AIR ENTRAINMENT ON TWO SIDES OF A WEB PASSING THROUGH THE NIP OF TWO RIGID ROLLS

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ABSTRACT

When web materials (paper, plastic films, or metal foils) are wound into rolls, excessive amounts of air can be entrapped between layers of the web, resulting in defective rolls. Entrapped air layer between a coated film and a heating/cooling drum can significantly reduce the heat transfer rate. The most widely adopted method for reducing the amount of entrapped air in winding rolls and at heating/cooling drums is to use a nip roller, which pushes down on the incoming web. A computational method was used to determine the amounts of air passing through the nip on the two sides of the web. The study model included the effects of air compressibility, but it was assumed that the two rolls are rigid. Main variables included the wrap angle of the incoming web, web speed, nip force, and diameters of the rolls. It was found that, when the nip force is not very small and the two rolls are rigid, the amounts of air on the two sides of the web are nearly the same and can be determined using a simple model which includes only a rigid roller and a flat surface.

INTRODUCTION

When a nonpermeable web material such as a plastic film or a coated paper is wound at high speeds, as shown in Figure 1, an excessive amount of air can be entrapped in the winding roll resulting in defective products. At a heating or cooling drum (Figure 1), the air film between the web and the drum becomes a barrier to heat transfer. A similar problem occurs in magnetic recording devices where high-speed motion of the tape induces an excessive amount of air between the recording head and the tape, degrading the recording quality. In order to reduce the air entrainment in winding rolls or at heating/cooling drums, nip rollers (also called packrolls or rider rollers) are widely used. Two typical configurations of web paths associated with the nip roller are shown in Figure 2. The web may wrap over the winding roll prior to the nip (Figure 2a) or it may wrap over the nip roller (Figure 2b). The nip roller is usually covered by an elastic material such as rubber. Depending on the material properties of the rubber and the winding conditions, the nip roller can be softer than the winding roll and vice versa. On the other hand, a heating or cooling drum is made of metal and considered rigid.

A computational method is used to determine the amounts of air passing through the nip on the two sides of the web. The model includes the effects of air compressibility, but it does not include the effects of elastic deformation of the rolls or asperity contact.

COMPUTATIONAL MODEL

Geometry of Study Model

The study model is schematically shown in Figure 3, which is similar to Figure 2(a). Note that the current model is applicable to both configurations in Figure 2 because both rolls are rigid and the wrapping condition downstream of the nip is not significant unless the web tension is very high. The length of web is $L = L_{in} + R_1(\theta_{in} + \theta_{out}) + L_{out}$, and s is a spatial variable which is straight for the incoming and outgoing web spans, but curved for the wrapped region. The air gap between the web and the wrapped roll is defined as $h_1 = w + \delta$ for the incoming and outgoing spans and $h_1 = w$ for the wrapped region. Note that h_1 is the gap measured in the radial direction for the wrapped region, but it is measured in the direction perpendicular to the tangent lines for the incoming and outgoing spans. The air gap between the web and the nip roller, h_2, is defined as

$$h_2 = h_s - h_1 \qquad \{1\}$$

where h_s is the vertical distance between the two rolls excluding the thickness of the web, that is,

$$h_s = \frac{x^2}{2R_e} + h_o \qquad \{2\}$$

and R_e is the effective radius defined as

$$R_e = \frac{R_1 R_2}{R_1 + R_2} \qquad \{3\}$$

and h_o is the air gap between the rolls at the center of the nip. Therefore, h_2 is approximately the vertical distance between the web and the nip roller as shown in Figure 3. These definitions of h_1 and h_2 are not consistent, but there seems to be no better way to define them. Note that the upper roll in the diagram is called nip roller in this paper for convenience. In real situations, the incoming web may wrap over either the winding roll or the nip roller.

Governing Equations

Solutions must satisfy both the Reynolds equation and the equation of web deflection. The Reynolds equation used in this study is

$$\frac{d}{ds}\left(ph^3 \frac{dp}{ds} + 6\lambda_a p_a h^2 \frac{dp}{ds} \right) = 12\mu u \frac{d(ph)}{ds} \qquad \{4\}$$

where the second term in the parentheses indicates the effect of a slip boundary, which becomes important when the air gap at the nip is not much larger than the mean-free-path of the air.

The second governing equation is related to web deflection:

$$\frac{Et^3}{12\left(1-\nu^2\right)} \frac{d^4 w}{ds^4} - T \frac{d^2 w}{ds^2} = p_1 - p_2 - p_w \qquad \{5\}$$

where $p_w = T / R_1$ in the wrapped region, and $p_w = 0$ for the incoming and outgoing spans.

Boundary Conditions

It is assumed that the position of the web is known at ends of the incoming and outgoing spans (at $s = 0$ and $s = L$), and the bending moment is zero at those points. That is, the following conditions are required at $s = 0$ and $s = L$:

$$w = 0 \qquad \{6\}$$

$$\frac{d^2 w}{ds^2} = 0 \qquad \{7\}$$

A boundary condition frequently used instead of Eq. {6} is $dw / ds = 0$. Equation {6} is preferred in this research because it allows faster and more stable convergence of solutions. The pressures at $s = 0$ and $s = L$ are assumed the same as the ambient pressure.

Method of Solution

An iterative method was used to obtain solutions that satisfy both the Reynolds equation and the web deflection equation. Details of the method are described in J. Y. Lee (1999).

RESULTS

Ballooning

When the nip force is extremely small, the air film profile under the web is similar to that for a typical foil bearing without a nip roller. When the nip force increases, there occurs a sudden change in the deflection profile of the incoming web span as shown in Figure 4. The abscissa in the graph, s^*, is the distance along the wrapped roll surface from the center of the nip. Note that each case was computed with the position of the nip roller kept constant (h_o kept constant), and the nip force was calculated by integrating the gage pressure of air between the web and the nip roller ($p_2 - p_a$). Therefore, the five cases in the figure represent the computation results obtained for five different values of h_o. The curves in the figure form two distinct groups. When the nip force is larger than a critical value (or when h_o is smaller than a certain value), the incoming span forms a balloon shape. No solution could be obtained that fell between the two distinct families of curves. That is, the results for $F = 4.20\,\mathrm{N/m}$ and $F = 15.1\,\mathrm{N/m}$ in Figure 4 were obtained for almost the same values of h_o; if one tried to obtain a solution between these two cases, it would jump toward either one of them.

Air gap profile under the web (h_1) was computed for various values of incoming wrap angles. The balloon shape is found to be strongly affected by the incoming wrap angle as shown in Figure 5. The maximum balloon height increases with the incoming wrap angle, while the minimum air gap of the incoming span does not depend on the wrap angle. Note that the nip forces indicated in the figure are the maximum values calculated; solutions could not be obtained for larger values of nip force.

Within the range of computations, bending stiffness (or thickness) of the web does not significantly affect the ballooning phenomenon (Figure 6). Web speed and tension, however, have noticeable effects on the ballooning phenomenon. The balloon height increases with web speed (Figure 7) but decreases with web tension (Figure 8).

Amount of Air Entrainment

The amount of air passing through the nip on each side of the web is determined. Note that the amount of air to be determined cannot be expressed simply by the air film thickness at the nip. The air pressure changes along the machine direction, and it can be very high near the center of the nip. One measure of the amount of air passing through the nip is mass flow rate. In this paper, however, we use the concept of equivalent air film thickness, which is the air film thickness corresponding to the standard atmospheric pressure. Under the assumption of isothermal process, the equivalent air film thickness is determined as

$$h_c = \frac{p_{max} h^*}{p_{atm}} \tag{8}$$

where p_{max} is the maximum pressure, and h^* is the air gap at the location where the pressure becomes maximum. The above equation is valid if the air film thickness varies gradually along the machine direction so that the flow velocity profile becomes uniform at the location where the pressure gradient is zero (or the pressure is maximum).

Typical calculation results are shown in Figure 9, where the incoming and outgoing wrap angles are 8 and 2 degrees, respectively. Other operating conditions are shown in the figure. It is seen that if the nip force increases from zero, the amount of air stays nearly constant up to a certain critical value of nip force. When the nip force is greater than the critical value, the amount of air passing through the nip dramatically reduces as the nip force increases. This critical point is the same as the critical point where ballooning occurs. Near the critical point, the amount of air passing through the nip between the web and the wrapped roll is larger than the amount of air on the other side of web. As the nip force increases in the supercritical region, the amounts of air on the two sides of the web tend to converge to the same curve. Results for 13 degrees of the incoming wrap angle show the same trend.

For large incoming wrap angles, it was difficult to make the solutions converge in subcritical regions. Solutions for 20 degrees of the incoming wrap angle are shown in Figure 10.

Comparison With a No-Web Simple Model

The fact that the amounts of air entrainment on the two sides of the web approach a common curve at high nip forces implies that the air gap profiles on the two sides of web become symmetrical. That is, the amounts of air entrainment (h_{1c} & h_{2c}) may be determined based on a simple model that does not include the web. Refer to Figure 11, where the radius of the rotating roll is

$$R = 2R_e = \frac{2R_1R_2}{R_1 + R_2} \tag{9}$$

The equation for the amount of air passing through the nip for the system shown in Figure 11 was obtained by Chang, Chambers and Shelton (1994) as

$$\frac{h_c}{R} = 2.4\frac{\mu u}{F} + 2.408\left(\frac{\mu u}{p_a R}\right)^{2/3} - 1.8\cdot 10^{-6} \tag{10}$$

The computational results are compared with Eq. {10} in Figure 12 and Figure 13. The equation appears to underpredict. Additonal computations were done in a wider range of nip force. Those results show better agreement with the prediction equation as shown in Figure 14 through Figure 18. The test conditions for computations are summarized in Table 1.

It is clearly seen in Figure 19 that the amount of air entrainment increases with web speed. The effect of web tension on air entrainment, as seen in Figure 20, is not significant.

CONCLUSIONS

The effects of a nip roller on air entrainment have been analyzed numerically. The study model includes the air compressibility effects but the effects of elastic deformation of rolls are not considered. The following conclusions were obtained from this study:

- There is a critical value of nip force above which ballooning occurs.
- Once ballooning has occurred, its shape is not strongly affected by the nip force.
- Ballooning does not occur when the incoming wrap angle is small.
- The balloon height is strongly affected by the incoming wrap angle, web tension, and web speed, but not by the bending stiffness of the web in the range of current study.
- When the nip force is large, the amounts of the air entrainment on the two sides of the web tend to approach the same curve, and they can be predicted using Eq. {10}.
- A nip roller with a smaller radius is more effective than a larger one.
- Air entrainment increases with web speed.

ACKNOWLEDGMENT

This research was supported by the Web Handling Research Center at Oklahoma State University and its member companies. The authors are grateful for their financial supports.

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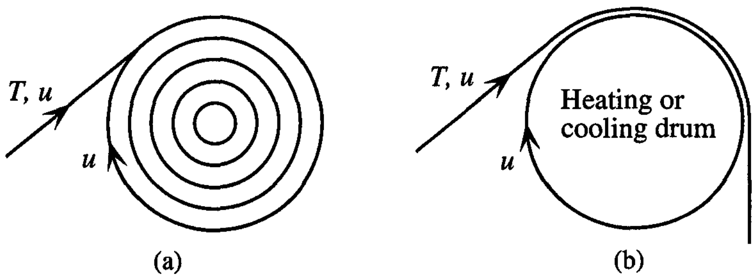

Figure 1. (a) Center winding; (b) heating/cooling

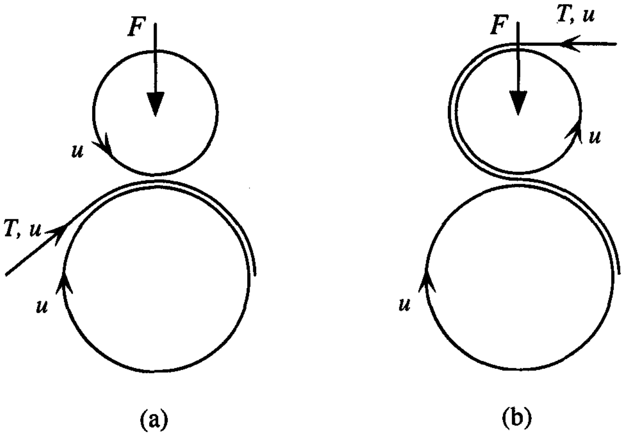

Figure 2. Typical configurations of web paths

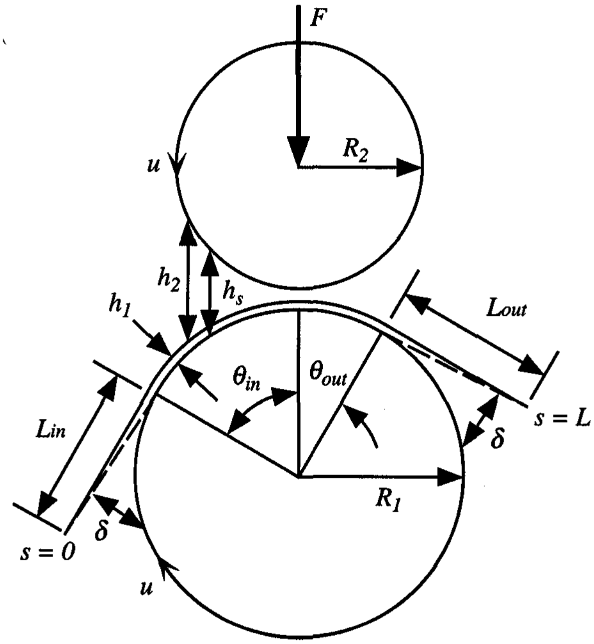

Figure 3. Study model and definition of variables

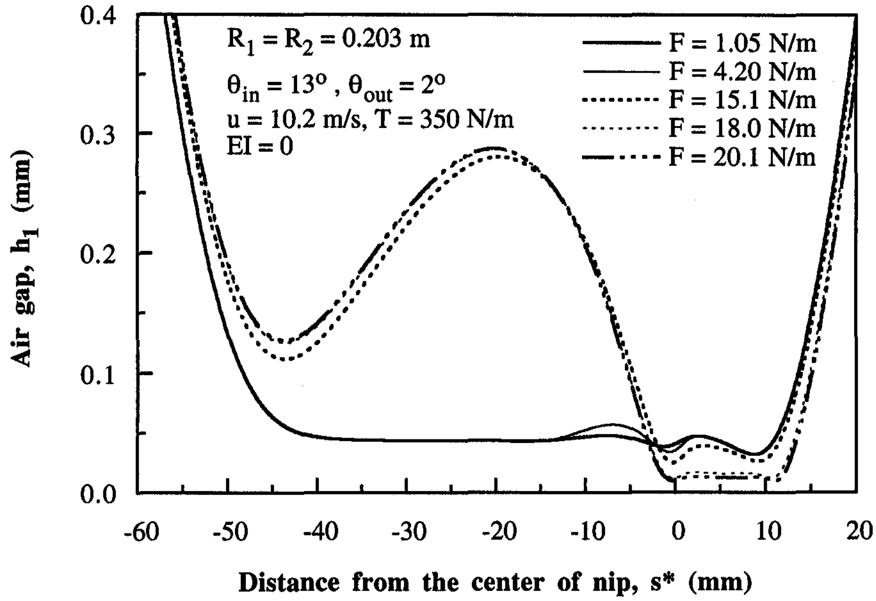

Figure 4. Profile of air gap between the web and the wrapped roll ($\theta_{in} = 13^o$)

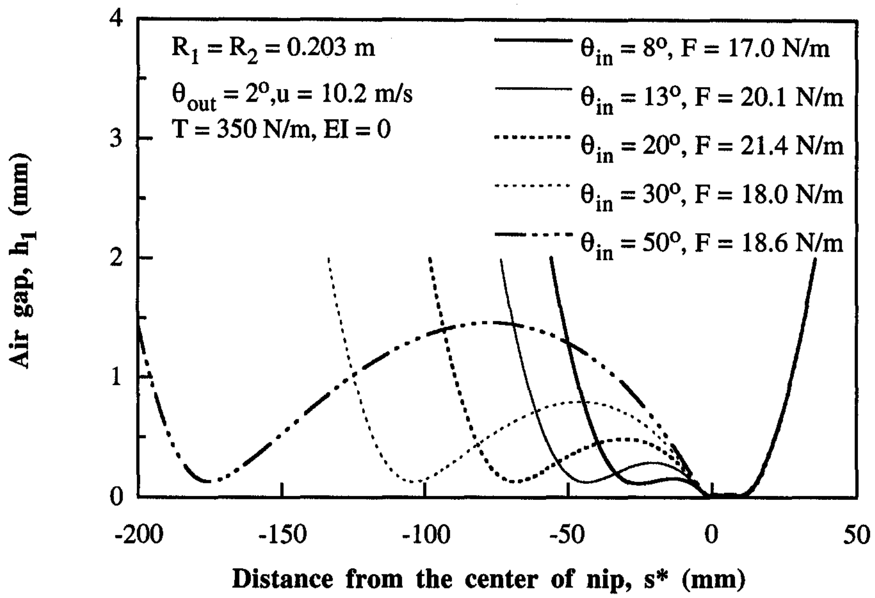

Figure 5. Effects of incoming wrap angle on ballooning

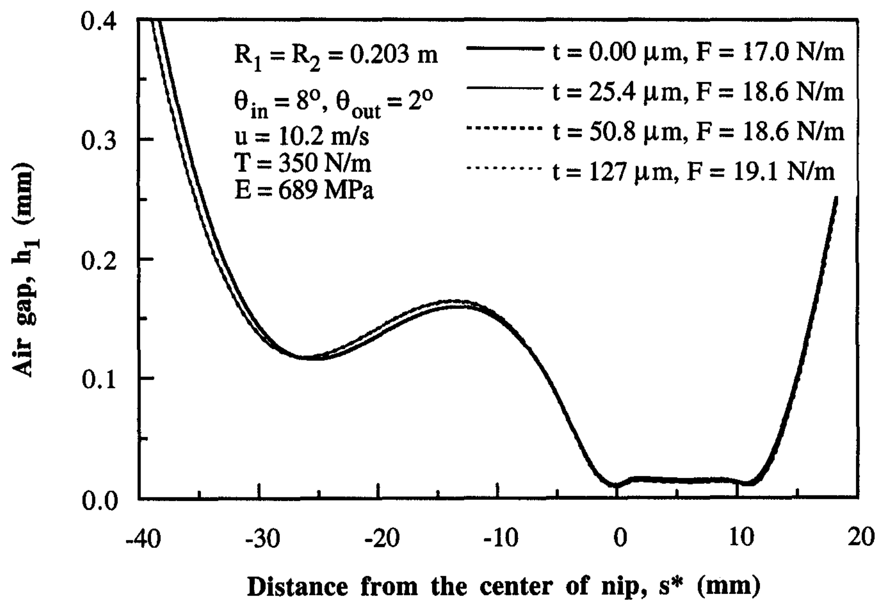

Figure 6. Effects of web stiffness (thickness) on ballooning

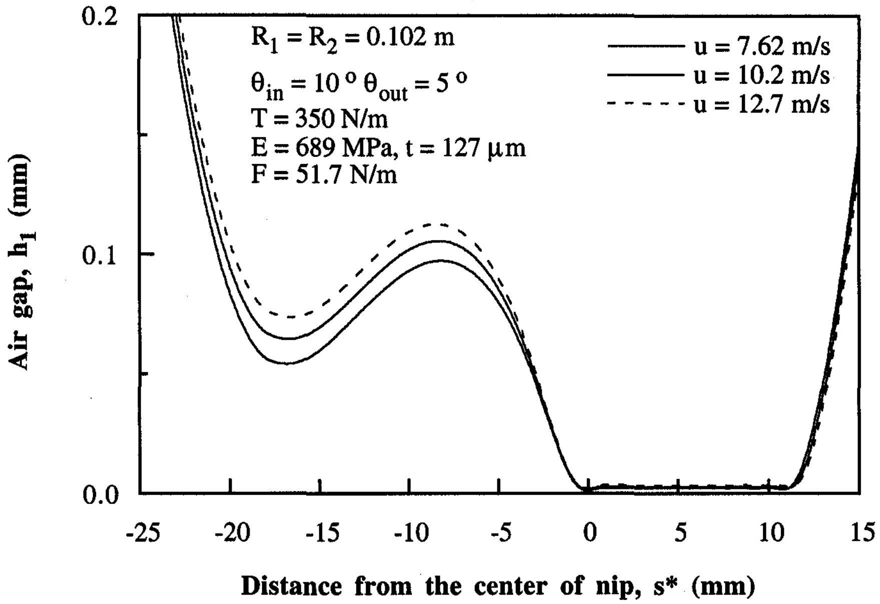

Figure 7. Effects of web speed on ballooning

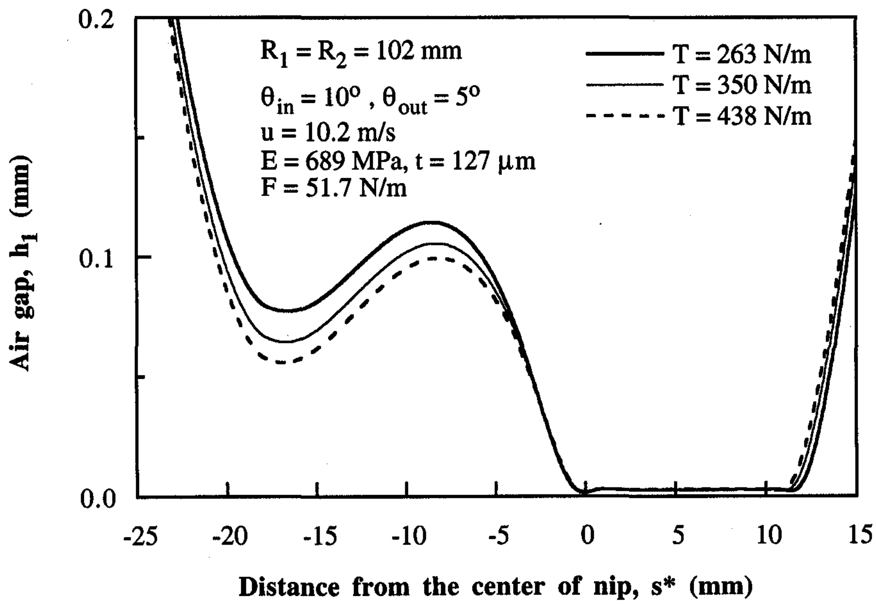

Figure 8. Effects of web tension on ballooning

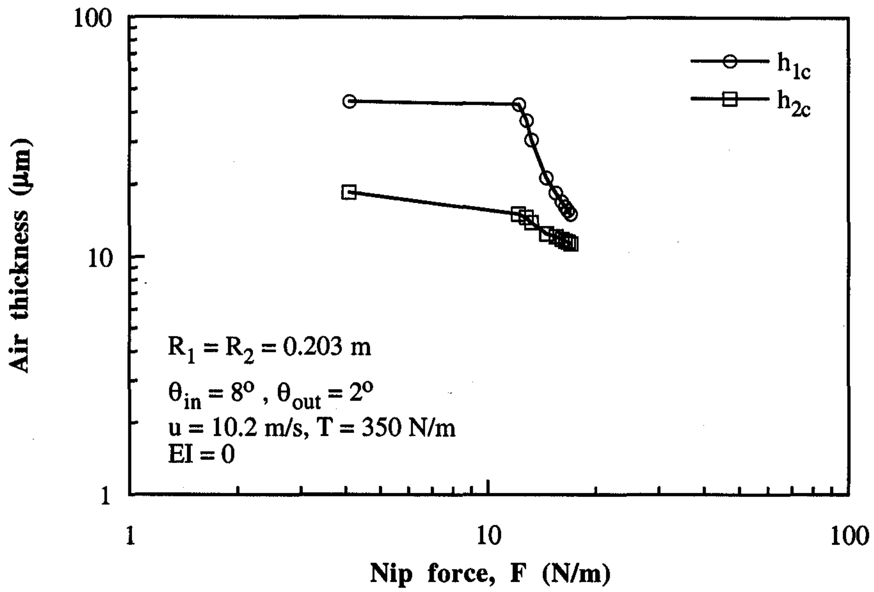

Figure 9. Air entrainment on two sides of web ($\theta_{in} = 8°$, $\theta_{out} = 2°$)

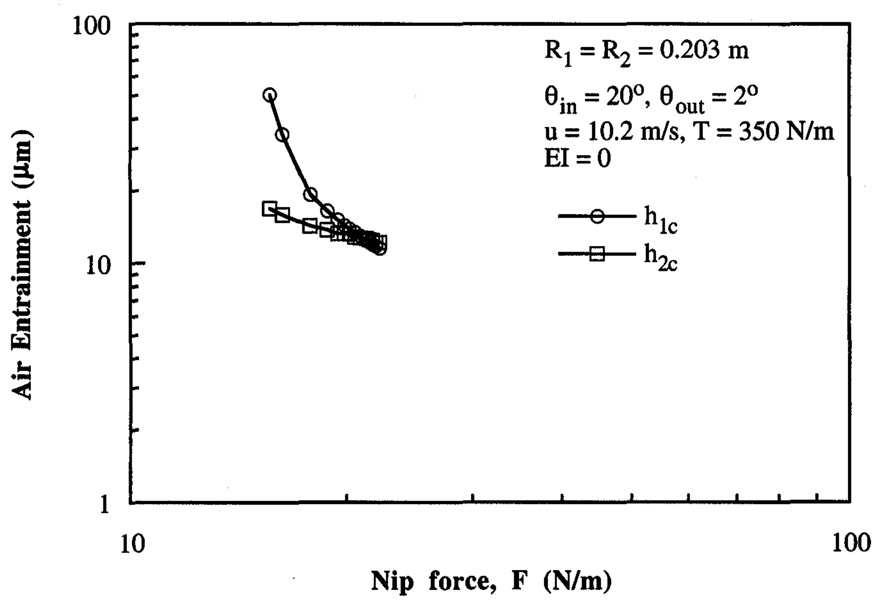

Figure 10. Air entrainment on two sides of web ($\theta_{in} = 20°$, $\theta_{out} = 2°$)

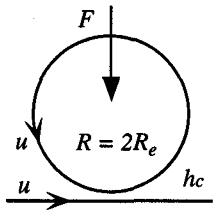

Figure 11. Equivalent model

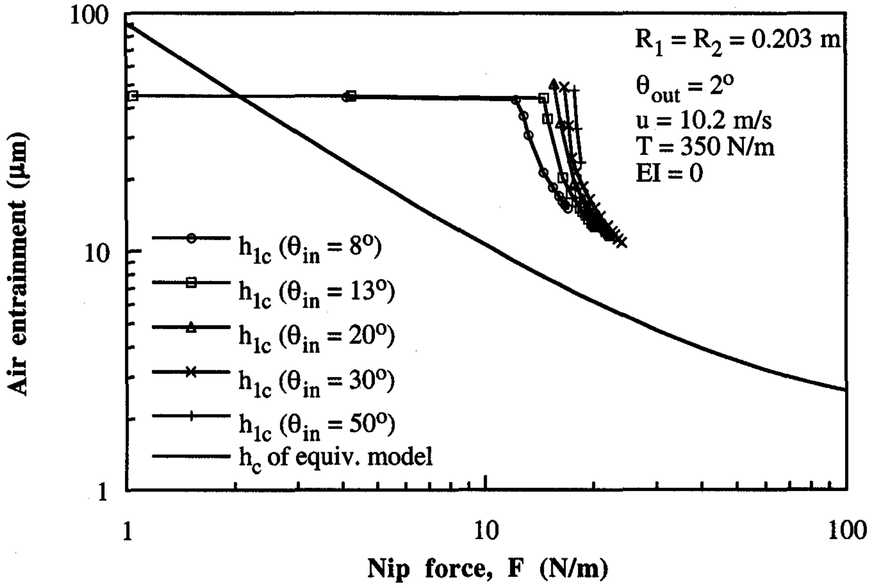

Figure 12. Air entrainment on two sides of web (EI = 0, $R_1 = R_2 = R = 0.203$ m)

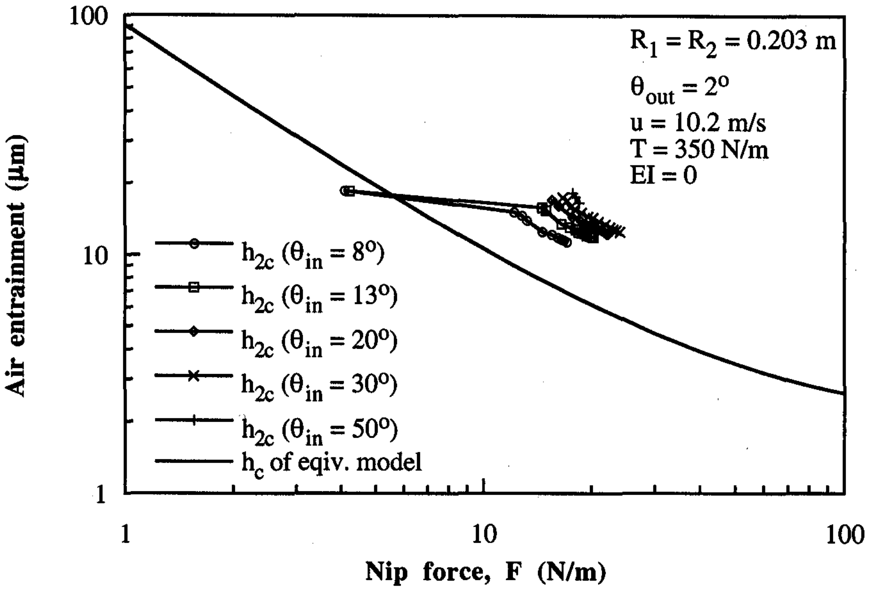

Figure 13. Air entrainment on two sides of web ($EI = 0$, $R_1 = R_2 = R = 0.203$ m)

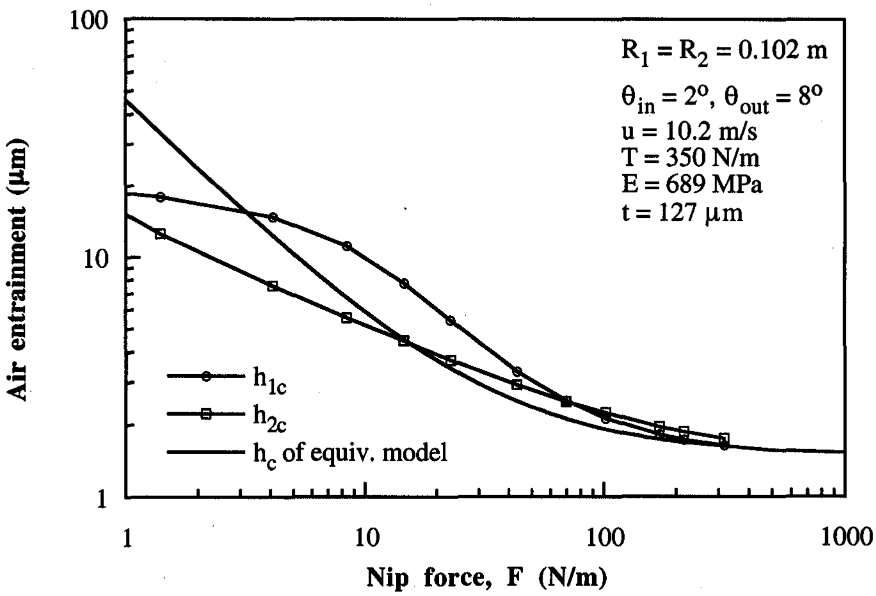

Figure 14. Air entrainment on two sides of web ($R_1 = R_2 = R = 0.102$ m)

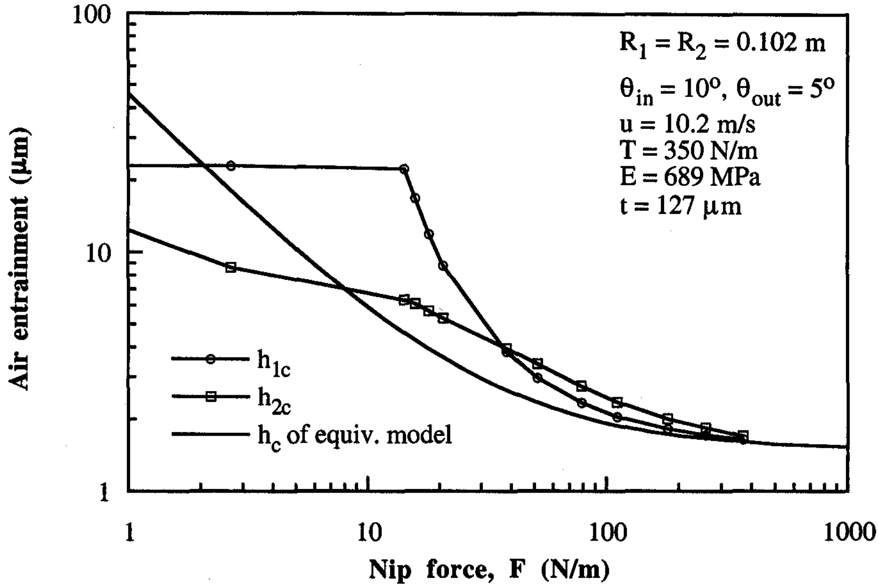

Figure 15. Air entrainment on two sides of web ($R_1 = R_2 = R = 0.102$ m)

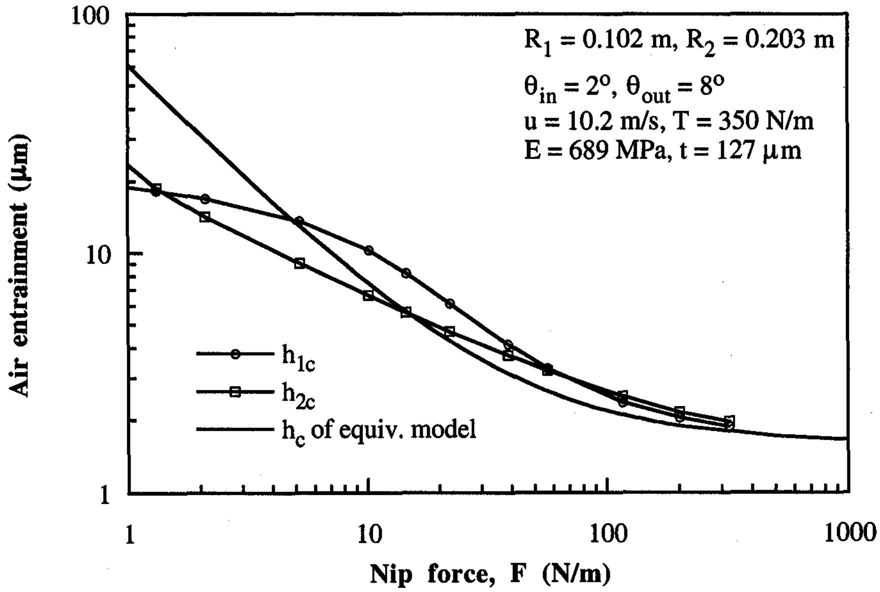

Figure 16. Air entrainment on two sides of web ($R_1 = 0.102$ m, $R_2 = 0.203$ m, R = 0.135 m)

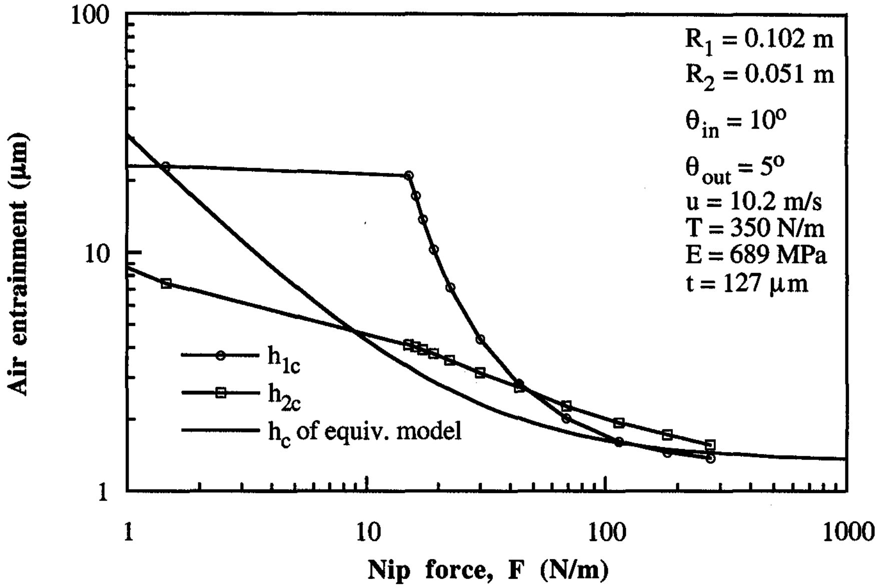

Figure 17. Air entrainment on two sides of web (R_1 = 0.102 m, R_2 = 0.051 m, R = 0.068 m)

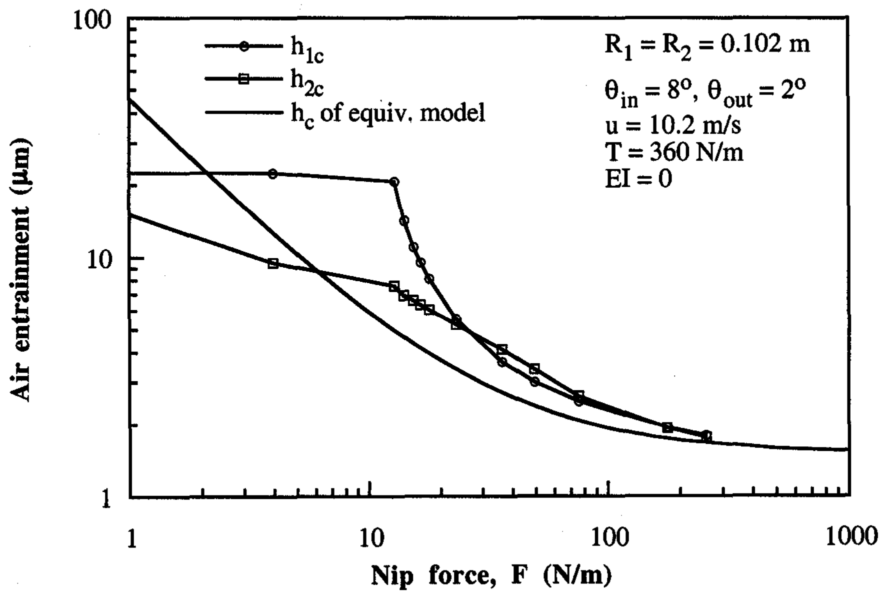

Figure 18. Air entrainment (EI = 0, R_1 = R_2 = R = 0.102 m)

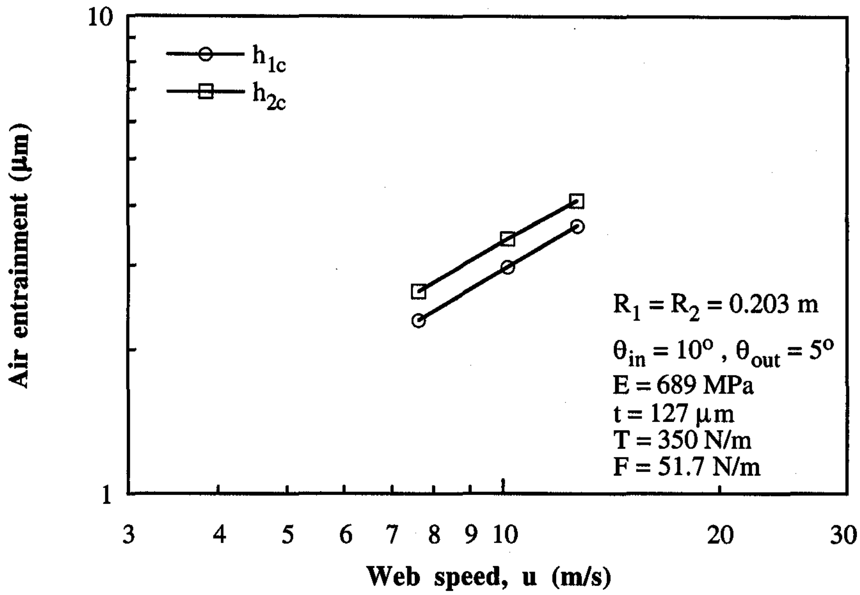

Figure 19. Effect of web speed of air entrainment

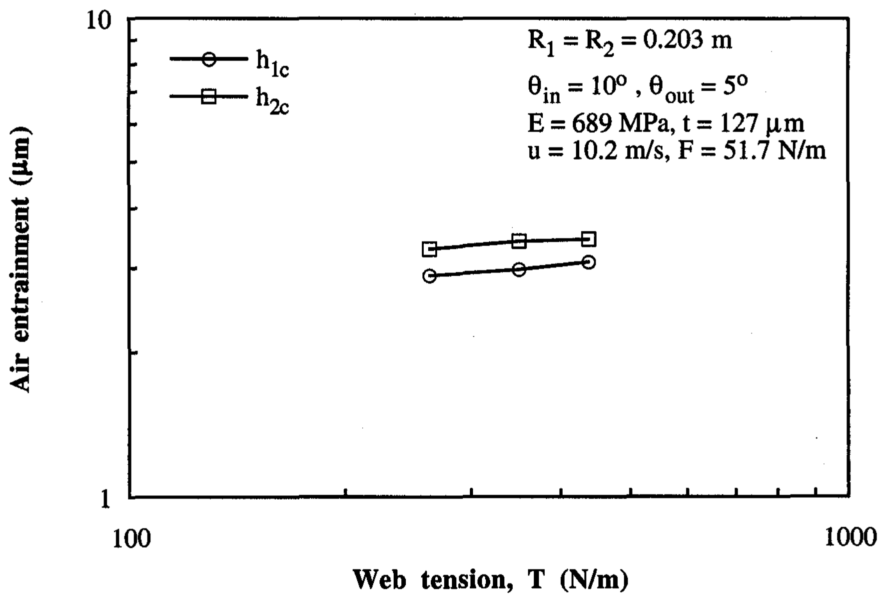

Figure 20. Effect of tension on air entrainment

Table 1. Design and operating conditions

Case #	R_1 (m)	R_2 (m)	T (N/m)	u (m/s)	θ_{in} (deg)	θ_{out} (deg)	E (MPa)	t (μm)	F (N/m)
1	0.203	0.203	350	10.2	**8**	2	0	0	0 - 17.0
2	0.203	0.203	350	10.2	**13**	2	0	0	0 - 20.1
3	0.203	0.203	350	10.2	**20**	2	0	0	0 - 21.4
4	0.203	0.203	350	10.2	**30**	2	0	0	0 - 18.1
5	0.203	0.203	350	10.2	**50**	2	0	0	0 - 18.6
6	0.203	0.203	350	10.2	8	2	689	**25.4**	0 - 18.6
7	0.203	0.203	350	10.2	8	2	689	**50.8**	0 - 18.6
8	0.203	0.203	350	10.2	8	2	689	**127**	0 - 19.1
9	0.102	0.102	350	**7.62**	10	5	689	127	0 - 51.7
10	0.102	0.102	350	**10.2**	10	5	689	127	0 - 51.7
11	0.102	0.102	350	**12.7**	10	5	689	127	0 - 51.7
12	0.102	0.102	**263**	10.2	10	5	689	127	0 - 51.7
13	0.102	0.102	**350**	10.2	10	5	689	127	0 - 51.7
14	0.102	0.102	**438**	10.2	10	5	689	127	0 - 51.7
15	0.102	**0.102**	350	10.2	**2**	**8**	689	127	0 - 317
16	0.102	**0.102**	350	10.2	**10**	**5**	689	127	0 - 370
17	0.102	**0.203**	350	10.2	**2**	**8**	689	127	0 - 323
18	0.102	**0.051**	350	10.2	**10**	**5**	689	127	0 - 273
19	0.102	**0.102**	350	10.2	**8**	**2**	0	0	0 - 255

Air Entrainment on Two Sides of a Web Passing Through the Nip of Two Rigid Rolls

J. Y. Lee, J. J. Shelton, and Y. B. Chang – Oklahoma State University, USA

Name & Affiliation	Question
H. Lei – Eastman Kodak Company	Is it simple to upgrade your model to consider one of the rollers to be a rigid one and the other one to be a soft one?
Name & Affiliation	**Answer**
Y. Chang – OSU	Actually, that work was done some time ago, but we could not get a definite conclusion because of a limited range of calculations. That might be something that we can study in the future.
Name & Affiliation	**Question**
D. Wager – Dupont Teijin Films	The fact that h_{1c} and h_{2c} are approaching the same value, do you think it has something to do with surface topography of the web?
Name & Affiliation	**Answer**
Y. Chang – OSU	That is an interesting subject but I'm not ready to answer that question because this model is based on the assumption that all surfaces are smooth. If one surface is rough and the other surface is smooth, that may affect the conclusion.
Name & Affiliation	**Question**
D. Jones – Emral Ltd.	I was wondering if you had any experimental data to verify the balloon shapes or maybe the critical force at the onset of ballooning?
Name & Affiliation	**Answer**
Y. Chang – OSU	We did not attempt any experimental verification.
Name & Affiliation	**Comment**
J. Shelton – OSU	The study was initiated because of observations of this happening, balloons so large that they were readily measurable. The balloon is not governed by the Knox-Sweeney equation; the web rides at a great height above the roller surface. The computer modeling was done because of observations. We have not, as Dr. Chang said, tried to verify quantitatively the heights. But since the height is so large, verification should be relatively easy if we had a setup to do it. But this ballooning does not happen very often. A rider roller on a winding roll with 180 degrees wrap is a fairly common design, but ballooning may not occur except at high speed. This may be seen with paper webs where the air can't go through the web fast enough to avoid having the balloon. I think this is a new subject in the literature. You may notice that the bibliography had three papers, with the third one being Mr. Lee's thesis and the other two are on different subjects. If you see a balloon but you don't understand the behavior,

	you might realize that it's not the first time that it has ever been seen. But we don't know much about how commonly it is a problem. It would certainly be a problem with heat transfer. If the nip were too far around the drum, it wouldn't be transferring heat well through the air where the balloon is.
Name & Affiliation	**Comment**
H. Lei – Eastman Kodak Company	We did observe a balloon in high speed paper winding and the balloon size was approximately 2 – 3 millimeters and just upstream of the nip.