EVALUATION OF AIR ENTRAINMENT BETWEEN A PAPER WEB AND A ROLLER

Yohachiro Watanabe* and Yasuhiro Sueoka*

Abstract: In offset press or paper machine, a paper web runs on many rollers, and a thin film of air is formed by air entrainment between the roller and the web.
The film of air influences the function of each roller, e.g. heat transfer, etc.
In this research, experiments and theoretical analysis of air entrainment, considering the permeability of paper web, have been conducted. Based on the theory of hydrodynamic lubrication, the air film was calculated numerically, and the results showed good agreement with the experiment.

Introduction

In such paper handling machines as offset presses, paper machines and corrugating machines, paper webs are carried forward via many rollers.
Figure 1 shows a commercial web offset press as an example. In the process line, the moving webs are supported and guided over many rollers, i.e. drag rollers which drive the web, guide rollers and torn bars which change moving direction of web, and cooling cylinders. Thus, when a paper web moves over rollers, air is entrained into the nip region between the web and the roller, presenting a phenomenon that the web floats on a thin film of air around the roller.
The air entrainment provides unfavorable effects on web handing, i.e. decrease of driving force of drag rollers, decrease of heat transfer on cooling cylinders, web slippage on guide rollers, etc. On the other hand, it gives a favorable effect for the turn bar as it prevents stains on printing image. As the moving speed of the web increases, this air entrainment increases. In order to improve the machine performance for high speed operation, the estimation of the air entrainment must be given to evaluate its influences on the function of each roller.

* Mitsubishi heavy Industries, Ltd.

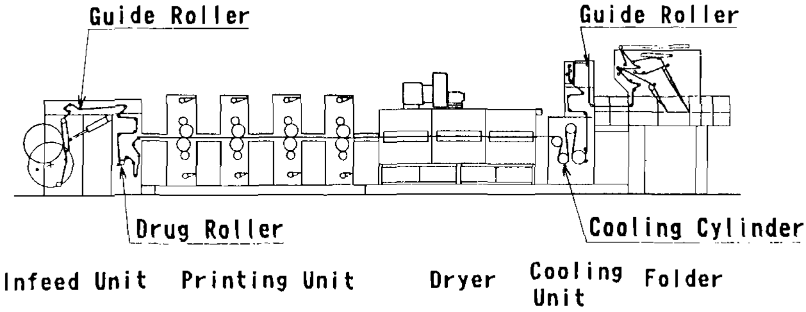


Figure 1. Many kinds of rollers in the commercial web offset press

In the past, this type of subject has been studied as air entrainment phenomena on foil bearing in connection with a magnetic tape storage for VTR, etc. in references [1~3]. However, little study [4] has ever been introduced on air entrainment between a paper web and a roller for offset presses and paper machines. Table 1 shows the features of our study at this time. This article reports on the experiments and theoretical analysis of air entrainment between a paper web and a roller, considering the permeability of a paper web.

Table 1. Feature of this research

Subject	Literature	Tape or Web	
		Impermeable	Permeable
Foil Bearing (Magnetic Tape Head, etc.) U or U; Roller Fixed, Tape Fixed	(1) ~ (3)	Theroretical Analysis & Experiment	—
Offset Press, Paper Machine, Corrugating Machine	(4)	Theoretical Analysis	—
U, U; Web moves and Roller rotates	This Research	Theoretical Analysis & Experiment	Theoretical Analysis & Experiment

Experiments

Prior to experiments and theoretical analysis, coordinates on the roller and designation of each part are defined as shown in Figure 2. The X-axis is taken along a stationary web with no air entrainment (A→ B → C → D → E in Figure 2) and the Y-axis is taken to the normal direction of the X-axis. The point "B" where the X-axis first touches a roller is called the "lapping start point" and the point "D" where the X-axis finally leave from the roller is called the "lapping end point". The lapping angle (θ) is taken downstream from the lapping start point. Upstream the lapping start point is referred to as the "entrance region", the region between the lapping start point and lapping end point as the "intermediate region" and downstream the lapping end point as the "exit region".

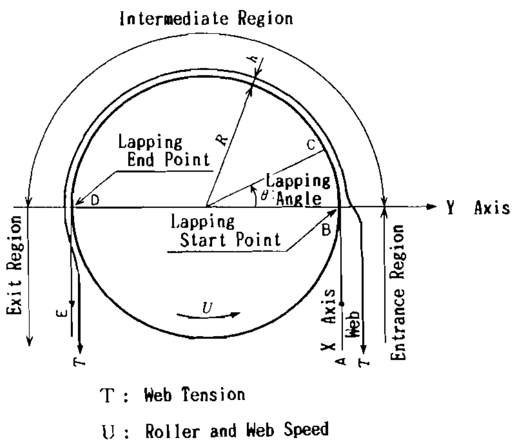


Figure 2. Web profile and coordinate around a roller

Test method: A view of the test apparatus is shown in Figure 3. The diameter of a roller which is a measuring object is 350 mm and the lapping angle of a paper web (angle between lapping start point and lapping end point) is 180° The web from the feeding reel is wound on the winding reel via measuring roller, guide roller, and reel drum. The winder reel is pressed on the reel drum and the web moves at the peripheral speed of reel drum. The measuring roller is driven together with the reel drum and is set to rotate at the same speed as the web speed. The web tension is adjusted by braking the feeding reel.

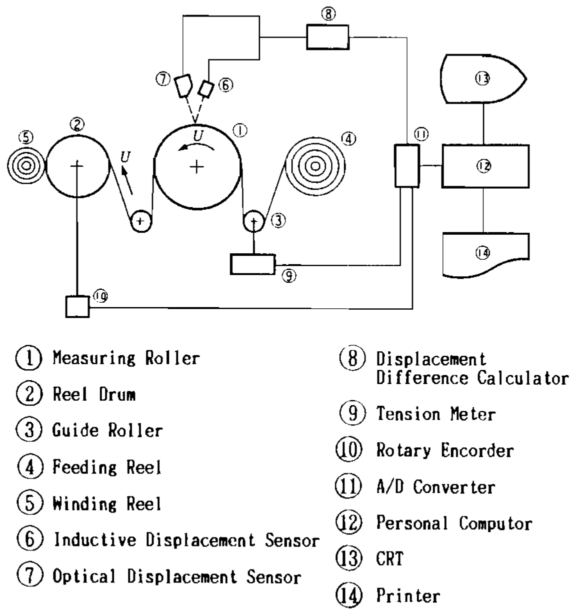


Figure 3. Test apparatus

Measurements were conducted on the air film thickness, speed and tension of the web. For measurement of the air film thickness, the web displacement was measured with an optical displacement sensor and the roller displacement with an inductive displacement sensor, then obtained it from a difference between the two values. This eliminated an error caused by the eccentricity of the roller, resulting in accurate measurement of air film thickness.
The moving speed of the web was obtained from the revolution output of encoder installed on the reel drum. While, the web tension was measured with a tension meter mounted on the guide roller which is located upstream the measuring roller. The signal from each measuring apparatus was entered into a personal computor via an A/D converter for average processing. The experiment was conducted in the conditions shown in Table 2 on two kinds of impermeable web and two kinds of permeable web.

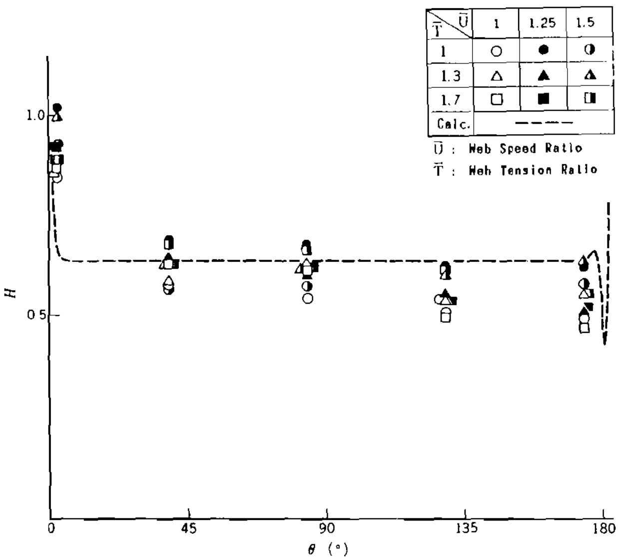
Table 2. Test condition

Web	Mass per Unit Area (g/m²)	Width (mm)	Speed (m/min)	Tension (N/m)
Impermeable (a)	76	380	400 ~ 600	300 ~ 500
Impermeable (b)	60.4	340	〃	200 ~ 400
Permeable (a)	51.6	407	〃	130 ~ 200
Permeable (b)	54.3	380	〃	100 ~ 230

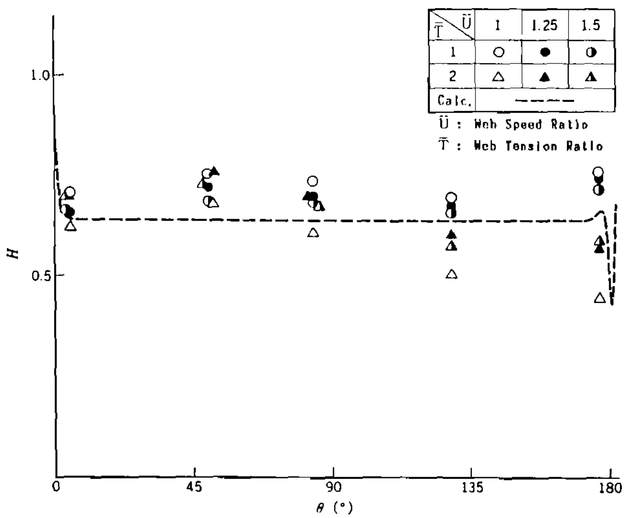
Test results: The variation of the air film thickness in the circumferential direction of the roller is shown in Figures 4 and 5. Here the air film thickness, in consideration of the theoretical analysis, was expressed by non-dimensional value defined in the following equation:

$$H = \left[\frac{h}{R} \right] \left[\frac{12\mu U}{T} \right]^{-2/3} \quad \cdots\cdots\cdots\cdots (1)$$

where; H: non-dimensional value of air film thickness
h: air film thickness
R: radius of roller
μ : viscosity of air
U: peripheral speed of roller
T: effective web tension = To - σU^2
To: web tension
σ : mass per unit area of web

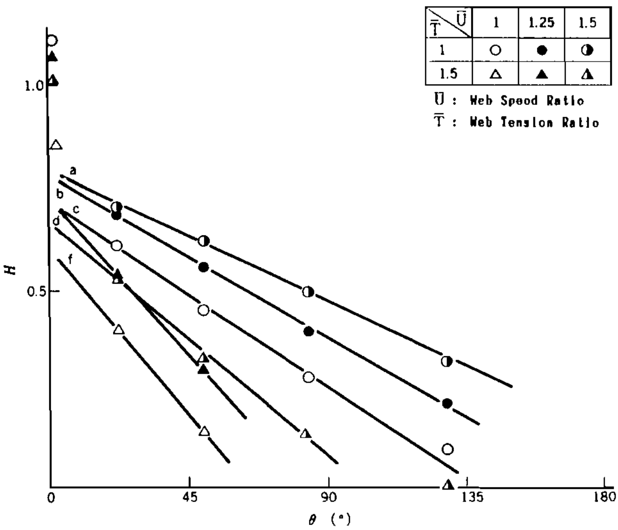


(a) impermeable web (A)

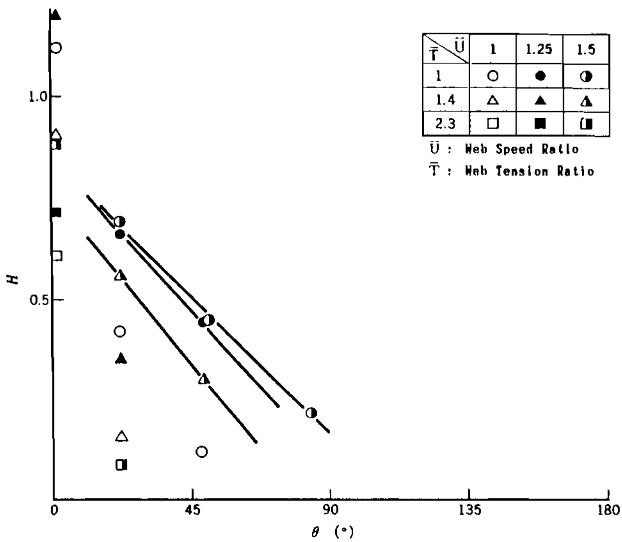


(b) impermeable web (B)

Figure 4. Change of the air film along a roller



(a) permeable web (A)



(b) permeable web (B)

Figure 5. Change of the air film along a roller

In case of an impermeable web, it can be seen from (a) & (b) in Figure 4 that H is great at the lapping start point but decreases drastically and converges to a constant value nearly at $\theta = 4^\circ$. After that point, it seems that H becomes constant or rather a slight decrease. This decreasing tendency is considered to be caused by air leak from the web edge toward the axial direction of the roller.

The test results of permeable webs are shown (a) & (b) in Figure 5. Immediately after the lapping start point, air film thickness is almost the same as the value of the impermeable web. However, with the increase of θ , it is seen that air film thickness decreases linearly. It is also seen that the decrease gradient varies by web speed and tension in accordance with the permeability of the web.

Theoretical Analysis

The equation for impermeable web is derived according to the reference [4], and to which the permeability coefficient of paper is introduced for analysis of permeable web. Assuming an infinitely wide and perfectly flexible web, for the small Reynolds number, the force balance between the shear stress and pressure is expressed as the following equation:

$$\frac{dp}{dx} = \frac{d\tau}{dy} = \mu \frac{d^2u}{dy^2} \quad \cdots\cdots (2)$$

where; p : pressure between a roller and a web
τ : shear stress
μ : viscosity of air
U : flow velocity between a roller and a web

Assuming that the roller and the web are at the same speed, if the above equation is integrated under the boundary condition of u = U using y = 0 and h, it is expressed as;

$$u = U - \frac{dp}{dx} \frac{y}{2\mu} (h - y) \quad \cdots\cdots (3)$$

The flow per unit width is given as below from the equation (3).

$$Q = \int_0^h u dy = Uh - \frac{h^3}{12\mu}\frac{dp}{dx}$$

When this is differentiated by x, it follows

$$\frac{dQ}{dx} = U\frac{dh}{dx} - \frac{d}{dx}\left[\frac{h^3}{12\mu}\frac{dp}{dx}\right] \cdots\cdots\cdots\cdots (4)$$

From the balance in normal direction of force acting on the micro area of the web per unit width, the pressure p between the roller and the web is given by the following equation:

$$p - pa = P = T/r \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where; pa= atmospheric pressure
P = gauge pressure between the roller and the web
r = radius of web curvature

The web curvature is as follows when $h \ll R$ (R: radius of roller).

$$\frac{1}{r} = \begin{cases} -\dfrac{d^2y}{dx^2} & (\theta < 0) \\ \dfrac{1}{R} - \dfrac{d^2y}{dx^2} & (\theta \geqq 0) \end{cases} \cdots\cdots\cdots (6)$$

Substitution of equation (6) into equation (5) yields;

$$P = \begin{cases} T\left[-\dfrac{d^2y}{dx^2}\right] & (\theta < 0) \\ T\left[\dfrac{1}{R} - \dfrac{d^2y}{dx^2}\right] & (\theta \geqq 0) \end{cases} \cdots\cdots\cdots (7)$$

When θ is smaller,

$$h \fallingdotseq \begin{cases} y + \dfrac{x^2}{2R} & (\theta < 0) \\ y & (\theta \geqq 0) \end{cases} \quad \cdots\cdots\cdots (8)$$

These are the basic equations to be used for analysis.

(1) Analysis for impermeable web
In case of impermeable web, since assuming an infinitely wide web, from the condition of continuity, it is expressed as follows

$$\frac{dQ}{dx} = 0$$

Substituting this into equation (4) yields;

$$U \frac{dh}{dx} - \frac{d}{dx} \left[\frac{h^3}{12\mu} \frac{dP}{dx} \right] = 0 \quad \cdots\cdots\cdots (9)$$

If this is rearranged by substituting equations (7) and (8) into equation (9),

(i) $\theta < 0$

$$\left[\frac{dh}{dx} + \frac{x}{R} \right] + \frac{T}{12\mu U} \frac{d}{dx} \left\{ \left[y + \frac{x^2}{2R} \right]^3 \frac{d^3y}{dx^3} \right\} = 0$$

(ii) $\theta \geqq 0$

$$\frac{dy}{dx} + \frac{T}{12\mu U} \frac{d}{dx} \left[y^3 \frac{d^3y}{dx^3} \right] = 0 \quad (10)$$

To simplify the equation, the coordinates x,y are non-demensionized in the following equations.

$$\left.\begin{aligned} Y &= (y / R)\ (12\mu U / T)^{-2/3} \\ X &= (x / R)\ (12\mu U / T)^{-1/3} \end{aligned}\right\} \cdots\cdots\cdots\cdots \quad (11)$$

Substitution of equation (11) into equation (10) yields;

(i) $\theta < 0$

$$\left[\frac{dY}{dX} + X \right] + \frac{d}{dX} \left\{ \left[Y + \frac{X^2}{2} \right]^3 \frac{d^3Y}{dX^3} \right\} = 0$$

(ii) $\theta \geqq 0$ (12)

$$\frac{dY}{dX} + \frac{d}{dX} \left[Y^3 \frac{d^3Y}{dX^3} \right] = 0$$

In accordance with the reference [4], the boundary conditions were assumed that dY/dX = 0, P = 0 at upstream point sufficiently distant from the lapping start point and dY/dX = 0, P = T/R at downstream point sufficiently distant from the lapping start point. Based on the above conditions, equation (12) was solved numerically using the Runge-Kutta-Gill method.

(2) Analysis for permeable web

The flow balance at the area from x to x + dx between a roller and a web in Figure 6 is dirived.

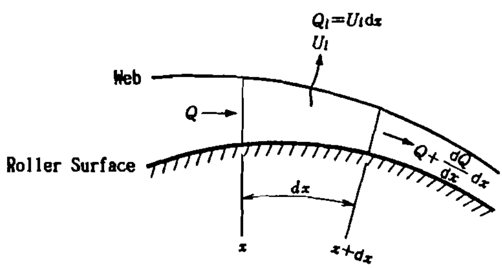


Figure 6. Flow balance in the passage between a roller and a web

In case of a permeable web, assuming an infinitely wide web, air leak occures only through the fiber layer of the web. Thus, the flow balance will be follows provided the air leak velocity through the web is $U\ell$.

$$\left[Q + \frac{dQ}{dx} dx \right] - Q = - U\ell \ dx$$

$$\therefore \frac{dQ}{dx} = - U\ell \quad \cdots\cdots\cdots\cdots\cdots\cdots (13)$$

Since the air flow in the fiber layer is regarded as laminar flow, the air leak velocity is considered to be proportional to the pressure at that point. [5] Namely, according to the reference [5], it is expressed as;

$$U\ell = \frac{kP}{L \mu} = KP \quad \cdots\cdots\cdots\cdots\cdots\cdots (14)$$

where; k : permeability coefficient
L : thickness of paper
μ : viscosity of air
$K = k / L \mu$

From equations (4), (13) and (14), an equation for a permeable web was derived for a similar analysis as in the case of an impermeable web. Considering that the boundary condition agrees with impermeable web configuration at upstream point sufficiently distant from the lapping start point, the differential coefficient up to a third differentiation of Y at upstream point sufficiently distant from the lapping start point obtained for an impermeable web as the boundary condition for a permeable web.

(3) Analysis result
Figure 7 shows the analysis result of a impermeable web. At entrance region, the value Y begins to very nealy at θ = -4° away from the lapping start point, and converges to a constant value nearly at θ = +4° . Thus, it can be seen that air film thickness varies in a very narrow range. It is also seen that pressure increases according to the variation of air film thickness and converges to the pressure P = T/R to be determined by the roller diameter and the web tension. At exit region, the value Y is an exponentially damped sine wave. Pressure varies according to the variation of Y and

negative pressure is produced immediately after the lapping end point. Such a phenomenon is seen in the analysis and experiment for foil bearing in references [(1) ~ (4)].

In the next place, the analysis result of a permeable web is shown in Figure 8. In this analysis, the value obtained as the permeability coefficient in a static pressure test for newsprint paper was used. The variation of Y and P before and after the lapping start point almost agreed with the analysis result of an impermeable web. The value P immediately after the lapping start point converges to constant value and Y decreases linearly. This tendency almost agrees with the prescribed test result.

Y almost agrees at the angle ($\theta \fallingdotseq 4^\circ$)where P becomes constant on both impermeable and permeable webs, and yields;

$$(ho\ /\ R) = 0.64\ (12\mu U/T)^{2/3} \quad \cdots\cdots\cdots\cdots \quad (17)$$

Therefore, assuming the value at $\theta = 4^\circ$,the test result is to be compared with equation (17).

An estimated result is shown in Figure 9 by linearly extrapolating the value at $\theta = 4^\circ$ based on the data downstream 4° as shown with a,b,c · · · in Figure 5(a). From Figure 9, the test result almost agreed with equation (17) obtained in the analysis and proved that analysis was reasonable.

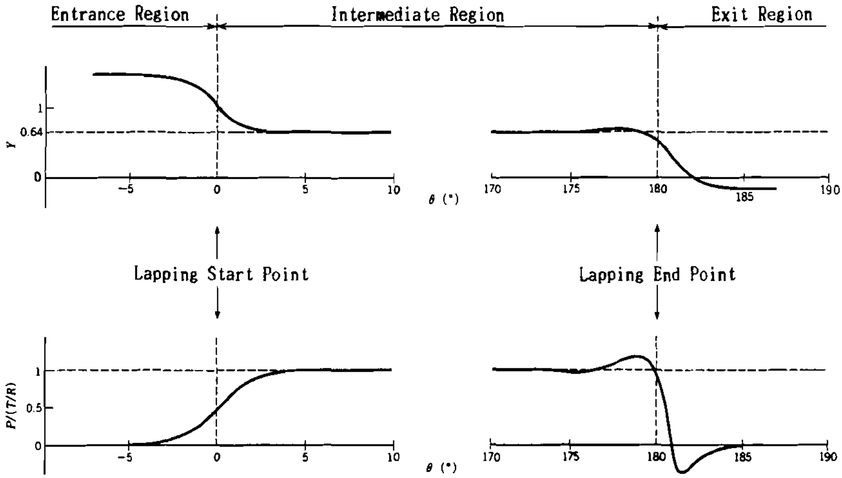


Figure 7. Numerical analysis of impermeable web

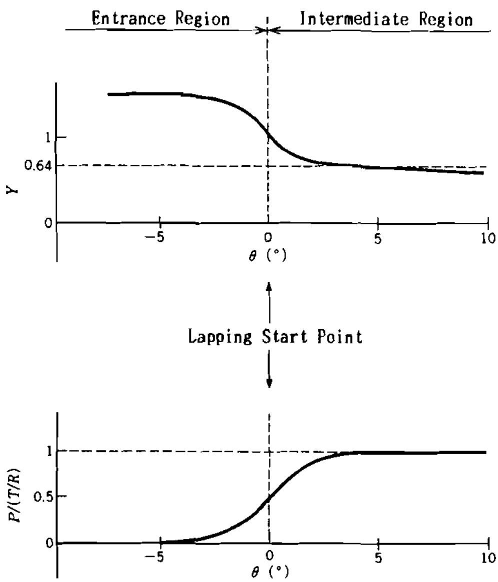


Figure 8. Numerical analysis of permeable web

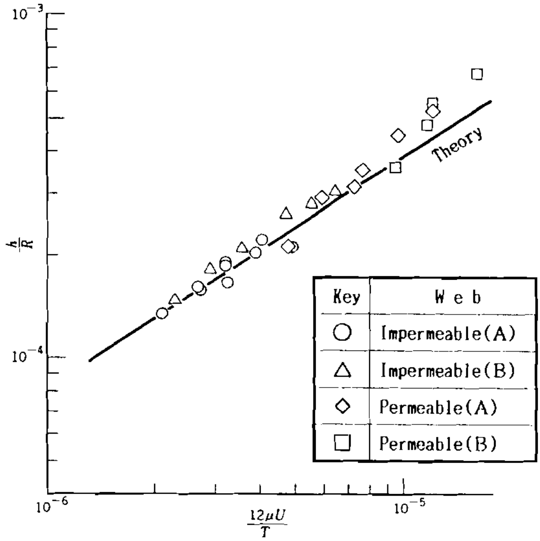


Figure 9. Relationship between the parameter (12μ U/T) and the air film

Conclusion

The characteristic of air entrainment between a roller and a web for printing machinery etc. was studied by experiments with theoretical analysis added.
The results are as follows,

(1) Air entrainment between a roller and a web was measured using an equipment in which the roller and the web move at the same speeds. The air film thickness is almost constant over the roller for impermeable web, but it decreases linearly with the increase of lapping angle for permeable web.

(2) For impermeable web, the analysis according to the method represented by Riddiford [4] showed good agreement with the test result.

(3) For permeable web, using an analysis method with the permeability coefficient applied, the analysis showed good agreement with the test result.

(4) On both impermeable & permeable webs, air entrainment immediately after the lapping start point is almost equal and expressed by the following equation;

$$ho / R = 0.64 \left[\frac{12 \mu U}{T} \right]^{2/3}$$

There is a fair prospect of theoretical estimation of air entrainment for both permeable & impermeable webs as mentioned above. In the future, we are going to step forward to practical research and studies, i.e. estimation of heat transfer and friction coefficient, and development of a preventive method of air entrainment based on the result of this research.

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