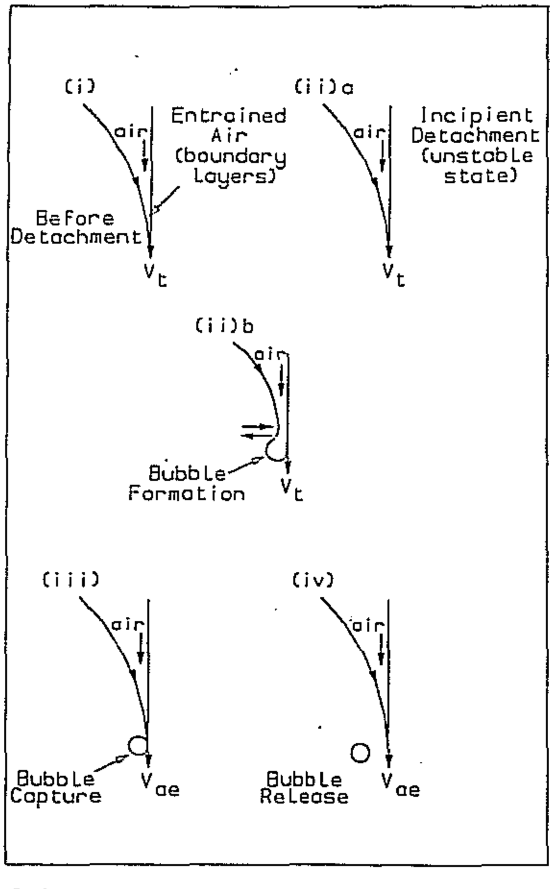

Figure 6 - Detachment of air bubbles (after Burley [62])

Question - You speak of paper not being porous. There are many shades of gray between black and white for sure, but if your operating film and continue the speed at which you're running you could probably say that paper is very porous. If you look at the film but there are a few of us in this room that are running paper winding equipment that is, we have one machine that is in production that is running in excess of 3300 meters/minute. Things happen at that speed that don't happen at 150 feet/minute.

Answer - I think that there is a competition between air entrainment and entrapment and the characteristics of air due to porosity going through the material effects it. In other words if you go to fast, air doesn't have time to escape through the material. There is a ratio of characteristic times. So I'm not surprised with your comment.